

Impact of climate change on the contribution of second order tributaries to the water balance of the Ferghana Valley



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1 Synopsis

1.1 Introduction

The climate change is a key issue for many branches of human livelihood, e.g. water, agriculture, economy, environment. The climate change is associated with temperature rise due to anthropogenic activity that leads to an increase of concentration of greenhouse gases (carbon dioxide, methane, nitrous oxide). The global warming will continue to accelerate in the future if the concentration of greenhouse gas emissions will not be reduced in the atmosphere (Collins et al. 2013). According to Stocker (2014), the period from 1982 to 2012 was the warmest 30-year period in the Northern Hemisphere. The air temperature has already increased by 2.4 °C in November–March during 1901–2009 in semi-arid region of Asia (Christensen et al. 2013). Likewise, the amount of precipitation increased significantly during 1900–2005 in Central Asia (Solomon 2007). In addition, Itibaev et.al. (2015) reported that the analysis of linear trend coefficients of air temperature anomalies for the period 1976–2014 shows an increase in annual temperature for Kyrgyzstan by 0.18 °C / 10 years, and even higher increase in spring temperature by 0.42 °C / 10 years and autumn – by 0.24 °C / 10 years. An increase in annual amount of precipitation for Kyrgyzstan for the period 1976–2014 is 2.9% / 10 years, the highest increase in precipitation appears in summer (7.0%), then in winter (5.2%), and insignificant increase in autumn (1.9%), while the analysis shows a decrease in spring precipitation by 1.6% (Itibaev et al. 2015). Further, the annual mean surface air temperature in Kyrgyzstan is projected to be increased by 0.6–4.4°C under different RCPs (Representative Concentration Pathways) scenarios by 2100 relative to 1986–2005, and the annual precipitation projections show an increase by 10–20% (Barros et al. 2014).

The indicators of global warming appear glaciers that are very sensitive to climatic changes (Aizen et al. 2007; Yao 2002). An increase in the air temperature leads to glacier retreat that plays crucial role for water needs in the arid regions such as Central Asia. Kyrgyzstan is situated on the north-eastern part of Central Asia. The topography of Kyrgyzstan is very complex due to its location at the Tien-Shan and Pamiro-Alai mountain systems (Figure 1-1), and more than 50% of the area of the country lies above 3000 m a.s.l. Kyrgyzstan is located in the centre of Eurasia, and therefore, the remoteness of Kyrgyzstan from the oceans and its closeness to deserts (Kyzyl-Kum, Muyun-Kum, Takla-Macan) condition semi-arid and arid

continental climate (Ryazantseva, 1965). However, the Pamiro-Alai and Tien-Shan mountain systems store water in the form of glaciers, perennial snow and snowpack. The glaciers and snowpack are key sources for freshwater generation. The water is extensively used for agricultural irrigation and the production of electrical power.



Figure 1-1 Geographical location of Kyrgyzstan.

The glacier recession has been accelerated since 1970s in the Tien Shan (Aizen et al. 2007). Accordingly, glacier shrinkage was detected in the Northern Tien Shan by 28% during 1963–2000 (Niederer et al. 2008), by 29% in the Western Tien Shan during 1955–1990 (Vilesov and Uvarov 2001), and by 23% in the Central Tien Shan during 1977–2001 (Khromova et al. 2003). On the other hand, (Aizen et al. 2007) calculated a slighter reduction (14.2%) of the Tien Shan's glaciers during 1943–2003, as well as Narama et al. (2010) found it in the range of 9 to 19% for the period 1970–2000. Further, the glaciers in Central Asia are projected to be reduced by 25–90% from 2006 to 2100 under CMIP5 (14 GCMs) single model simulations, and mean reduction derived from 14 GCMs is 55% for RCP4.5 and 75% for RCP8.5 (Field et al. 2014; Radić et al. 2014). Sorg et al. (2012) suggest further decrease in glacier area in the Tien Shan despite an increase in future precipitation. Therefore, the global warming accelerates the glacier melt and most likely will lead to the runoff reduction in the future. Thus, the runoff from the main water artery of the lowlands in Kyrgyzstan and Uzbekistan – Syrdarya River is projected to decrease by 10-25% to 2100 (Nohara et al. 2006; Sehring and

Diebold 2012). Nevertheless, Immerzeel and Bierkens (2012) reported that the water balance of the Syrdarya River is at an average level of risk mainly because of uncertainty in future precipitation.

The Syrdarya River is originated at the confluence of the Naryn and Karadarya Rivers that are mainly fed by glacier and snow melt from the mountainous system of the Tien Shan (Figure 1-1, Figure 1-4). In addition, small upper rivers (Figure 1-4) that are mainly fed by precipitation contribute to the Syrdarya River. Due to temperature increase and glacier melt acceleration (Aizen et al. 2007), the runoff will most likely increase in short term and decrease in long term. Therefore, it is of important interest to study the potential impact of climate change on the runoff of the small upper catchments (n=18) that could have greater value in the future due to its topographic openness to the moist air from the west and adiabatic cooling effect that is associated with orographic precipitation (Price 1986). Figure 1-2 shows the distribution of annual amount of precipitation in Kyrgyzstan. Thus, one of the wettest place (about 1100 mm) is the meridionally oriented ridge in the south-western part of Kyrgyzstan, which surrounds the Ferghana Valley in the lowland. On the contrary, there is low amount of precipitation (300–400 mm) in the central and south-eastern part of Kyrgyzstan, where the Naryn River originates (Unger-Shayesteh et al. 2013).

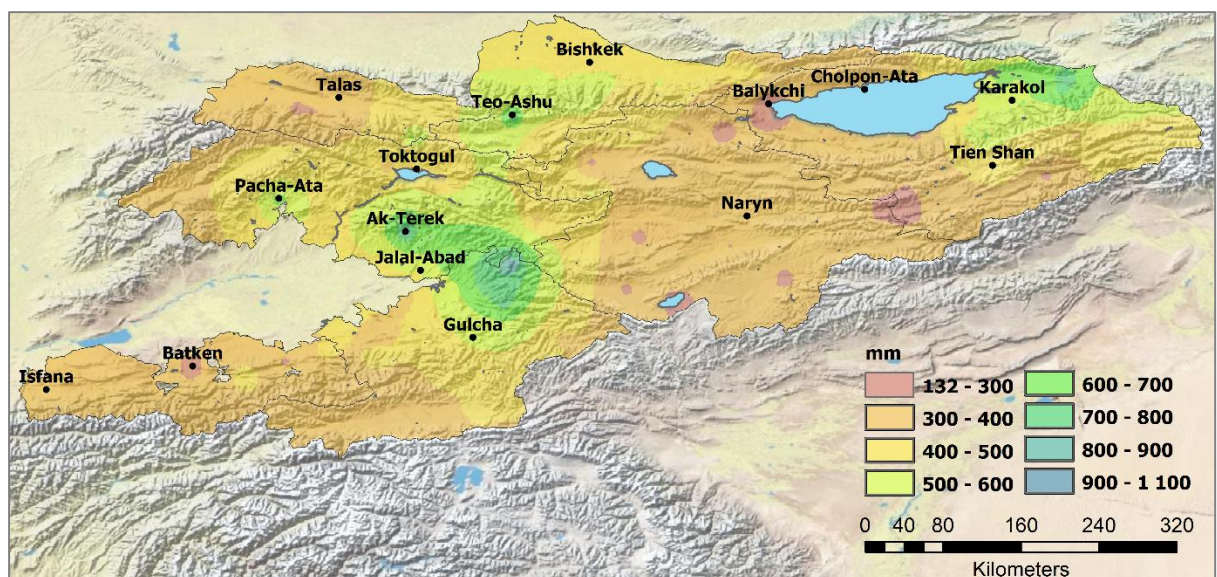


Figure 1-2 Distribution of annual amount of precipitation in Kyrgyzstan for the period 1961-1990 (data from Kyrgyzhydromet).

Any future prediction of water resource availability is depended on a thorough understanding of the hydrological cycle under current conditions and a robust hydrological modelling approach that allows to project into the future. Consequently, it is of great interest to investigate runoff and the water balance to improve our understanding of the past, present and future water resource generation in the Ferghana Valley.

1.2 General objectives

The main objectives of this dissertation are (i) to estimate the relative contribution of the small upper catchments and the two large Naryn and Karadarya rivers to the Ferghana Valley water balance under current climatic conditions and (ii) to assess the potential impact of the climate change on the discharge contribution of small catchments.

1.3 Study area and available data

The presented dissertation was carried out in the frame of the CiNCA (Climate Change Network for Central Asia) project in the 18 small upper river catchments of the Ferghana Valley (Kyrgyzstan) that inflow into the Syrdarya River Basin (Figure 1-4). The investigated catchments are situated in the Tien-Shan and Pamiro-Alai mountain systems (Figure 1-1), which store freshwater sources in the form of glaciers and snow for the formation of mountain rivers. The upper river catchments in the Ferghana Valley in the valley-piedmont zone (500–1200 m) are characterized by hot summers and warm winters, in the mid-mountain zone (900–2200 m) – by warm summers and moderate–cool winters, and in the high-mountain zone (2000–3500 m) the river catchments are characterized by cool summer and cold winter (Itibaev et al. 2015). The average annual temperature for the mean elevations (centroids) of the 18 river catchments varies from -1.3 to 8.8°C, and average annual precipitation for the centroids range between 525 and 971 mm (Table 1-1). The mean elevation of the 18 investigated catchments varies from 1703 to 3,421 m a.s.l. and the area of the catchments ranges from 126 to 2,480 km² (Table 1-1). The discharge of the studied river catchments varies from 148 to 638 mm year⁻¹ (Table 1-1).

Table 1-1 Geographical and hydro-meteorological characteristics of the 18 studied catchments [from *Radchenko et al.*, 2016].

Catchment		Area	Altitude	Mean elevation	Discharge	Precipitation	Temperature	Forest	Cropland/ Grassland	Sparsely vegetated/ Bare land	Glaciers
		[km ²]	[m]	[m]	[mm]	[mm]	[°C]	[%]	[%]	[%]	[% (km ²)]
1	Gavasay	361	1,716	2,803	364	908	0.7	–	92	8	–
2	Kassansay	1,130	1,350	2,535	166	897	2.3	1	95	4	–
3	Padshaata	366	1,536	2,685	400	971	1.8	1	88	8	3 (11)
4	Aflatun	863	2,000	1,965	392	808	6.0	7	91	1	1 (9)
5	Maylisuu	530	985	2,459	482	845	5.8	10	87	1	2 (11)
6	Shidansay	126	1,016	1,946	433	714	8.8	8	92	–	–
7	Tentyaksay	1,300	1,023	2,217	638	802	7.2	17	81	1	1 (13)
8	Kugart	1,010	1,168	2,418	536	797	3.2	21	79	–	–
9	Changet	381	813	1,703	162	604	6.5	41	59	–	–
10	Kurshab	2,010	1,543	3,093	276	689	–1.3	14	58	24	4 (80)
11	Akbura	2,260	1,327	3,186	275	718	–1.3	3	52	37	8 (181)
12	Abshirsay	230	1,500	2,654	205	609	2.8	15	68	17	–
13	Isfirmsay	2,220	1,017	3,248	262	703	–0.8	–	53	38	9 (200)
14	Shakimardan	1,180	1,065	2,761	251	596	1.9	–	65	32	3 (35)
15	Sokh	2,480	1,140	3,421	557	699	–1.0	–	41	48	11 (273)
16	Isfara	1,560	1,283	3,158	269	647	0.3	–	11	82	7 (109)
17	Khodjabakirgan	1,740	1,730	2,392	179	525	3.9	2	79	16	3 (52)
18	Aksu	712	1,100	2,816	148	751	1.6	–	10	88	2 (14)

The main water artery of the Ferghana Valley is the Syrdarya River with a total discharge of about 38–39 km³ year⁻¹ flowing into the Aral Sea basin (Dukhovny and de Schutter 2011; Savoskul et al. 2003; Belyaev 1995). The most part of the discharge of the Syrdarya River basin (70–74%) forms in Kyrgyzstan mountain ranges (Dukhovny and de Schutter 2011; Belyaev 1995). According to the State Water Cadastre and Global Runoff Data Centre database (1980–1985), the studied 18 catchments in comparison with the Naryn and Karadarya rivers contribute about 35% (≈ 7 km³ year⁻¹) to the Syrdarya River within the Ferghana Valley (Table 1-2).

Table 1-2 The total and seasonal contribution of discharge of the 18 studied river catchments versus the Naryn and Karadarya rivers to the Ferghana Valley for the period 1980–1985.

Discharge	18 studied catchments		Naryn and Karadarya	
	km ³	%	km ³	%
winter	0.7	3.5	1.8	9.2
spring	1.8	9.3	3.5	17.8
summer	3.1	16.2	5.9	30.3
autumn	1.1	5.8	1.6	8.0
Sum, km ³ year ⁻¹	6.8	34.7	12.7	65.3

The total contribution of discharge of the 18 small upper river catchments in comparison with two big Naryn and Karadarya rivers to the water balance of the Ferghana Valley on monthly time scale for the period 1980–1985 is represented in Figure 1-3. The water flow rise for the 18 catchments is observed from May to July, as well as for the Naryn and Karadarya rivers. The seasonal distribution of the discharge of the 18 river catchments to the Ferghana Valley varies from 0.7 km³ in winter to 3.1 km³ in summer, and the discharge of the Naryn and Karadarya basins varies from 1.8 km³ in winter to 5.9 km³ in summer (Table 1-2). The contribution of the 18 river catchments to the water balance of the Ferghana Valley in comparison with the two big Naryn and Karadarya rivers in percentage varies from 3.5 (winter) to 16.2 (summer), and in spring the contribution is 9.3 % (Table 1-2).

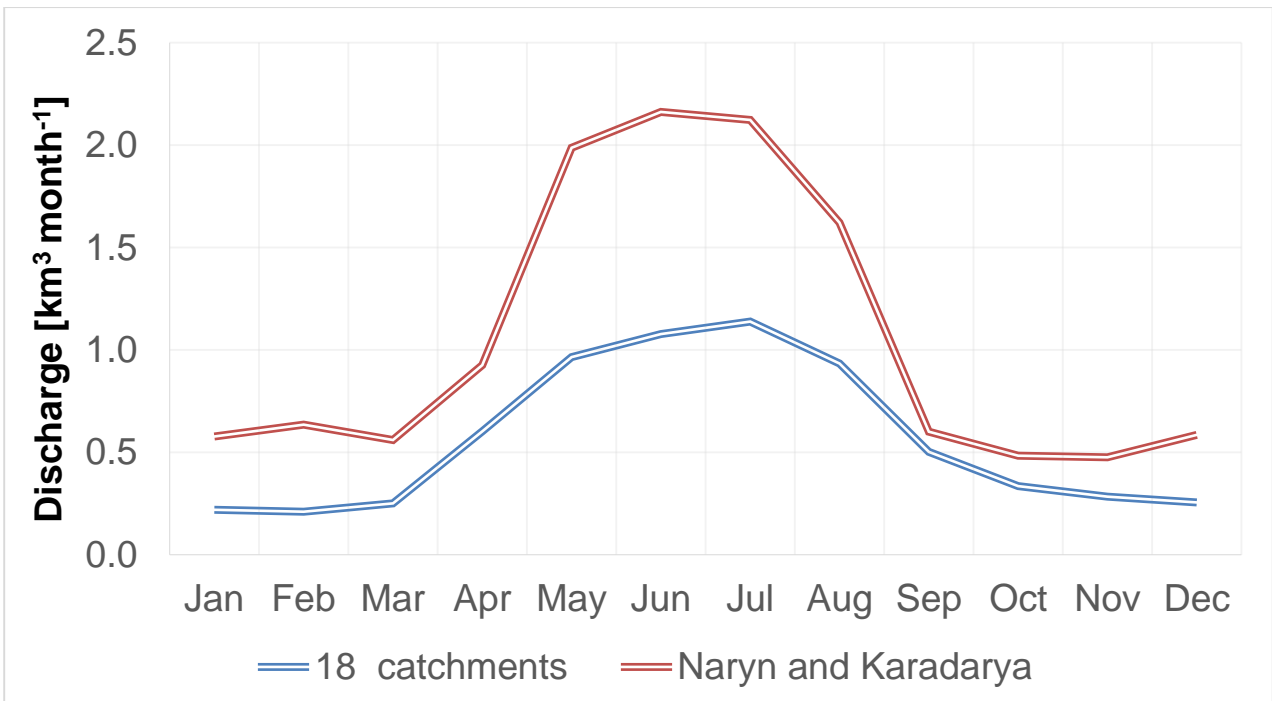


Figure 1-3 Total contribution of the 18 river catchments versus the Naryn and Karadarya rivers to the water balance of the Ferghana Valley on monthly time scale for the period 1980–1985.

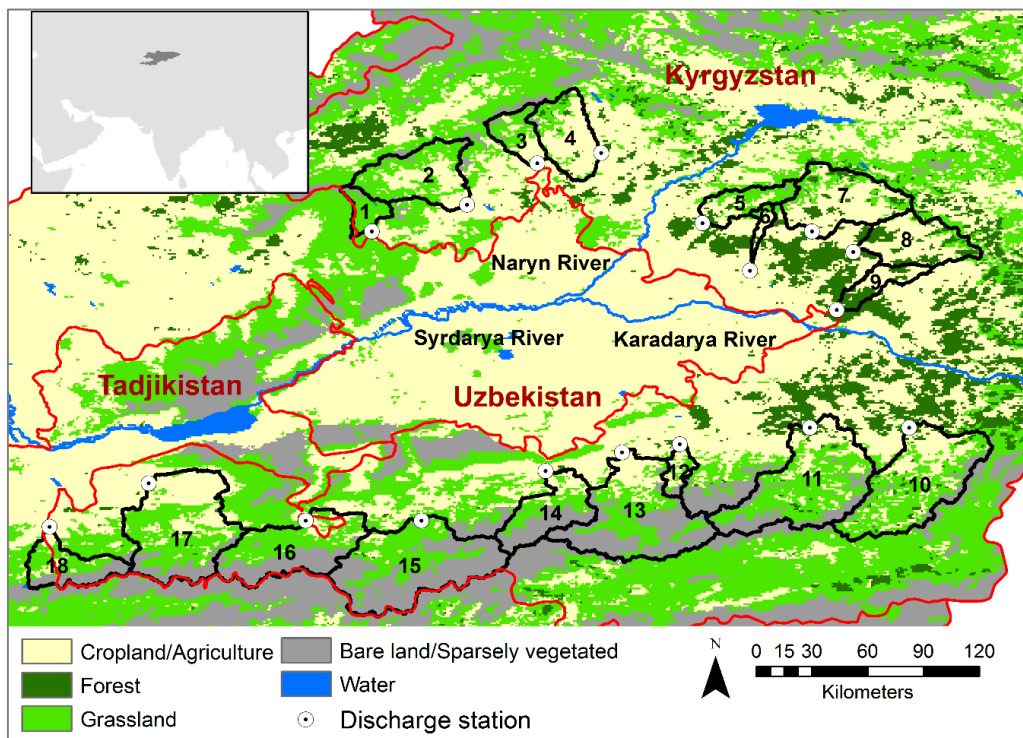


Figure 1-4 FAO land-use map and delineated 18 studied catchments (in black) in the Ferghana Valley using SRTM DEM (90 m).

According to land-use data from the Food and Agriculture Organization of the United Nations (FAO) (Team 2007), the prevailing land-cover type is grassland at higher elevation and cropland at lower elevation of the catchments (10–95%), followed by sparsely vegetated/bare lands (1–88%) and forests (1–41%) (Table 1-1, Figure 1-4). Additionally, from Table 1-1 it can be seen that the glacial cover in glaciated catchments varies from 1 to 11% (9–273 km²) (Landsat Multispectral Scanner System (MSS)). According to the FAO-UNESCO Soil Map (Team 2007) and referring to the World Reference Base for soil resources (Michéli et al. 2006), the dominant soils in the study area are Leptosols, Cambisols and Fluvisols. Leptosols correspond to sparsely vegetated/bare lands, while Fluvisols and Cambisols correspond to grassland/cropland land type.

1.3.1 Observed data

Daily discharge data (1980-1985) for the 18 catchments were obtained partly from Central-Asian Institute of Applied Geosciences (CAIAG), Kyrgyz-Russian Slavic University (Department of Meteorology), and Global Runoff Data Center (GRDC). The meteorological data such as daily precipitation (20 stations) and monthly air temperature (12 stations) were obtained from GeoForschungsZentrum (GFZ) Potsdam in the frame of CAWa (Central Asian Water) project. Additionally, daily air temperature was available from NCDC (National Climatic Data Center) for six weather stations (Figure 1-5). The data coverage varies from 9 to 99% year⁻¹, and on average for all temperature data from the six weather stations for the period 1980–1985 it is ≈77%. The temperature data gaps were filled using the linear regression method and within-station approach that averages the previous and following days of the values (Bacchi and Kottegoda 1995; Celleri et al. 2007; Makhuvha et al. 1997). For monthly temperature data we used MODAWEC weather generator that disaggregates it into daily (Liu et al. 2009). Before, the MODAWEC was tested in the study area using four pilot river catchments (Kugart, Kurshab, Akbura, Shakhimardan) and daily temperature data for correlation between measured and generated data (Radchenko et al. 2014). According to Radchenko et al. (2014), the MODAWEC model showed that the mean maximum, minimum and average generated temperature data are highly correlated with the respective measured data (0.80 to 0.91). The map with available meteorological data is illustrated in Figure 1-5.

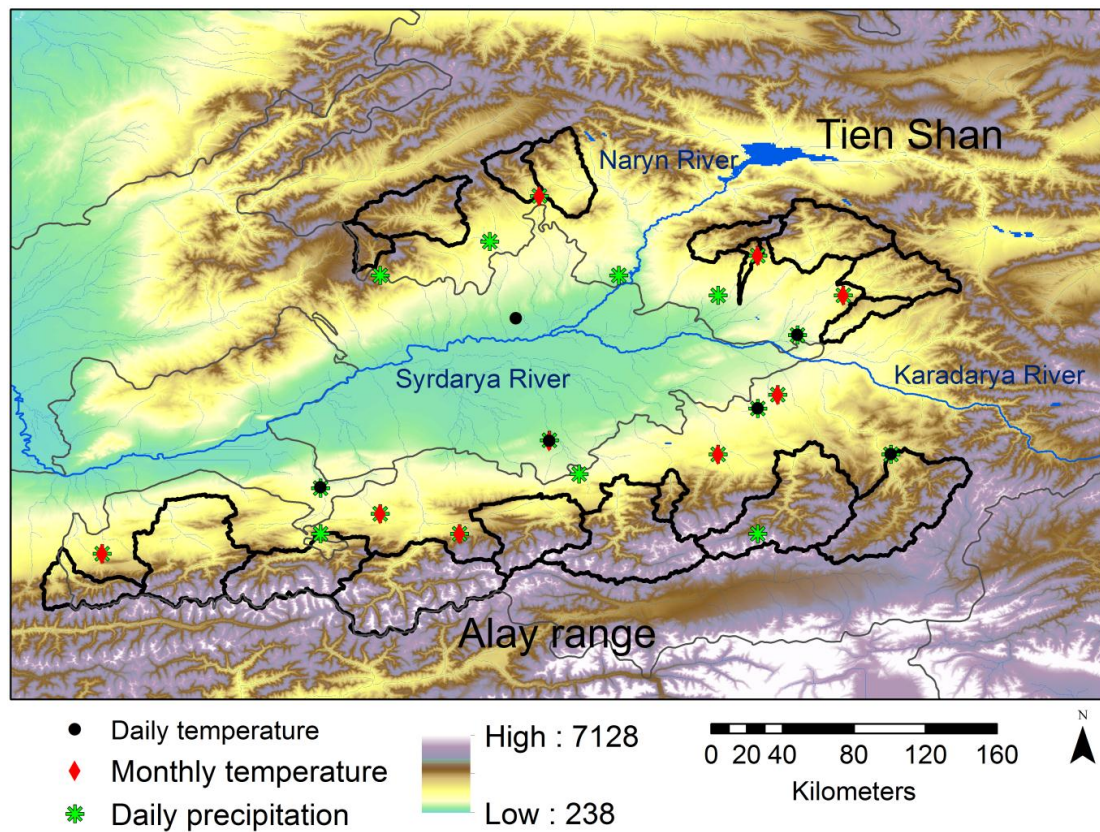


Figure 1-5 Available meteorological data in the 18 studied catchments in the Ferghana Valley and SRTM DEM (90 m).

Further, bearing in mind the remoteness of the climate stations from the river basins (Figure 1-5), the meteorological data were allocated to the centroids of the catchments using lapse rate and multiple linear regression methods, see (Radchenko et al. 2014) for further details on the approach.

The potential evapotranspiration on daily basis was calculated for the centroids of the catchments based on the FAO Penman-Monteith method (Allen et al. 1998) using the FAO CROPWAT model that requires maximum and minimum temperatures, altitude, latitude and longitude data (Smith 1992).

Glacier and snowfield data were calculated for the glaciated catchments (Table 1-1) using Landsat MSS (Multispectral Scanner System) satellite images that were acquired from the United States Geological Survey. The images were selected based on the qualitative and cloudless properties as well as availability. The data archive is available since 1972; therefore, we used the period of 1972-1979 for the analysis. In addition, the physical and glacial maps, constructed during Soviet time using aerial photographs in 1977–1980 (Kuzmichenok 2006), were used for the visual comparison.

1.3.2 Climate scenarios

The Global Circulation Models (GCM) operate at coarse spatial resolution of 100–300 km due to limitations of computer power, and give insufficient results at the local scale (Giorgi et al. 2001; Grotch and MacCracken 1991; Houghton 2009). Therefore, to consider the local topography, land-use characteristics and clouds, the Regional Climate Models (RCM) with resolution of 10–50 km were elaborated (Christensen and Christensen 2007; Giorgi et al. 2001; Houghton 2009). Thus, in this study dynamically downscaled data by means of RCM REMO was used (Mannig et al. 2013). The period 1971–2000 was selected as baseline period, and period 2071–2100 was selected as the future period for the runoff simulations in the 18 mountainous catchments of the Ferghana Valley.

In the investigated area, we applied the commonly used SRES (Special Report on Emission Scenarios) A1B scenario. The obtained climate data under A1B scenario were allocated to the centroids of the 18 studied catchments, likewise for the observed data, using the methods of lapse rate for available daily temperature series and multiple linear regression (based on 20 weather stations) for the precipitation series (Figure 1-5). The potential evaporation was calculated based on maximum and minimum monthly long-term averages for 1971–2000 and 2071–2100 periods using the FAO CROPWAT model method (Allen et al. 1998).

1.4 Thesis outline

The thesis consists of two papers that focus on hydrological modelling and climate change impact on water resources in the Ferghana Valley, Central Asia. Chapter 2 deals with hydrological modelling in arid and semi-arid region of Central Asia with daily temperature data scarcity. Hereby, MODAWEC (MOnthly to DAily WEather Converter) weather generator was tested in four river catchments with available daily climate data for its applicability for monthly temperature data disaggregation into daily. Additionally, the impact of the weather generator on the efficiency of HBV (Hydrologiska Byråns Vattenavdelning)-light model was analyzed using goodness-of-fit criteria (cumulative bias, coefficient of determination, model efficiency coefficients (NSE) for high flow and base flow). The parameter uncertainty was examined using Monte Carlo simulation technique and equifinality concept, where only behavioral parameter sets were selected based on the goodness-of-fit criteria. Chapter 3 addresses the use of upper mentioned weather generator for hydrological modelling in other 14 river catchments, and equifinality concept for the selection of the acceptable parameter sets for further research in the study area. Moreover, the SRES A1B scenario was used for climate change impact on water resource availability in the Ferghana Valley during the period of 2071–2100. The study area is represented by

the 18 mountains catchments (126–2,480 km²) that surround the Ferghana Valley and contribute to the Syrdarya River.

1.5 Summary of Results

The water sector is a vulnerable sphere in arid regions, especially during the global warming. Therefore, the assessment of the climate change impact on the river runoff and future availability of water resources in arid climate of the Ferghana Valley is the focus of this dissertation.

Chapter 2 describes hydrological model setup in a data-scarce arid region of Central Asia (Ferghana Valley). The main objective of the respective paper is to test several data pre-processing methods (MODAWEC model, gap filling, lapse rate, simple linear and multiple linear regression methods) and their impact on the efficiency of the HBV-light model in four pilot river catchments with relatively complete dataset. The MODAWEC model was applied in the four mountainous catchments (Kugart, Akbura, Kurshab and Shakhimardan) to convert monthly temperature data into daily. Further, temperature and precipitation data were allocated to the centroids (mean elevation) of the catchments because of remoteness from the catchments using the lapse rate and multiple linear regression methods accordingly. The HBV-light model was forced successfully with both measured and generated (temperature) allocated data to the centroids of the four catchments in the Ferghana Valley (Table 2-4, Figure 2-8). The parameter uncertainties were reduced using Monte Carlo simulation technique and equifinality concept, where the behavioral parameter sets with acceptable measures of goodness-of-fit criteria (cumulative bias, coefficient of determination, model efficiency coefficients for high flow (NSE) and base flow (NSE_log)) were chosen for the four catchments. The results show that the efficiency coefficients for high flow (NSE) in the studied area during calibration period vary from 0.50 to 0.70 for measured temperature data and from 0.50 to 0.66 for generated temperature data, and during validation period the range of the coefficients increased to 0.50–0.88 and 0.50–0.80 accordingly (Table 2-4). The efficiency coefficients for low flow (NSE_log) for measured temperature data in the calibration period vary in the range 0.50–0.76 and for generated temperature data the range is 0.50–0.77, whereas the upper values of the range of the coefficients in the validation period increased to 0.85 for both temperature data sets (Table 2-4). The water balance bias is represented by the difference between observed and simulated discharge and it does not exceed ± 20 mm year⁻¹ in the studied catchments. Overall, the HBV-light model is successfully applied in the study area and it shows the capability to capture the main peaks of discharge and to simulate the base flow both for generated and measured temperature data, as well as to reproduce the observed discharge time series (Figure 2-8).

