Assessing the integrated water resources development potential of Wadi systems in Iran and their vulnerability to climate change

Dissertation

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Nariman Mahmoodi M.Sc.
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Erste Gutachterin: Prof. Dr. Nicola Fohrer

Zweite Gutachterin: Prof. Dr. Natascha Oppelt

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Abstract

Similar to other Middle Eastern countries, Iran is experiencing a serious water crisis. Water resources become increasingly stressed in the Wadi regions of central and eastern Iran. Assessing water resources there is thus essential due to growing water demand and possible effects of future climate change.

Due to the lack of readily available surface water resources, different water use systems (WUSs) exist that provide water mainly for drinking, irrigation and further domestic use. In addition, many soil and water conservation measures (SWCMs) have been established to slow down the velocity of water and to increase infiltration and percolation rates. These alter hydrological components in Wadi regions that need to be considered.

Such characteristics particularly apply to the Wadi basin Halilrood in central Iran. Halilrood River is the largest river in terms of discharge in the Kerman Province and the major water provider for the downstream Jazmorian wetland. The Soil and Water Assessment Tool (SWAT) is employed to model the hydrological processes of the Wadi. WUSs and SWCMs are implemented into the hydrological model to simulate streamflow and major hydrological components under current and future climate change conditions. Moreover, groundwater sustainability and possible alterations in the ecological flow regime are evaluated by taking both climate change and population growth into account.

Results of the SWAT model simulation show that the hydrological processes of the Wadi system are better represented when WUSs and SWCMs are implemented. The improvement in model performance varies for different segments of the hydrograph. Peak and mean flows are simulated more accurately due to the improved depiction of infiltration rates and the slower release of water to the channels. The investigation of hydrological components reveals that the contribution of surface runoff and groundwater flows to the streams decrease in all sub-basins with WUSs. On the contrary, a higher contribution of groundwater to the streams is shown in most sub-basins with SWCMs. In sub-basins with both WUSs and SWCMs, groundwater contribution increases or does not show any change.

To assess the impact of climate change on the water resources in the near and far future (2030-2059 and 2070-2099) in comparison to the baseline period (1979-2009), the projections from 11 climate models and two bias correction methods (LS: linear scaling and DM:

distribution mapping) for two Representative Concentration Pathways (RCP4.5 and RCP8.5) are used as input data for the calibrated hydrologic model. The results indicate a slight increase of streamflow in winter season for both RCPs and both bias correction methods, due to higher precipitation intensity. Besides that, a shift is simulated in the timing of the seasonal peak-flow. This is due to increases in temperature and changes in the precipitation pattern. The Halilrood Basin is expected to be vulnerable to climate change as different segments of the flow duration curve (FDC) show increasing variability that can also be interpreted as an alteration of the future flood and drought extremes. A decrease for very high and high flows is projected under both RCPs. Climate change is causing a slight increase in evaporation and less available water for infiltration and percolation, which eventually leads to zero contribution of groundwater to the main channel.

The impacts of climate change and growing water demand on the sustainability of groundwater use and the hydrologic regime of the Wadi are analyzed by linking the SWAT model results to the Indicators of Hydrologic Alteration (IHA) and the Range of Variability Approach (RVA). An unsustainable water resources situation (groundwater recharge is equal or greater than groundwater demand) is expected in the future for the vast majority of sub-basins with WUSs. Due to the imbalance between the groundwater recharge under climate change and estimated groundwater demand in the future, a decline of groundwater levels is anticipated for the entire Halilrood Basin. This is not only resulting in unsustainable groundwater use, but also changes the hydrologic regime and poses a significant threat to downstream ecosystems.

The presented modeling framework is a useful approach, providing beneficial information on the water resources of Iranian Wadi systems and their vulnerability to climate change and population growth. The results of this research can contribute to long-term planning there, which is required for a sustainable water resources management under changing future conditions.

Zusammenfassung

Ähnlich wie andere Länder des Nahen Ostens erlebt auch der Iran eine ernste Wasserkrise. In den Wadi-Regionen des zentralen und östlichen Irans sind die Wasserressourcen zunehmend überlastet. Die Untersuchung der dortigen Wasserressourcen ist aufgrund des wachsenden Wasserbedarfs und möglicher Auswirkungen des zukünftigen Klimawandels von wesentlicher Bedeutung.

Aufgrund des Mangels an verfügbaren Oberflächenwasserressourcen existieren verschiedene Wassernutzungssysteme (WUSs), die Wasser hauptsächlich zum Trinken, zur Bewässerung und zur weiteren häuslichen Nutzung bereitstellen. Darüber hinaus wurden viele Boden- und Wasserschutzmaßnahmen (SWCMs) eingerichtet, um das Abfließen des Wassers zu verlangsamen und die Infiltrations- und Versickerungsraten zu erhöhen. Diese verändern hydrologische Komponenten in Wadi-Regionen, die berücksichtigt werden müssen.

Diese Eigenschaften treffen insbesondere auf das Wadi-Becken Halilrood im Zentraliran zu. Der Halilrood-Fluss ist der abflussstärkste Fluss in der Provinz Kerman und der wichtigste Wasserspender für das flussabwärts gelegene Jazmorian-Feuchtgebiet. Das Soil and Water Assessment Tool (SWAT) wird zur Modellierung der hydrologischen Prozesse des Wadis eingesetzt. WUSs und SWCMs werden in das hydrologische Modell implementiert, um das Ablussregime und die wichtigsten hydrologischen Komponenten unter aktuellen und zukünftigen Bedingungen des Klimawandels zu simulieren. Darüber hinaus werden die Nachhaltigkeit des Grundwassers und mögliche Veränderungen im ökologischen Abflussregime unter Berücksichtigung des Klimawandels und des Bevölkerungswachstums bewertet.

Die Ergebnisse der SWAT-Modellsimulation zeigen, dass die hydrologischen Prozesse des Wadi-Systems besser dargestellt werden, wenn WUSs und SWCMs implementiert werden. Die Verbesserung der Modellleistung variiert für verschiedene Segmente der Abflussganglinie. Spitzen- und mittlere Abflüsse werden aufgrund der verbesserten Darstellung von Infiltrationsraten und der langsameren Abgabe von Wasser an das Fließgewässer genauer simuliert. Die Untersuchung der hydrologischen Komponenten zeigt, dass der Beitrag des Oberflächenabflusses und der Grundwasserströme zu den Fließgewässern in allen Teileinzugsgebieten mit WUSs abnimmt. Im Gegensatz dazu zeigt sich in den meisten Teileinzugsgebieten mit SWCMs ein höherer Anteil des Grundwasserabflusses. In

Teileinzugsgebieten mit sowohl WUSs als auch SWCM nimmt der Grundwasseranteil zu oder zeigt keine Veränderung.

Um die Auswirkungen des Klimawandels auf die Wasserressourcen in der nahen und fernen Zukunft (2030-2059 und 2070-2099) im Vergleich zur Baseline (1979-2009) zu beurteilen, werden die Projektionen von 11 Klimamodellen und zwei Bias-Korrekturmethoden (LS: lineare Skalierung und DM: Korrektur der Verteilung) für zwei repräsentative Konzentrationspfade (RCP4.5 und RCP8.5) werden als Eingabedaten für das kalibrierte hydrologische Modell verwendet. Die Ergebnisse zeigen eine leichte Zunahme des Abflusses in der Wintersaison für beide RCPs und beide Bias-Korrekturmethoden, was auf eine höhere Niederschlagsintensität zurückzuführen ist. Außerdem wird eine Verschiebung des Zeitpunkts des saisonalen Spitzenabflusses simuliert. Dies ist auf den Temperaturanstieground und die Änderungen im Niederschlagsmuster zurückzuführen. Es wird erwartet, dass das Halilrood-Becken anfällig für den Klimawandel ist, da verschiedene Segmente der Abflussdauer-Kurve (FDC) eine zunehmende Variabilität aufweisen, die auch als eine Veränderung der zukünftigen Hochwasser- und Trockenheitsextreme interpretiert werden kann. Eine Abnahme für hohe und sehr hohe Abflüsse wird unter beiden RCPs projiziert. Der Klimawandel führt zu einem leichten Anstieg der Evaporation und zu weniger verfügbarem Wasser für Infiltration und Versickerung, was letztendlich zu einem Verlust des Grundwasserbeitrags zum Abfluss führt.