Therefore, the findings indicate that the hydrological modelling using upper mentioned techniques is applicable for the remaining 14 catchments in the Ferghana Valley.

Chapter 3 presents the research of the potential climate change impact on the water resource availability in the Ferghana Valley. The developed approach, which was described in Chapter 2, was applied for the 14 mountainous catchments using a hydrological HBV-light model and MODAWEC weather generator. After the HBV-light model set-up and selection of the behavioral parameter sets during validation for the studied catchments (Table 3-3), a dynamically downscaled SRES A1B scenario was applied for the period 2071–2100. The climate data were received in the frame of CAWa (Central Asian Water) project from the researchers from the Wuerzburg University, Germany. In addition, the uncertainty of glacier coverage in the future was considered for the glaciated catchments using different glacier coverage scenarios, which were created by means of stepwise eliminating of the glacier cover at each elevation band (range is 500 m) starting with the lowest band (Figure 3-4). The results reveal an increase in winter–spring runoff by 44–107% and a decrease in summer runoff by 12–42%, when the water is necessary for irrigation in the Ferghana Valley. For the majority of the studied river catchments there is a seasonal shift of runoff to earlier time due to temperature rise (Figure 3-4). In general, the findings indicate $\approx 10\%$ reduction of the total runoff in the Ferghana Valley. Although, considering a reduction in discharge of the Naryn and Karadarya Rivers by 20%, the contribution of the 18 upper catchments to the Syrdarya River within the Ferghana Valley will be increased up to 37%. Taking into consideration the runoff decrease for the studied river catchments and two Naryn and Karadarya Rivers, there is a need to mitigate climate change impact on future water resource availability in the Ferghana Valley. The study suggests paying attention to the elaboration of the adaptation and mitigation methods, which may include the enhancement of old irrigational systems to reduce water loss, the adaptation of other agricultural crop in changing climate, the application of water reuse technique and the construction of new water reservoirs.

1.6 Future directions

The current global warming and glacier shrinkage is a live issue; therefore, the dissertation provides the results on the assessment of climate change impact on future water resource availability in a semi-arid region – the Ferghana Valley (Central Asia). The obtained results of this work may guide to develop a strategy for the mitigation and adaptation to climate change in the region. For example, our findings indicate an increase in winter–spring runoff and a decrease in summer runoff of the tributaries of the Syrdarya River that is a crucial consequence for agricultural irrigation in the arid region of the Ferghana Valley (Unger-Shayesteh et al. 2013; Hagg et al. 2007). Therefore, the adaptation and

mitigation procedures for the region may include water reservoir construction, implementation of innovated irrigational systems to reduce water loss, water reuse, afforestation, cropland management, usage of bioenergy and solar energy (Pachauri et al. 2014; Field et al. 2014; Thomas 2008).

Since the land-use land-cover change and its impact on water resources were not considered in the present dissertation, therefore it could be a good question for future research in the region. However, this research requires a wealth of information: soil characteristics, land cover, species, meteorological data, population size, population density, population growth and socio-economic variables (Veldkamp and Fresco 1996; Agarwal et al. 2002). Another potentially interesting future research is the dynamic of glacial and snowfield cover in a semi-arid to arid climate of Central Asia. Therefore for this aim the glacier dynamic model or mass balance model can be applied (Naz et al. 2014; Marzeion et al. 2012). However, the simulation of the future glacier cover area dynamic is associated with uncertainty due to a model's structure, model's parameters, future climate data projections and natural climate variability (Lutz et al. 2013). Thus, the additional information on land-use land cover change and glacier extent in future can help the decision-makers in management of transboundary water resources in the Ferghana Valley.

2 Simulating water resource availability under data scarcity – a case study for the Ferghana Valley (Central Asia)

Abstract

Glaciers and snowmelt supply the Naryn and Karadarya rivers, and about 70% of the water available for the irrigated agriculture in the Ferghana Valley. Nineteen smaller catchments contribute the remaining water mainly from annual precipitation. The latter will gain importance if glaciers retreat as predicted. Hydrological models can visualize such climate change impacts on water resources. However, poor data availability often hampers simulating the contributions of smaller catchments. We tested several data pre-processing methods (gap filling, MODAWEC (MOnthly to DAily WEather Converter), lapse rate) and their effect on the performance of the HBV (Hydrologiska Byråns Vattenavdelning)-light model. Monte Carlo simulations were used to define parameter uncertainties and ensembles of behavioral model runs. Model performances were evaluated by constrained measures of goodness-of-fit criteria (cumulative bias, coefficient of determination, model efficiency coefficients (NSE) for high flow and log-transformed flow). The developed data pre-processing arrangement can utilize data of relatively poor quality (only monthly means or daily data with gaps) but still provide model results with NSE between 0.50–0.88. Some of these may not be accurate enough to directly guide water management applications. However, the pre-processing supports producing key information that may initiate rigging of monitoring facilities, and enable water management to respond to fundamentally changing water availability.

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2.1 Introduction

The Aral-Caspian basin is the major internal drainage area of Central Asia. Its 4,000,000 km² are 75% steppe and desert (Dukhovny and Schutter 2010). However, large amounts of water are stored in glaciers, permafrost and snow on high mountain ridges in Kyrgyzstan and Tajikistan in the East of Central Asia. At present, these water storages play the key role in the water management that has to regulate the supply for the livelihood in the Central Asian lowlands including main parts of the Ferghana valley in Uzbekistan (Figure 2-1, 39.4–42 N, 69.2–73.8 E) (Hagg and Braun 2006; Aizen et al. 1995; Aizen et al. 2007; Rakhmatullaev et al. 2010). The valley floor at about 400 m is surrounded by the mountain ranges of the Tien Shan and the Alay mountain systems that reach up to 5000 m a.s.l.: the Chatkal ridge in the north, the Ferghana ridge in the east and the Alay ridge in the south. These orographic conditions protect the valley against the invasion of cold air masses from the north but open it to relatively moist air from the west (Alam and Kidwai 1987; Aizen et al. 1995; Aizen et al. 1997). Therefore, the Ferghana Valley has relatively warm winters and hot summers (Fekete et al. 2002). As the moist air from the west is forced to move upwards, which includes adiabatic cooling, the precipitation generally increases with elevation and reaches up to 1300 mm per year at the northwestern slopes of the Ferghana ridge (Price 1986; Fekete et al. 2002).

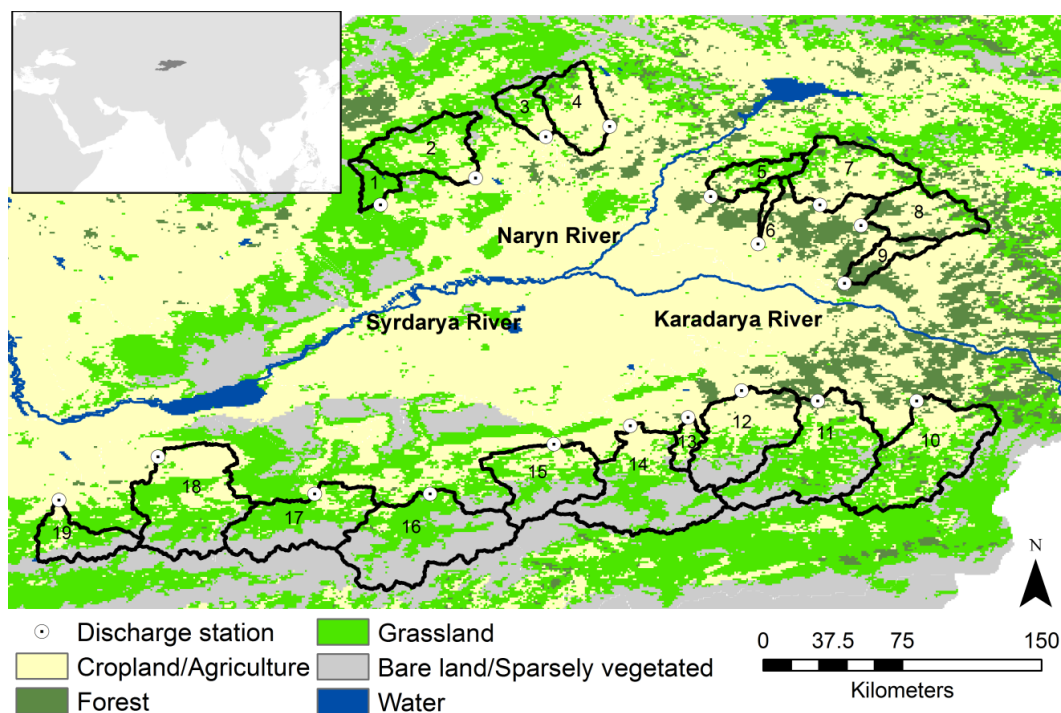


Figure 2-1 The Ferghana Valley with FAO (Food and Agriculture Organization) land-use map and delineated upper catchments (in black) using SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model, 90 m) and ArcGIS (10) software.

The Karadarya and Naryn rivers have their source in the eastern part of the Ferghana Valley and the Tien Shan mountain system in Kyrgyzstan, from where during summer they are mainly fed by glaciers and snow melt. The confluence of the two rivers in the Uzbek part of the Ferghana Valley forms the Syrdarya River. This river is the main water artery of the valley with a mean discharge of about $39 \text{ km}^3 \cdot \text{year}^{-1}$ (Savoskul et al. 2003). Kyrgyzstan and the three countries Tajikistan, Uzbekistan and Kazakhstan contribute 74% and 26% of the water volume of the Syrdarya River, respectively (Dukhovny and Schutter 2010). Smaller streams and catchments at the proximate northern, eastern and southern ridges around Ferghana Valley contribute water mainly from annual rain and snowfall and only a few streams to the south include some glacial melt.

A data compilation of the contributions of the two main and the most relevant smaller rivers shows that (a) the 19 smaller catchments (individually $71\text{--}2480 \text{ km}^2$) cover together an area of around $23,700 \text{ km}^2$ or 36% of the combined headwater areas of the Naryn and Karadarya catchments; and (b) the contribution in discharge to the Syrdarya River is around 7.7 km^3 or $\approx 34\%$ for the 19 catchments (0.2%–6.6% for single catchments), whereas it is $\approx 13\%$ for the Karadarya and 53% for the Naryn River (Table 2-1, data period 1980–1985).

Based on the analysis of observed climatic data of Central Asia for the 20th century, air temperatures are increasing especially in the lowlands and during winter months (Granit et al. 2010). The Intergovernmental Panel on Climate Change (IPCC) predicted a further increase in winter ($+2.6 \text{ }^\circ\text{C}$) and summer ($+3.1 \text{ }^\circ\text{C}$) temperatures by 2050 under its lowest future emission scenario B1 (Parry et al. 2007). The same study expects precipitation to increase by +4% in winter seasons and to decrease by -2% to -4% in spring and summer seasons.

The total area covered by glaciers in Kyrgyzstan decreased from 8076 km^2 in 1960 to 7400 km^2 at around 1980 and further to 6500 km^2 in 2000 (Kuzmichenok 2009). This corresponds to a 20% glacier recession for the period 1960–2000. The Tien Shan glaciers alone showed a reduction of 14.2% between 1943–2003 (Aizen et al. 2007). According to Narama et al. (2010), glacier recession for the period 1970–2000 varied from 9% to 19% in different regions of the Tien Shan. Finally, many authors assume that the rate of glacial melt in Central Asia has accelerated since the 1970s (Aizen et al. 2007; Bolch 2007; Khromova et al. 2006).

Table 2-1 Comparison of discharge data ($\text{km}^3 \cdot \text{year}^{-1}$) of the 19 upper sub-catchments flowing into the Syrdarya in relation to the inflows from the Naryn and Karadarya rivers (Data compiled from State Water Cadaster (1987), obtained from the Central-Asian Institute of Applied Geosciences (CAIAG), Kyrgyz-Russian Slavic University (KRSU), and the Global Runoff Data Center (GRDC), retrieved 19.04.2011, (D)—data with gaps).

Catchment	Area	Elevation (gauge station)	Discharge	Contribution to Total Discharge	Temporal Resolution of Data (Daily = D, Monthly = M)		
Name	(km^2)	(m a.s.l.)	($\text{km}^3 \cdot \text{year}^{-1}$)	(%)	Precipitation	Temperature	Discharge
1 Gavasay	361	1716	0.13	0.6	D	M	D (1980–1985)
2 Kassansay	1130	1350	0.19	0.9	D	M	D (1980–1985)
3 Padshaata	366	1536	0.15	0.7	D	M	D (1980–1985)
4 Aflatun	863	2000	0.29	1.4	D	M	D (1980–1985)
5 Maylisuu	530	985	0.26	1.3	D	M	D (1980–1985)
6 Shidansay	126	1016	0.05	0.2	D	M	D (1980–1985)
7 Tentyaksay	1300	1023	0.83	4.1	D	M	D (1980–1985)
8 Kugart	1010	1168	0.54	2.7	D	D	D (1980–1985)
9 Changet	381	813	0.06	0.3	D	M	D (1980–1983, 1985)
10 Kurshab	2010	1543	0.55	2.7	D	(D)	D (1980–1985)
11 Akbura	2260	1327	0.62	3.0	D	(D)	D (1980–1985)
12 Aravansay	1680	1068	0.22	1.1	D	M	D (1980–1985)
13 Abshirsay	230	1500	0.05	0.2	D	M	D (1980–1985)
14 Isfirmsay *	2220	1017	0.59	2.9	D	M	D (1980–1985)
15 Shakimardan	1180	1065	0.25	1.2	D	(D)	D (1980–1985)
16 Sokh *	2480	1140	1.35	6.6	D	M	D (1980–1985)
17 Isfara	1560	1283	0.43	2.1	D	(D)	D (1980)
18 Khodjabakirgan	1740	1730	0.29	1.4	D	M	D (1980–1983)
19 Aksu	712	1100	0.11	0.5	D	M	D (1980–1983)
Major rivers				~34			
Naryn *	58,400	498	10.7	~53			
Karadarya *	7402	890	2.68	~13			

According to Immerzeel and Bierkens (2012), the future changes in precipitation, glacial melt, groundwater extraction, reservoir construction, and population growth will involve only a moderate risk of water shortage in the Syrdarya River basin. In contrast, the IPCC emphasized with very high confidence that Central Asia is under high water stress, and that water resources are extremely vulnerable to climate change (Parry et al. 2007). Accordingly, the further decrease of glaciers will most likely lead to runoff changes from the Naryn and Karadarya rivers. The volume of water discharged into the major rivers of the region may increase in the short-term but decrease over the long-term.

With respect to climate change scenarios, a reduction in discharge by 6%–10% in the Syrdarya River basin is projected by 2050 (Dukhovny and Schutter 2010). Thus, the contributions of small, mainly precipitation-driven catchments may become more important for the water balance of the Ferghana Valley in coming decades. As the people in the region depend on irrigated agriculture, it is of significant interest to assess the contribution of the small upper-catchments under current conditions, and to simulate the future runoff dynamics (Bucknall 2003; Sokolov 1999).

About 12 million people live in the Ferghana valley (Dankov 2007), and most of the local families as well as many other people in Central Asia depend on the agricultural production of this specific area. Thus, for many water-users in the Ferghana Valley and beyond, information about future water availability is of utmost importance. Therefore, model projections are urgently needed that capture the impact of changes in precipitation patterns on annual flows with sufficient accuracy to support reservoir management and water resource planning. However, available meteorological and hydrological data for the aforementioned 19 catchments are limited (Table 2-1). For example, although temperature is important for estimating evapotranspiration and thereafter for closing the water balance in semi-arid regions (Tateishi and Ahn 1996; Jackson et al. 2001), daily temperature data sets for several years are at hand only for five weather stations. Only monthly temperature data exist for the rest of the stations (Figure 2-2). Accordingly, the term “data scarcity” in this study refers to insufficient climate network coverage across the Ferghana Valley, especially regarding temperature data where the density of stations is less than 1 per 5000 km² (Piper and Stewart 1996; Zhang et al. 2014).

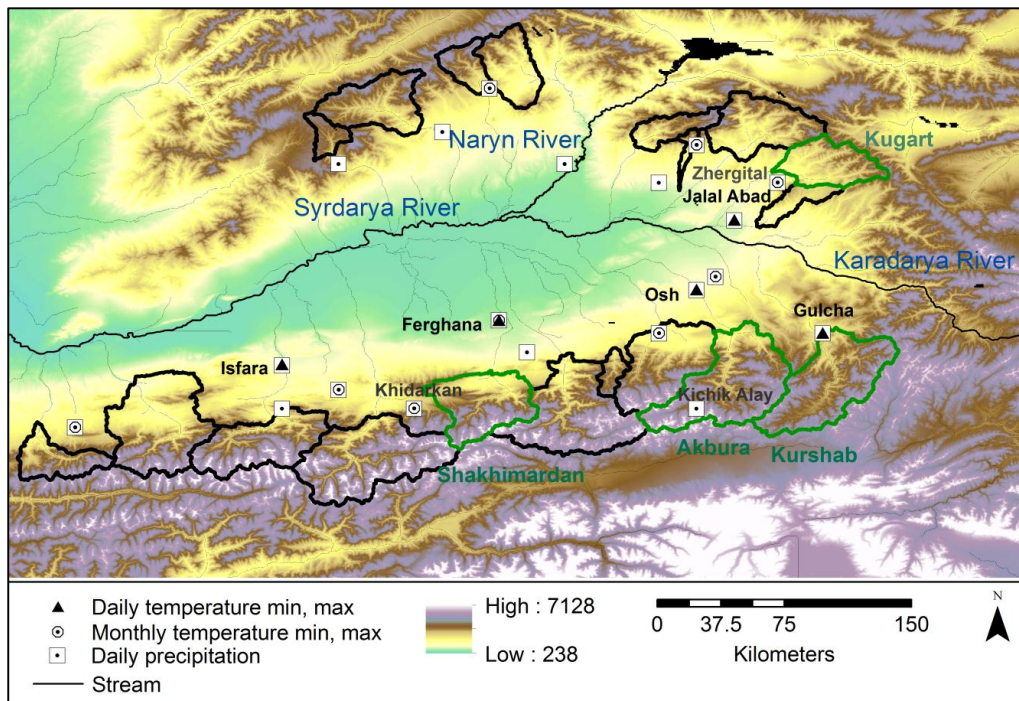


Figure 2-2 The Ferghana Valley with available meteorological data and four studied catchments (in green).

Widespread data scarcity cannot be gap-filled in a way that the output enables local water managements to rely on the synthesized data for the decisions in water allocation to users. Thus, results from synthesizing regional scale data with larger gaps may not be overstated. However, even rough estimations on the potential direction of change are highly appreciated by stakeholders and decision-makers, because water resources are so vulnerable in this area of the world. Hence, the scope of the present work was to develop an approach that can facilitate hydrological modeling of water resource availability under current climatic conditions based on a number of limited data sets (Figure 2-3).

Our straightforward approach to hydrological modeling agrees well with suggestions by Bárdossy and Singh (2008) and Guerrero et al. (2013), and takes into account a number of performance criteria (Nash-Sutcliffe efficiency for high log-transformed flow, and difference in annual water balance), and provides a meaningful representation of hydrological processes, the transformation of behavioral parameter sets in time (validation), and a sensitivity analysis of the model's parameters. We selected the four river catchments with the most complete data and tested hydrological model performance given these aspects. Moreover, we tested MODAWEC weather generator for its applicability in the study region. MODAWEC converts monthly temperature data into daily values since only several weather stations are available at daily resolution (Figure 2-2). To decide whether or not MODAWEC can be used for research on the other 15 catchments of the valley, the results of simulated hydrological

outputs were compared, in terms of results from the two databases representing either generated or measured temperature (Figure 2-3).

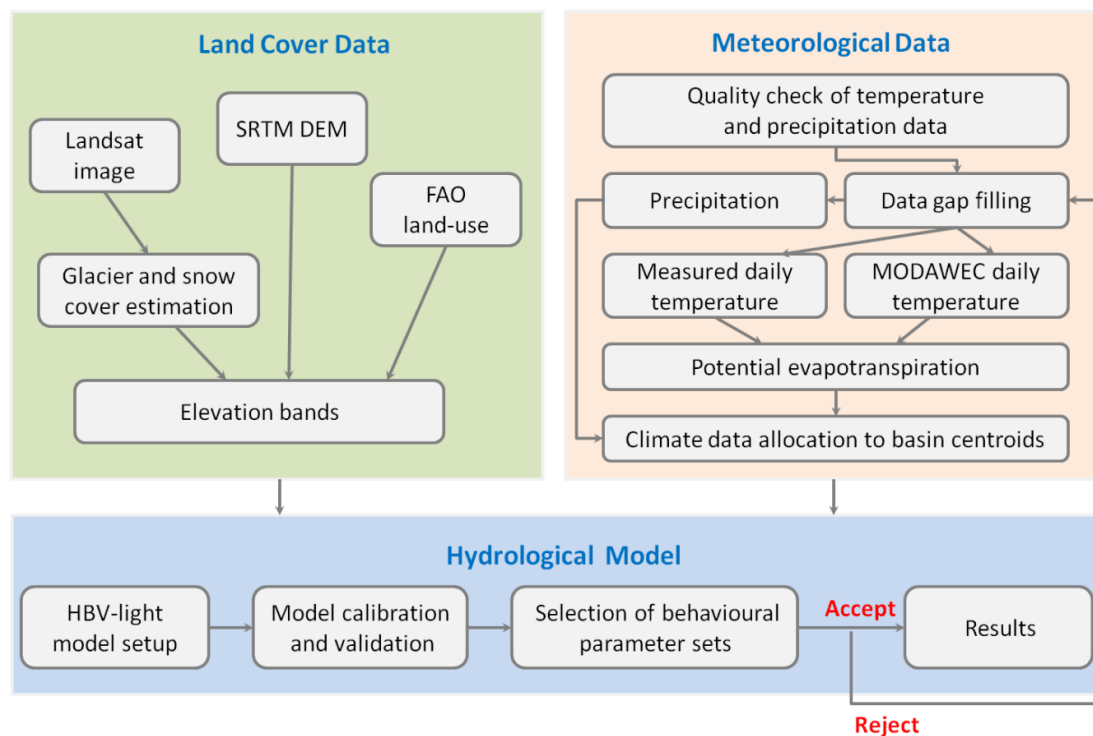


Figure 2-3 Schematic representation of the selected model approach.

Preference was given to a lumped hydrological model for the hydrological simulation because of the limited quality of forcing data, *i.e.*, referring to the completeness of observed daily meteorological data for the study period. Amongst others, models from the HBV (Hydrologiska Byråns Vattenavdelning) family have proven to provide reliable results for mountainous catchments of Central, East and South Asia, and have recently been used for climate change impact studies in the region (Akhtar et al. 2008; Akhtar et al. 2009; Chen et al. 2012; Chen, Xu, and Guo 2012; Gao et al. 2012; Hagg et al. 2007; Kang et al. 1999). We used the recently upgraded version of the HBV-light model for the water balance investigation of the Ferghana Valley, because this version is capable of simulating glacial melt (Konz and Seibert 2010; Jan Seibert and Vis 2012). We used a Monte Carlo approach to investigate the effect of model parameter uncertainty (Uhlenbrook et al. 1999; Steele-Dunne et al. 2008), which is only one part of the global model uncertainty that can arise from errors in input data, the model parameters, or the model structure (Muleta and Nicklow 2005; Uhlenbrook et al. 1999; Beven and Binley 1992; Butts et al. 2004). In addition, the influence of the input parameters on the model's output was assessed using sensitivity analysis (Ratto et al. 2007; Hamby 1994).

2.2 Materials and Methods

2.2.1 Study Area

The four pilot watersheds with the most comprehensive data sets are the Kugart River, the Akbura River, the Kurshab River and the Shakhimardan River basins. A complete record of daily air temperature was available only for one weather station (Jalal Abad) provided by the NCDC (National Climatic Data Center), while for four other stations (Osh, Gulcha, Ferghana, Isfara) there are temporal gaps in the database (Figure 2-2). The average monthly temperature for the period 1980–1985 at lower elevations (Ferghana, El. 577 m a.s.l.) varies from -0.4 °C in January to 28.9 °C in July. At medium elevations (Gulcha, El. 1542 m a.s.l.) temperatures range from -4.5 to 20.3 °C and decreases to between -8.3 to 15.8 °C at high elevations (Kichik Alay, El. 2360 m a.s.l.) (Figure 2-2). The patterns of monthly mean temperature are similar for the four studied catchments, with warm periods starting in April–May and ending in September–October (Figure 2-4). Likewise, annual precipitation patterns are comparable between locations with maximum precipitation occurring during April–May and a secondary peak in October–November (Figure 2-4).

Hydrometeorological and land-use characteristics of the studied catchments are presented in Table 2-2. The annual discharge varies from 274 (Akbura) to 537 mm (Kugart) for the studied period with rainfall/runoff ratios of 0.48 (Shakhimardan) to 0.86 (Akbura). The Kugart River basin is mainly precipitation and snowmelt fed, while the other three studied basins are primarily snow and glacial-melt fed.

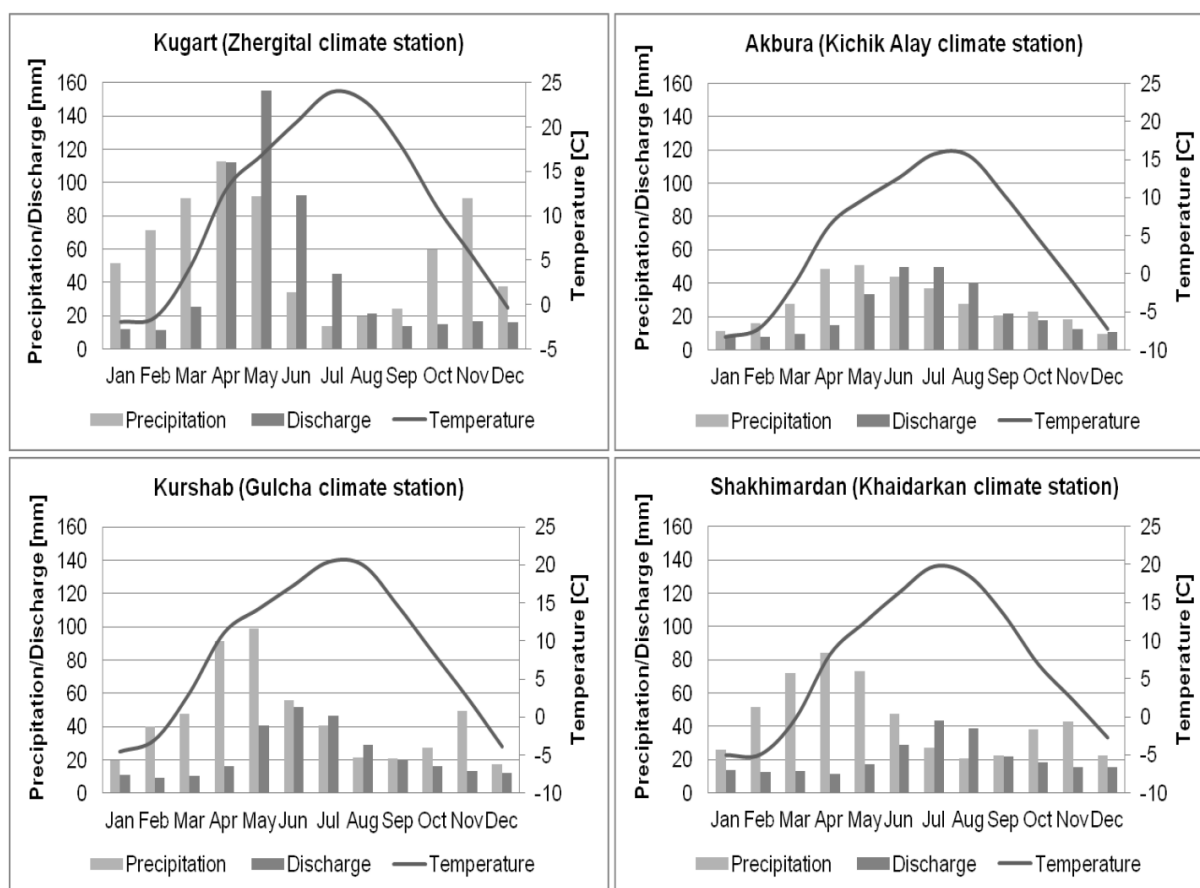


Figure 2-4 Hydrometeorological regime for the four studied catchments for the period 1980–1985 (constructed based on the available database).

Table 2-2 Hydrometeorological and land-use characteristics of the four studied catchments.

River Catchments	Kugart	Akbura	Kurshab	Shakhimardan
Annual discharge, mm	537	274	277	251
Annual precipitation, mm	710	319	530	527
Average annual temperature, °C	11.0	4.2	8.3	7.0
Forest, %	21.0	2.5	14.0	0.1
Grassland/Cropland, %	79.0	52.0	58.0	65.4
Sparsely vegetated/Bare lands, %	-	45.5	28.0	34.4

The dominant vegetation zones were classified based on FAO land-use/land-cover data (Team 2007). Forests cover up to 21% (Kugart), while the largest portions of the catchments are made up of grassland/cropland (52%–79%) and sparsely vegetated and bare lands. Based on the World Reference Base for soil resources (Michéli et al. 2006), the prevalent soils in the research area are Leptosols, Cambisols and Fluvisols, whereby the first and the latter two correspond roughly to sparsely vegetated/bare lands and grassland/cropland, respectively. In addition, the river terraces along the

studied catchments are often used for agriculture, producing cotton, cereals, grapes, sugar beets, fruits and nuts.

Information about the distribution of glacial and snowfield areas in different elevation ranges is presented in Table 2-3. Glacier and permanent snow cover are illustrated in Figure 2-5.

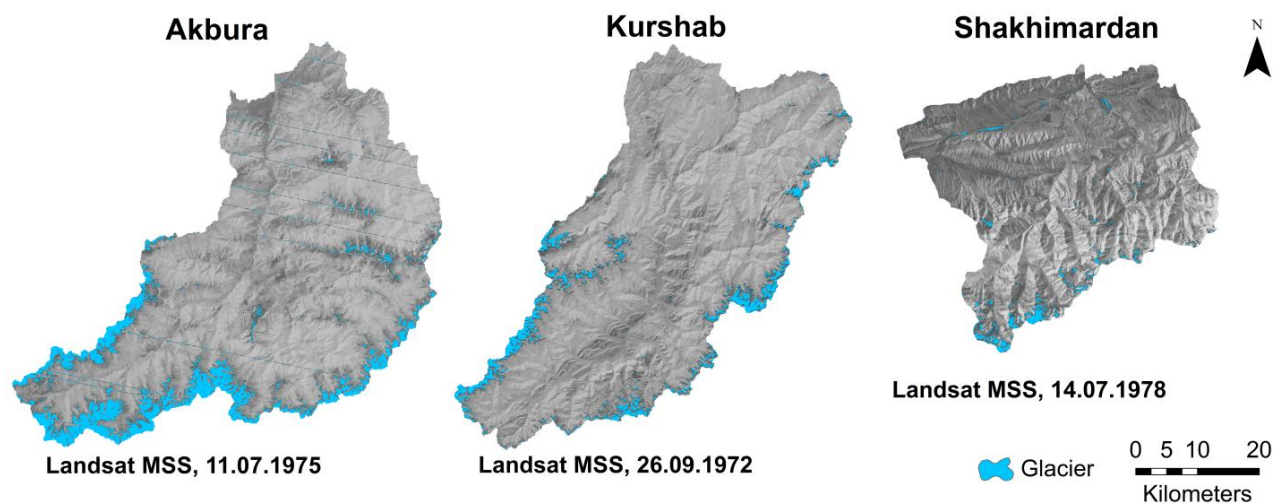


Figure 2-5 The Landsat MSS (Multispectral Scanner System) satellite images (79 m) with delineated glacial and snowfield area.

Table 2-3 Distribution of the glacier and permanent snow covered area at different elevations in the Akbura, Kurshab and Shakhimardan river basins (Kugart river basin is non-glaciated).

Elevation Zone (m a.s.l.)	Akbura Basin Coverage, 1975		Kurshab Basin Coverage, 1972		Shakhimardan Basin Coverage, 1978	
	(km ²)	(%)	(km ²)	(%)	(km ²)	(%)
5000–5500	-	-	-	-	0.6	0.05
4500–5000	46.5	2.06	0.2	0.01	8.4	0.71
4000–4500	124.5	5.51	33.7	1.68	18.7	1.58
3500–4000	16.9	0.75	43.2	2.15	6.8	0.58
3000–3500	0.5	0.02	3.1	0.15	0.2	0.02
2500–3000	1.8	0.08	-	-	-	-
2000–2500	1.4	0.06	-	-	-	-
Sum	191.6	8.48	80.2	3.99	34.7	2.94

For the Akbura River basin the glacial and snowfield area is 8.5% (192 km²), in the Shakhimardan watershed the glacial and permanent snow cover extends over ≈3% (≈35 km²) and for Kurshab over ≈4% (80 km²) of the catchment’s area.

2.2.2 Glacial and Snowfield Area

As the HBV-light model requires more detailed information on vegetation and glacial coverage for different elevation ranges within a catchment, the area of glacier and snowfield was derived from Landsat 1–3 MSS satellite images for the Akbura (1975), Kurshab (1972) and Shakhimardan (1978) (Figure 2-5). The geo-referenced satellite images were obtained from the United States Geological Survey (USGS). The images were chosen based on their availability in the archive and cloud cover criteria. Snow and glaciers are represented in white color in visible bands due to high reflectivity (Joseph 2005). Different methods for glacial and snow cover mapping exist, e.g., visual, normalized difference snow index, supervised and unsupervised classification. We distinguished the snow covered area based on satellite images using the spectral reflectance characteristics of snow. Hence, a threshold method was implemented using the brightness values (0–255) in properties of the images. The glacial and permanent snow cover areas were reclassified in ArcGIS (10) based on the different thresholds (as natural break) for the three images due to quality differences in the images. Instead of ground truth data we used soft information from published data on glacier extent close to the period when images were taken (Usabaliev et al. 2012). Additionally, glacier and snowfield borders were defined by visual interpretation using scanned, published physical maps from archives. Finally, elevation zone maps of the Akbura, Kurshab and Shakhimardan river basins were derived from DEM and overlapped with glacial and snowfield cover maps to calculate the areas on each elevation zone (Figure 2-5).

2.2.3 Data Gap Filling

A major problem for many Central Asian study regions is data limitation. The best data coverage available for the catchments is for 1980–1985 (Table 2-1), but even these time series have gaps of many days in the temperature records and for April, 1985 in the precipitation records. Gap filling details relative to the two parameters are explained hereinafter.

Temperature

A linear regression method was used in order to bridge the gaps in the temperature records (Bacchi and Kottegoda 1995; Celleri et al. 2007; Makhuvha et al. 1997). The best data set within the study area refers to the Jalal Abad climate station, which has only small gaps (0.5%) in the temperature records. Here we used a within-station method based on the averaging of previous and following days of the temperatures. The daily temperature data for the Ferghana climate station contains 0.3%–4.4% gaps, which were filled using the within-station and linear interpolation methods. The temperature records for the Osh climate station cover 64%–92% of a year, and this is respectively 9%–61% for the Gulcha climate station. The monthly correlation coefficients of the temperature data between the Jalal Abad

and Osh climate stations span from 0.70–0.97, and between the Gulcha and Osh climate stations the coefficients range from 0.60–0.92.

Temperature data of each station were allocated to the centroids (*i.e.*, mean elevation) of the four respective basins (Figure 2-2) considering monthly temperature lapse rates (DeGaetano et al. 1995; Prieto et al. 2004; Villazón and Willems 2010). Allocation to the centroids worked well, as they represent the mean elevations in the catchments. The HBV-light model further corrects temperature and precipitation at different elevation zones using lapse rates based on the reference elevation (J. Seibert 2005). Since the model uses an annual lapse rate, we calculated monthly ones to allocate and correct temperature. The monthly lapse rates were estimated based on the available annual average temperature data (1980–1985) from 17 climate stations in the Ferghana Valley (Figure 2-2), ranging in elevation from 577 to 2360 m a.s.l. The temperature lapse rates vary from 0.34 °C/100 m (December) to 0.82 °C/100 m (June), and the average lapse rate is 0.58 °C/100 m.

Precipitation

Within the study area five weather stations with complete precipitation time series (except for April 1985) are available for the period 1980–1985. These climate stations were tested for correlation with the other 15 stations to select the most suitable weather station based on the highest correlation coefficient (0.45–0.96) in order to fill the gaps for April 1985 using the linear regression method.

Similar to the temperature data, precipitation data were also corrected for altitude when allocating to the centroids. A stepwise multiple linear regression (MLR) method (Basist et al. 1994; Daly et al. 1994; Hay et al. 1998; Marquínez et al. 2003; Ranhos et al. 2008) using R 2.15 (Daly et al. 1994) was used considering annual data from 20 precipitation gauges (ranging in elevation from 826 to 1551 m a.s.l., 1980–1985, Figure 2-2), including information on altitude, latitude and longitude. The resulting equation was $p \text{ (mm)} = -8531 + 211.2 \text{ Lat} + 0.219 \text{ Alt}$, with $r = 0.70$. For quality control, we checked correlation coefficients between measured precipitation at neighboring weather stations and generated precipitation for the centroids ($r = 0.65\text{--}0.84$; $p \leq 0.05$).

2.2.4 Weather Generator

Weather generators produce data that can be used as inputs for hydrological models (Hoogenboom 2000; Ivanov et al. 2007; Kou et al. 2007). MODAWEC was chosen for the required input data (mean monthly precipitation, mean monthly maximum and minimum temperature, and number of wet days) corresponding to the data available for the study area. According to (Richardson 1981; Liu et al. 2009), precipitation is considered as an independent variable and it is calculated using a first-order Markov chain approach. The Markov chain model describes the occurrence of precipitation based on the

probability that a dry day is followed by a wet day and a wet day occurs after previous wet days (Richardson 1981; Liu et al. 2009). The amount of precipitation is calculated using a modified exponential distribution considering the status (wet or dry) of the previous day (Richardson 1981; Liu et al. 2009). Temperature is dependent on precipitation insofar that during rainy days the temperature is usually lower than in dry days. Therefore, the daily temperature was generated based on correlations with rainfall events (Liu et al. 2009). MODAWEC-derived data were tested for their applicability in replacing measured daily temperature in running the HBV-light model.

2.2.5 The HBV-Light Model, Calibration and Validation

The conceptual, lumped HBV-light model (Seibert and Vis 2012; Seibert 2005) simulates daily discharge using daily precipitation, temperature and potential evapotranspiration (PET) as input data. In depth details and descriptions on the model are available (Harlin and Kung 1992; Lindström et al. 1997; Seibert 1999; Seibert and Vis 2012). Briefly, the model includes four different routines: snow, soil, groundwater and routing. The snow routine is based on a degree—day method, where precipitation is considered to be rain or snow with respect to a threshold temperature, TT ($^{\circ}\text{C}$) (Lindström et al. 1997; Seibert and Vis 2012; Seibert et al. 2000). The soil routine simulations depend on actual evaporation and water storage properties (Seibert et al. 2000; Seibert 1997). The groundwater routine is governed by percolation rate (PERC) and recession coefficients (K_1 , K_2) (Seibert 1997; Seibert and Vis 2012). Finally, the runoff generation is characterized by the shape of a triangular weighting function (Lindström et al. 1997; Seibert et al. 2000).

This study used the most recent version of the HBV-light model, which differs from the previous versions by being able to reflect glacial melt (Konz and Seibert 2010). The glacial melt is calculated after snowpack disappearance using a degree-day factor method and depending on slope and exposition (Konz and Seibert 2010; Seibert and Vis 2012). In our set-up we separated catchments into 500 m elevation zones, resulting in 6, 8, 7 and 9 zones for Kugart (elevation range 1118–3717 m a.s.l.), Akbura (1395 to 4977 m a.s.l.), Kurshab (1562 to 4623 m a.s.l.), and Shakhimardan (1213 to 5316 m a.s.l.), respectively.

The HBV-light model considers temperature and precipitation changes with elevation. We used the annual average temperature lapse rate of $0.58\text{ }^{\circ}\text{C } 100\text{ m}^{-1}$ calculated for the study area. We further used a straightforward 10% increase in precipitation for every 100 m increase in elevation as suggested by Seibert (2005). A more complex MLR for precipitation, which considers the elevation and latitude as described above, is not readily compatible to HBV-light inputs. Reference evapotranspiration was calculated based on the FAO Penman-Monteith approach (Allen et al. 1998; Allen et al. 2006) using the CROPWAT 8.0 model (Smith 1992). The CROPWAT model requires input data on elevation,

latitude, longitude, and daily means of maximum and minimum temperature (Smith 1992). It further requires a crop coefficient for calculation of PET (Allen et al. 1998). In this study, the crop coefficient was averaged for the different vegetation types in the region.

HBV-light is a conceptual model and its parameters are not physically-based. We used a lumped model set up with up to nine elevation bands and three vegetation zones, but no additional sub-catchments or spatially variable model parameters due to missing hydrological data. Apart from a manual calibration, the model allows for a Monte Carlo (MC)-based random allocation of parameters from pre-defined parameter ranges. According to the equifinality concept, there is no optimal parameter set but several behavioral sets (Beven and Binley 1992; Beven and Freer 2001; Freer et al. 1996). This concept best matches the uncertainty of the model set-up that is characterized by relatively poor quality forcing data. We thus used the MC-based parameter estimation technique. The available time series was split into calibration (1980–1983) and validation (1984–1985) periods. Initially, the model was run 10,000 times with broader parameter ranges to identify suitable parameter bounds for each catchment. Afterwards, 500,000 model runs within these parameter bounds were used to derive behavioral parameter sets for 12 (Kugart; excluding glacial melt parameters) and 14 (Akburu, Kurshab, Shakhimardan) parameters considering both measured and MODAWEC-generated daily temperature data.

The parameter sets were treated as being behavioral in calibration and validation periods according to three goodness-of-fit criteria: (1) The Nash Sutcliff efficiency (NSE) which needs to be ≥ 0.50 to consider the model efficient in matching dominant runoff events; (2) The Nash-Sutcliffe efficiency of log-transformed flow (NSE_{\log}) ≥ 0.50 was used to assess the model's capability in simulating recession flow periods; (3) The cumulative mean difference between observed and simulated runoff predictions for the entire simulation period shall not be outside the range of 0 ± 20 mm as a measure of the model's suitability for simulating overall available water resources (e.g., for agricultural production). The same objective functions have been applied in other studies (Samuel et al. 2012; Shields and Tague 2012; Viviroli et al. 2011; Wöhling et al. 2006; Zappa and Kan 2007). In addition, NSE results were crosschecked using the coefficient of determination (R^2). Three months were selected as a model warm-up period so that evaluated simulation starts in April 1980. During the validation the year 1983 was used for warm-up.

2.3 Results and Discussion

MODAWEC was tested using the database of the four studied catchments for its applicability in the region as the converter from monthly into daily temperatures. Results reveal that measured and generated mean maximum, minimum and average temperature data for corresponding weather stations (Figure 2-2) are highly correlated (0.80 to 0.91). Figure 2-6 shows generated and measured average temperature values at the four corresponding weather stations of the studied basins. Thus, the generator is capable of representing the main features and fluctuations that are similar to the observed temperatures.

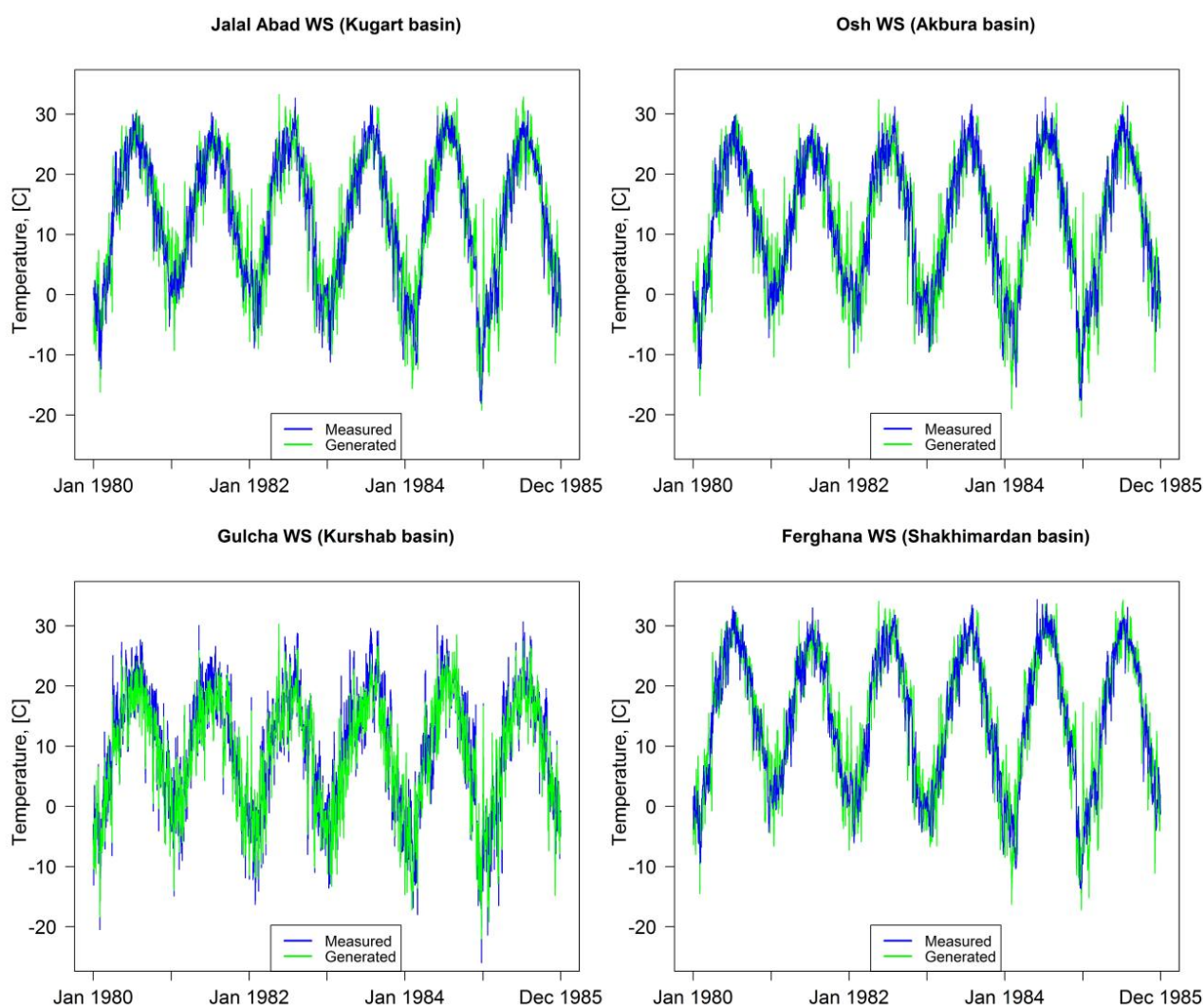


Figure 2-6 Time series plots of generated and measured temperature at the corresponding weather stations (WS) of the four studied river catchments.

The corrected precipitation for the mean elevations of the studied catchments using MLR method and measured precipitation at the neighbor stations (Figure 2-2) are presented in Figure 2-7. The correlation coefficients vary from 0.65 in the Kugart river basin to 0.84 in the Shakhimardan river basin. It can be assumed that the calculated and measured precipitation time series are mostly similar

and the main precipitation events occur in both cases at the same time. PET rates were calculated for the temperature data allocated to the centroids of each catchment. Correlation coefficients of PET calculated based on measured versus MODAWEC temperatures vary from 0.84 to 0.92 for the researched basins.

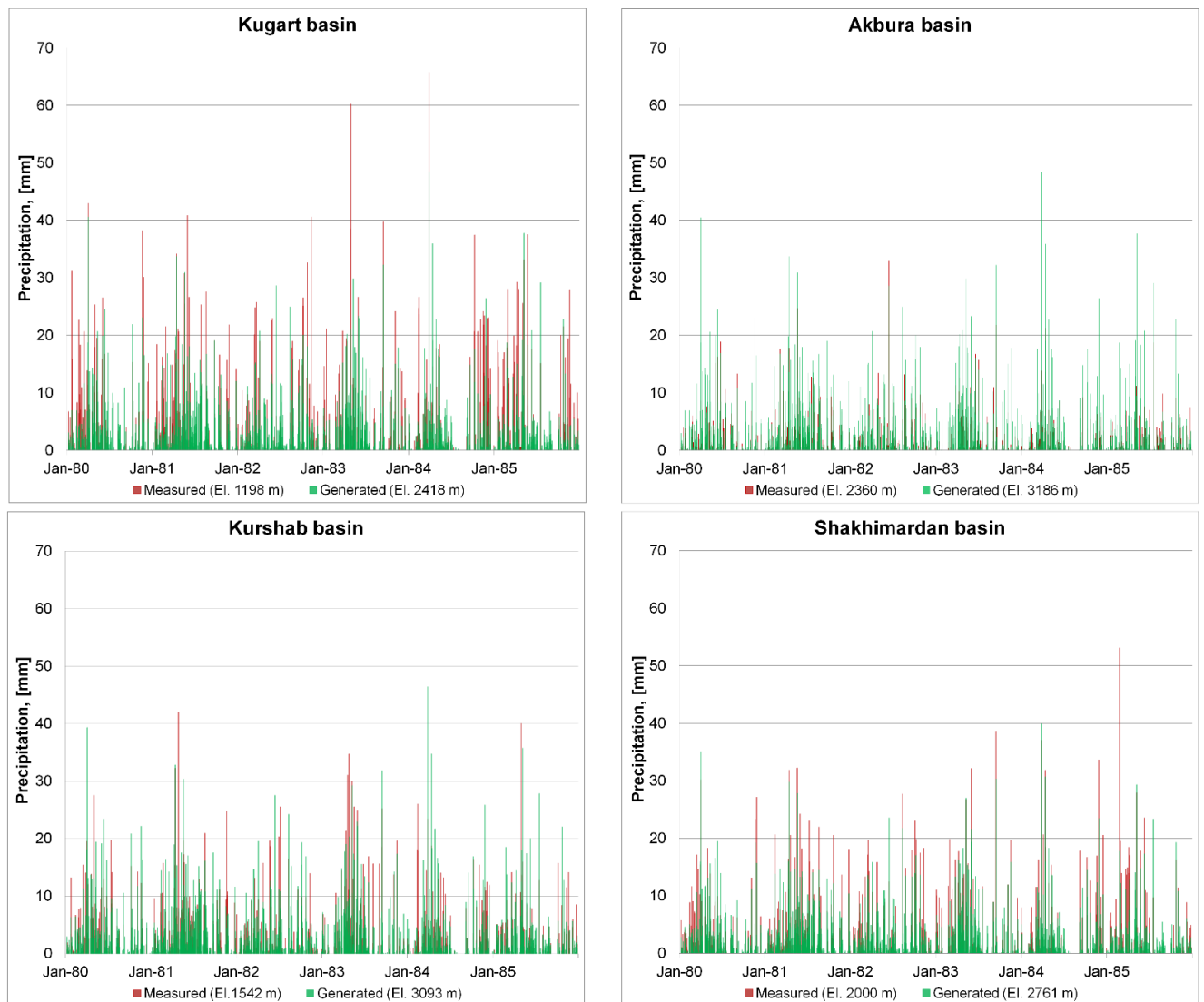


Figure 2-7 Time series plots of allocated precipitation to the centroids and measured precipitation at neighboring weather stations of the four river catchments.

Results of the HBV-light model using both measured as well as MODAWEC input data for the calibration (1980–1983) and validation (1984–1985) period for the four different catchments are presented in Table 2-4. In general, the HBV-light model is able to replicate the main peaks of discharge ($NSE = 0.50\text{--}0.88$) and simulate the base flow ($NSE_{\log} = 0.50\text{--}0.85$) in the study area (Figure 2-8). Higher NSE coefficients were often found for the validation than the calibration period. Similarly, the coefficient of determination (R^2) is higher for the validation (0.51–0.89) than the calibration (0.50–0.79) period. Some extreme discharge peaks are underestimated throughout all

catchments, which is mainly attributable to an underestimation of snowmelt in late spring or early summer. From a visual inspection of hydrographs (Figure 2-8) as well as from the statistical performance criteria (Table 2-4) we did not find large differences between MODAWEC and measured temperature data-driven HBV-light simulations. Even though in some cases (e.g., Shakhimardan) the NSE dropped slightly, there were other cases where efficiency even increased (e.g., NSE_{log} for Akbura). For three of the four catchments the number of overall accepted model runs during calibration period increased when MODAWEC data were used.

Table 2-4 Results of calibration and validation of the HBV-light model using allocated measured and generated temperature data, and MLR-calculated precipitation of the four pilot catchments.

Goodness-of-Fit	Calibration, Allocated Measured Data	Validation	Calibration, Allocated Generated Temp. Data (MODAWEC)	Validation
	1980–1983	1984–1985	1980–1983	1984–1985
<i>Kugart river basin</i>				
No Parameter sets	2556	47	6973	14
NSE	0.50–0.63	0.50–0.88	0.50–0.61	0.50–0.65
NSE _{log}	0.50–0.71	0.50–0.77	0.50–0.69	0.50–0.67
R ²	0.50–0.65	0.65–0.89	0.50–0.63	0.54–0.65
Cumulative mean difference, mm	–20 to 20	–20 to 6	–20 to 20	–20 to 8
<i>Akbura river basin</i>				
No Parameter sets	79	14	540	12
NSE	0.50–0.61	0.50–0.68	0.50–0.65	0.50–0.60
NSE _{log}	0.50–0.72	0.50–0.72	0.50–0.77	0.50–0.77
R ²	0.50–0.67	0.51–0.72	0.50–0.69	0.52–0.61
Cumulative mean difference, mm	–20 to 20	–20 to 19	–20 to 20	2 to 19
<i>Kurshab river basin</i>				
No Parameter sets	55	19	449	18
NSE	0.50–0.65	0.50–0.65	0.50–0.66	0.50–0.58
NSE _{log}	0.50–0.71	0.50–0.81	0.50–0.71	0.50–0.76
R ²	0.51–0.68	0.52–0.70	0.50–0.66	0.54–0.69
Cumulative mean difference, mm	–20 to 20	–17 to 18	–20 to 20	–1 to 20
<i>Shakhimardan river basin</i>				
No Parameter sets	174	66	102	64
NSE	0.50–0.70	0.50–0.80	0.50–0.64	0.50–0.80
NSE _{log}	0.50–0.76	0.50–0.85	0.50–0.77	0.50–0.85
R ²	0.51–0.79	0.52–0.87	0.53–0.73	0.52–0.82
Cumulative mean difference, mm	–20 to 20	–20 to 19	–20 to 20	–17 to 20

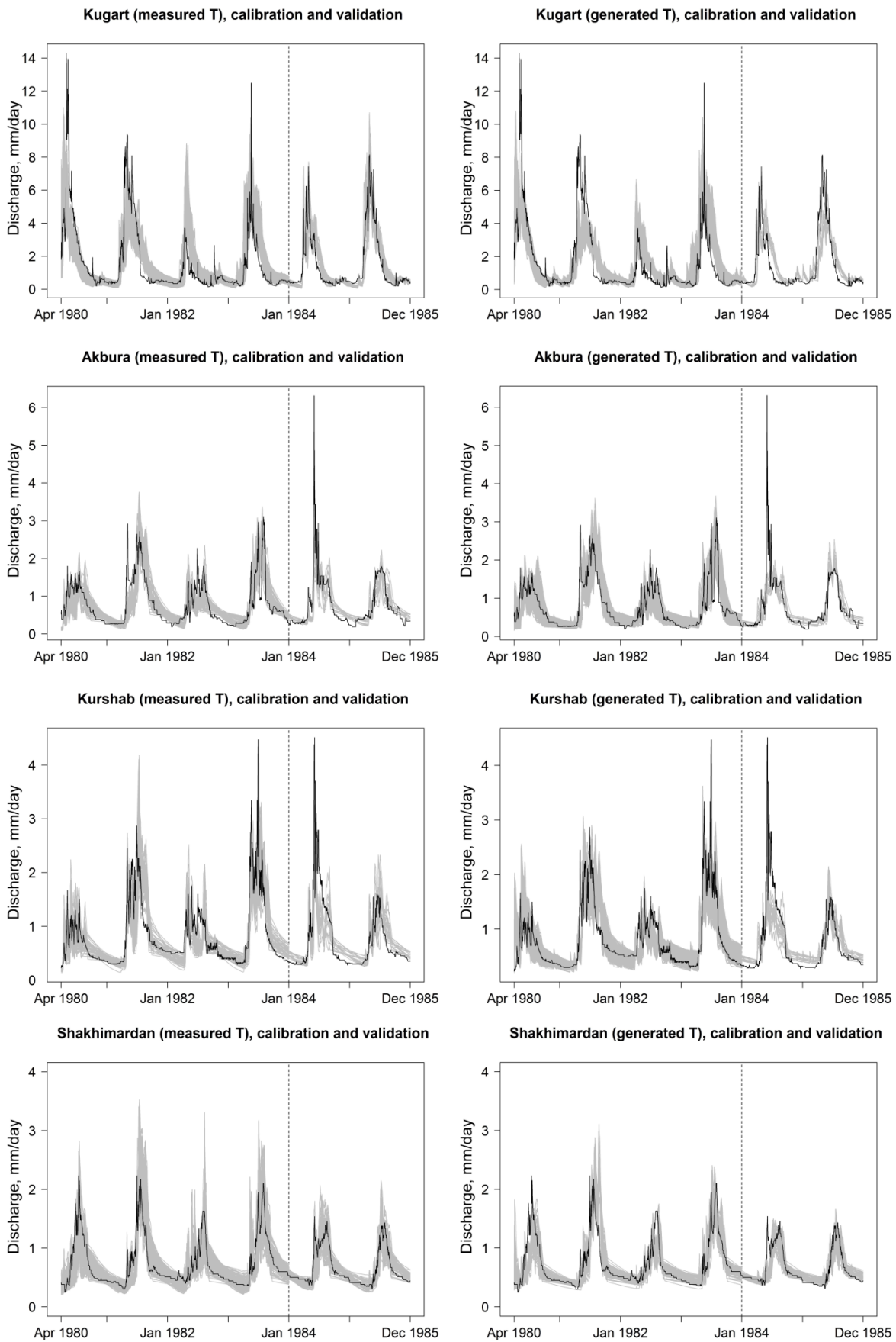


Figure 2-8 Observed (black line) and simulated (grey lines) discharge series for calibration and validation periods (separated by vertical dashed line) using allocated measured (**left**) and generated (**right**) temperature and precipitation data for the studied basins.