Die Auswirkungen des Klimawandels und des wachsenden Wasserbedarfs auf die Nachhaltigkeit des Grundwassernutzung und das hydrologische Regime des Wadis werden durch die Verknüpfung der SWAT-Modellergebnisse mit den Indicators of Hydrologic Alteration (IHA) und dem Range of Variability Approach (RVA) analysiert. Für die überwiegende Mehrheit der Teileinzugsgebiete mit WUSs wird für die Zukunft eine nicht nachhaltige Wasserressourcensituation (Grundwasserneubildung ist gleich oder größer als die Grundwasserentnahme) erwartet. Aufgrund des Ungleichgewichts zwischen der Grundwasserneubildung unter dem Klimawandel und der geschätzten Grundwasserentnahme in der Zukunft wird für das gesamte Halilrood-Becken ein Rückgang des Grundwasserspiegels erwartet. Dies führt neben einer nicht nachhaltigen Grundwassernutzung auch zu einer Veränderung des hydrologischen Regimes und stellt eine signifikante Bedrohung für die flussabwärts gelegenen Ökosysteme dar.

Das vorgestellte Modellierungssystem ist ein nützlicher Ansatz, der wichtige Informationen über die Wasserressourcen iranischer Wadi-Systeme und deren Anfälligkeit gegenüber Klimawandel und Bevölkerungswachstum liefert. Die Ergebnisse dieser Forschung können dort zu einer langfristigen Planung beitragen, die für ein nachhaltiges Wasserressourcenmanagement unter sich ändernden zukünftigen Bedingungen erforderlich ist.

Contents

Chapter 1 General introduction

Water resources in many arid and semi-arid regions such as Wadi systems in Iran are limited, and are becoming major constrains for sustainable socio-economic development at different scales (Madani et al., 2016; Hallegatte et al., 2017). Moreover, the existence of sufficient water is vital to maintain ecosystem health (Abbaspour and Nazaridoust, 2007; Zeng et al., 2019). The limited water resources in these regions are under severe and increasing pressure due to population growth. High spatio-temporal imbalances of water demand and supply, seasonal water use, different water use systems, massive withdrawal of groundwater, and improper water management policies, that ignore the specific features of Wadi systems, cause a major threat to those scarce water resources (Wada et al., 2010; Chitsaz and Azarnivand, 2017; Chen et al., 2020). Ecosystems are very fragile, and under stress from groundwater withdrawal and the management of surface water (Shekhawat et al., 2012). Climate change poses an additional stress on the current state (Danesh et al., 2016; Guermazi et al., 2019). Appropriate plans, new methods, and innovative approaches for effective water management are essential to improve the critical water situation. Hydrological models are useful tools to assess impacts of climate change and growing water demands and to develop and test suitable water management strategies (Bhatta et al., 2019). However, these models need to represent the specific features of Wadi regions.

1.1 Wadi systems

Almost one third of the world's land mass lies in the dry climate zone (Köppen Climate Classification System Group B), mainly between 10 and 35 latitude (Peel et al., 2007). Iran is located in the mid-latitude belt of arid and semi-arid regions of the Earth and therefore, arid and semi-arid regions cover more than 70% of the country (Shifteh Some'e, et al., 2013). Hyper arid (a region with an aridity index – ratio of mean annual precipitation (P) and mean annual potential evapotranspiration (PEP) – of less than 0.05, Middleton and Thomas, 1997) and arid regions with distinct Wadis are mostly located in central part of the country (Lyons et al., 2020). These regions are places with special climatic and hydrologic characteristics such as high temperatures, high evaporation rates that exceed the annual precipitation, low humidity, and high variation of precipitation in space and time (Tabari et al., 2014). The nature of the scarce and sporadic precipitation in Wadis, where half of the average annual precipitation can fall in one day or as one event, cause a sudden rise in water erosion and flooding, which leads to limited water resources due to the rapid and instantaneous discharge events. This needs to be taken into consideration by water resources planners. The Halilrood Wadi, located in south-central Iran, is the principal river in the Kerman Province (Figure 1.1). It provides various ecosystem services, as the water is used for domestic, industrial, energy (Jiroft Dam, Figure 1.1(a)), and agricultural (small scale farming) purposes, and it supplies water to the Jazmorian wetland (Figure 1.1(a)). The temporally variable flow events of Halilrood Basin determines temporal persistence of Jazmorian wetland, which has specific ecological significance, playing a major role in sustaining the ecosystem of the Wadi. The three cities Baft, Bazanjan, Rabor with a total population of about 125000 inhabitants are located in the northern part of the basin (Figure 1.1b). The water from the shallow aquifers from springs, qanats, and wells drilled in different parts of the basin (Figure 1.1(c)) and water stored in two dams in the northern part (Baft and Rabor) (Figure 1b), is used to supply water to the cities and villages mainly for drinking, washing, and irrigating small farmlands.

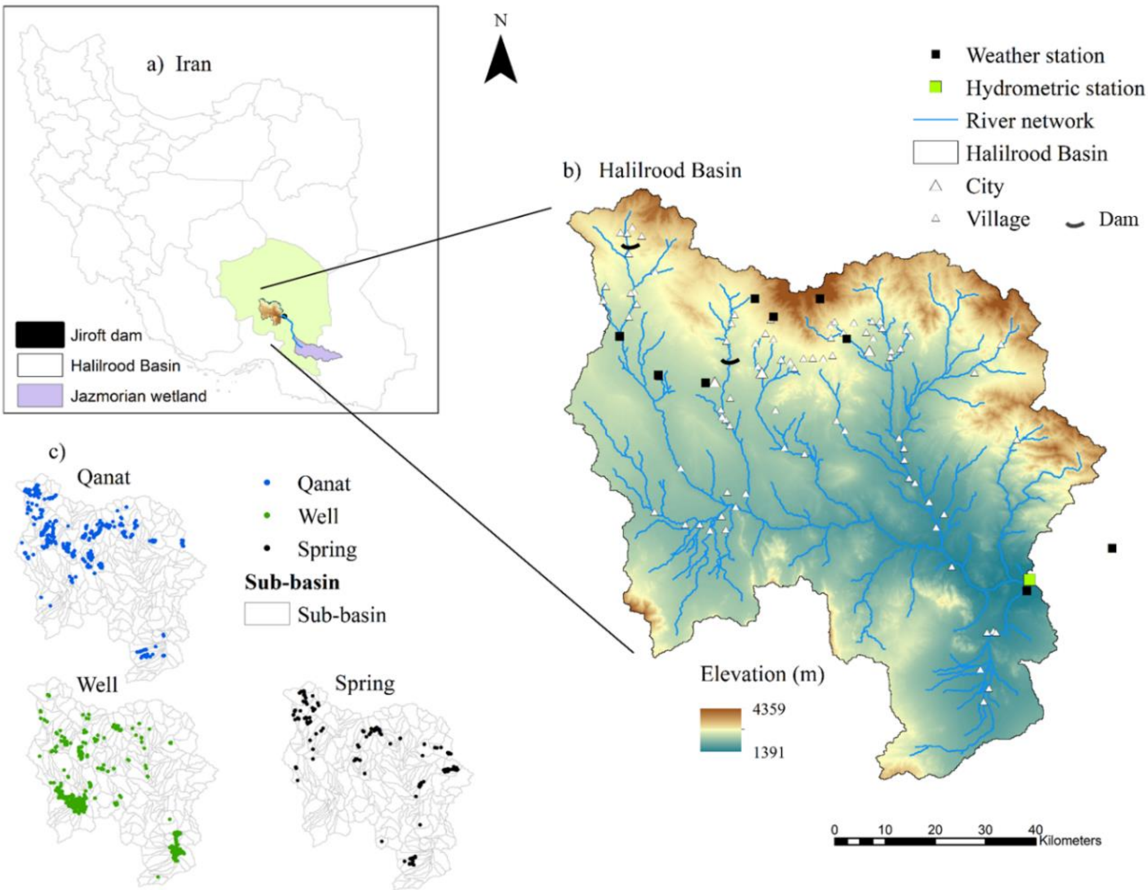

Figure 1.1 Location of the Halilrood Basin, water use systems, and monitoring stations

1.2 Water Use Systems

Different water use systems exist in Wadi regions of Iran and other parts of the world, including qanats, springs, wells, and dams. The residents of the Iranian Wadis have been traditionally using these water use systems for different purposes. WUSs are a reliable way to secure access to safe and affordable water for drinking, washing and irrigation. While springs are natural sources of water, qanats, wells and dams are man-made WUSs. Qanats and drilled wells are considered to be the most stable and successful water supply systems in hot and arid climates (Boustani, 2008; Hussain et al., 2008; Mostafaeipour, 2010). Iran Water Resource Management Company (IWPCO, 2001, 2006) provides further information about the WUSs.

1.2.1 Qanats

Qanats are common water supply systems in Iran and up to about 2500 years old (Ahmadi et al., 2010). They provide about 7.6 billion m^3 water annually (15% of country's total water demand) (Ahmadi et al., 2010) mainly for drinking and irrigation purposes. A qanat is a traditional method to transfer groundwater to the surface through a slightly sloped underground tunnel using gravity (Figure 1.2). Drilling a mother well is the first step to establish a qanat. The mother well is the deepest well, which is dug deep into the water table. The location of the mother well specifies the origin of the water. The mother wells are mostly built on alluvial depositions. Usually, a few wells are dug to find the best location iteratively. The outlet is located mainly at close proximity to the points of water consumption, such as e.g. villages, farmlands, and industries. Once the mother well and outlet are specified, these two will be connected by a slightly sloped underground tunnel (Figure 1.2). The slope needs to be slight to decrease erosion and avoid collapse of the tunnel (Hosseini et al., 2010). Moreover, along the underground tunnel a series of wells (shafts) are constructed to facilitate the removal of soil and to provide ventilation and access for qanat builders (Yazdi and Khaneiki, 2016). The water from the aquifer is transferred to the surface through the underground tunnel, which helps preserve water quality, keeps the water temperature low and limit evaporation losses (Yezdandoost 2016).

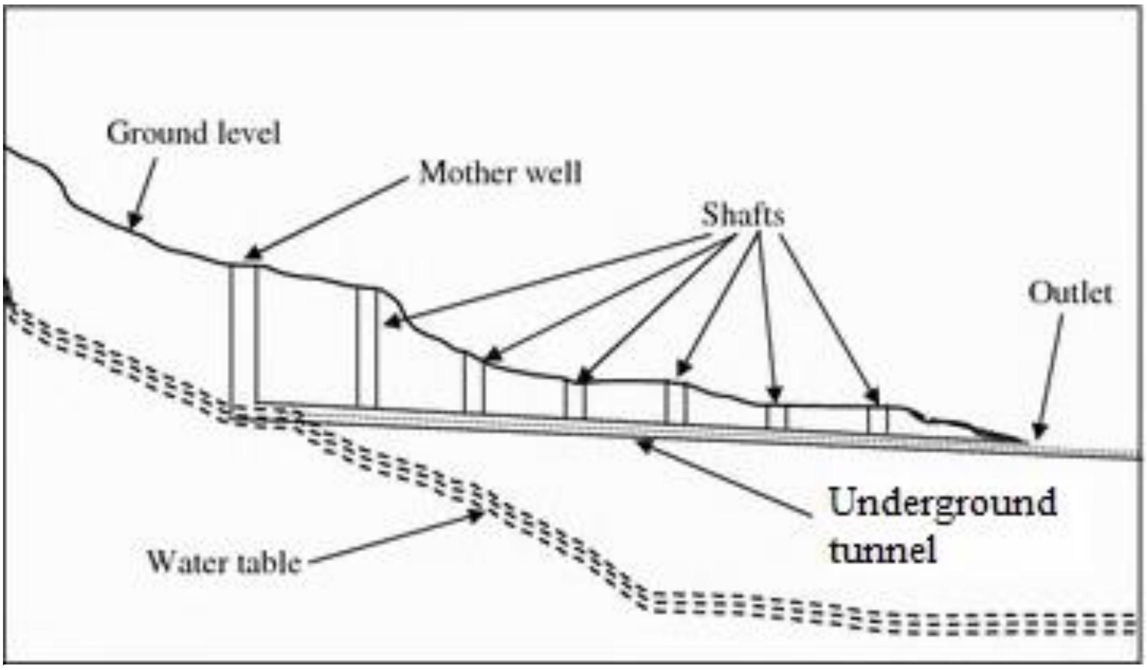

Figure 1.2 Structure of the qanat system (modified from Nasiri and Mafakheri, 2015)

Figure 1.1d illustrates the location of the active qanats in the Halilrood Basin. The water withdrawn from the shallow aquifer through qanats is observed for each month of the year, but in 5-year intervals only. Due to changes in groundwater recharge and excessive consumption of groundwater and anthropogenic activities, some of the qanats (around 80) have fallen dry and are deactivated nowadays. Qanats with pools at the end of the underground tunnel are identified by IWPCO (2001, 2006). Moreover, the location of the mother well for each qanat was considered to ensure that water was not taken from outside of the catchment.

1.2.2 Wells

Wells are providing water from groundwater mostly for domestic, industrial purposes, and irrigation in the Halilrood basin. Wells in arid and semi-arid regions of Iran are classified into two groups, shallow and semi-deep wells (Tizro and Voudouris, 2008). Due to a drop in groundwater levels, some of the shallow wells were extended to semi-deep wells (IWPCO, 2001) and drilled deeper into Quaternary sedimentary formations of the Wadis.

1.2.3 Springs

Springs are located mainly in the mountainous area of the Wadi systems (Figure 1.1). They are naturally bringing water to the surface and people living near the Wadis are using it as drinking water and for washing. Some of the springs have recently fallen dry, as consequences of climate change and reduction the groundwater level (IWPCO 2001, 2006).

1.2.4 Reservoirs

Since Wadis are regions with high seasonal variability of precipitation, surface water is only available during specific times of the year; therefore, nowadays building reservoirs is one of most popular approaches to store surface water resources (Yazdandoost, 2016). Due to the flat elevation of Wadi regions, usually reservoirs are constructed in the headwaters of the Wadi basins and supply water to different sectors. Reservoirs are playing a critical role in managing water resources in Wadi regions where rivers are seasonal and high spatio-temporal variation of precipitation leads to heavy floods and extreme droughts.

1.3 Soil and water conservation measures

Due to the soil properties and climatic conditions in the Halilrood Basin, Semi-Circular Bunds (so called Eyebrows) and Soil Bunds have been constructed in bare areas to protect the soil from erosion and to collect surface water. These Soil and Water Conservation (SWC) measures alter hydrological processes by reducing surface runoff and increasing evaporation and infiltration. Azari et al, (2017) indicate that SWC measures are more effective at reducing sediment yields under future climate condition compared to other management practices in northeastern Iran.

1.3.1 Semi-Circular Bunds

Semi-Circle Bunds (Eyebrows) are usualy made of compacted soil or stone to collect surface runoff and therefore increase soil moisture and prevent soil erosion. They are set on the contour line, facing upslope to the flow of water. Bunds are up to one meter high and have commonly a diameter of 100-300 m in Halilrood Basin (Figure 1.3). They are constructed on slopes up to 15-20%. This tichnique usualy used for proteting the smal-scale farmlands from flood and erosion or fodder production.