Overall, the simulation of hydrological fluxes using HBV-light in combination with MODAWEC input data provided encouraging results, which suggests that using MODAWEC derived data represents a suitable method for water balance assessment in the data-scarce region. The MODAWEC weather generator was also used successfully as pre-processing tool for environmental modeling including the EPIC (Environmental Policy Integrated Climate) model (Liu et al. 2009). In the same study, crop yield and evapotranspiration were similar using measured and generated daily meteorological data. Various other studies employed MODAWEC and report acceptable to very good results (NSE = 0.55–0.93) (Berhane 2011; Khoi and Suetsugi 2012; Mahmood and Babel 2012; Xu et al. 2013).

Furthermore, the results show that HBV-light is an acceptable model to be used in the data scarce application of this study. Similar results for HBV-light have been found by others with NSE ranging between 0.49 to 0.85 in catchments of Central Asia, China, Central and Northern Europe, and Ethiopia (Hagg and Braun 2006; Konz and Seibert 2010; Seibert et al. 2000; Steele-Dunne et al. 2008; Uhlenbrook et al. 2010). For mountainous catchments in the Himalayan and Central Tibetan Plateau, reported NSE values also vary in comparable ranges of 0.43–0.95 (Braun et al. 1993) and 0.67–0.82 (Gao et al. 2012), respectively. Different versions of the HBV models were applied in Central Asia. The HBV-ETH model was used in glacial catchments of Kyrgyzstan (Hagg et al. 2007) and in the Amu-Darya River basin in Tajikistan (Hagg et al. 2013). Their results showed accurate runoff simulations with NSE coefficients between 0.83–0.89 and 0.86–0.94, respectively. For the HBV-IWS version applied in Uzbekistan (Chirchik River) NSE ranged between 0.69 and 0.94 (Gafurov 2005).

The reasons for differences in model performance are manifold, including divergent model structures (HBV-light *versus* HBV-ETH and HBV-IWS), varying geographical and meteorological conditions (*i.e.*, a direct comparison of model performance is only valid if different model structures are applied to the same catchment and same boundary conditions), length and split of calibration and validation periods, methods of calibration, and types of efficiency criteria (we used three validation criteria that must be met by the HBV-light model at the same time, while others used single or different combinations of performance criteria).

The majority of the HBV-light model's parameters were calibrated within moderate parameter ranges comparable to other studies (Uhlenbrook et al. 1999; Steele-Dunne et al. 2008; Konz and Seibert 2010) (Tables 2-5 and 2-6).

Table 2-5 Description of model parameters and their ranges for allocated measured temperature data and calculated precipitation of the four studied catchments.

Parameter	Description/Unit	Min	Max	Min	Max	Min	Max	Min	Max
		Kugart River	Akbura River	Kurshab River	Shakhimardan River				
TT	Threshold temperature/°C	-0.5	1	-0.5	0.5	-0.5	0.5	-0.5	0.5
CFMAX	Degree-day factor/mm·°C ⁻¹ ·d ⁻¹	2	15	2	15	2	15	1	12
SFCF	Snowfall correction factor/-	0.5	3	0.1	1.5	0.1	1.5	0.3	1
CWH	Water holding capacity/-	0.2	0.5	0.05	0.5	0.05	0.5	0.2	0.5
CFR	Refreezing coefficient/-	0.2	0.9	0.05	0.6	0.05	0.6	0.05	0.5
CFGlacier	Glacier correction factor/-	-	-	0.9	1.2	0.8	1.2	0.4	1.3
CFSlope	Slope correction factor/-	-	-	1	1.1	1	1.1	0.6	1.3
Soil and evaporation routine									
FC	Field capacity/mm	50	350	100	350	50	350	250	550
LP	Threshold for reduction of evaporation/-	0.4	1	0.4	1	0.3	1	0.3	1
BETA	Shape coefficient/-	0.3	3	1.5	2.5	1	5	1.5	5
Ground water and response routine									
K1	Recession coefficient (upper box)/d ⁻¹	0.001	0.03	0.01	0.04	0.01	0.04	0.02	0.1
K2	Recession coefficient (lower box)/d ⁻¹	0.005	0.03	0.001	0.01	0.001	0.01	0.001	0.01
PERC	Maximal flow from upper to lower box/mm·d ⁻¹	>0	4	1	4.5	1	4.5	>0	4
MAXBAS	Routing, length of weighting function/d	1	5	1	5	1	5	1	5

The SFCF (Snowfall correction factor) and CFMAX (Degree-day factor) parameters were calibrated within wider ranges. SFCF depends on wind speed and temperature, the greater the wind speed, the greater the SFCF (Goodison, Sevruk, and Klemm 1989; Singh and Singh 2001). In addition, Goodison (1987) showed that the gauge catch efficiency ranges between 23% and 106% due to gauge type and wind speed. Thus, SFCF can reach large values of 1.5 or greater, which was also shown by others

(Braun and Renner 1992; Goodison et al. 1989; Hagg et al. 2013; Konz and Seibert 2010; Mayr et al. 2012). CFMAX is low in forested areas (Martinec and Rango 1986) and high in glacial regions and zones with high elevation and incoming solar radiation (Hock 2003). For example, high values of CFMAX in the Himalayan ranged from 7 to 37 $\text{mm}\cdot\text{day}^{-1}\cdot\text{°C}^{-1}$ on debris cover, and 17 $\text{mm}\cdot\text{day}^{-1}\cdot\text{°C}^{-1}$ over pure ice (Kayastha et al. 2000; Konz et al. 2007). Other findings of CFMAX were 10 $\text{mm}\cdot\text{day}^{-1}\cdot\text{°C}^{-1}$ in Austria and Switzerland (Konz and Seibert 2010) and 14 $\text{mm}\cdot\text{day}^{-1}\cdot\text{°C}^{-1}$ for west China (Matsuda 2003). Hock (2003) reviewed a number of studies and reported maxima of up to 20 $\text{mm}\cdot\text{day}^{-1}\cdot\text{°C}^{-1}$ in Sweden and Greenland. Overall, the ranges used in the present study are relatively high but still in agreement with other published values.

Table 2-6 Parameter ranges for the MODAWEC-generated temperature data allocated to the centroids.

Parameter	Min	Max	Min	Max	Min	Max	Min	Max
Snow routine	Kugart River		Akbura River		Kurshab River		Shakhimardan River	
TT *	-0.5	0.5	-0.5	0.5	-0.5	0.5	-0.5	0.5
CFMAX	2	15	1	15	2	12	1	12
SFCF	1	3	0.1	1.5	0.5	1.5	0.4	1.2
CWH	0.2	0.5	0.1	0.5	0.05	0.5	0.1	0.5
CFR	0.2	0.7	0.3	0.5	0.05	0.6	0.05	0.5
CFGlacier	-	-	0.9	1.2	0.9	1.2	0.5	1.4
CFSlope	-	-	1	1.06	1	1.1	0.6	1.3
Soil and evaporation routine								
FC	150	350	50	350	150	350	250	550
LP	0.5	1	0.4	0.7	0.5	0.9	0.3	1
BETA	0.3	2.5	3	5	1.5	2.5	2	7
Groundwater and response routine								
K1	0.01	0.02	0.01	0.03	0.01	0.04	0.02	0.06
K2	0.009	0.03	0.001	0.003	0.001	0.005	0.001	0.003
PERC	>0	4	0.5	3	>0	3	>0	2
MAXBAS	1	3	1	4	1	5	1	4

* Parameter's description see in Table 2-5.

Scatter plots for all parameters and NSE coefficients of the four catchments were drawn using results of the MODAWEC-driven HBV-light application to perform sensitivity analysis, as suggested by (Hamby 1994; Muleta and Nicklow 2005; Saltelli et al. 1995). Examples of two parameters for the studied basins are presented in Figure 2-9. While PERC was rather constrained for Kugart and Akbura, it was less clear to find optimal parameter values for PERC in the Kurshab and Shakimardan catchments. MAXBAS on the other hand was not constrained for any of the four catchments. We further tested the importance of model parameters for the model outputs by a regression analysis (Muleta and Nicklow 2005; Saltelli et al. 2000), for which results are given in Table 2-7. The importance of the predictors indicates the influence of the parameters on the model's efficiency coefficients (NSE, NSE_{log}). The regression technique is used among other studies for evaluation of parameter influence on the results (Chao et al. 2008; Hamby 1994; Schielzeth 2010). In addition, Hamby (1994) noticed that parameter sensitivity analyses contribute to output uncertainty reduction and identifiability of parameters which require additional research. The stepwise regression models were calculated using dependency of NSE and NSE_{log} coefficients on HBV-light parameters accordingly for different vegetation zones (Jha 2011), since the snow and soil routine are calculated individually for each vegetation zone (Seibert 2005). The adjusted coefficients of determination for the NSE and NSE_{log} vary from 0.25 to 0.86 and from 0.26 to 0.98 (Table 2-7). In general, the adjusted coefficients of determination are higher in validation, which indicates better explanation of the variability in the model's efficiency coefficients because of parameter combination (Perry et al. 2004). The total number of parameters in the regression models varies from 2 to 18 (Table 2-7). The standardized beta coefficients are included in the table only if they are statistically significant (p -value ≤ 0.05). The beta values determine how strongly the parameters affect the dependent variable. The higher the beta value the greater the contribution of a parameter to model results (Perry et al. 2004). In addition, Cramer and Howitt (2004), Miller (2001) and Nathans et al. (2012) reported that the standardized beta coefficients vary from -1 to 1 and show the decrease or increase in the dependent variable accordingly. Thus, in the studied catchments PERC and K1 have significant influences on the goodness-of-fit coefficients with inverse relationship (0.412 – 0.936) and positive direction (0.548 – 0.730) accordingly. In general, the following parameters are relevant for high-flow simulations: PERC, CFMAX, SFCF, CWH, K1, and LP. The most important parameters responsible for recession flows are PERC, CFMAX and TT, followed by K1, Alpha, LP and CWH.

Harlin and Kung (1992) carried out a parameter sensitivity analysis of HBV-light in Sweden and reported that SFCF, MAXBAS, CFMAX and K1 were the most sensitive parameters. Ma (2013) applied HBV-light in North-Eastern Germany, and revealed that the most sensitive parameters were SFCF, CFMAX, FC (Field capacity), LP (Limit for potential evaporation), BETA (Shape coefficient), Alpha, K1 and MAXBAS (Length of triangular weighting function). In an Ethiopian case study

Uhlenbrook et al. (2010) derived FC, PERC, BETA and K2 as most sensitive, while K1, MAXBAS, PERC, FC, BETA and LP proved to be relevant for a US catchment (Abebe et al. 2010). Lidén and Harlin (2000) used the HBV-96 model in four different climate zones and found out that the most important parameters for the model are the routing parameter MAXBAS and the recession coefficient KHQ, whereas FC and PERC were insensitive. Obviously, there is not a single most important parameter for HBV applications, but MAXBAS was most often found to be sensitive followed by FC, BETA, K1, as well as LP, SFCF and CFMAX. Surprisingly, MAXBAS was a rather insensitive parameter in our model application. We explain this by the importance of snow and glacial melt that drives the hydrology in the studied catchments.

Finally, we investigated the interaction between the parameters using correlation analysis (Liu et al. 2009). Correlations between parameters were analyzed for each catchment with both measured and MODAWEC-generated time series. Instead of many pages of tables, Table 2-8 summarizes the ranges of all correlation coefficients for each catchment. The linear relationship among parameters was mainly weak. Moderate correlations (0.4–0.6) were mainly found between PERC and K2, Alpha and K1, SFCF with CWH (Water holding capacity), BETA, LP, and CFMAX with SFCF, CFGlacier, TT and CFR for the studied catchments. These results indicate a large equifinality of parameters (Allen et al. 1998) and many unconstrained parameters.

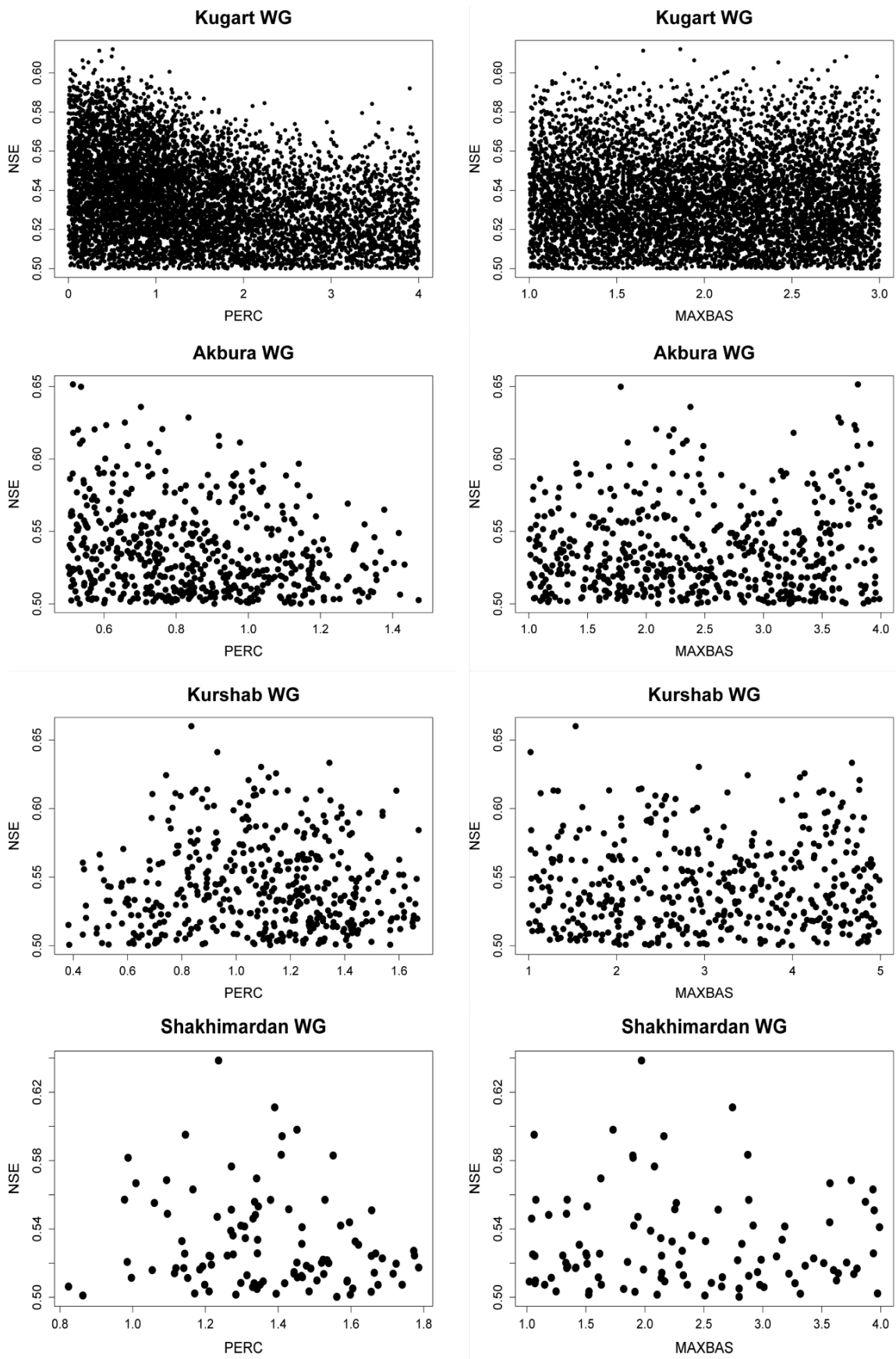


Figure 2-9 Examples of scatter plots with sensitive (PERC) and insensitive (MAXBAS) parameters for the four studied catchments with MODAWEC generated temperature data.

Table 2-7 Contribution of parameters in HBV-light model for the four studied catchments based on the adjusted coefficient of determination and standardized beta coefficient (VZ * = vegetation zone).

		Kugart WG				Akburu WG				Kurshab WG				Shakhimardan WG				
		Calibration		Validation		Calibration		Validation		Calibration		Validation		Calibration		Validation		
	<i>Dependent</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	
	<i>R² adjusted</i>	0.25	0.38	0.75	0.52	0.28	0.77	0.86	0.98	0.30	0.44	0.64	0.95	0.29	0.26	0.76	0.86	
№	Parameters	Standardized Beta Coefficient																
1	PERC	-0.412	-0.368			-0.201	-0.826		-0.493	-0.127	-0.579	-0.851	-0.887			-0.432	-0.819	-0.936
2	Alpha		0.326					-0.453	-0.382		-0.116							
3	K1	0.029	0.195	0.730	0.508		-0.067	0.548		-0.183	-0.258							
4	K2	0.166	0.027			-0.201				-0.090	0.095							0.133
5	MAXBAS		-0.019															
6	TT_VZ*1	-0.085	-0.120	-0.598	-0.646					-0.088								
7	CFMAX_VZ1	0.029	0.407															
8	SFCF_VZ1	0.043	-0.155							0.186								
9	CFR_VZ1	-0.042	-0.027						-0.134	0.116	0.089							
10	CWH_VZ1	-0.043	-0.047															
11	CFGlacier_VZ1	-	-	-	-							-0.515		0.229				
12	CFSlope_VZ1	-	-	-	-							-0.072						
13	FC_VZ1		-0.026							-0.095								
14	LP_VZ1	0.060											0.164		-0.258	-0.193	-0.132	
15	BETA_VZ1		0.073							0.085		-0.381						
16	TT_VZ2	-0.046	-0.062			-0.173				-0.275	-0.073							
17	CFMAX_VZ2	-0.297	0.068			0.162	-0.103	-0.403	-0.549	0.353								
18	SFCF_VZ2	0.231	0.116			-0.194												
19	CFR_VZ2	-0.076																
20	CWH_VZ2	0.036				-0.174				-0.357	-0.135							
21	CFGlacier_VZ2	-	-	-	-													
22	CFSlope_VZ2	-	-	-	-													
23	FC_VZ2		-0.062			-0.087	-0.103			-0.206								
24	LP_VZ2	0.148					0.077			-0.128	-0.131							

Table 2-7 Cont.

		Kugart WG				Akburu WG				Kurshab WG				Shakhimardan WG			
		Calibration		Validation		Calibration		Validation		Calibration		Validation		Calibration			
<i>Dependent</i>		<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>	<i>NSE</i>	<i>NSE_{log}</i>		
R² adjusted		0.25	0.38	0.75	0.52	0.28	0.77	0.86	0.98	0.30	0.44	0.64	0.95	0.29	0.26	0.76	0.86
№	Parameters	Standardized Beta Coefficient															
25	BETA_VZ2	-0.180	0.175							0.100	0.110						
26	TT_VZ3	-	-	-	-	0.247											
27	CFMAX_VZ3	-	-	-	-	-0.400				-0.258	-0.079					0.449	0.341
28	SFCF_VZ3	-	-	-	-	0.335	-0.050			0.171			-0.129	0.293			
29	CFR_VZ3	-	-	-	-									-0.198			
30	CWH_VZ3	-	-	-	-	0.270	-0.097										
31	CFGlacier_VZ3	-	-	-	-												
32	CFSlope_VZ3	-	-	-	-												
33	FC_VZ3	-	-	-	-		-0.064			-0.112	-0.099						
34	LP_VZ3	-	-	-	-				0.166	-0.096	-0.092			0.395			
35	BETA_VZ3	-	-	-	-		0.045							0.202			
	Total	16	17	2	2	11	9	3	5	18	13	3	3	5	2	3	4

Table 2-8 The range of correlation coefficients among the parameters generated using the MC method for the studied basins. NA = not available, parameter is only needed for glaciated catchments.

Parameters	Akburu		Akburu_WG		Kugart		Kugart_WG		Kurshab		Kurshab_WG		Shakhimardan		Shakhimardan_WG	
	max	min	max	min	max	min	max	Min	max	min	max	min	max	min	max	min
PERC	0.4	-0.2	0.4	-0.1	0.3	-0.1	0.4	-0.1	0.3	-0.2	0.3	-0.1	0.3	-0.1	0.4	-0.3
Alpha	0.2	-0.3	0.1	-0.1	0.1	-0.6	0.0	-0.3	0.3	-0.3	0.1	-0.4	0.1	-0.1	0.3	-0.2
K1	0.3	-0.3	0.1	-0.2	0.1	-0.2	0.0	-0.1	0.2	-0.3	0.1	-0.1	0.3	-0.2	0.3	-0.2
K2	0.2	-0.3	0.1	-0.3	0.2	-0.3	0.1	0.0	0.2	-0.3	0.1	-0.3	0.3	-0.3	0.1	-0.3
MAXBAS	0.2	-0.2	0.1	-0.1	0.0	0.0	0.0	0.0	0.3	-0.3	0.1	-0.1	0.2	-0.2	0.2	-0.1
TT	0.3	-0.3	0.1	0.0	0.0	-0.1	0.0	0.0	0.3	-0.3	0.1	-0.1	0.2	-0.2	0.2	-0.2
CFMAX	0.4	-0.2	0.1	-0.1	0.1	-0.1	0.1	-0.1	0.3	-0.3	0.1	-0.1	0.2	-0.1	0.2	-0.2
SFCF	0.2	-0.3	0.1	-0.1	0.1	-0.6	0.3	-0.3	0.5	-0.6	0.1	-0.2	0.2	-0.3	0.4	-0.1
CFR	0.2	-0.1	0.1	-0.1	0.0	-0.1	0.0	0.0	0.2	-0.4	0.1	-0.1	0.2	-0.1	0.2	-0.1
CWH	0.2	-0.2	0.1	-0.1	0.0	0.0	0.0	0.0	0.2	-0.3	0.1	-0.1	0.1	-0.1	0.2	-0.1
CFGlacier	0.2	-0.2	0.1	0.0	NA	NA	NA	NA	0.4	-0.4	0.1	-0.1	0.1	-0.1	0.2	-0.3
CFSlope	0.2	-0.3	0.1	-0.1	NA	NA	NA	NA	0.4	-0.2	0.1	-0.1	0.1	-0.1	0.1	-0.1
FC	0.2	-0.2	0.1	-0.1	0.0	0.0	0.0	0.0	0.2	-0.2	0.1	-0.1	0.1	-0.2	0.2	-0.1
LP	0.2	-0.3	0.1	-0.1	0.1	0.0	0.1	0.0	0.3	-0.3	0.1	-0.2	0.2	-0.2	0.3	-0.2
BETA	0.1	-0.2	0.1	-0.1	0.0	-0.1	0.1	-0.1	0.2	-0.3	0.1	0.0	0.1	-0.1	0.2	-0.2

2.4 Conclusions

We have developed a stratified approach to overcome data scarcity and investigate water resource availability for an agricultural hot spot within semi-arid Central Asia. The data scarcity problem associated with shortages in complete temporal coverage and spatial coverage in the studied mountainous area was resolved by inserting a sequence of pre-processing steps including application of lapse rate, simple linear and multiple linear regression methods. In addition, the MODAWEC weather generator was tested for its applicability as a converter of monthly temperature data into daily values for further research in the study area (*i.e.*, catchments with only monthly temperature data). The uncertainty arising from possible errors in hydrometeorological data, gaps filling procedure, parameters identification was reduced using a Monte Carlo simulation approach, the equifinality concept, and a number of goodness-of-fit criteria (NSE, NSE_{\log} , mean difference in annual water balance, coefficient of determination) with acceptable thresholds. With respect to the relatively short validation period the results indicated acceptable goodness-of-fit. Therefore, the study suggests that HBV-light in combination with MODAWEC input data proves to be an applicable tool to simulate water resources for the four river catchments in the Ferghana Valley. Accordingly, we aim at applying the developed approach to the remaining catchments in the area in the near future. Future research would profit from more thorough definitions of the ranges of parameters during calibration. This will allow narrowing of behavioral parameter sets and thus improvement of model output.

3 Climate change impacts on runoff in the Ferghana Valley (Central Asia)

Abstract

The main freshwater source of arid/semi-arid Central Asia is stored in its high mountain glaciers. Water for the downstream countries is mainly supplied through the Syrdarya River that originates at the confluence of the Naryn and Karadarya rivers in the Ferghana Valley. Runoff generation from glaciers plays a crucial role, although a considerable number of small tributaries supply the river with additional runoff from snowmelt and rain in the mountains surrounding the Ferghana Valley. Observations of rising air temperature and accelerated glacier shrinkage make it most likely that the relative contributions of the smaller tributaries will increase. Hitherto, assessments of climate change effects on the water resource availability have largely neglected the growing importance of the runoff from smaller tributaries. We used a dynamically downscaled A1B SRES scenario for climate change effects for the period 2071–2100 in relation to the reference period of 1971–2000 and a version of the conceptual hydrological Hydrologiska Byråns Vattenavdelning model (HBV-light) to estimate runoff contributions with particular respect to the small tributaries. The simulations showed a 12–42% decrease in summer runoff; and a 44–107% increase in winter-spring runoff. This indicates the hydrological regime is shifting towards a runoff from snowmelt earlier in the year. The study suggests that actions for climate change adaptation should be complemented by land management configured to secure optimal runoff supplement from the smaller catchments.

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3.1 Introduction

Freshwater from the Central Asian mountain systems ensures the livelihood of more than 100 million people in downstream countries (Aizen et al. 2007; Hagg et al. 2007). Its dominant source areas are the high-mountain glaciers and permafrost of the Tien Shan and Pamiro-Alay systems. In addition, snow and rain contribute to freshwater storage in unglaciated areas. The melt water from glaciers and snow plays a crucial role in runoff generation, and is especially important for the intense irrigated agriculture in the arid and semi-arid regions of Central Asia during summer (Hagg et al. 2007).

The current understanding is that global warming will accelerate in the 21st century if the concentration of greenhouse gas emissions is not reduced (Collins et al. 2013). During 1901–2009, the mean winter air temperature (November–March) has increased by 2.4°C in the semi-arid regions of Asia (Christensen et al. 2013). Based on 1986–2005 climate data, different scenarios predict an increase of 0.6–4.4°C in the global mean surface air temperature by 2100 (Collins et al. 2013). Climate records of 1900–2005 show a significant increase in precipitation in Central Asia (Solomon 2007), and the latest projections of future annual precipitation indicate larger changes in precipitation as reported in the 5th Coupled Model Intercomparison Project (CMIP5) (Collins et al. 2013).

Glaciers are very sensitive to climatic changes and indicative of global warming (Aizen et al. 2007). The glacier melting in the Tien Shan has accelerated since the 1970s and continued into the 21st century (Aizen et al. 2007). Increases in temperature and the corresponding shift to rainfall reduces snow accumulation and the albedo of glacier surfaces, which in turn causes glacier shrinkage (Ageta et al. 2001). A significant decrease in the global glacier mass during 2003–2009, especially in high-mountain Asia, Arctic Canada and Alaska, and the southern Andes has been reported (Gardner et al. 2013). Monitoring data indicate a reduction of glaciers in the Northern Tien Shan by 32% (Bolch 2007), by 29% in the Western Tien Shan (Vilesov and Uvarov 2001), 23% in the Central Tien Shan (Khromova et al. 2003), and 36% in the Alay mountains (Konovalov and Shchetinnicov 1994). Projections for the period 2006–2100 suggest reduction of individual glaciers of up to 90%, and a mean reduction for all Central Asian glaciers to 55-75% (Field et al. 2014; Radić et al. 2014).