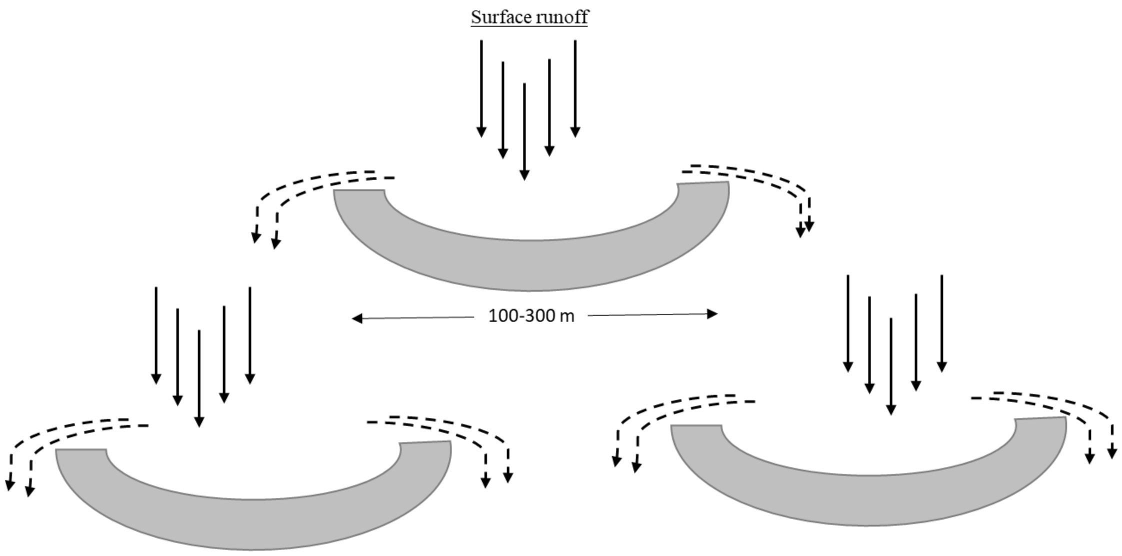

Figure 1.3 Structure of the Semi-Circle Bunds techniques.

1.3.2 Soil Bunds

Soil Bunds (Contour Bunds) are among the most common techniques used in Halilrood Basin to collect dispersed surface runoff, increase water infiltration and enhanced soil moisture and prevent soil erosion. Depending on their purpose, the area behind the Soil Bunds are used for planting trees, bushes and/or grasses. Soil Bunds, similar as the Semi-Circle Bunds, are built along the contour lines on gentale or moretare slopes. Bunds are usually constructed either with soil or stones.

Figure 1.4 Soil Bunds used for planting trees and grasses in the northern part of the Halilrood Basin, Iran, 2019.

1.4 Hydrological modeling in arid region

Predicting the spatial and temporal variation of the hydrological processes that occur within arid and semi-arid regions is difficult (Wheater et al., 2007). The use of hydrological models has therefore been of interest for simplified representation of a real-world system using a set of equations that may be empirically found or based on physical laws or a set of conceptual dependencies. A great variety of hydrological models has been developed as relevant tools for a better management of land and water from simpler lumped and conceptual catchments models such as Hydrologiska Byrans Vattenavdelning, HBV model (Bergstrom, 1976) to complex distributed and physically based models such as Systeme Hydrologique European, MIKE SHE model (Refshaard and Storm, 1995). To be able to simulate both spatial and temporal characteristics of the catchment, distributed and semi-distributed models are the model category of choice. The use of physically based hydrological models has been increasing over time because of their capabilities to incorporate physical processes of the system. The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998, Arnold and Fohrer 2005) is a semi-distributed physically-based model (Devia et al., 2015), which is widely applied in many areas with different climatic conditions. The aim of the development of the SWAT model was to quantify the impacts of water and agricultural management practices on streamflow and other hydrological components (Arnold and Fohrer 2005). The model enables the simulation of detailed hydrological processes in data scarcity regions (e.g., Wagner et al., 2011 and 2012; Schmalz et al., 2016) such as Wadis (e.g., Ouessar et al., 2009; Hallouz et al., 2018) through the utilization of a wide range of parameters, which however requires experience for a successful application of the model. SWAT calculates the water balance for the four storage volumes snow, soil profile, shallow aquifer, and deep aquifer, and considers precipitation, interception, evapotranspiration, surface runoff, infiltration, percolation, and subsurface runoff (Arnold et al., 1998; Neitsch et al., 2002). The surface runoff from daily precipitation is modelled using a modification of the SCS curve number method (Srinivasan et al., 2010) taking into account land use, soil type and antecedent soil moisture. The model subdivides the soil profile into multiple layers and considers infiltration, evaporation, plant uptake, interflow as well as up- and downward redistribution processes for each layer (Schuol et al 2008). Land surface topography obtained from a Digital Elevation Model (DEM) is used as an input data by the SWAT model to delineate the basin, sub-basins and the stream network. Sub-basins are divided into different hydrologic response units (HRUs), where soil, land use, and slope attributes are unique. The model is capable of simulating spatially distributed water balance components based on these HRUs.

The model has shown its capability of modeling water fluxes in Iran (Abbaspour et al., 2009) even in its arid and semi-arid basins with the integration of WUSs and SWCMs (Azari et al., 2017). Consumptive water use is an embedded method in SWAT to remove water from the basin on a monthly time step where the average monthly amount of water (in m^3/d) is removed from the specified source. In the SWAT model, water can be removed from specific sources such as the shallow aquifer (parameter WUSHAL), the deep aquifer (WUDEEP), the reach (WURCH), or ponds (WUPND) within any sub-basin in the catchment (Neitsch et al., 2002). The SWAT model faces difficulties to represent specific hydrological processes such as Hortonian Overland Flow (Easton et al., 2008) –movement of water on the land surface as sheetwash or concentrated into rills with few millimeters depth–, which is more pronounced in Wadi regions with thin soil layers and poor vegetation covers (Ries, 2016). Nevertheless, to address the long-term variations of water balance components in a large basin and implementing water use systems and soil and water conservation measures, the SWAT model is an appropriate choice (Abouabdillah et al., 2014; Khelifa et al., 2017).

1.5 Implementation of water use systems and soil and water conservation measures into the hydrological model SWAT

The existence of different water use systems (WUSs) such as qanats, wells, springs affect natural hydrological processes by extracting water from the aquifer, and alter the contribution of the groundwater to the main channels. Moreover, the implementation of numerous soil and water conservation measures (SWCMs) such as semi-circular bunds and soil bunds in order to protect the vulnerable soils to water erosion cause an impact on the hydrological components by decreasing the velocity of surface runoff and consequently increasing the infiltration and percolation rates in the Halilrood Basin. Generally, the WUSs and SWCMs in the Wadis has led to complex hydrological impacts that are not well understood (Ouessar et al., 2009; Abouabdillah et al., 2014; Hashemi et al., 2015). The discharge is separately measured for the qanats, springs, and wells. The amount of released or utilized water from these water supply systems has not been recorded so far. Hence, the amount of extracted water that is released to rivers as return flow is unknown.

The extracted amount of water from the shallow aquifer by WUSs (qanats, wells and springs) is summed up and included in our model. All water supply systems (qanats, wells, and springs) mentioned above can be modeled by taking water from the shallow aquifer using the variable WUSHAL on a monthly basis. To include the reservoirs in the model, in addition to the location of the reservoirs, all required information, i.e. the operational years, initial reservoir volumes, reservoir surface area when the reservoirs are filled to the emergency or principal spillways, and volume of water needed to fill the reservoir to the emergency or principal spillways need to be entered. Since the SWAT model is using a modification of the SCS curve number method to simulate runoff from daily precipitation, SWC measures can be implemented into the model through a reduction of the CN values, which consequently decreased the amount of surface runoff and increased the amount of infiltration. The influences of SWC measures on the water balance can be estimated through a reduction of the curve number (CN) values which consequently decreases the amount of surface runoff and increases the amount of infiltration (Arabi et al., 2007; Adimassu et al., 2014; and Taye et al., 2013). Based on previous studies, this surface runoff reduction varies from 28% (Adimassu et al., 2014) to 50-80% (Taye et al., 2013) for all respective sub-basins and HRUs.

1.6 Climate change and water demand

Water resources are under pressure from climate change (IPCC, 2014). The intensity and characteristics of climate change can vary significantly from region to region and climate change impacts are expected to be more severe in regions with drier climatic conditions (Faramarzi et al, 2013). In these regions, climate change is likely to result in a stronger increase of the number of people at risk of water scarcity (Abu-Allaban et al., 2015). Climate change will cause a significant reduction in Iran's total precipitation by 35% in the future (Mansouri Daneshvar et al., 2019). In addition, a study by Abbaspour et al. (2009) showed that the variations in magnitude and duration of precipitation are more intense under climate change at arid parts of Iran in comparison to the wet regions. They also reported that the number of days where precipitation is higher than 10 mm day^{-1} is projected to increase dramatically in most arid regions in the future, while smaller amounts of precipitation are expected for those regions. Currently, extreme events such as droughts and floods have threatened the lives and livelihood of millions of people living in arid and semi-arid parts of the world (Kundzewicz et al., 2014; Modarres et al., 2016). The frequency and magnitude of floods and droughts are very likely to increase in those areas due to climate change (Herrera-Pantoja and Hiscock, 2015; Metzger et al., 2020). In addition, existence of bare land as the dominant land cover and the sparse vegetation cover increase the flood susceptibility in arid regions, especially when high amount of precipitation occurs in a very short time period (Zaman et al., 2012). In arid regions, floods and faster runoff are mainly caused by intense precipitation events (Subyani 2011), which are projected to happen more often under future climate conditions (Polade et al., 2014). Therefore, for a long-term strategic planning of arid regions' water resources in the face of the evolving climate change impacts, it is important that these effects are quantified, ideally in a high spatial and temporal resolution.

In climate change impact studies, an ensemble of climate models is used to consider the model related biases, uncertainties and represent natural climate variability (Christensen and Lettenmaier 2006; Kling et al., 2012; Velázquez et al., 2013). Assessing the impacts of future climate change and developing mitigation and adaptation strategies for water resources management require climate change projections with a better resolution, including an evaluation of their robustness and their inherent uncertainties. In the past decades, methods for downscaling climate projections to the catchment scale (e.g., dynamic and statistical downscaling techniques) have become available (Kotlarski et al 2014). Research projects such as MERCURE (e.g., Hagemann et al., 2004), PRUDENCE (Christensen et al., 2007), NARCCAP (Mearns et al., 2009), and ENSEMBLES (van der Linden and Mitchell, 2009) enabled considerable advancements regarding methodological and technical developments for future climate simulations. A more recent generation of regional climate projections, the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Jacob et al., 2014) as an international climate downscaling initiative aims to provide a new data set from a multi-model multi-scenario ensemble of regional climate simulations with a high resolution for the entire world. The CORDEX initiative covered regional climate projections for Asia with a spatial resolution of 50 km for climate impact assessment and adaptation. CORDEX uses the time series of possible future concentrations and emissions of greenhouse gases and air pollutants and different trajectories of land use change, radiative forcing, social and economic as well as political storylines combined from the four Representative Concentration Pathways (RCPs) to provide climate projections. These four RCPs are named according to the radiative forcing levels of 8.5, 6, 4.5 and 2.6 w m^{-2}, by the end of the century (IPCC 2014).

On a local scale, climate model simulations are frequently subject to systematic biases (Ehret et al., 2012). To deal with these, scientists recommended applying different bias correction methods to account for differences between the climate model data and the measured data (e.g. Piani et al., 2010; Teutschbein et al., 2011). In many climate change impact studies, two groups of bias correction methods, simple (e.g. linear scaling, delta-change approach) and sophisticated (e.g. distribution mapping, power transformation), are applied (Teutschbein and Seibert 2012; Troin et al., 2015). However, individual bias correction methods reduce the deviations between model and measurements in unique ways, resulting in different absolute values as well as a different variability (Ehret et al., 2012). It is therefore recommended to apply different bias correction methods, such as linear scaling (LS) and distribution mapping (DM) and test their possibly different impact (Fang et al., 2015, 2018; Luo et al., 2018).

The impact of climate change can be more severe if it coincides with increasing water demand. Increasing water demand follows population growth, economic development and changing consumption patterns (WWAP, 2018). Global water demand has increased by 600% over the last century (Wada et al 2016). As the world's population grows, global water demand is estimated to increase significantly over the next decades in all the three sectors, industry, domestic and agriculture (WWAP, 2018). It is critical in arid regions where not only population and development are rising, but also drier climatic conditions are expected in the future (IPCC, 2014). Iran is one of the driest developing countries in the world, which experienced a high increase in the population over the last few decades, i.e., from 33.7 million in 1976 to more than 80 million in 2017 (Dienel et al., 2017). Population growth adds further stress to the limited water resources available in the drier regions of the country (Ashraf et al., 2019), where fragile ecosystems like Wadi systems are located, since water use efficiency would have not been adjusted accordingly.

Therefore, the impacts of climate change and growing water demand should be jointly assessed with regards to the overall water resources.

Groundwater provides approximately 20% of total water use worldwide (Zektser & Everett 2004). It is the most important resource of freshwater for sustaining life (Wheater et al., 2010). The existence of groundwater is more crucial in arid regions, where the ecosystem is more fragile and groundwater can ensure the functioning of the freshwater ecosystems by contributing to the base flow (Boulton and Hancock, 2006; Kath et al., 2018). Groundwater is extracted to supply water for different purposes, which resulted in rapid groundwater depletion worldwide (Gleeson and Wada, 2013). Groundwater depletion can be more severe in arid and semi-arid regions, where groundwater recharge is very small especially during drought periods and surface water has very high variability in space and time (Long et al., 2016; Taylor, 2014). Local residents recognized these characteristics of surface water and developed different water use systems and water management solutions such as qanats and wells. Rapid development, population growth and consequently increases in the number of those water use systems can lead to pronounced groundwater depletion (Eissa et al., 2016; Perrone and Jasechko, 2019). The level of groundwater can persistently drop if there is an imbalance between groundwater withdrawal and total recharge from infiltration and river transmission losses over the basin (de Graff et al., 2019; Acero Triana et al., 2020). Richey et al., 2015 considered the ratio of groundwater withdrawal to the recharge as an indicator of regional water security. Hence, estimation of groundwater recharge under pressure of climate change is essential to guide management strategies for groundwater resources (Dash et al., 2019). Hydrological models are recommended as essential tools to represent natural groundwater recharge since characterizing its process and observe the subsurface are difficult and often highly uncertain (Wheater et al., 2010).

Climate change and growing water demand not only have substantial impacts on groundwater, but also can alter the surface water. Changes in volumes and timing of surface water availability have been reported for most of arid parts of Iran (Ashraf et al., 2019) and other countries e.g., United States of America (Caldwell et al., 2012), Algeria (Achite and Ouillon 2016), China (Xue et al., 2017), and Jordan (Al Qatarneh et al., 2018). Ecosystems are highly vulnerable to the alteration of the streamflow regime world-wide (Moiwo et al., 2010, Wen et al., 2013, Nielsen and Brock, 2009). Similar changes in water level of the lakes and wetlands were observed in Iran due to reduction in streamflow of rivers (e.g., Urmia lake in the northwest (Khazaei et al., 2019) and the Bakhtegan and Tashk wetlands in the south of Iran (Haghighi and Kløve 2017). Moreover, the research by Sharifikia (2012) showed that the variation of surface water in Hirmand Basin in southwestern Iran resulted in severe environmental problems such as a decrease in size of the Hamoun wetland, increasing wildlife death rates, and increasing air pollution and consequently health problems by suspended soil particles during the windy period of the year (from June to September). The existence of the Jazmorian Wetland in southwestern Iran has already been threatened by high potential evapotranspiration (more than 2800 mm yr^{-1}) and decreases in the inflow from the Halilrood River (Qaderi Nasab and Rahnema, 2020). Lower inflow to the Jazmorian Wetland and lower soil moisture in the wetland area as the consequence, increased the vulnerability of the wetland to wind erosion and raised the number of dusty days in cities surrounding the wetland (Modarres and Sadeghi, 2018). Similar environmental problems are reported for other arid regions such as northwestern China where the Ebinur Lake has been dried up and became one of the main dust sources (Bao et al., 2006). Therefore, assessing the future susceptibility of fragile ecosystems such as Iranian Wadi regions to climate change and rising water demands is essential.