The Syrdarya River is a main artery of freshwater in the Ferghana Valley. It is basically formed by the confluence of the Naryn and Karadarya Rivers, which are mainly fed by the snow and glacier melt in the high mountain ranges of the Tien-Shan system. With respect to the climate change effects mentioned above, some studies project the runoff supplying the

Syrdarya River to decrease by 10–25% by 2100 (Nohara et al. 2006; Sehring and Diebold 2012). Albeit, it has been suggested by Immerzeel and Bierkens (2012) that there is only an average risk level for the river's water balance because of the high uncertainty in future precipitation patterns. The aforementioned studies estimate potential changes in runoff by considering the release of water from glacier and snow melt. However, considering an increase in air temperature and accelerated glacier melt (Aizen et al. 2007), the annual runoff will most likely increase in the short term and decrease in the long term. Additionally, the topographic openness of the Ferghana Valley bears greater potential in the future to direct moist air from the west towards the high mountain ranges with subsequent adiabatic cooling and increasing precipitation (Price 1986). Hence, it appears to be of great importance to study the potential impact of climate change on the runoff generation of those small upstream catchments surrounding the Ferghana Valley. To date, studies have mostly disregarded the runoff from upstream catchments that feed the Syrdarya River mainly with the rain and snowmelt from the mountainous area (Figure 3-1, Table 3-1). Understanding of this runoff contribution is lacking, as in particular the expected seasonal changes in precipitation patterns are likely to increase the relevance of those smaller tributaries. The main objective of the present study was therefore to assess the climate change impact on the water resources that are generated by smaller tributaries in the Tien Shan and Alay mountains (Figure 3-1). We hypothesize that tributaries from 18 upper catchments significantly contribute to total discharge of the Syrdarya River in the Ferghana Valley (Radchenko et al. 2014):

1. The contribution of tributaries will increase under climate change, as glacier runoff will be reduced by 2100.
2. Discharge will peak earlier in the year in the course of climate change.

For this study, we used data from 18 tributaries that surround the Ferghana Valley (Figure 3-1). Data scarcity represented a major obstacle to the study objectives, although the same applies to most of Central Asia (Radchenko et al. 2014; Unger-Shayesteh et al. 2013). Hence, we selected the hydrological model HBV-light for our study, which requires a minimum set of input data. The model has proved applicable for climate change studies of mountain regions in Europe (Bergstrom et al. 2001), Canada (Dibike and Coulibaly 2005; Stahl et al. 2008), and Asia (Akhtar et al. 2008; Akhtar et al. 2009; Chen et al. 2012; Chen et al. 2012; Gao et al. 2012; Hagg et al. 2007; Kang et al. 1999). Still, pre-processing and gap-filling of the limited and incomplete daily meteorological observations was necessary.

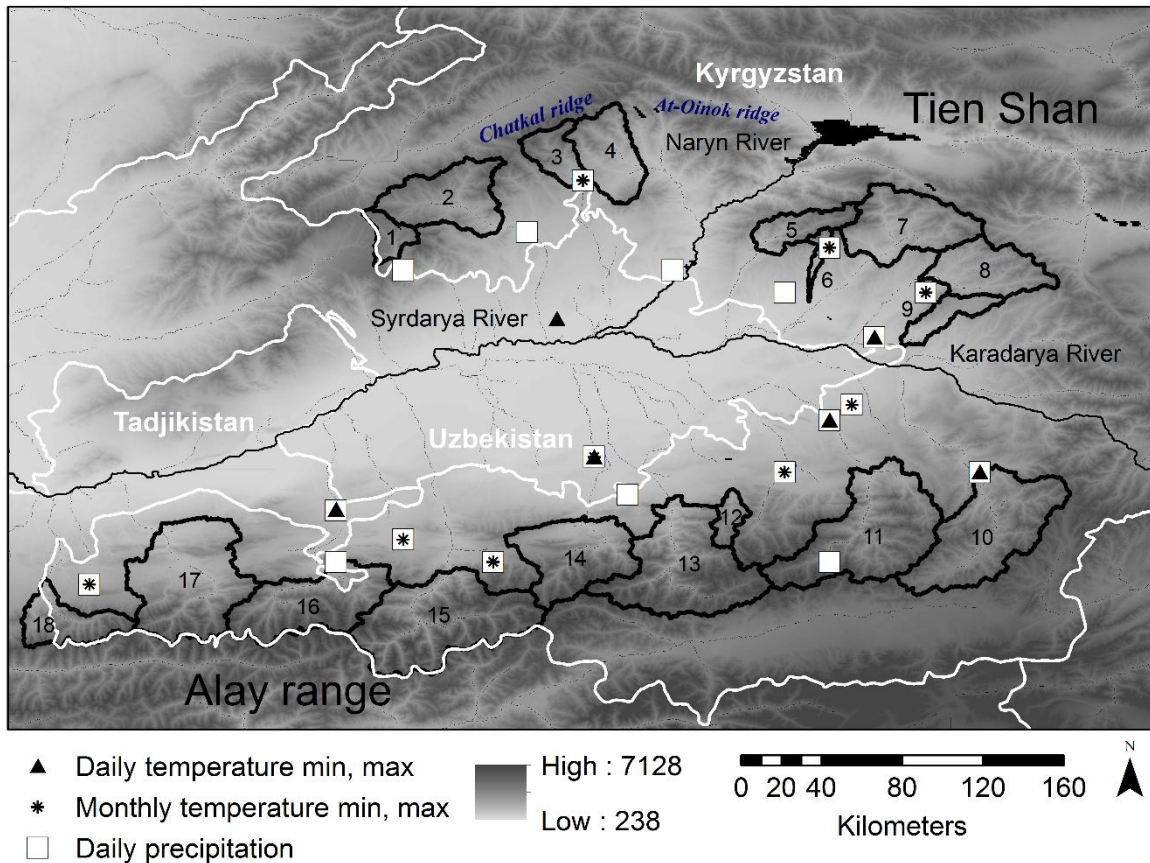


Figure 3-1 The Ferghana Valley with the 18 investigated catchments and available climate data. The white line indicates country boundaries, the black line catchment boundaries.

The uncertainty in model parameters was assessed using Monte Carlo simulations and an equifinality-based approach (Beven and Binley 1992; Beven and Freer 2001; Freer et al. 1996; Steele-Dunne et al. 2008; Uhlenbrook et al. 1999). The uncertainty of the likely glacier retreat in the glacierised catchments in the south of the valley (Table 3-1) was considered through a sensitivity analysis (Akhtar et al. 2008; Hagg and Braun 2006; Rees and Collins 2006; Stahl et al. 2008). The results of our study provide detailed insight into the potential climate change impact on the runoff generation from small tributaries in the Ferghana Valley.

Table 3-1 Geographical and hydro-meteorological characteristics of the 18 catchments.

Catchment	Area	Altitude	Mean elevation	Discharge	Precipitation	Temperature	Forest	Cropland/ Grassland	Sparsely vegetated/ Bare land	Glaciers	Orientation
	[km ²]	[m]	[m]	[mm]	[mm]	[°C]	[%]	[%]	[%]	[% (km ²)]	
1 Gavasay	361	1,716	2,803	364	908	0.7	–	92	8	–	Northern
2 Kassansay	1,130	1,350	2,535	166	897	2.3	1	95	4	–	Northern
3 Padshaata	366	1,536	2,685	400	971	1.8	1	88	8	3 (11)	Northern
4 Aflatun	863	2,000	1,965	392	808	6.0	7	91	1	1 (9)	Northern
5 Maylisuu	530	985	2,459	482	845	5.8	10	87	1	2 (11)	Eastern
6 Shidansay	126	1,016	1,946	433	714	8.8	8	92	–	–	Eastern
7 Tentyaksay	1,300	1,023	2,217	638	802	7.2	17	81	1	1 (13)	Eastern
8 Kugart	1,010	1,168	2,418	536	797	3.2	21	79	–	–	Eastern
9 Changet	381	813	1,703	162	604	6.5	41	59	–	–	Eastern
10 Kurshab	2,010	1,543	3,093	276	689	–1.3	14	58	24	4 (80)	Southern
11 Akbura	2,260	1,327	3,186	275	718	–1.3	3	52	37	8 (181)	Southern
12 Abshirsay	230	1,500	2,654	205	609	2.8	15	68	17	–	Southern
13 Isfiramsay	2,220	1,017	3,248	262	703	–0.8	–	53	38	9 (200)	Southern
14 Shakhimardan	1,180	1,065	2,761	251	596	1.9	–	65	32	3 (35)	Southern
15 Sokh	2,480	1,140	3,421	557	699	–1.0	–	41	48	11 (273)	Southern
16 Isfara	1,560	1,283	3,158	269	647	0.3	–	11	82	7 (109)	Southern
17 Khodjabakirgan	1,740	1,730	2,392	179	525	3.9	2	79	16	3 (52)	Southern
18 Aksu	712	1,100	2,816	148	751	1.6	–	10	88	2 (14)	Southern

3.2 Materials and Methods

3.2.1 Study Area

The elevation of the Tien Shan and Alay mountains (Figure 3-1) ranges from 800 to 5,500 m a.s.l. The mean elevation of the 18 chosen catchments varies from 1,703 to 3,421 m a.s.l. (Table 3-1). The catchment areas range between 126 and 2,480 km². Based on FAO (Food and Agriculture Organization) land-use data (Team 2007), the dominant land-cover type is grassland at higher elevation and cropland at lower elevation of the catchments (10–95%), followed by sparsely vegetated/bare lands (1–88%) and forests (1–41%). The glacial cover varies from 1 to 11% (9–273 km²) (Landsat Multispectral Scanner System (MSS)).

Topography and elevation play a crucial role for the climate of the Ferghana Valley (Aizen et al. 1995). With the valley mouth located to the west, the climate differs from most of Central Asia. The northern ridges protect the valley from arctic air masses (Aizen et al. 1995; Aizen et al. 1997), and the north–south oriented Ferghana ridge provides a mountain barrier that forces westerly air flows to rise, leading to cloud formation and precipitation (Aizen et al. 1995; Aizen et al. 1997; Alam and Kidwai 1987). Ferghana Valley is characterized by hot summers and warm winters. Precipitation and temperature for the centroids (mean elevations) of the 18 catchments range between 525 and 971 mm year⁻¹ and -1 and 9°C, respectively (Table 3-1).

The main source of water in the Ferghana Valley is the Syrdarya River with a total discharge of about 38–39 km³ year⁻¹ draining into the Aral Sea basin. 70–74% of the runoff of Syrdarya River basin originates in Kyrgyzstan mountain ranges (Belyaev 1995; Dukhovny and Schutter 2010; Savoskul et al. 2003). According to the State Water Cadastre and Global Runoff Data Centre database (1980–1985), the 18 catchments in relation to the two rivers Naryn and Karadarya contribute about 34% (7 km³ year⁻¹) to the upper part of Syrdarya River within the Ferghana Valley (Castles et al. 2005; Gafurov et al. 2006). The discharge distribution for the 18 tributaries varies from 148 to 638 mm year⁻¹ (0.05–1.4 km³ year⁻¹; Table 3-1).

3.2.2 Data

Observed data

The daily runoff data of the 18 catchments were obtained from three sources: the State Water Cadastre through the Central-Asian Institute of Applied Geosciences (CAIAG) and the Kyrgyz-Russian Slavic University (KRSU), as well as the Global Runoff Data Center (GRDC) (Radchenko et al. 2014). The available data encompass the period 1980–1985. Despite the dependence of the Ferghana Valley on water resources and its importance for regional agricultural production, there are no better and longer term time series of discharge measurements available for the area (Radchenko et al. 2014).

Daily temperatures for six climate stations (Figure 3-1) were taken from the National Climatic Data Center (NCDC). The data coverage is on average 78%, and varies from 9 to 99% year⁻¹. Data gaps in temperature were filled either using a linear regression approach between stations for longer gaps and a within-station method based on averaging the previous and the following daily values in the case of daily gaps (Bacchi and Kottegoda 1995; Celleri et al. 2007; Makhuvha et al. 1997). Further nine climate stations from the Geoforschungszentrum (GFZ) in Potsdam only reported monthly means. We used the MODAWEC (MOntlyly to DAily WEather Converter) weather generator for disaggregation of monthly into daily temperature data, see (Radchenko et al. 2014) for further details on the method. The meteorological data were allocated to the centroids of the catchments using lapse rate and multiple linear regression methods. The lapse rates for the temperature data were calculated for each month because of the intra-annual variability. Daily precipitation was calculated for the centroids of the catchments using the relationship of precipitation with latitude and elevation of 20 precipitation gauging stations (Figure 3-1).

Climate scenario

Projections of local climate cannot be derived from global General Circulation Models (GCM) as current limitations of computational power reduce their spatial resolutions to 100–300 km (Giorgi et al. 2001; Grotch and MacCracken 1991; Houghton 2009). Therefore, Regional Climate Models (RCM) with resolution of 10–50 km were developed (Christensen and Christensen 2007; Giorgi et al. 2001; Houghton 2009) to process the available

information on local topography, land use and clouds. We used previously published dynamically downscaled data (Mannig et al. 2013) from the RCM REMO (REgional MOdel), which is driven through simulations of the GCM ECHAM5 (European Center model with HAMburg physics). REMO is capable of simulating precipitation and air temperature in Central Asia in accordance with observations (Mannig et al. 2013). The periods 1971–2000 and 2071–2100 were chosen as the baseline and the simulation period for future runoff in the 18 Ferghana Valley mountainous catchments, respectively.

To compare potential future changes with current conditions, we used the commonly applied SRES A1B scenario for the simulation period. It features a medium increase in greenhouse gas emissions in comparison with other SRES scenarios (Ines and Hansen 2006). The scenario assumes rapid economic growth including balanced usage of fossil fuel and non-fossil fuel energy sources, as well as an increase of population until the mid-century and a decrease in the second part of the century (Bernstein et al. 2007; Houghton 2009; Nakicenovic and Swart 2000). Similar to the procedure with the observed data, the A1B scenario data were allocated to the centroids of the 18 catchments. We used the lapse rate and multiple linear regression approaches accordingly to account for temperature dependence on elevation and precipitation dependence on elevation and latitude.

The REMO data was corrected using statistical bias correction, which includes deriving a transfer function between simulated and observed data using empirical or theoretical cumulative distribution functions (CDFs) (Mannig et al. 2013). For temperature, a linear transfer function was derived for the empirical CDFs, i.e. corrected values are a linear function of simulated values, and the coefficients are obtained through the relationship between observed and simulated CDFs during the baseline period. If T_{min} and T_{max} are corrected independently, a large error in the daily temperature cycle might occur. Therefore, we do not correct both variables independently, but correct the skewness ($T_{sk} = (T_{mean} - T_{min}) / (T_{max} - T_{min})$) and temperature range ($T_r = T_{max} - T_{min}$) instead. (Piani et al. 2010) have shown that the resulting error in T_{min} and T_{max} is in the range of the error of a direct bias correction. The transfer function for the temperatures was defined for each day of the year by applying a moving window of 30 days around each day. Therefore, with a 30-year baseline, each transfer function is based on 930 values.

Projected precipitation was corrected by distribution based quantile mapping. Distributions were fitted to modeled and observed data of the baseline period. Then, for each modeled

value, its corresponding cumulative probability on the constructed CDF (of modeled data) is determined. Based on this probability, the corrected value is searched on the quantile function of observed data (Ines and Hansen 2006). To fit CDFs to the lower 80% of precipitation values, the Gamma distribution was used, and for a better representation of extreme values, the General Pareto Distribution for the remaining 20% of data values. For precipitation, one transfer function was defined for each month (Ines and Hansen 2006). For further details on the methods applied see (Mannig et al. 2013).

3.2.3 Hydrological model set-up

HBV-light model

The hydrological HBV model (Bergström 1992; Bergstrom 1976) was developed at the Swedish Meteorological and Hydrological Institute and has been applied widely in Europe, Asia and other parts of the world (Abebe et al. 2010; Akhtar et al. 2008; Braun and Renner 1992; Driessen et al. 2010; Hagg et al. 2007; Konz and Seibert 2010; Lindström et al. 1997; Moore 1993; Seibert et al. 2000). We used a recent version of the HBV-light model that also considers runoff generation from glaciated areas. HBV-light is a semi-distributed model that allows (a) the division of a river catchment into several sub-catchments, and (b) the separation of an area into different elevation and vegetation zones. The model requires daily input data on temperature, precipitation, potential evapotranspiration and discharge. The HBV-light model is composed of four routines: snow, soil, groundwater and routing. The algorithm for snow accumulation and snowmelt/glacier melt is based on the daily temperature degree-day method. Additionally, we consider the aspect and correction factor for the melt (Konz and Seibert 2010; Seibert and Vis 2012). In the soil and groundwater routines the water storage properties and evaporation play the leading roles. Finally, the computed discharge is simulated by a triangular weighting function. In addition, there is a built-in routine to run Monte Carlo simulations for calibration and batch simulations for validation procedures. Further information on the specific model set up in the Ferghana Valley region is given in (Radchenko et al. 2014).

To run HBV-light potential evapotranspiration (PET) data are required as model input. We applied the widely used FAO model CROPWAT 8.0 to estimate monthly PET for current climate (1971-2000) and for future projection (2071-2100). CROPWAT 8.0 is based on the Penman-Monteith method and requires monthly maximum and minimum temperatures,

elevation, latitude and longitude information (Smith 1992). PET data were calculated for the centroids of each of the 18 catchments.

Calibration and Validation

Model calibration and validation was challenging due to limited data availability in space and time. The general modeling concept used in the study presented here was tested in a previous study for four out of the 18 catchments where comprehensive daily data are available (Radchenko et al. 2014). The HBV-light model was calibrated for 14 of the 18 catchments from 1980 to 1983. Due to a lack of daily runoff in four catchments, the calibration period was set to 1980–1982 (Changet), 1981–1983 (Abshirsay), 1980–1981 (Khodjabakirgan) and January–June 1981 (Aksu) (Figure 3-2).

The parameters of the HBV-light model were calibrated using a Monte Carlo simulation procedure that is inbuilt to the model. The parameter ranges (Table 3-2) were selected using information from a previous study in the Ferghana Valley (Radchenko et al. 2014). The model contains parameters that are responsible for snow and glacier melt (7), soil and evaporation (3), ground water and response (4) routines. Taking into consideration the equifinality concept (Beven and Binley 1992; Beven and Freer 2001; Freer et al. 1996; Steele-Dunne et al. 2008; Uhlenbrook et al. 1999), which states that there is no one optimal parameter set but several behavioral or acceptable parameter sets, we applied 1,000,000 model runs and selected behavioural parameter sets considering three goodness-of-fit criteria given in Table 3-3. We then used the selected behavioral parameter sets for the validation runs and again selected those parameter sets that performed well according our goodness-of-fit criteria (Table 3-3).

Table 3-2 Groups of catchments and the goodness-of-fit criteria used for model evaluation. NSE=Nash Sutcliff Efficiency, log=logarithmized

Group	Catchment	NSE	NSE _{log}	Bias
1	Abshirsay, Akbura, Aksu, Isfiramsey, Khodjabakirgan, Kugart, Kurshab, Padshaata, Shakhimardan, Shidansay, Sokh	≥0.5	≥0.5	±20 mm yr ⁻¹
2	Aflatun, Changet, Isfara, Kassansay, Maylisuu, Tentyaksay	≥0.4	≥0.4	±50 mm yr ⁻¹
3	Gavasay	≥0.4	≥0.4	±100 mm yr ⁻¹

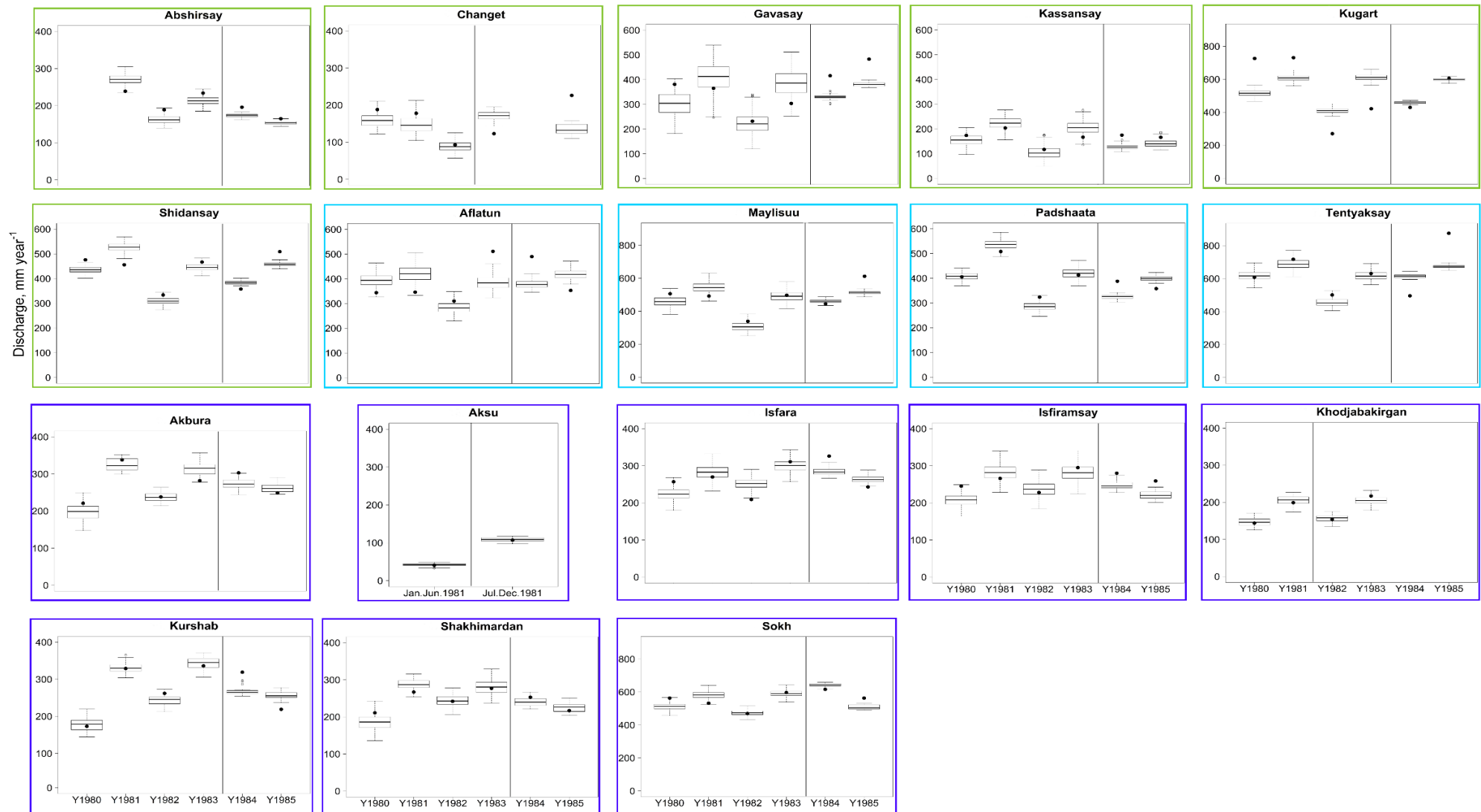


Figure 3-2 Measured (dot) and simulated (box plots) range of annual runoff for the period 1980–1985. Colours indicate different glacier coverage: non-glacierised (green), slightly-glacierised (turquoise) and glacierised (blue) catchments. Whiskers of box plots indicate 5 and 95% percentiles, the boxes the 25 and 75% percentiles and the black line the median of simulations. Note that for Maylisuu, Tentyaksay, Abshirsay, Sokh and Isfara only the best $n=10,000$ model runs are depicted due to its complexity in construction.

Table 3-3 Results of the MC based calibration and validation runs for HBV-light for the 18 catchments with three levels of likelihood functions (in brackets; for definition of likelihood function see Table 3-2). n=accepted parameter sets; NSE = Nash Sutcliff Efficiency; log = logarithmized, green = non-glacierised, turquoise = slightly-glacierised, blue = glacierised catchments.

Goodness-of-fit criteria	Calibration	Validation	Calibration	Validation
	<i>Abshirsay (1)</i>		<i>Changet (2)</i>	
Parameter sets	54,346	104	1,284	32
NSE	0.83	0.67	0.71	0.57
NSE log	0.87	0.73	0.62	0.55
Bias [mm]	-20...20	10...20	-50...50	-16...46
	<i>Gavasay (3)</i>		<i>Kassansay (2)</i>	
Parameter sets	5,977	53	1,172	299
NSE	0.68	0.77	0.59	0.80
NSE log	0.84	0.86	0.84	0.88
Bias [mm]	-100...100	76...100	-50...50	3...50
	<i>Kugart (1)</i>		<i>Shidansay (1)</i>	
Parameter sets	2,556	47	891	127
NSE	0.63	0.88	0.82	0.78
NSE log	0.71	0.77	0.82	0.73
Bias [mm]	-20...20	-20...6	-20...20	-5...20
	<i>Aflatun (2)</i>		<i>Maylisuu (2)</i>	
Parameter sets	11,048	416	53,512	963
NSE	0.68	0.55	0.75	0.67
NSE log	0.66	0.58	0.83	0.77
Bias [mm]	-50...50	-34...50	-50...50	12...50
	<i>Padshaata (1)</i>		<i>Tentyaksay (2)</i>	
Parameter sets	906	63	34,653	452
NSE	0.75	0.65	0.79	0.59
NSE log	0.85	0.83	0.83	0.66
Bias [mm]	-20...20	-8...20	-50...50	9...50
	<i>Akbura (1)</i>		<i>Aksu (1)</i>	
Parameter sets	79	14	2,098	122
NSE	0.61	0.68	0.75	0.74
NSE log	0.72	0.72	0.80	0.84
Bias [mm]	-20...20	-20...19	-20...20	-20...19
	<i>Isfara (1)</i>		<i>Isfiramsay (2)</i>	
Parameter sets	45,939	360	1,705	70
NSE	0.86	0.92	0.61	0.66
NSE log	0.90	0.91	0.73	0.76
Bias [mm]	-20...20	-20...20	-50...50	15...50

	<i>Khodjabakirgan (1)</i>		<i>Kurshab (1)</i>	
Parameter sets	88	54	55	19
NSE	0.81	0.83	0.65	0.65
NSE log	0.82	0.78	0.71	0.81
Bias [mm]	-20...20	-11...19	-20...20	-17...18
	<i>Shakhimardan (1)</i>		<i>Sokh (1)</i>	
Parameter sets	174	66	78,114	29
NSE	0.70	0.80	0.78	0.71
NSE log	0.76	0.85	0.87	0.80
Bias [mm]	-20...20	-20...19	-20...20	1...20

As mentioned, the behavioural parameter sets (Beven and Binley 1992; Beven and Freer 2001; Freer et al. 1996) were selected based on three, equally weighted goodness-of-fit criteria: (1) Nash Sutcliff efficiency (NSE) that especially considers the fit of modelled runoff peaks. (2) NSE of log-transformed flow (NSE_{log}) that places emphasis on the recession and low flows. (3) Difference in the water balance described by the bias that plays an important role in assessing the availability of water resources in the long term (Table 3-3). Considering the differences in data quality (i.e. completeness of observed data), three levels of threshold criteria were applied (Table 3-2):

The behavioural parameter sets were validated for the period 1984–1985 in the aforementioned 14 catchments with the best data availability. With respect to limited daily discharge data for four catchments, the validation period was adapted for Changet (1983, 1985), Khodjabakirgan (1982–1983), Aksu (July–December, 1981) and Abshirsay (1984–1985). Table 3-3 presents the results of behavioral parameter sets that were obtained during calibration and validation. These final behavioural parameter sets were then used to run the HBV-light model for the baseline and future projections.

Glacier cover and glacier change scenarios

Glacier and snowfield extent was calculated for the glacierised catchments (Table 3-1) based on Landsat MSS satellite images, available from the United States Geological Survey – Landsat MSS platform. The selection criteria for images were availability and cloudless properties. Therefore, we used images from the period 1972–1979. For visual comparison, we used also physical and glacier maps derived from aerial photographs in the 1960s and satellite images from 1977–1980 (Kuzmichenok 2009). Using this information, the 18 catchments were classified into non-glacierised (Gavasay, Kassansay, Shidansay, Kugart, Changet, Abshirsay), slightly-glacierised (Padshaata, Aflatun, Maylisuu, Tentyaksay) and glacierised

(Kurshab, Akbura, Isfiramsay, Shakhimardan, Sokh, Isfara, Khodjabakirgan, Aksu) (Table 3-1).

The impact of different stages of glacier cover (100%, 50% and 0%) on the runoff was also studied in Central Asia, Pakistan and Austria (Akhtar et al. 2008; Hagg and Braun 2006). To account for climate change and resulting glacier change others suggested to reduce glacier area by removal from elevation bands (Rees and Collins 2006; Stahl et al. 2008). In order to account for the uncertainty in future glacier coverage, we applied a glacier sensitivity analysis according to the latter approach by means of stepwise elimination of glacier cover at each elevation band (elevation range of elevation bands was 500 m) starting with the lowest elevation band. The removed glacier cover is treated as sparsely vegetated/bare land type. We then projected discharge for each glacier realization along with the current glaciation distribution as a benchmark.

It should be noted that the stepwise elimination of glacier cover method has some limitations since it does not consider the real dynamics of glacier melt. However, we applied this kind of sensitivity assessment since the simulation of glacier dynamics is complex and it requires additional data of glacier characteristics (mass balance measurements, ice thickness, snow water equivalent, albedo, solar radiation, wind speed etc.) that are not available in our study area. We consider that the climate change will continuously influence glacier recession, and we assume that the glaciers will most likely disappear or remain at high elevations only. Therefore, we particularly pay attention to those glacier change scenarios that are most likely by 2100.