1.7 Research gaps and research questions

Existence of different water use systems and soil and water conservation measures cause an alteration of natural hydrological processes in arid and semi-arid regions where water resources are limited. This complexity is mostly neglected in hydrological modelling and impact assessments (Ouessar et al., 2009; Abouabdillah et al., 2014; Hashemi et al., 2015). Hydrological processes of arid and semi-arid regions were simulated by a variety of models in different parts of the world, and a large number of studies focused on streamflow simulations in arid catchments (e.g., Hernandez et al., 2000; Riad et al., 2004; Ignatius and Jones, 2017; Hallouz et al., 2018). Despite considerable progress in hydrological simulations of Wadis during the last two decades (Lange et al., 1999, Al-Qurashi et al., 2008; McIntyre and Al-Qurashi, 2009; Ben and Abida, 2016), only few efforts have been made to include WUSs and SWCMs in hydrological models to simulate streamflow. Although the impacts of different WUSs and SWCMs on surface runoff are shown in these, the accuracy of the hydrological model on representing water balance components can still be improved. For this reason, the first research question of this PhD dissertation is as follows:

(1) How can Wadi systems be more accurately represented in a hydrological model?

Assessing the impacts of climate change on hydrological components is an issue of preference for hydrologists (Blöschl et al., 2019). Recent studies have revealed that climate change impact will be more severe in regions where the climate is drier (Chen et al., 2005; Wang et al., 2012). Sporadic precipitation and high potential evapotranspiration coupled with increasing water demand causes a higher vulnerability of Wadis to a drier climate. Therefore, changes in streamflow caused by climate change have become the most important topic for future water resources management in arid regions in different parts of the world (Saharia and Sarma 2018; Oeurng et al., 2019). Several studies have been carried out in Iran to assess the impact of climate change on water resources (e.g., Abbaspour et al., 2009; Vaghefi et al., 2014).

They reported variabilities in the impact of climate change in different regions, where frequency, length, and magnitude of changes vary from region to region. In addition, the impact of climate change on the water resources of Wadis in the center of the country have not been studied so far due to limited data availability and sparse population. To support long-term water resources management and planning, assessing the impact of climate change on different part of the hydrograph and all relevant hydrological components such as streamflow, evapotranspiration, groundwater and water yield are necessary, which have not been considered in previous studies, which leads to the second research question:

(2) How does climate change affect the water resources of a Wadi system?

In addition to climate change, growing water demand due to development and population growth poses a serious threat to the sustainable use of water resources in different sectors (Oki and Kanae, 2006 and Panahi et al., 2020). Groundwater depletion occurs in different parts of the world due to intensive extractions (Gleeson and Wada, 2013). Groundwater extraction is more severe in arid and semi-arid regions, where water demand is greater than available surface water, thus effective groundwater withdrawal systems such as qanats and wells are developed to supply water for different human activities (Taylor, 2014; Long et al., 2016). Higher groundwater withdrawal and lower natural groundwater recharge due to population growth and climate change lead to a persist drops in water level in the aquifers (Eissa et al., 2016; Perrone and Jasechko, 2019). The implications of climate change and rising water demand are not only limited to groundwater, but also change magnitude and duration of streamflow for different arid regions (Ashraf et al., 2019; Caldwell et al., 2012; Achite and Ouillon 2016; Xue et al., 2017; Al Qatarneh et al., 2018). Hence, sustainable use of limited water resources in Wadis should be jointly assessed regarding both surface water and groundwater. Furthermore, any alteration in limited water resources of Wadis caused by natural or anthropogenic activities might have strong environmental impacts (Oki and Kanae, 2006 and Panahi et al., 2020). Therefore, the following two questions are addressed in this research to enhance our understanding about the sustainability of water resources in Iranian Wadis by including both climate change and increasing water demands in our modeling projections.

(3) How does the combination of climate change and growing water demand affect groundwater sustainability of a Wadi system?

(4) **How does climate change and growing water demand affect the ecological flow regime of a Wadi system?**

1.8 Thesis structure

This PhD thesis addresses the four research questions in different chapters. The following chapter (second chapter) deals with a better representation of Wadi system in a hydrological model. In the third chapter, the impact of climate change on streamflow and major hydrological components are addressed. The fourth chapter evaluates the hydrologic regime alteration and sustainability of groundwater use under pressure of climate change and growing water demands.

Chapter 2 Integrating water use systems and soil and water conservation measures into a hydrological model of an Iranian Wadi system

Nariman Mahmoodi[1*], Jens Kiesel[1,2], Paul D Wagner[1], Nicola Fohrer[1]

[1]Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel 24118, Germany

[2]Department of Ecosystem Research, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin 12489, Germany

[*]Corresponding author: Nariman Mahmoodi (E-mail: nmahmoodi@hydrology.uni-kiel.de)

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Abstract

Water resources are precious in arid and semi-arid areas such as the Wadis of Iran. To sustainably manage these limited water resources, the residents of the Iranian Wadis have been traditionally using several water use systems (WUSs) which affect natural hydrological processes. In this study, WUSs and soil and water conservation measures (SWCMs) were integrated in a hydrological model of the Halilrood Basin in Iran. The Soil and Water Assessment Tool (SWAT) model was used to simulate the hydrological processes between 1993 and 2009 at daily time scale. To assess the importance of WUSs and SWCMs, we compared a model setup without WUSs and SWCMs (Default model) with a model setup with WUSs and SWCMs (WUS-SWCM model). When compared to the observed daily streamflow, the number of acceptable calibration runs as defined by the performance thresholds (Nash-Sutcliffe efficiency (NSE)≥0.68, −25%≤percent bias (PBIAS)≤25% and ratio of standard deviation (RSR)≤0.56) is 177 for the Default model and 1945 for the WUS-SWCM model. Also, the average Kling-Gupta efficiency (KGE) of acceptable calibration runs for the WUS-SWCM model is higher in both calibration and validation periods. When WUSs and SWCMs are implemented, surface runoff (between 30% and 99%) and water yield (between 0 and 18%) decreased in all sub-basins. Moreover, SWCMs lead to a higher contribution of groundwater flow to the channel and compensate for the extracted water by WUSs from the shallow aquifer. In summary, implementing WUSs and SWCMs in the SWAT model enhances model plausibility significantly.

Keywords: SWAT model; streamflow; Wadis; multi-metric framework; water use systems; soil and water conservation measures; Halilrood Basin

2.1 Introduction

Over-exploitation of water resources and water scarcity have become a worldwide and prevalent problem in most arid and semi-arid regions such as the Wadis in Iran (Voss et al., 2013). In addition to a strong variability of precipitation in space and time in arid and hyper arid climates, these regions experience the lowest amounts of precipitation in Iran (Khalili and Bazrafshan, 2004; Motiee et al., 2006). In arid environments, most of the rainwater is lost to evaporation (Tavakoli et al., 2010). Under such circumstances, the limited available freshwater is a fundamental and valuable resource for the population and the natural environment. On the one hand, over the past centuries, traditional water use systems (WUSs) such as qanats (a slightly sloping tunnel constructed to accumulate and transfer water from the groundwater to the land surface), wells, springs and dams have been used by native residents to manage limited water resources (Motiee et al., 2006; Ouessar et al., 2009; Nasiri and Mafakheri, 2015). Qanats and drilled wells are considered the most stable and successful water supply systems in hot and arid climates (Boustani, 2008; Hussain et al., 2008; Mostafaeipour, 2010). Hence, WUSs are a reliable way to secure access to safe and affordable water for several purposes, e.g., drinking, washing and irrigating. On the other hand, numerous soil and water conservation measures (SWCMs) such as semi-circular bunds and soil bunds have been constructed to decrease the velocity of surface runoff and erosion rate, and to consequently increase the infiltration and percolation in the Halilrood Basin of Iran. The existence of WUSs and SWCMs in the Wadis has led to complex hydrological impacts that are not well understood (Ouessar et al., 2009; Abouabdillah et al., 2014; Hashemi et al., 2015). The WUSs are used to not only transfer water from shallow aquifers to the land surface for various purposes, but also release water into rivers in some cases, which makes it difficult to include these water usages in a hydrological model. Although streamflow may be separately measured for the qanats, springs and wells, the amount of released or utilized water from these water supply systems has not been recorded so far. Hence, the amount of extracted water that is released to rivers is unknown. In addition, in a Wadi catchment, the amount of water which is extracted by these traditional water supply systems can significantly affect river runoff (Ouessar et al., 2009).

In previous studies that have been carried out in Iran, mostly the impacts of WUSs and SWCMs on groundwater were evaluated, but they were not included in a catchment model to simulate streamflow. For instance, Sadeghi-Tabas et al. (2017) integrated qanats, springs and wells in a groundwater model with a genetic multi-algorithm method to define the pumping rates within a series of Pareto solutions. Naghibi et al. (2018) used the location of qanats to model the groundwater extraction potential of Beheshtabad Basin in the center of Iran. Understanding hydrological processes and providing reasonable strategies and plans for policy makers for a better management of water resources in these regions are important. In this regard, hydrological models can be used to depict complex hydrological conditions and investigate the impacts of WUSs and SWCMs on hydrological processes in a Wadi catchment. Due to the specific hydrological and climatic conditions and limited data availability, using a model that is capable of simulating hydrological processes under these conditions, is critically important.

Hydrological processes and streamflow of arid and semi-arid regions were simulated by a variety of models in different parts of the world, and a large number of studies focused on streamflow simulations in dry basins. For instance, Hernandez et al. (2000) applied two hydrological models in a small semi-arid watershed in southeastern Arizona, USA; Peugeot et al. (2003) employed the r.water.fea model in Sahelian West Niger; Riad et al. (2004) used an artificial neural network (ANN) model for the Qurika Wadi Basin in Morocco; McMichael et al. (2006) estimated the monthly streamflow of a semi-arid basin in central California using MIKE SHE model; and Lesschen et al. (2009) simulated runoff of Carcavo Basin with the LAPSUS (landscape process modelling at multidimensions and scales) model in Southeast Spain. Also the Soil and Water Assessment Tool (SWAT) model was already applied in arid and semi-arid basins with limited data availability in different parts of the world (Yebdri et al., 2007; Ning et al., 2015; Cheng et al., 2017; Ignatius and Jones, 2017; Hallouz et al., 2018). In addition, the SWAT model has successfully been used in different parts of Iran, mostly to simulate streamflow (Rostamian et al., 2008) and groundwater (Izady et al., 2015), as well as to estimate sediment (Rostamian et al., 2008) and nitrate transport (Jamshidi et al., 2010), and to assess impacts of climate change (Zahabiyoun et al., 2013; Rafiei et al., 2015), land use change (Ghaffari et al., 2009; Aghsaei et al., 2020) and engineering projects (e.g., dam construction) (Ghobadi et al., 2015) on hydrology. In summary, the SWAT model has shown its capability of modeling water fluxes in Iran as well as in arid and semi-arid basins in the world.

Despite considerable progress in hydrological simulations of Wadis during the last two decades (Al-Qurashi et al., 2008; McIntyre and Al-Qurashi, 2009; Ben and Abida, 2016), only few efforts have been made to include WUSs and SWCMs in hydrological models to simulate streamflow. As the SWAT model is an open source model that includes subroutines and parameters related to agricultural management practices as well as water uses, it is often used to consider different WUSs and SWCMs in the simulation of streamflow. For instance, Ouessar et al. (2009) applied the SWAT model to investigate the effect of WUSs on the water balance components of an arid watershed of Wadi Koutine in Southeast Tunisia, based on 38 runoff events between 1973 and 1985. Abouabdillah et al. (2014) employed the SWAT model to evaluate the impact of SWCMs (i.e., contour ridges) on hydrological components and erosion in Merguellil catchment in the center of Tunisia. The model predicted that contour ridges produced an annual reduction in surface runoff, an increase in aquifer recharge and a retention of large proportions of entrained sediment. Moreover, Khelifa et al. (2017) used the SWAT model to analyze the effect of bench terraces on water and sediment yield in an experimental catchment (3.2 km^2) and found that the local terraces reduced both surface runoff and sediment yield by around 20%. Although the impacts of different WUSs and SWCMs on surface runoff are shown in these previous studies, the influences on different segments of the hydrograph and on model performance have not been evaluated when WUSs and SWCMs are implemented.

Therefore, the aims of this study are (1) to integrate traditional WUSs and SWCMs in the Halilrood Basin of Iran into a hydrological model, (2) to assess the performance of this integration, and (3) to quantify and discuss the impacts of this integration on hydrological processes of the Halilrood Basin.

2.2 Materials and methods

2.2.1 Study area

Halilrood Basin is located in Kerman Province in the center of Iran (Figure 2.1) and comprises an area of approximately 7224 km^2. The Halilrood River is the largest river in terms of discharge in Kerman Province and is one of the major water sources for Jazmorian wetland, which is crucial for the natural ecosystems in Southeast Iran (Skandari et al., 2016). Due to the mountainous area in the north, elevation of the entire basin varies from approximately 1391 to 4359 m a.s.l. About 75% of the basin is covered by bare land (ESA, 2010). Limited rainfed agriculture and irrigated farming are taking place only in the surroundings of the river and qanat channels.

Lithosol, Calcaric Regosol and Calcic Yermosols are the dominant soils in the basin, which are classified into soil hydrologic group C (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) with a slow infiltration rate and a high runoff potential. Lithosol and Calcic Yermosols are shallow and moderately deep soils, containing a higher sand content and a lower silt and clay content. Specifically, the top soil layer consists of a nearly equal percentage of sand (44%) and silt (36%). Calcaric Regosol is a deep soil and typically has a clay-loam texture with a high clay content.

Halilrood Basin is characterized by a desert climate with hot and dry summers according to the Köppen–Geiger climate classification. The maximum daily average temperature can reach up to 40°C at Kenaroyeh station located near the outlet of the basin. The long-term annual average temperature is 13°C. The long-term average annual precipitation in the basin is less than 225 mm (1993–2009), most of which is received between January and May, whereas precipitation ism negligible between June and December. The annual potential evapotranspiration (PET) ranges from 2039 to 2569 mm based on the observation data from the Baft synoptic station (Figure 2.1). Five hydrometric, nine climatic and one synoptic station are in operation in the upstream of Kenaroyeh station, for which daily climate (from 1979 to 2010) and discharge (from 1993 to 2011) data are available. The outlet of the basin is located in the upstream of Jiroft dam at Kenaroyeh station (shown in Figure 2.1). The mean annual discharge from 1993 to 2011 is 7.68 $m^3\ s^{-1}$. In the northern part of the basin, Baft and Rabor (Nabi-e-Akram) dams (ratio of reservoir volume to mean annual runoff volume is 0.140 and 0.002, respectively) are in operation since 2007 and 2009, respectively (IWPCO, 2018).

In addition to using surface water, extracting groundwater is common to overcome dry periods and particularly the drought disasters of the last decade. Hence, the necessary water for domestic, industrial and agricultural purposes is supplied from 422 wells, 347 qanats, 2 dams and 184 springs scattered throughout the basin (Figure 2.1).