3.3 Results

3.3.1 Calibration and validation

The HBV-light model was calibrated and validated in total for the 18 tributaries using a Monte Carlo based approach considering parameter uncertainty. We then investigated how potential climate change affects the future water resources availability in the Ferghana Valley. For this, we compared results of the ensemble model runs of the baseline period with future projection runs under the assumption of stable model parameters.

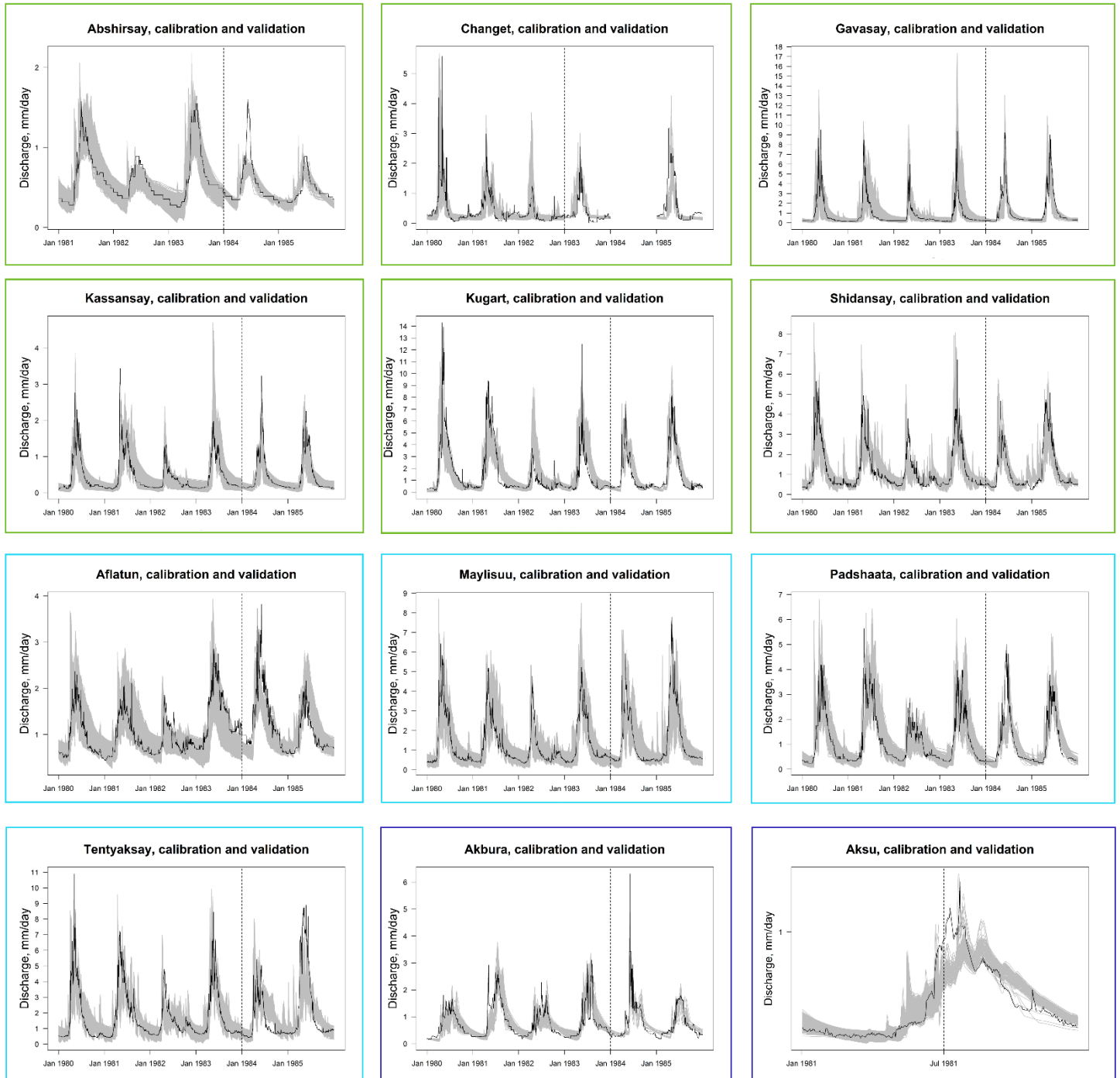
The upper limit of NSE varied from 0.59 to 0.86 for the calibration period and from 0.55 to 0.92 for the validation period (Table 3-3). Similarly, NSE_{\log} ranged from 0.62 to 0.90 for the

calibration period and from 0.55 to 0.91 for the validation period. For eight catchments (44%), we found better results in the validation period with regard to both NSE and NSE_{log}. Improvements were only found for glacierised and non-glacierised catchments but not for slightly-glacierised ones. This could hint at a problem with HBV-light in simulating such intermediate catchments. However, this observation could also be attributed to the lower quality of discharge data available and the resulting likelihood group 2 to which three out of the four slightly-glacierised catchments belong (Table 3-3). Overall, the behavioral parameter sets ranged from n=88 to n=78,114 through the calibration period and n=29 to n=963 in the validation period (Table 3-3). Obvious is the tremendous drop in the number of behavioral parameter sets from calibration to validation, such as in the Abshirsay, Isfara or Sokh catchments. HBV-light shows a lower range of bias in many catchments in the validation period with a tendency to overestimate discharge, indicated by biases with larger values above than below zero (Table 3-3). The NSE_{log} was most often superior compared to the NSE, revealing that the efficiency of HBV-light to simulate discharge peaks was less, compared to simulating low or moderate flows.

For the calibration period, the measured annual runoffs are within the range of simulated runoffs for most years and most catchments (Figure 3-2). Only the Kugart catchment shows somewhat larger deviations, as the HBV-light model overestimates the first half of the calibration period 1980 and 1981 and underestimates the second part 1982 and 1983. Results during the validation period scatter slightly more. Here larger variation was found between measured and modeled discharge for six catchments, i.e. Aflatun, Changet, Gavasay, Kurshab, Padshaata, Tentyaksay (Figure 3-2). However, there was no clear pattern with regard to under- or overestimation and the NSE during the validation period ranged between 0.55 and 0.77 for these catchments (Table 3-3). HBV-light shows generally better model performance in glacierised catchments.

The simulated daily runoff and associated uncertainties, and thus the temporal behavior of the HBV-light models for the 18 catchments during the calibration and validation period, is depicted in Figure 3-3. HBV-light is able to match most peaks and simulates the base flow well. The uncertainty bands capture most flows, despite that the model tends to overestimate peaks in the calibration period. This is likely explained by an overestimation of snowmelt in the spring-summer period. In the validation period, simulated and observed discharge are in agreement. Some problems occur in simulating the high flows in June 1984, for instance in the Abshirsay, Akbura and Kurshab catchments. Overall, considering the match of annual

simulated and measured flows given in Figure 3-2, the temporal model behaviour and its uncertainty depicted in Figure 3-3, as well as the model's summary statistics shown in Table 3-3, we conclude that the HBV-light model is applicable for the study area.



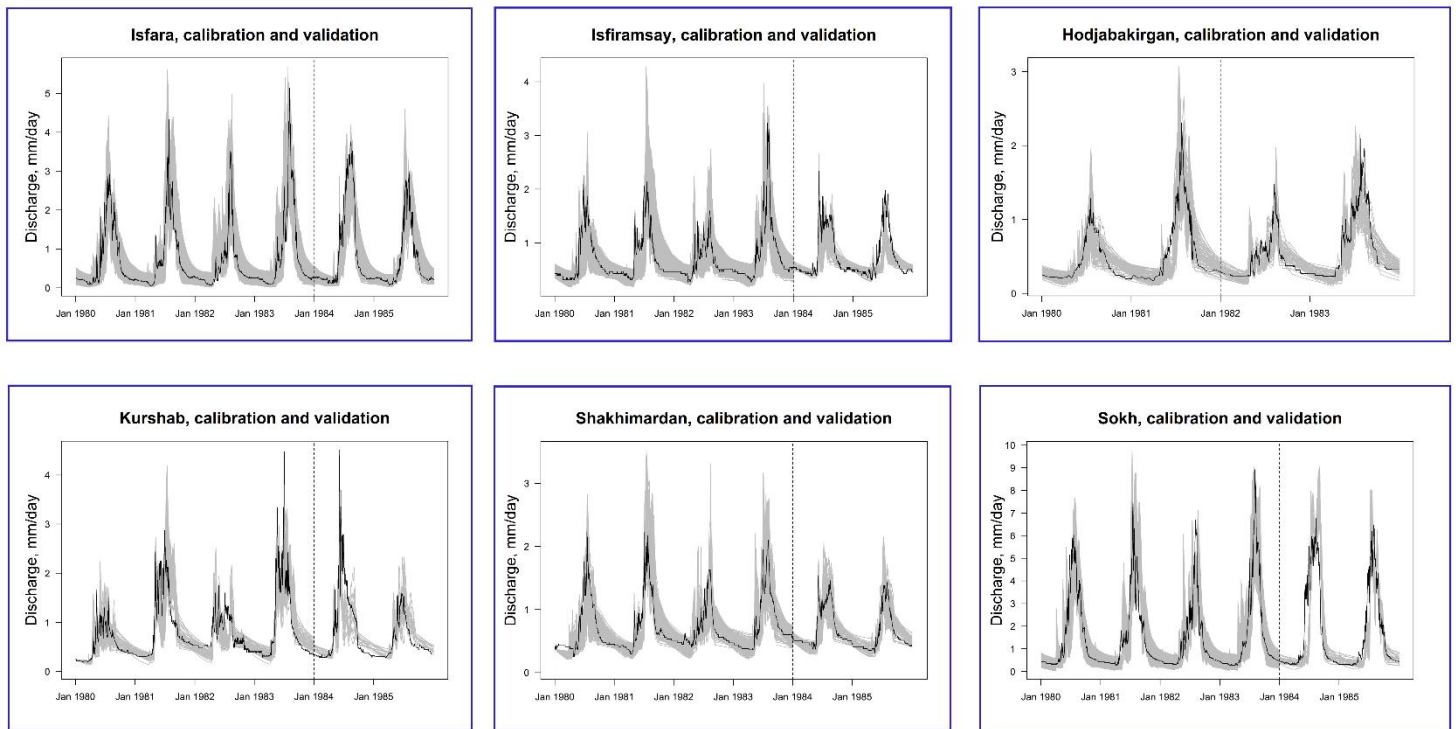


Figure 3-3 Measured (black line) and simulated (grey lines) runoff for calibration and validation periods (separated by vertical dashed line) for 18 catchments (non-glacierised (green), slightly-glacierised (turquoise) and glacierised (blue) catchments).

3.3.2 Climate change projection

The A1B scenario for the 18 catchments projects an increase in annual temperature by 3.7–3.9°C and in precipitation by 11–13% (71–108 mm) for the future period (2071–2100) in relation to the baseline period (1971–2000). The average (30-year monthly mean) projected changes in precipitation and temperature for the southern, northern and eastern parts of the Ferghana Valley (Table 3-1) within the period 2071–2100 are shown in Figure 3-4. The monthly temperatures in the study area increase by 2.7–4.7 °C with maxima in October–November, a secondary maximum in February for the eastern, in March for the northern and in April for the southern regions. Minima in January are projected for the southern and northern regions, and in May for the eastern region. Figure 3-4 also shows that the temperature for the eastern region changes differently compared to the northern and southern regions for January–March. The temperature change will influence evapotranspiration and lead to higher PET, particularly in summer. An increase in monthly precipitation sums of more than 10% (13–30 mm) is projected for November–January, April and July, with a

maximum in November. Precipitation changes for the southern region tend to be higher compared to the other regions. The increases in precipitation predominantly occur in the cold period (October–April); during the irrigation period the changes are small. The increase in precipitation is associated with evapotranspiration increase, which is driven by temperature increase in the region (Solomon 2007).

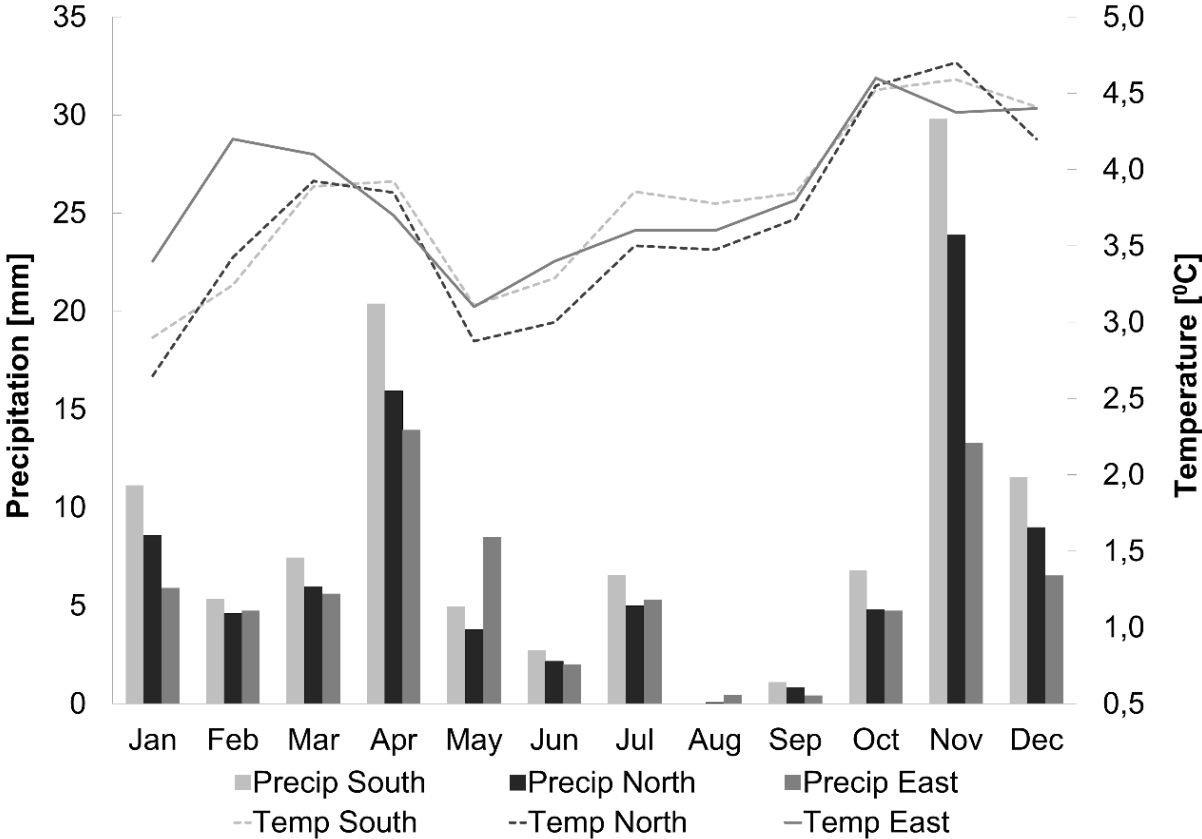
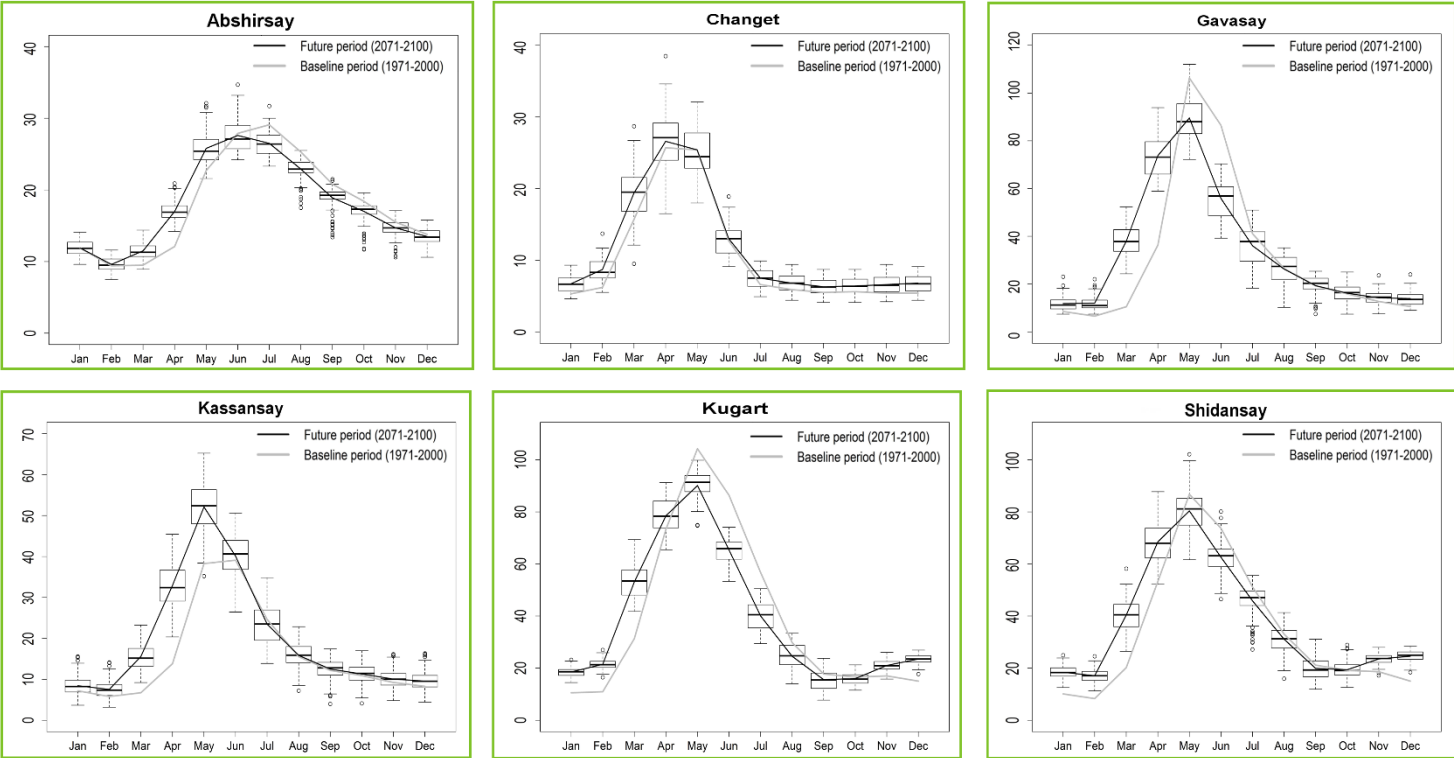


Figure 3-4 Projected precipitation and temperature changes in the Ferghana Valley under the A1B SRES scenario.

The results of runoff simulation for the baseline (1971–2000) and future periods (2071–2100) using the SRES A1B projections are presented in Figure 3-5. Overall, runoff increases in non-glacierised catchments in the cold period (October–April) and decreases in the warm period (May–September). Discharge still peaks in May, and only in the Kassansay catchment it moves from June to May and in the Abshirsay catchment it moves from July to June. On average the height of the peaks decrease. In slightly glacierised catchments, the future projections of runoff show an increase in January–May and a decrease in June–November. Peaks of runoff remain in May, and only in the Padshaata and Aflatun catchments they move from June to May. The peaks of runoff decrease in the Aflatun and Tentyaksay catchments, increase in the Padshaata catchment, and stay almost the same in the Maylisuu catchment.

Box plots show the uncertainty of the runoff projections. The spread of runoff given all behavioral parameter sets is generally higher for spring and summer seasons and lower for winter and autumn (Figure 3-5). For some catchments the parameter uncertainty in projections is apparent for only a few months (e.g. Akbura, Kurshab), whilst for other catchments it is dominant for much of the runoff season (Changet, Tentyaksay).

A sensitivity analysis on the effects of glacier coverage and its reaction to climate change was carried out for all glacierised catchments (Akbura, Aksu, Isfara, Isfiramsay, Khodjabakirgan, Kurshab, Shakhimardan, Sokh; Figure 3-5). It shows the potential runoff generation under different glacier coverage scenarios starting with current glaciation and continues with reduction in glacier coverage at each elevation zone per 500 m. Runoff with climate change projection and current glacier cover is highest. With a reduction in glacier coverage per elevation zone, we found decreasing discharge peaks, particularly in the late summer time and a shift of these peaks towards early summer and even spring. Only in the Isfiramsay and Shakhimardan catchments do the runoff patterns remain almost stable and peaks remain in July. The decrease in runoff of the eight glacierised catchments will affect their current contribution of $4 \text{ km}^3 \text{ yr}^{-1}$ (20% in comparison with the Karadarya and Naryn Rivers) to the discharge of the Syrdarya River (Radchenko et al. 2014). Therefore, our projection shows a decrease to about $3.5 \text{ km}^3 \text{ yr}^{-1}$. However, some of the reduced glacier melt water will probably be compensated for by an increase in precipitation (Figure 3-4).



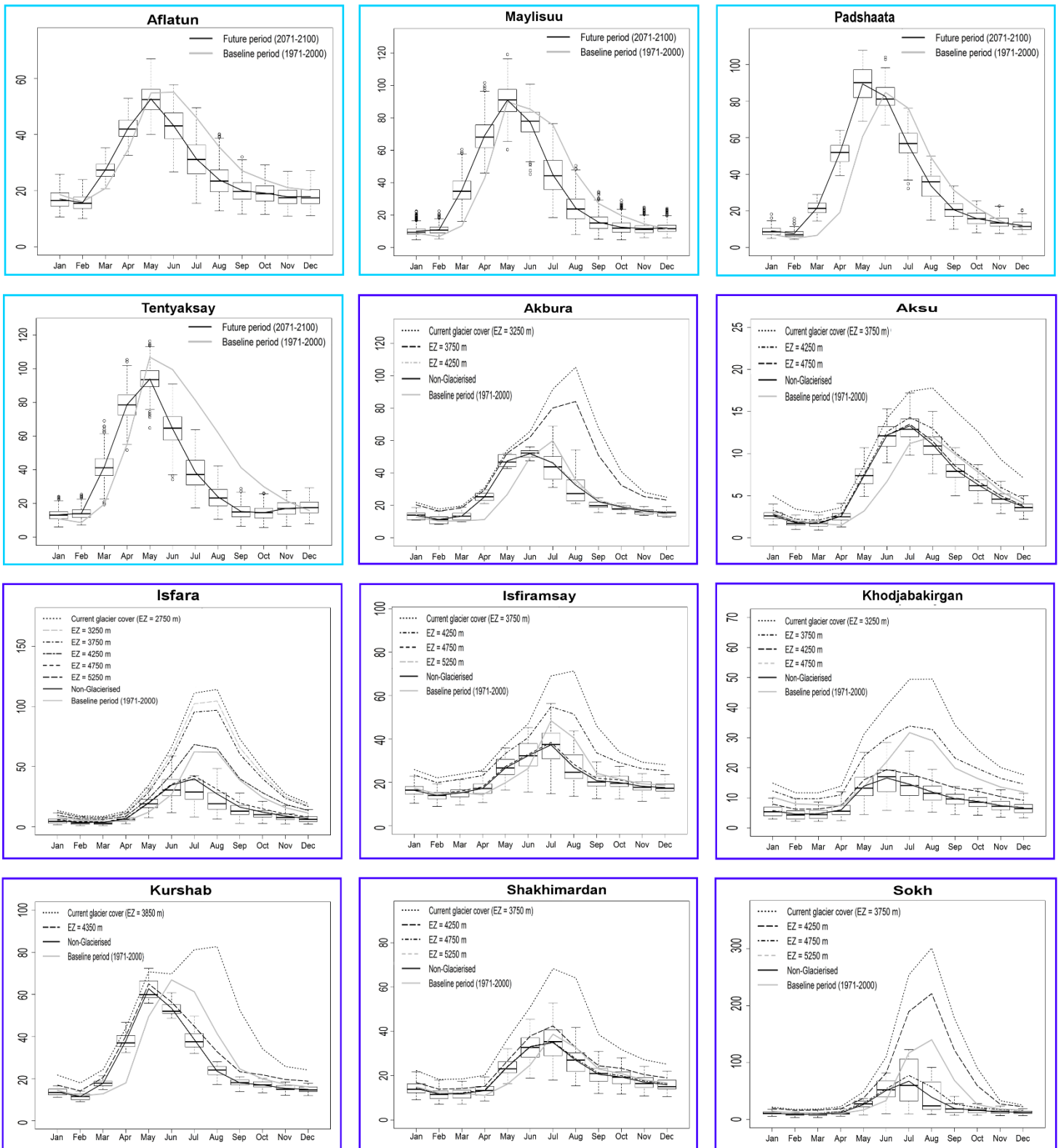


Figure 3-5 Mean runoff simulations under the A1B SRES scenario for the baseline (1971–2000) and future (2071–2100) periods with different glacier scenarios and elevation zones (EZ). Means are calculated from the range of behavioral parameter sets. Box-plots show range of monthly behavioral parameter sets for future projections (not shown for baseline projection for better reading). Grey and black line show mean runoff as obtained from the behavioral parameter sets. Colours indicate different glacier coverage: non-glacierised (green), slightly-glacierised (turquoise) and glacierised (blue) catchments.

The relative and projected change of runoff under the assumption of the scenario with no glacier cover for the catchments in the Ferghana Valley is shown in Figure 3-6. Seasonal runoff in non-glacierised catchments increases by 4–14 mm (2–101%) in January–May and October–December with a maximum in March, and it decreases by 1–10 mm (2–12%) in June–September with a minimum in June. For slightly-glacierised catchments the future runoff is projected to increase in a similar range of 1–18 mm (2–107%) in winter and spring. However, projected decreases in June–November are substantially larger, up to 21 mm (15–37%). The projections for glacierised catchments are somewhat similar to the slightly glacierised catchments with monthly increases in runoff of 3–9 mm (14–44%) for April to June and a decreasing runoff for most of the year that peaks in a reduction of up to 28 mm in August (average reduction 2–42%). On average, the annual runoff in non-glacierised catchments increases by 21 mm (9%), whereas it decreases by 32 mm (5%) and 56 mm (17%) in slightly glacierised and glacierised catchments, respectively.

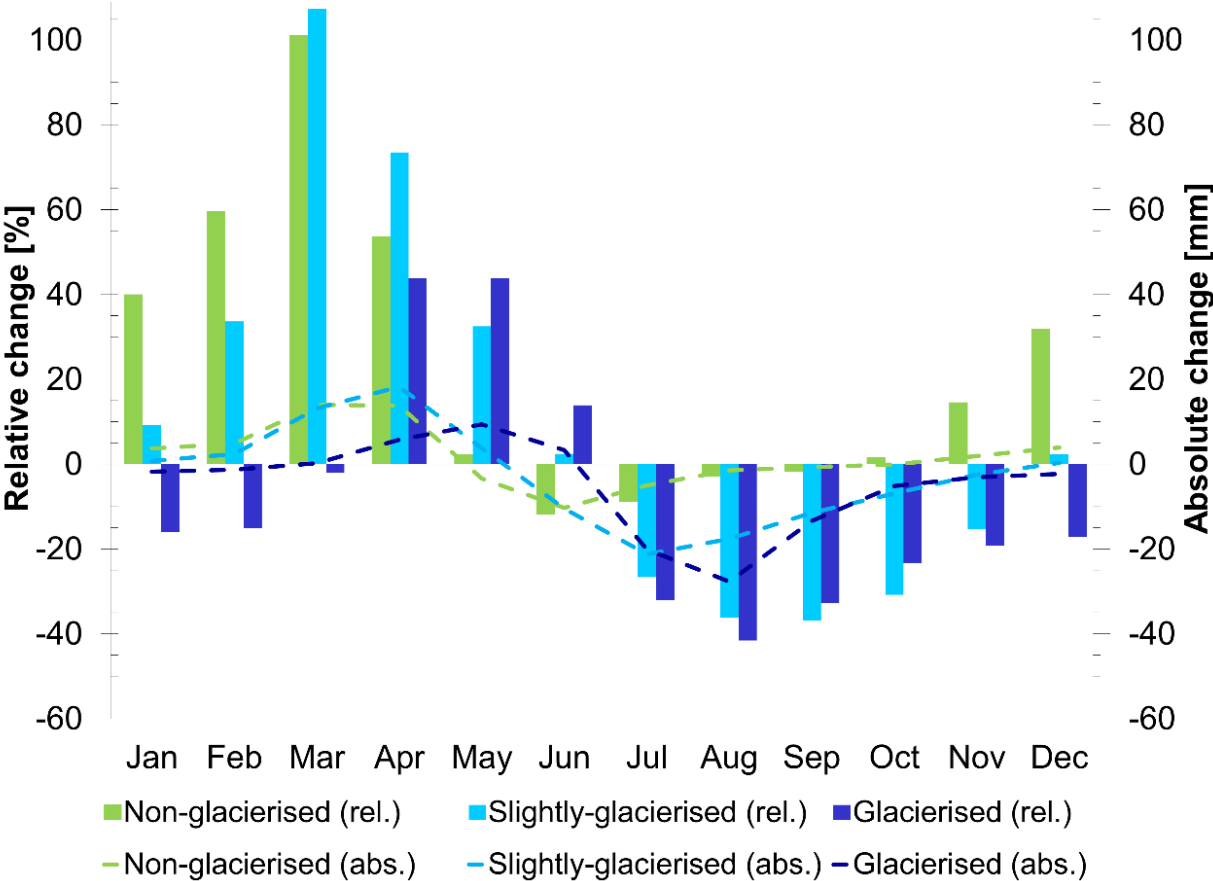


Figure 3-6 Relative and projected change of runoff in the 18 catchments of the Ferghana Valley.

In spite of projected increase in precipitation for all months and for all parts of the study area, the runoff decrease in slightly-glacierised and glacierised catchments is projected by 2100, especially in July-October. For example, the contribution of runoff in July-September in relation to annual runoff is projected to change from 34 to 22% in future period for slightly-glacierised catchments and from 45 to 36% in glacierised catchments. An increase in evapotranspiration and infiltration into non-frozen soil due to temperature rise as well as a decrease of snow accumulation and its further release in form of snowmelt can explain this.

Further investigation was performed on the sensitivity of the hydrological regimes to climate change impact using the Pardé coefficient (Figure 3-7). The Pardé coefficient characterizes the annual distribution of runoff. It is determined by the ratio of mean monthly discharge to mean annual discharge and has a maximum of 12 (Bormann 2010; Meile et al. 2011; Pardé 1933). The Pardé coefficient indicates different runoff regimes: a glacial regime with maximum values of 1.5–2 in July–August, a nival regime with maximum values of 2–3 in May–June and a pluvial regime with maximum values of 3–3.5 in April–May (Pardé 1933). Additionally, the regimes can be classified as glacio-nival (glacial-snow regime) with maximum values of the coefficients from 2 to 3.5 in June–July, nivo-glacial (snow-glacial regime) with maximum values of the coefficients from 2 to 3 in June, nivo-pluvial (snow-precipitation regime) with maximum values of the coefficients from 2 to 3 in May and pluvio-nival (precipitation-snow regime) with maximum values from 1.5 to 2 in April–May (Bormann 2010; Meile et al. 2011). Accordingly, the hydrological regime of non-glacierised catchments in the Ferghana Valley can be described as nival and nivo-pluvial, slightly-glacierised catchments as being nivo-glacial, nival and nivo-pluvial, and finally, glacierised catchments being glacio-nival (Figure 3-7). Considering climate change projections, the hydrological regime is to change in slightly-glacierised catchments to nivo-pluvial and pluvio-niva. Glacierised catchments will change to nivo-glacial and nival. Non-glacierised catchments will stay the same. The results reveal an increase in winter and spring Pardé coefficients and a decrease in summer values for almost all catchments (Figure 3-7). The peaks of the coefficients increase for catchments that are situated in the northeastern part of the Ferghana Valley (Aflatun, Kassansay, Maylisuu), and only for Padshaata it moves one month earlier. Here the Chatkal and At-Oinok ridges conjunct, favoring higher precipitation occurrence that leads to an increase in runoff (Figure 3-1). The peaks of Pardé coefficients shift one month earlier for non-glacierised catchments such as Padshaata, Aflatun and Abshirsay, which can be explained by earlier snowmelt due to an increase in mean monthly

temperatures. For the glacierised catchments Isfara, Isfiramsay and Shakhimardan, the runoff peaks remain in July and for other glacierised catchments they move a month earlier. The peaks of Pardé coefficients for non-glacierised and glacierised catchments indicate a decrease of runoff in summer that can be explained by a decreased contribution of snow and glacier melt, an earlier melt in spring due to temperature rise, and an increase in evapotranspiration. Regarding glacier sensitivity, there is an alteration in the runoff regime of the glacierised catchments with decreasing glacier extent. The main tendency of the runoff regime shifting occurs after a reduction of the glaciers by 50%. In general, the Pardé coefficients show a shift of runoff distribution to earlier months that is driven by climate change, especially in slightly-glacierised and glacierised catchments.

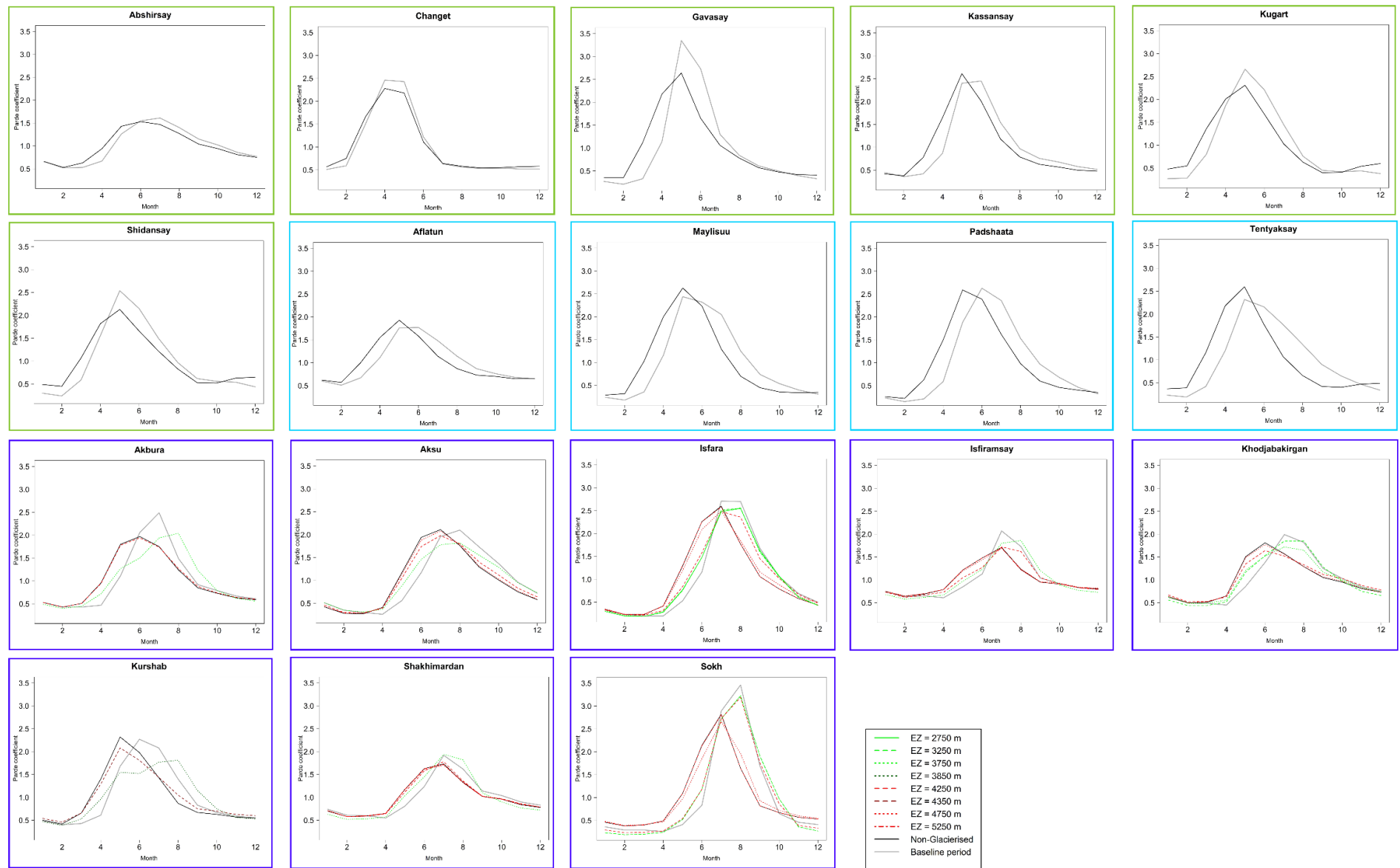


Figure 3-7 Changes in the hydrological regimes of the 18 catchments under different glacier cover conditions per elevation zone (EZ) using Pardé coefficients. Colours indicate different glacier coverage: non-glacierised (green), slightly-glacierised (turquoise) and glacierised (blue) catchments.

3.4 Discussion

Calibration and validation results of the conceptual hydrological HBV-light model suggest that the model can be applied to the data-scarce mountainous area of the 18 catchments in the Ferghana Valley. The Monte Carlo simulations resulted in acceptable goodness-of-fit criteria (Table 3-3) within the defined thresholds (Table 3-2). Our objective was to find behavioural parameter sets that account for peak flows (indicated by an acceptable NSE), but as important, to reveal robust results with regard to total water yields (reflected by a low bias and high NSE_{\log}). The number of behavioural model runs was large in many cases (Table 3-3) and one could question whether it had made sense to increase the acceptance level of the goodness-of-fit criteria. However, we decided *a priori* which acceptance level the models should meet (Table 3-2, criteria in row #1) and only iteratively changed these levels for those catchments where our parameter search was otherwise unsuccessful (Table 3-2, rows #2 and #3). The thresholds we set for NSE were similar to other HBV-light model applications (Plesca et al. 2012; Gao et al. 2012; Seibert 1997), but even higher compared to the $NSE=0.3$ given in (Freer et al. 1996).

The underestimation and overestimation of the simulated annual discharge in the Kugart river catchment can be explained by a relatively large difference of around 400 mm yr^{-1} in the measured discharge between the first part (1980–1981) and the second part (1982–1983) of the calibration period. This difference in annual discharges occurred due to substantially lower precipitation in the second period. HBV-light underestimated annual discharge in five catchments (Changet, Gavasay, Maylisuu, Shidansay, Tentyaksay) in the validation period due to greater water availability (Figure 3-2), and most likely due to the underestimation of precipitation. It has to be noted that we only had data available from a single precipitation gauge for model simulations. Given the large topographic variability in the catchments, there is substantial spatial variability of precipitation in the region (Gao et al. 2012). In contrast the model slightly overestimated the annual discharge over the validation period of another six catchments (Kassansay, Padshaata, Aflatun, Shidansay, Tentyaksay, Kurshab) because of overestimation of snowmelt (Radchenko et al. 2014). Similarly, W. Hagg et al. (2007) noted that HBV underestimated precipitation and overestimated glacial melt in catchments of the Tien Shan and Alay mountains. In addition, Moore (1993) suggested that overestimation of spring snowmelt by the HBV model may be caused by rainfall misclassification.

The analysis of climate change impacts indicates a winter increase and summer decrease of the runoff in the 18 catchments by 2100. Runoff simulations for the period 2071–2100 reveal a significant runoff reduction in glacierised catchments in July–September ($\approx 35\%$), and an increase in non-glacierised catchments in February–April ($\approx 71\%$) (Figure 3-5). The runoff increase in winter–spring and the decrease in summer can be explained by increases in precipitation in winter together with the overall increase in temperature. These changes prevent snowpack accumulation and consequently lead to less runoff in spring and summer (Bormann 2010; Scherrer et al. 2004). The shift of the peak flows to earlier months was observed for both river types subjected to a glacio-nival regime and those with a nival regime (Figure 3-7). This result is in agreement with previous studies conducted in Asia, Canada and Europe (Akhtar et al. 2008; Dibike and Coulibaly 2005; Driessen et al. 2010; Hagg et al. 2007; Kang et al. 1999; Steele-Dunne et al. 2008), which basically suggest a general trend of runoff increasing in winter–spring and decreasing in summer periods, and which includes temporal shift in main discharge (Stahl et al. 2008).

The uncertainty in the model outputs can arise from possible errors in input data, the model structure and parameters definition (Butts et al. 2004; Muleta and Nicklow 2005; Uhlenbrook et al. 1999). The uncertainty in parameter estimation was examined using the Monte Carlo simulation approach (Harlin and Kung 1992; Seibert 1997; Steele-Dunne et al. 2008; Uhlenbrook et al. 1999) and a number of behavioural parameter sets were found both in the calibration as well as validation phase. The uncertainty in climate change assessments may be associated with a specific choice of a general circulation model (GCM), a regional climate model (RCM), the downscaling technique and the climatic scenario (Fowler et al. 2007; Räisänen 2007; Xu et al. 2005). The general circulation model employed in this study (ECHAM5) has been successfully applied in many other studies. For example, (Hagemann et al. 2006) studied the impact of ECHAM5 model resolution on the hydrological cycle. The authors found that precipitation and air surface temperature were simulated reasonably well, and ECHAM5 even captured many regional details in different climate zones. (Jungclaus et al. 2006) emphasize that ECHAM5 also simulates sea surface temperature and sea ice realistically, which is important in climate modeling with respect to its ice-albedo feedback. In addition, the East Asian summer monsoon system was investigated using ECHAM5. The model simulated precipitation in agreement with observed characteristics (Kripalani et al. 2007), and it was one of the best models among the CMIP3 models (phase 3 of the Coupled Model Intercomparison Project) (Song and Zhou 2013). In addition, ECHAM5 model appears

to be one of the favorable GCMs for Antarctic and global research (Connolley and Bracegirdle 2007).

The dynamic downscaling technique proved to be acceptable for mountainous area since RCMs are able to reflect the topography and land cover influence at the local scale, and have a resolution that is suitable for hydrological simulations (Fowler et al. 2007). The RCM REMO applied is able to generate climate data similar to observed data in different climatic zones such as the Baltic Sea drainage basin and South and Central Asia (Haensler et al. 2011). The selected SRES A1B emission scenario is in the medium range of the SRES scenarios (Bernstein et al. 2007) and has been used in different climate studies and zones. For example, the SRES A1B scenario was applied to investigate the climate change impact on water resources on the global scale (Nohara et al. 2006). The study reported that projection of future (2081–2100) changes in discharge varies for different climate zones. (Nohara et al. 2006) suggest increases in runoff by 10–25% in the high latitude zone and of 4–5% in the tropical zone. In contrast, discharge projections for the mid-latitude rainy zone varied between -22% and +10%, and for the arid zone even between dramatic -38% and +12%.

The annual runoff in the 18 catchments of the Ferghana Valley will likely decline by $\approx 10\%$ ($\approx 6.3\text{km}^3$), though an increase in runoff is projected for non-glacierised catchments (Figure 3-6). The growing seasonal runoff (April–October) of the Karadarya River will be reduced by 1% under A scenarios (A1B, A2) for the period 2066–2095 (Dukhovny and Schutter 2010). The runoff simulations during the growing season for the 18 catchments reveal an increase by 5% in non-glacierised catchments, by 1% in slightly-glacierised catchments and a decrease by 1% in glacierised catchments (Figure 3-6). Even though this seems to be negligible, any reduction in water yield with associated increasing PET due to increasing temperatures will have a pronounced effect on irrigation agriculture in the Ferghana Valley. Despite this, a reduction of discharge in the small tributaries is only one part of the story. The runoff projections for the entire Ferghana Valley for the 2080s are reported by (Chub 2007). In his combined A2 and A1B scenario analysis, runoff will decrease by 10–30% in southern parts of the valley (i.e., mainly glacierised catchments) and by 20–30% in northern and eastern parts (non-glacierised and slightly-glacierised) during the growing season (vegetation period). In total, the Naryn and Karadarya runoff will be reduced by even 20%. In turn, this will lead to a gaining importance of the 18 tributaries in sustaining water resource availability in the future. In summary, our results agree with other studies in that future water availability will be shaped by an increase in winter–spring runoff and a decrease in summertime when water is

necessary for irrigation in the Ferghana Valley. While also attesting to a seasonal shift of runoff to the earlier season due to temperature rise, the current study emphasizes the increasing contribution of water from rain and snowmelt in smaller catchments surrounding the Ferghana Valley. Considering a 20% reduction in runoff of the Naryn and Karadarya Rivers (Chub 2007), the contribution of the 18 catchments to the Syrdarya River discharge will increase up to 37% in relation to the large Naryn and Karadarya Rivers, despite a reduction in total discharge of up to 6.3 km³. With respect to options for climate adaptation, our results suggest inclusion of land management and potentially engineering solutions for the area of the smaller catchments to counteract climate change impacts. Possible adaptation methods may include the construction of water reservoirs, rehabilitation of old irrigation systems to reduce water loss, a revision of forest management, and consideration of changes in crop choice and water reuse (Biemans et al. 2011; Field et al. 2014; Ngoundo et al. 2007; Thomas 2008).

3.5 Conclusions

We investigated the climate change impact on water resources in the Ferghana Valley using a hydrological modelling approach and dynamically downscaled SRES A1B climate change scenarios for the future period 2071-2100 under the assumption of stable model parameters. The hydrological modelling approach followed a Monte Carlo simulation technique that is based on the equifinality concept where no unique optimal parameter set exists, but rather several equally good parameter sets can be used for runoff simulations. Overall, the total runoff in the Ferghana Valley is projected to be reduced by $\approx 10\%$. Results for the majority of the 18 studied river catchments reveal a seasonal shift of runoff to earlier phases. Overall, an increase in winter–spring runoff is projected by 44–107% and a decrease in summer runoff is projected by 12–42%. The latter is particularly critical, as water during this time of the year is necessary for irrigation in the Ferghana valley. We conclude that the 18 investigated tributaries will be even more important in terms of contribution to water resources in the Ferghana Valley by 2100. Considering the runoff decrease for the 18 river catchments there is a need to mitigate climate change impact on future water resource availability in the Ferghana Valley. Therefore, adaptation measures may include water reservoirs construction, enhancement of the irrigational systems to reduce water loss, change of crop choice and water reuse.

4 References

Abebe, Nibret A., Fred L. Ogden, and Nawa R. Pradhan. 2010. "Sensitivity and Uncertainty Analysis of the Conceptual HBV Rainfall–runoff Model: Implications for Parameter Estimation." *Journal of Hydrology* 389 (3): 301–10.

Agarwal, Chetan, Glen M. Green, J. Morgan Grove, Tom P. Evans, and Charles M. Schweik. 2002. "A Review and Assessment of Land-Use Change Models: Dynamics of Space, Time, and Human Choice." <http://www.treesearch.fs.fed.us/pubs/5027>.

Ageta, Yutaka, Nozomu Naito, Masayoshi Nakawo, Koji Fujita, Kiran Shankar, Adarsha P. Pokherl, and Dorji Wangda. 2001. "Study Project on the Recent Rapid Shrinkage of Summer-Accumulation Type Glaciers in the Himalayas, 1997-1999." *Bulletin of Glaciological Research* 18: 45–49.

Aizen, V. B., E. M. Aizen, and J. M. Melack. 1995. "Climate, snow cover, glaciers, and runoff in the Tien Shan, Central Asia." *JAWRA Journal of the American Water Resources Association* 31 (6): 1113–29.

Aizen, V. B., V. A. Kuzmichenok, A. B. Surazakov, and E. M. Aizen. 2007. "Glacier Changes in the Tien Shan as Determined from Topographic and Remotely Sensed Data." *Global and Planetary Change* 56 (3): 328–40.

Aizen, Vladimir B., Elena M. Aizen, John M. Melack, and Jeff Dozier. 1997. "Climatic and Hydrologic Changes in the Tien Shan, Central Asia." *Journal of Climate* 10 (6): 1393–1404. doi:10.1175/1520-0442(1997)010<1393:CAHCIT>2.0.CO;2.

Akhtar, M., N. Ahmad, and M. J. Booij. 2008. "The Impact of Climate Change on the Water Resources of Hindukush–Karakorum–Himalaya Region under Different Glacier Coverage Scenarios." *Journal of Hydrology* 355 (1): 148–63.

Akhtar, M., N. Ahmad, and M. J. Booij. 2009. "Use of Regional Climate Model Simulations as Input for Hydrological Models for the Hindukush-Karakorum-Himalaya Region." *Hydrology and Earth System Sciences* 13 (7): 1075–89.

Alam, Shah Manzoor, and Atiya Habeeb Kidwai. 1987. *Regional Imperatives in Utilization and Management of Resources: India and the USSR*. Concept Publishing Company.

Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. 1998. "Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56." *FAO, Rome* 300: 6541.

Allen, Richard G., William O. Pruitt, James L. Wright, Terry A. Howell, Francesca Ventura, Richard Snyder, Daniel Itenfisu, et al. 2006. "A Recommendation on Standardized

Surface Resistance for Hourly Calculation of Reference ETo by the FAO56 Penman-Monteith Method.” *Agricultural Water Management* 81 (1–2): 1–22. doi:10.1016/j.agwat.2005.03.007.

Dankov Artem. 2007. “Ferghana Valley: Problems of Maintaining Economic Stability.” *Central Asia and the Caucasus*, no. 2 (44).

Bacchi, Baldassare, and Nathabandu T. Kottegoda. 1995. “Identification and Calibration of Spatial Correlation Patterns of Rainfall.” *Journal of Hydrology* 165 (1–4): 311–48. doi:10.1016/0022-1694(94)02590-8.

Bárdossy, A., and S. K. Singh. 2008. “Robust Estimation of Hydrological Model Parameters.” *Hydrology and Earth System Sciences Discussions* 5 (3): 1641–75.

Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, et al. 2014. *IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Basist, Alan, Gerald D. Bell, and Vernon Meentemeyer. 1994. “Statistical Relationships between Topography and Precipitation Patterns.” *Journal of Climate* 7 (9): 1305–15.

Belyaev, A. V. 1995. “Water Balance and Water Resources of the Aral Sea Basin and Its Man-Induced Changes.” *GeoJournal* 35 (1): 17–21.

Bergstrom, S. 1976. “Development and Application of a Conceptual Runoff Model for Scandinavian Catchments.”

Bergström, S. 1992. *The HBV Model: Its Structure and Applications*. Swedish Meteorological and Hydrological Institute.

Bergstrom, S., Bengt Carlsson, Marie Gardelin, G. Lindstrom, Anna Pettersson, and Markku Rummukainen. 2001. “Climate Change Impacts on Runoff in Sweden-Assessments by Global Climate Models, Dynamical Downscaling and Hydrological Modelling.” *Climate Research* 16 (2): 101–12.

Berhane, Fisseha G. 2011. “Model Based Assessment of Potential Impacts of Climate Change on the Flow of the Main Headwaters of the Nile River: Equatorial Lakes Region and Blue Nile Basins.”

Bernstein, Lenny, Peter Bosch, Osvaldo Canziani, Zhenlin Chen, Renate Christ, Ogunlade Davidson, William Hare, et al. 2007. “Climate Change 2007: Synthesis Report. An Assessment of the Intergovernmental Panel on Climate Change.” Retrieved March 20: 2011.

Beven, Keith, and Andrew Binley. 1992. “The Future of Distributed Models: Model Calibration and Uncertainty Prediction.” *Hydrological Processes* 6 (3): 279–98. doi:10.1002/hyp.3360060305.

Beven, K., and J. Freer. 2001. "Equifinality, Data Assimilation, and Uncertainty Estimation in Mechanistic Modelling of Complex Environmental Systems Using the GLUE Methodology." *Journal of Hydrology* 249 (1): 11–29.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R. W. A. Hutjes, J. Heinke, W. Von Bloh, and D. Gerten. 2011. "Impact of Reservoirs on River Discharge and Irrigation Water Supply during the 20th Century." *Water Resources Research* 47 (3).

Bolch, T. 2007. "Climate Change and Glacier Retreat in Northern Tien Shan (Kazakhstan/Kyrgyzstan) Using Remote Sensing Data." *Global and Planetary Change* 56 (1): 1–12.

Bormann, Helge. 2010. "Runoff Regime Changes in German Rivers due to Climate Change." *Erdkunde*, 257–79.

Braun, L. N., W. Grabs, and B. Rana. 1993. "Application of a Conceptual Precipitation-Runoff Model in the Langtang Kfaola Basin, Nepal Himalaya." In *Snow and Glacier Hydrology, Proceedings of the Kathmandu Symposium*, Young GJ (ed). IAHS Publ: Wallingford, UK, 221–37.

Braun, L. N., and C. B. Renner. 1992. "Application of a Conceptual Runoff Model in Different Physiographic Regions of Switzerland." *Hydrological Sciences Journal* 37 (3): 217–31.

Bucknall, Julia. 2003. *Irrigation in Central Asia: Social, Economic and Environmental Considerations*. World Bank, Europe and Central Asia Region, Environmentally and Socially Sustainable Development.

Butts, Michael B., Jeffrey T. Payne, Michael Kristensen, and Henrik Madsen. 2004. "An Evaluation of the Impact of Model Structure on Hydrological Modelling Uncertainty for Streamflow Simulation." *Journal of Hydrology* 298 (1): 242–66.

Castles, Stephen, Mark J. Miller, and Giuseppe Ammendola. 2005. "The Age of Migration: International Population Movements in the Modern World: New York: The Guilford Press, 338 Pages."

Celleri, Rolando, Patrick Willems, Wouter Buytaert, and Jan Feyen. 2007. "Space-time Rainfall Variability in the Paute Basin, Ecuadorian Andes." *Hydrological Processes* 21 (24): 3316–27. doi:10.1002/hyp.6575.

Chao, Yi-Chun E., Yue Zhao, Lawrence L. Kupper, and Leena A. Nylander-French. 2008. "Quantifying the Relative Importance of Predictors in Multiple Linear Regression Analyses for Public Health Studies." *Journal of Occupational and Environmental Hygiene* 5 (8): 519–29.

Chen, Hua, Tiantian Xiang, Xing Zhou, and Chong-Yu Xu. 2012. "Impacts of Climate Change on the Qingjiang Watershed's Runoff Change Trend in China." *Stochastic Environmental Research and Risk Assessment* 26 (6): 847–58.

Chen, Hua, Chong-Yu Xu, and Shenglian Guo. 2012. "Comparison and Evaluation of Multiple GCMs, Statistical Downscaling and Hydrological Models in the Study of Climate Change Impacts on Runoff." *Journal of Hydrology* 434: 36–45.

Christensen, Jens Hesselbjerg, and Ole Bøssing Christensen. 2007. "A Summary of the PRUDENCE Model Projections of Changes in European Climate by the End of This Century." *Climatic Change* 81 (1): 7–30.

Christensen, Jens Hesselbjerg, Krishna Kumar Kanikicharla, Gareth Marshall, and John Turner. 2013. "Climate Phenomena and Their Relevance for Future Regional Climate Change."

Chub V. E. 2007. "Climate change impact on the hydrometeorological processes, agro-climatic and water resources in Uzbekistan." Tashkent, VORIS-NASHRIOT. (In Russian).

Collins, M., R. Knutti, J. M. Arblaster, J.-L. Dufresne, Thierry Fichefet, P. Friedlingstein, X. Gao, et al. 2013. "Long-Term Climate Change: Projections, Commitments and Irreversibility."

Connolley, William M., and Thomas J. Bracegirdle. 2007. "An Antarctic Assessment of IPCC AR4 Coupled Models." *Geophysical Research Letters* 34 (22): L22505. doi:10.1029/2007GL031648.

Cramer, Duncan, and Dennis Howitt. 2004. *The SAGE Dictionary of Statistics: A Practical Resource for Students in the Social Sciences*. SAGE.

Daly, Christopher, Ronald P. Neilson, and Donald L. Phillips. 1994. "A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain." *Journal of Applied Meteorology* 33 (2): 140–58.

DeGaetano, Arthur T., Keith L. Eggleston, and Warren W. Knapp. 1995. "A Method to Estimate Missing Daily Maximum and Minimum Temperature Observations." *Journal of Applied Meteorology* 34 (2): 371–80. doi:10.1175/1520-0450-34.2.371.

Dibike, Yonas B., and Paulin Coulibaly. 2005. "Hydrologic Impact of Climate Change in the Saguenay Watershed: Comparison of Downscaling Methods and Hydrologic Models." *Journal of Hydrology* 307 (1): 145–63.

Driessen, T. L. A., R. Hurkmans, W. Terink, P. Hazenberg, P. Torfs, and R. Uijlenhoet. 2010. "The Hydrological Response of the Ourthe Catchment to Climate Change as Modelled by the HBV Model." *Hydrology and Earth System Sciences* 14 (4): 651.

Dukhovny, Victor A., and Joop de Schutter. 2010. *Water in Central Asia: Past, Present and Future*. 1st ed. CRC Press.

Fekete, B., C. Vörösmarty, and W. Grabs. 2002. "Global Composite Runoff Fields on Observed River Discharge and Simulated Water Balances/Water System Analysis Group.

University of New Hampshire, and Global Runoff Data Centre. Koblenz, Federal Institute of Hydrology (BfG).” Koblenz, Germany, Federal Institute of Hydrology (BfG).

Field, C. B., V. Barros, D. J. Dokken, and others. 2014. “Climate Change 2014: Impacts, Adaptation, and Vulnerability.” Volume I: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

Fowler, H. J., S. Blenkinsop, and C. Tebaldi. 2007. “Linking Climate Change Modelling to Impacts Studies: Recent Advances in Downscaling Techniques for Hydrological Modelling.” *International Journal of Climatology* 27 (12): 1547–78.

Freer, J., K. Beven, and B. Ambrose. 1996. “Bayesian Estimation of Uncertainty in Runoff Prediction and the Value of Data: An Application of the GLUE Approach.” *Water Resources Research* 32 (7): 2161–73.

Gafurov, Abror. 2005. “Water Balance Modelling for Meso-Scale Catchments under Data Limited Conditions.” Master Thesis, Institut für Wasserbau, Universität Stuttgart, 3/2005.

Gafurov, Davrondzhon, Kirsi Helkala, and Torkjel Søndrol. 2006. “Biometric Gait Authentication Using Accelerometer Sensor.” *Journal of Computers* 1 (7): 51–59.

Gao, Hongkai, Xiaobo He, Baisheng Ye, and Jianchen Pu. 2012. “Modeling the Runoff and Glacier Mass Balance in a Small Watershed on the Central Tibetan Plateau, China, from 1955 to 2008.” *Hydrological Processes* 26 (11): 1593–1603.

Gardner, Alex S., Geir Moholdt, J. Graham Cogley, Bert Wouters, Anthony A. Arendt, John Wahr, Etienne Berthier, et al. 2013. “A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009.” *Science* 340 (6134): 852–57.

Giorgi, Filippo, J. Christensen, M. Hulme, H. Von Storch, P. Whetton, R. Jones, L. Mearns, et al. 2001. “Regional Climate Information-Evaluation and Projections.” *Climate Change 2001: The Scientific Basis. Contribution of Working Group to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, JT et Al.(eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, US.

The Global Runoff Data Centre, Germany. Available online: <http://www.bafg.de/GRDC> (accessed on 18 April 2011).

Goodison, B. E. and R. J. Vet. 1987. “Precipitation data compatibility in North America and the impact on studies of acid deposition.” *JACQUES W. DELLEUR*, 47.

Goodison, B. E., B. Sevruk, and S. Klemm. 1989. “WMO Solid Precipitation Measurement Intercomparison: Objectives, Methodology, Analysis.” *Atmospheric Deposition* 179: 57–64.

Granit, J., A. Jägerskog, R. Löfgren, A. Bullock, G. de Gooijer, S. Pettigrew, and A. Lindström. n.d. “Regional Water Intelligence Report Central Asia.”

Grotch, Stanley L., and Michael C. MacCracken. 1991. "The Use of General Circulation Models to Predict Regional Climatic Change." *Journal of Climate* 4 (3): 286–303.

Guerrero, José-Luis, Ida K. Westerberg, Sven Halldin, Lars-Christer Lundin, and Chong-Yu Xu. 2013. "Exploring the Hydrological Robustness of Model-Parameter Values with Alpha Shapes." *Water Resources Research* 49 (10): 6700–6715.

Haensler, A., S. Hagemann, and D. Jacob. 2011. "Dynamical Downscaling of ERA40 Reanalysis Data over Southern Africa: Added Value in the Simulation of the Seasonal Rainfall Characteristics." *International Journal of Climatology* 31 (15): 2338–49. doi:10.1002/joc.2242.

Hagemann, Stefan, Klaus Arpe, and Erich Roeckner. 2006. "Evaluation of the Hydrological Cycle in the ECHAM5 Model." *Journal of Climate* 19 (16): 3810–27.

Hagg, W., L. N. Braun, M. Kuhn, and T. I. Nesgaard. 2007. "Modelling of Hydrological Response to Climate Change in Glacierized Central Asian Catchments." *Journal of Hydrology* 332 (1): 40–53.

Hagg, Wilfried, and Ludwig Braun. 2006. "The Influence of Glacier Retreat on Water Yield from High Mountain Areas: Comparison of Alps and Central Asia." In *Climate and Hydrology in Mountain Areas*, edited by Carmen de Jong, David Collins, and Roberto Ranzi, 261–75.

Hagg, Wilfried, Martin Hoelzle, Stephan Wagner, Elisabeth Mayr, and Zbynek Klose. 2013. "Glacier and Runoff Changes in the Rukhk Catchment, Upper Amu-Darya Basin until 2050." *Global and Planetary Change*.

Hamby, D. M. 1994. "A Review of Techniques for Parameter Sensitivity Analysis of Environmental Models." *Environmental Monitoring and Assessment* 32 (2): 135–54. doi:10.1007/BF00547132.

Harlin, J., and C. S. Kung. 1992. "Parameter Uncertainty and Simulation of Design Floods in Sweden." *Journal of Hydrology* 137 (1): 209–30.

Hay, Lauren, Roland Viger, and GREGORY McCABE. 1998. "Precipitation Interpolation in Mountainous Regions Using Multiple Linear Regression." *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences* 248: 33–38.

Hock, Regine. 2003. "Temperature Index Melt Modelling in Mountain Areas." *Journal of Hydrology* 282 (1): 104–15.

Hoogenboom, Gerrit. 2000. "Contribution of Agrometeorology to the Simulation of Crop Production and Its Applications." *Agricultural and Forest Meteorology* 103 (1): 137–57.

Houghton, John. 2009. *Global Warming: The Complete Briefing*. Cambridge University Press.

Immerzeel, W. W., and M. F. P. Bierkens. 2012. "Asia's Water Balance." *Nature Geoscience* 5 (12): 841–42. doi:10.1038/ngeo1643.

Ines, Amor VM, and James W. Hansen. 2006. "Bias Correction of Daily GCM Rainfall for Crop Simulation Studies." *Agricultural and Forest Meteorology* 138 (1): 44–53.

Itibaev, Z. S., R. G. Asankhodzhaev, T. G. Chernikova, Z. A. Kretova, V. V. Grebnev, Y. V. Radchenko, M. R. Kasymova, E. A. Omorova, V. A. Kokulova, G. B. Kadyrova and B. B. Sharshenov 2015. Newsletter: "Current climate status and change in the Kyrgyz Republic.", Bishkek: Agency on hydrometeorology, UNDP (Empowered Lives. Resilient Nations), 32 Pages.

Ivanov, Valeriy Y., Rafael L. Bras, and David C. Curtis. 2007. "A Weather Generator for Hydrological, Ecological, and Agricultural Applications." *Water Resources Research* 43 (10). doi:10.1029/2006WR005364.

Jackson, Robert B., Stephen R. Carpenter, Clifford N. Dahm, Diane M. McKnight, Robert J. Naiman, Sandra L. Postel, and Steven W. Running. 2001. "WATER IN A CHANGING WORLD." *Ecological Applications* 11 (4): 1027–45.

Jha, Manoj Kumar. 2011. "Evaluating Hydrologic Response of an Agricultural Watershed for Watershed Analysis." *Water* 3 (2): 604–17.

Joseph, George. 2005. *Fundamentals of Remote Sensing - 2nd Edition*. Universities Press.

Jungclaus, J. H., Noel Keenlyside, M. Botzet, H. Haak, J.-J. Luo, Mojib Latif, J. Marotzke, U. Mikolajewicz, and E. Roeckner. 2006. "Ocean Circulation and Tropical Variability in the Coupled Model ECHAM5/MPI-OM." *Journal of Climate* 19 (16): 3952–72.

Kang, Ersi, Guodong Cheng, Yongchao Lan, and Huijun Jin. 1999. "A Model for Simulating the Response of Runoff from the Mountainous Watersheds of Inland River Basins in the Arid Area of Northwest China to Climatic Changes." *Science in China Series D: Earth Sciences* 42 (1): 52–63.

Kayastha, Rijan Bhakta, Yukari Takeuchi, Masayoshi Nakawo, and Yutaka Ageta. 2000. "Practical Prediction of Ice Melting beneath Various Thickness of Debris Cover on Khumbu Glacier, Nepal, Using a Positive Degree-Day Factor." *IAHS PUBLICATION*, 71–82.

Khoi, Dao Nguyen, and Tadashi Suetsugi. 2012. "Uncertainty in Climate Change Impacts on Streamflow in Be River Catchment, Vietnam." *Water and Environment Journal*.

Khromova, T. E., M. B. Dyurgerov, and R. G. Barry. 2003. "Late-Twentieth Century Changes in Glacier Extent in the Ak-Shirak Range, Central Asia, Determined from Historical Data and ASTER Imagery." *Geophysical Research Letters* 30 (16): 1863. doi:10.1029/2003GL017233.

Khromova, T.E., G.B. Osipova, D.G. Tsvetkov, M.B. Dyurgerov, and R.G. Barry. 2006. "Changes in Glacier Extent in the Eastern Pamir, Central Asia, Determined from Historical

Data and ASTER Imagery.” *Remote Sensing of Environment* 102 (1–2): 24–32. doi:10.1016/j.rse.2006.01.019.

Konovalov, V. G., and A. S. Shchetinnicov. 1994. “Evolution of Glaciation in the Pamiro-Alai Mountains and Its Effects on River Run-Off.” *Journal of Glaciology* 40 (134): 149–57.

Konz, M., and J. Seibert. 2010. “On the Value of Glacier Mass Balances for Hydrological Model Calibration.” *Journal of Hydrology* 385 (1): 238–46.

Konz, M., S. Uhlenbrook, L. Braun, A. Shrestha, and S. Demuth. 2007. “Implementation of a Process-Based Catchment Model in a Poorly Gauged, Highly Glacierized Himalayan Headwater.” *Hydrology and Earth System Sciences* 11 (4): 1323–39.

Kou, Xiaojun, Jianping Ge, Yi Wang, and Cunjie Zhang. 2007. “Validation of the Weather Generator CLIGEN with Daily Precipitation Data from the Loess Plateau, China.” *Journal of Hydrology* 347 (3): 347–57.

Kripalani, R. H., J. H. Oh, A. Kulkarni, S. S. Sabade, and H. S. Chaudhari. 2007. “South Asian Summer Monsoon Precipitation Variability: Coupled Climate Model Simulations and Projections under IPCC AR4.” *Theoretical and Applied Climatology* 90 (3-4): 133–59. doi:10.1007/s00704-006-0282-0.

Kuzmichenok, V. 2009. “Monitoring of Water, Snow and Glacial Resources of Kyrgyzstan.” *Assess. Snow Glacier Water Resources Asia* 8: 84–99.

Kuzmichenok, V. A. 2006. “Monitoring of Water, Snow and Glacial Resources of Kyrgyzstan.” In *Regional Workshop on Assessment of Snow-Glacier and Water Resources in Asia*. Almaty, Kazakhstan, 28–39.

Lidén, R., and J. Harlin. 2000. “Analysis of Conceptual Rainfall–runoff Modelling Performance in Different Climates.” *Journal of Hydrology* 238 (3): 231–47.

Lindström, Göran, Barbro Johansson, Magnus Persson, Marie Gardelin, and Sten Bergström. 1997. “Development and Test of the Distributed HBV-96 Hydrological Model.” *Journal of Hydrology* 201 (1): 272–88.

Liu, Hung-Jen, Nien-Sheng Hsu, and Tim Hau Lee. 2009. “Simultaneous Identification of Parameter, Initial Condition, and Boundary Condition in Groundwater Modelling.” *Hydrological Processes* 23 (16): 2358–67. doi:10.1002/hyp.7344.

Liu, J., J. R. Williams, X. Wang, and H. Yang. 2009. “Using MODAWEC to Generate Daily Weather Data for the EPIC Model.” *Environmental Modelling & Software* 24 (5): 655–64.

Lutz, A. F., W. W. Immerzeel, A. Gobiet, F. Pellicciotti, and M. F. P. Bierkens. 2013. “Comparison of Climate Change Signals in CMIP3 and CMIP5 Multi-Model Ensembles and Implications for Central Asian Glaciers.” *Hydrology and Earth System Sciences* 17 (9): 3661–77.

Mahmood, Rashid, and Mukand S. Babel. 2012. "Evaluation of SDSM Developed by Annual and Monthly Sub-Models for Downscaling Temperature and Precipitation in the Jhelum Basin, Pakistan and India." *Theoretical and Applied Climatology*, 1–18.

Makhuvha, Tondani, Geoffrey Pegram, Ross Sparks, and Walter Zucchini. 1997. "Patching Rainfall Data Using Regression Methods.: 1. Best Subset Selection, EM and Pseudo-EM Methods: Theory." *Journal of Hydrology* 198 (1-4): 289–307.

Ma, Miaomiao. 2013. "Correlation Dimension Analysis of Complex Hydrological Systems: What Information Can the Method Provide?" Berlin, Freie Universität Berlin, Diss., 2013.

Mannig, Birgit, Markus Müller, Eva Starke, Christian Merckenschlager, Weiyi Mao, Xiefei Zhi, Ralf Podzun, Daniela Jacob, and Heiko Paeth. 2013. "Dynamical Downscaling of Climate Change in Central Asia." *Global and Planetary Change*.

Marquínez, Jorge, Javier Lastra, and Pilar García. 2003. "Estimation Models for Precipitation in Mountainous Regions: The Use of GIS and Multivariate Analysis." *Journal of Hydrology* 270 (1): 1–11.

Martinec, J., and A. Rango. 1986. "Parameter Values for Snowmelt Runoff Modelling." *Journal of Hydrology* 84 (3–4): 197–219. doi:10.1016/0022-1694(86)90123-X.

Marzeion, Ben, A. H. Jarosch, and Marlis Hofer. 2012. "Past and Future Sea-Level Change from the Surface Mass Balance of Glaciers." *The Cryosphere* 6 (6): 1295–1322.

Matsuda, Yoshihiro. 2003. "Positive Degree-Day Factors for Ice Ablation on Four Glaciers in the Nepalese Himalayas and Qinghai-Tibetan Plateau." *Bulletin of Glaciological Research* 20: 7–14.

Mayr, Elisabeth, Wilfried Hagg, Christoph Mayer, and Ludwig Braun. 2012. "Calibrating a Spatially Distributed Conceptual Hydrological Model Using Runoff, Annual Mass Balance and Winter Mass Balance." *Journal of Hydrology*.

Meile, T., J.-L. Boillat, and A. J. Schleiss. 2011. "Hydropeaking Indicators for Characterization of the Upper-Rhone River in Switzerland." *Aquatic Sciences* 73 (1): 171–82. doi:10.1007/s00027-010-0154-7.

Michéli, Erika, Peter Schad, Otto Spaargaren, David Dent, and Freddy Nachtergaele. 2006. *World Reference Base for Soil Resources: 2006: A Framework for International Classification, Correlation and Communication*. FAO.

Miller, Jon D. 2001. *Biomedical Communications: Purpose, Audience, and Strategies*. Academic Press.

Moore, R. D. 1993. "Application of a Conceptual Streamflow Model in a Glacierized Drainage Basin." *Journal of Hydrology* 150 (1): 151–68.

Muleta, Misgana K., and John W. Nicklow. 2005. "Sensitivity and Uncertainty Analysis Coupled with Automatic Calibration for a Distributed Watershed Model." *Journal of Hydrology* 306 (1): 127–45.

Nakicenovic, Nebojsa, and Robert Swart. 2000. "Special Report on Emissions Scenarios." *Special Report on Emissions Scenarios*, Edited by Nebojsa Nakicenovic and Robert Swart, Pp. 612. ISBN 0521804930. Cambridge, UK: Cambridge University Press, July 2000.

Narama, C., A. Kääb, M. Duishonakunov, and K. Abdrakhmatov. 2010. "Spatial Variability of Recent Glacier Area Changes in the Tien Shan Mountains, Central Asia, Using Corona (~ 1970), Landsat (~ 2000), and ALOS (~ 2007) Satellite Data." *Global and Planetary Change* 71 (1): 42–54.

Nathans, Laura L., Frederick L. Oswald, and Kim Nimon. 2012. "Interpreting Multiple Linear Regression: A Guidebook of Variable Importance." *Practical Assessment, Research & Evaluation* 17 (9): 2.

Naz, Bibi S., C. D. Frans, G. K. C. Clarke, P. Burns, and D. P. Lettenmaier. 2014. "Modeling the Effect of Glacier Recession on Streamflow Response Using a Coupled Glacio-Hydrological Model." *Hydrology and Earth System Sciences* 18 (2): 787–802.

Ngoundo, Molengar, Chun-E. Kan, Yu-Chuan Chang, Shioh-Long Tsai, and I. Tsou. 2007. "Options for Water Saving in Tropical Humid and Semi-Arid Regions Using Optimum Compost Application Rates." *Irrigation and Drainage* 56 (1): 87–98.

Niederer, Peter, Viktor Bilenko, Natasha Ershova, Hans Hurni, Sergeji Yerokhin, and Daniel Maselli. 2008. "Tracing Glacier Wastage in the Northern Tien Shan (Kyrgyzstan/Central Asia) over the Last 40 Years." *Climatic Change* 86 (1-2): 227–34.

Nohara, Daisuke, Akio Kitoh, Masahiro Hosaka, and Taikan Oki. 2006. "Impact of Climate Change on River Discharge Projected by Multimodel Ensemble." *Journal of Hydrometeorology* 7 (5): 1076–89. doi:10.1175/JHM531.1.

Pachauri, Rajendra K., M. R. Allen, V. R. Barros, J. Broome, W. Cramer, R. Christ, J. A. Church, et al. 2014. "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." <http://epic.awi.de/37530/>.

Pardé, Maurice. 1933. "Fleuves et Rivières."

Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Intergovernmental Panel on Climate Change.

Perry, R. H., B. Charlotte, M. Isabella, and C. Bob. 2004. *SPSS Explained*. London: Routledge.

Piani, C., G. P. Weedon, M. Best, S. M. Gomes, P. Viterbo, S. Hagemann, and J. O. Haerter. 2010. "Statistical Bias Correction of Global Simulated Daily Precipitation and Temperature for the Application of Hydrological Models." *Journal of Hydrology* 395 (3): 199–215.

Piper, Stephen C., and Elisabeth F. Stewart. 1996. "A Gridded Global Data Set of Daily Temperature and Precipitation for Terrestrial Biospheric Modeling." *Global Biogeochemical Cycles* 10 (4): 757–82.

Plesca, I., E. Timbe, J. -F. Exbrayat, D. Windhorst, P. Kraft, P. Crespo, K. B. Vaché, H. - G. Frede, and L. Breuer. 2012. "Model Intercomparison to Explore Catchment Functioning: Results from a Remote Montane Tropical Rainforest." *Ecological Modelling, Simulating ecosystem functioning of tropical mountainous cloud forests in southern Ecuador*, 239: 3–13. doi:10.1016/j.ecolmodel.2011.05.005.

Price, Larry W. 1986. *Mountains and Man: A Study of Process and Environment*. University of California Press.

Prieto, Luis, Ricardo García Herrera, Julio Díaz, Emiliano Hernández, and Teresa del Teso. 2004. "Minimum Extreme Temperatures over Peninsular Spain." *Global and Planetary Change* 44 (1–4): 59–71. doi:10.1016/j.gloplacha.2004.06.005.

Radchenko, Iuliia, Lutz Breuer, Irina Forkutsa, and Hans-Georg Frede. 2014. "Simulating Water Resource Availability under Data Scarcity—A Case Study for the Ferghana Valley (Central Asia)." *Water* 6 (11): 3270–99.

Radić, Valentina, Andrew Bliss, A. Cody Beedlow, Regine Hock, Evan Miles, and J. Graham Cogley. 2014. "Regional and Global Projections of Twenty-First Century Glacier Mass Changes in Response to Climate Scenarios from Global Climate Models." *Climate Dynamics* 42 (1-2): 37–58. doi:10.1007/s00382-013-1719-7.

Räisänen, Jouni. 2007. "How Reliable Are Climate Models?" *Tellus A* 59 (1): 2–29.

Rakhmatullaev, Shavkat, Frédéric Huneau, Philippe Le Coustumer, Mikael Motelica-Heino, and Masharif Bakiev. 2010. "Facts and Perspectives of Water Reservoirs in Central Asia: A Special Focus on Uzbekistan." *Water* 2 (2): 307–20. doi:10.3390/w2020307.

Ranhao, Sun, Zhang Baiping, and Tan Jing. 2008. "A Multivariate Regression Model for Predicting Precipitation in the Daqing Mountains." *Mountain Research and Development* 28 (3): 318–25.

Ratto, M., P. C. Young, R. Romanowicz, F. Pappenberger, A. Saltelli, A. Pagano, and others. 2007. "Uncertainty, Sensitivity Analysis and the Role of Data Based Mechanistic Modeling in Hydrology." *Hydrology and Earth System Sciences Discussions* 11 (4): 1249–66.

Rees, H. Gwyn, and David N. Collins. 2006. "Regional Differences in Response of Flow in Glacier-Fed Himalayan Rivers to Climatic Warming." *Hydrological Processes* 20 (10): 2157–69.

Richardson, Clarence W. 1981. "Stochastic Simulation of Daily Precipitation, Temperature, and Solar Radiation." *Water Resources Research* 17 (1): 182–90.

Ryazantseva Z.A. 1965. "The Climate of the Kyrgyz SSR." Frunze, Ilim, 291 Pages. (In Russian).

Saltelli, A., T. H. Andres, and T. Homma. 1995. "Sensitivity Analysis of Model Output. Performance of the Iterated Fractional Factorial Design Method." *Computational Statistics & Data Analysis* 20 (4): 387–407.

Saltelli, A., S. Tarantola, and F. Campolongo. 2000. "Sensitivity Analysis as an Ingredient of Modeling." *Statistical Science* 15 (4): 377–95. doi:10.2307/2676831.

Samuel, Jos, Paulin Coulibaly, and Robert A. Metcalfe. 2012. "Identification of Rainfall–runoff Model for Improved Baseflow Estimation in Ungauged Basins." *Hydrological Processes* 26 (3): 356–66.

Savoskul, O. S., E. V. Chevnina, F. I. Perziger, L. Y. Vasilina, V. L. Baburin, A. I. D. AI, B. Matyakubov, and R. R. Murakaev. 2003. "Water, Climate, Food, and Environment in the Syr Darya Basin." *Adaptation Strategies to Changing Environments*.

Savoskul, Oxana S., Elena V. Chevnina, Felix I. Perziger, Ludmila Yu Vasilina, Viacheslav L. Baburin, Alexander I. Danshin, Bahtiyar Matyakubov, and Ruslan R. Murakaev. 2003. "Water, Climate, Food, and Environment in the Syr Darya Basin." *Contribution to the Project ADAPT, Adaptation Strategies to Changing Environments*.

Scherrer, Simon C., Christof Appenzeller, and Martin Laternser. 2004. "Trends in Swiss Alpine Snow Days: The Role of Local-and Large-Scale Climate Variability." *Geophysical Research Letters* 31 (13).

Schielzeth, Holger. 2010. "Simple Means to Improve the Interpretability of Regression Coefficients." *Methods in Ecology and Evolution* 1 (2): 103–13. doi:10.1111/j.2041-210X.2010.00012.x.

Sehring, Jenniver, and Alfred C. Diebold. 2012. *Water Unites: From the Glaciers to the Aral Sea*. Trescher Verlag.

Seibert, J. 1997. "Estimation of Parameter Uncertainty in the HBV Model." *Nordic Hydrology* 28 (4): 247–62.

Seibert, J. 1999. "Regionalisation of Parameters for a Conceptual Rainfall-Runoff Model." *Agricultural and Forest Meteorology* 98 (1): 279–93.

Seibert, J. 2005. "HBV Light Version 2 User's Manual." Stockholm University.

Seibert, Jan, and M. J. P. Vis. 2012. "Teaching Hydrological Modeling with a User-Friendly Catchment-Runoff-Model Software Package." *Hydrology and Earth System Sciences* 16 (9): 3315–25.

Seibert, J, S Uhlenbrook, C Leibundgut, and S Halldin. 2000. "Multiscale Calibration and Validation of a Conceptual Rainfall-Runoff Model." *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 25 (1): 59–64. doi:10.1016/S1464-1909(99)00121-5.

Shields, Catherine A., and Christina L. Tague. 2012. "Assessing the Role of Parameter and Input Uncertainty in Ecohydrologic Modeling: Implications for a Semi-Arid and Urbanizing Coastal California Catchment." *Ecosystems* 15 (5): 775–91.

Singh, P., and Vijay P. Singh. 2001. *Snow and Glacier Hydrology*. Springer.

Smith, Martin. 1992. *CROPWAT: A Computer Program for Irrigation Planning and Management*. Food & Agriculture Org.

Sokolov, Vadim I. 1999. "Integrated Water Resources Management in the Republic of Uzbekistan." *Water International* 24 (2): 104–15. doi:10.1080/02508069908692146.

Solomon, Susan. 2007. *Climate Change 2007-the Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC. Vol. 4*. Cambridge University Press.

Song, Fengfei, and Tianjun Zhou. 2013. "Interannual Variability of East Asian Summer Monsoon Simulated by CMIP3 and CMIP5 AGCMs: Skill Dependence on Indian Ocean–Western Pacific Anticyclone Teleconnection." *Journal of Climate* 27 (4): 1679–97. doi:10.1175/JCLI-D-13-00248.1.

Sorg, Annina, Tobias Bolch, Markus Stoffel, Olga Solomina, and Martin Beniston. 2012. "Climate Change Impacts on Glaciers and Runoff in Tien Shan (Central Asia)." *Nature Climate Change* 2 (10): 725–31. doi:10.1038/nclimate1592.

Stahl, K., R. D. Moore, J. M. Shea, D. Hutchinson, and A. J. Cannon. 2008. "Coupled Modelling of Glacier and Streamflow Response to Future Climate Scenarios." *Water Resources Research* 44 (February): 13 PP. doi:200810.1029/2007WR005956.

State Water Cadastre. 1987. "Annual Data about the Regime and Resources of Surface Water." Kyrgyz SSR: Obninsk, Russia, 9, 269 Pages. (In Russian).

Steele-Dunne, S., P. Lynch, R. McGrath, T. Semmler, S. Wang, J. Hanafin, and P. Nolan. 2008. "The Impacts of Climate Change on Hydrology in Ireland." *Journal of Hydrology* 356 (1): 28–45.

Stocker, Thomas F. 2014. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Tateishi, Ryutaro, and C. H. Ahn. 1996. "Mapping Evapotranspiration and Water Balance for Global Land Surfaces." *ISPRS Journal of Photogrammetry and Remote Sensing* 51 (4): 209–15.

Team, GeoNetwork. 2007. "GeoNetwork Opensource Portal to Spatial Data and Information." Interactive Resource.

Thomas, R. J. 2008. "Opportunities to Reduce the Vulnerability of Dryland Farmers in Central and West Asia and North Africa to Climate Change." *Agriculture, Ecosystems & Environment* 126 (1): 36–45.

Uhlenbrook, S., Y. Mohamed, and A. S. Gragne. 2010. "Analyzing Catchment Behavior through Catchment Modeling in the Gilgel Abay, Upper Blue Nile River Basin, Ethiopia." *Hydrology and Earth System Sciences* 14 (10): 2153–65.

Uhlenbrook, S., J. Seibert, C. Leibundgut, and A. Rodhe. 1999. "Prediction Uncertainty of Conceptual Rainfall-Runoff Models Caused by Problems in Identifying Model Parameters and Structure." *Hydrological Sciences Journal* 44 (5): 779–97.

Unger-Shayesteh, Katy, Sergiy Vorogushyn, Daniel Farinotti, Abror Gafurov, Doris Duethmann, Alexander Mandychev, and Bruno Merz. 2013. "What Do We Know about Past Changes in the Water Cycle of Central Asian Headwaters? A Review." *Global and Planetary Change, Water in Central Asia – Perspectives under global change*, 110, Part A (November): 4–25. doi:10.1016/j.gloplacha.2013.02.004.

Usubaliev, R.A., Dudashvili, A.S., Elemanov, O.I. 2012. "Glaciation of the northern slopes of Turkestan and Alay Range and its current dynamics." 1, 24–28. (In Russian).

Veldkamp, A., and L. O. Fresco. 1996. "CLUE: A Conceptual Model to Study the Conversion of Land Use and Its Effects." *Ecological Modelling* 85 (2–3): 253–70. doi:10.1016/0304-3800(94)00151-0.

Vilesov, E. N., and V. N. Uvarov. 2001. "The Evolution of Modern Glaciation of the Zailiyskiy Alatau in the XXth Century." Kazakh State University, Almaty. (In Russian).

Villazón, M.F., and P. Willems. 2010. "Filling Gaps and Daily Disaccumulation of Precipitation Data for Rainfall-Runoff Model."

Viviroli, D., DR Archer, W. Buytaert, HJ Fowler, GB Greenwood, AF Hamlet, Y. Huang, G. Koboltschnig, and others. 2011. "Climate Change and Mountain Water Resources: Overview and Recommendations for Research, Management and Policy." *Hydrology and Earth System Sciences* 15 (2): 471–504.

Wöhling, Th, F. Lennartz, and M. Zappa. 2006. "Technical Note: Updating Procedure for Flood Forecasting with Conceptual HBV-Type Models." *Hydrology and Earth System Sciences* 10 (6): 783–88.

Xu, Chong-yu, Elin Widén, and Sven Halldin. 2005. “Modelling Hydrological Consequences of Climate Change—progress and Challenges.” *Advances in Atmospheric Sciences* 22 (6): 789–97.

Xu, Yue-Ping, Xujie Zhang, Qihua Ran, and Ye Tian. 2013. “Impact of Climate Change on Hydrology of Upper Reaches of Qiantang River Basin, East China.” *Journal of Hydrology* 483: 51–60.

Yao, T. D. 2002. “Dynamical Features of Cryosphere in Middle Tibetan Plateau.” Beijing: Geological Press 207: 233.

Zappa, Massimiliano, and Caroline Kan. 2007. “Extreme Heat and Runoff Extremes in the Swiss Alps.” *Natural Hazards and Earth System Science* 7 (3): 375–89.

Zhang, W., T. Li, Y. Huang, Q. Zhang, J. Bian, and P. Han. 2014. “Estimation of Uncertainties due to Data Scarcity in Model Upscaling: A Case Study of Methane Emissions from Rice Paddies in China.” *Geoscientific Model Development Discussions* 7 (1): 181–216.

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Erklärung

Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ niedergelegt sind, eingehalten.

Iuliia Radchenko

Sankt Petersburg, April 2016