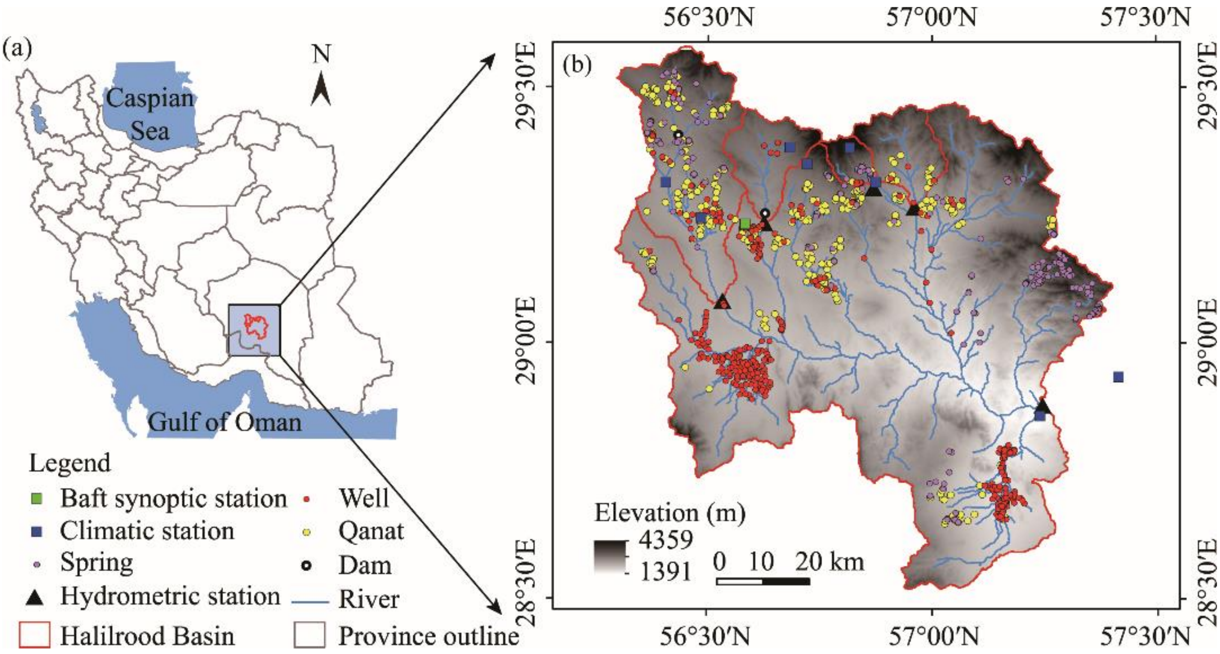

Figure 2.1 Location of Halilrood Basin in Kerman Province of Iran (a) and water use systems, climatic and hydrometric stations in the Halilrood Basin (b)

2.2.2 Hydrological model

The SWAT model (Arnold et al., 1998) is one of the most widely used catchment models which can be applied to simulate hydrological processes in different climatic regions and under various conditions. It is a semi-distributed model that splits the basin into several sub-basins, where each sub-basin consists of hydrological response units (HRUs) with unique combinations of soil, land use and slope (Arnold et al., 2012). The SWAT model has been developed to quantify the impacts of water and agricultural management practices on streamflow and other hydrological components. The model enables the complex simulation of detailed hydrological process in Wadis through the utilization of a wide range of parameters, which however requires experience for a successful application of the model. In addition, the model has shown its capability of modeling water fluxes in Iran as well as in arid and semi-arid basins elsewhere with the integration of WUSs and SWCMs.

2.2.3 Data input and model setup

2.2.3.1 Model parameterization

A QGIS interface for SWAT (QSWAT) model was used to prepare the SWAT model input files (Dile et al., 2016). We used the SRTM (shuttle radar topography mission) digital elevation model (Jarvis et al., 2008), soil data from the harmonized world soil database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) and a Globcover 2009 land use map (ESA, 2010) to set up the SWAT model. It should be noted that we divided the Halilrood Basin into 285 sub-basins with 6091 HRUs using five slope bands (<3%, 3%–5%, 5%–8%, 8%–15% and >15%) based on the FAO classification. This setup provided a sufficient spatial resolution for implementing the SWCMs in the SWAT model.

Precipitation data from nine climatic stations scattered within the Halilrood Basin were used (Figure 2.1). Additional climate data of wind speed, temperature, solar radiation and relative humidity were collected from the Baft synoptic station in the north of the basin (Figure 2.1). We determined two model setups by running the model without (Default model) and with (WUS-SWCM model) WUSs and SWCMs, to analyze the impacts of WUSs and SWCMs in the SWAT model.

Discharge data from the hydrometric station located at the outlet of the basin (Kenaroyeh station) was divided into calibration and validation datasets. We selected the years for calibration and validation based on representative climatic conditions in each period, i.e., equal distribution of dry year (total precipitation<200 mm), wet year (total precipitation>270 mm) and average year (200–270 mm annual precipitation). The calibration and validation periods chosen for the simulation runs were 1995–2003 and 2004–2009, respectively, with a two-year spin-up phase prior to 1995.

2.2.3.2 Water use systems (WUSs)

The WUSs in the Halilrood Basin include qanats, springs, wells and dams. Qanats are regarded as a traditional water use system in the study area, and more details can be available in Nasiri and Mafakheri (2015) and Mostafaeipour (2010). Qanats, wells and springs are providing water from shallow groundwater for domestic and industrial purposes and irrigation in the Halilrood Basin. To consider qanats, spring and wells in the SWAT model, we applied consumptive water use (an embedded approach in the SWAT model) to remove water from the basin on a monthly time step. The average monthly amount of water (m^3 d^{-1}) was therefore removed from the specified source such as the shallow aquifer (WUSHAL), the deep aquifer (WUDEEP), the reach (WURCH) or ponds (WUPND) within any sub-basins in the basin. All water supply systems (qanats, wells and springs) mentioned above were modeled by taking water from the shallow aquifer using the variable WUSHAL (Table 2.1). The actual locations of qanats, wells and springs were used to specify the respective sub-basins and HRUs in the SWAT model. It is notable that, due to the structure of qanats, the location of the mother well (the last and deepest well) for each qanat was considered to find out the origin of the water. Moreover, we summed up the extracted amount of water from the shallow aquifer by qanats, wells and springs based on the measured discharge provided by Iran Water & Power Resources Development Company (IWPCO) in 2001 and 2006 and included it in the SWAT model. Due to changes in groundwater recharge and excessive consumption of groundwater, some of the qanats are dry and deactivated nowadays based on the measured discharge provided by IWPCO in 2001 and 2006. These were kept out of the calculation (Table 2.1). In addition, the wells were classified into two groups, i.e., shallow and semi-deep wells. Due to a drop in groundwater table, 3% of the wells were extended to semi-deep wells based on the measured discharge provided by IWPCO in 2001 and these wells were drilled deeper in Quaternary sedimentary formations (>80 m). Since those wells extracted water from the deep aquifer, they were neglected in the SWAT model. Further information about the implemented qanats, wells and springs is given in Table 2.1.

Table 2.1 Characteristics of the water use systems (WUSs) in the study area

WUSs	Number	Number of deactivated	SWAT-variables affected	Hydrological components affected	Implemented scales	Total annual extracted water ($10^4 m^3$)	Average daily discharge (L/s)	Date of drilling		
								1966–1980	1981–1994	1995–2011
Qanats	347	85	WUSHAL	groundwater, baseflow	Sub-basin	16.67	1.52	*	*	*
Springs	184	14	WUSHAL	groundwater, baseflow	Sub-basin	9.99	1.36	*	*	*
Wells	422	93	WUSHAL	groundwater, baseflow	Sub-basin	48.56	*	65	59	268

Notes: SWAT, Soil and Water Assessment Tool; WUSHAL, removal water from the shallow aquifer; *, no data available.

Baft and Rabor dams are two constructed reservoirs in the headwaters of the basin (Figure 2.1), which supplied water for irrigation and domestic purposes since 2007 and 2009, respectively. Table 2.2 shows the reservoir parameters used in the SWAT model.

2.2.3.3 Soil and water conservation measures (SWCMs)

Due to the soil properties and climatic conditions in the Halilrood Basin, semi-circular bunds (so called Eyebrows) and soil bunds have been constructed in bare land to protect the soil from erosion and to collect surface water. The semi-circular bunds and soil bunds, belonging to SWCMs, can alter hydrological processes by reducing surface runoff and by increasing evapotranspiration and infiltration. Those might also change the small surface runoff routing schemes. However, since we are mainly interested in the impact on the water balance, the influence of SWCMs was estimated by changing the curve number (CN) for the affected HRUs, which is in agreement with the studies of Arabi et al. (2007), Adimassu et al. (2014) and Taye et al. (2013).

Table 2.2 Hydrological details of Baft and Rabor reservoirs

Parameter	Unit	Description	Baft	Rabor
SUB-BASIN	–	Number of the sub-basin in which the reservoir is located	169	198
IYRES	–	The operational year	2007	2009
RES_ESA	hm^2	Reservoir surface area when the reservoir is filled to the emergency spillway	8.0	85.0
RES_EVOL	$10^4\ m^3$	Volume of water needed to fill the reservoir to the emergency spillway	70	4000
RES_PSA	hm^2	Reservoir surface area when the reservoir is filled to the principal spillway	7.4	32.0
RES_PVOL	$10^4\ m^3$	Volume of water needed to fill the reservoir to the principal spillway	65	3500
RES_VOL	$10^4\ m^3$	Initial reservoir volume	30	2000

Notes: –, no unit.

In the SWAT model, SWCMs are implemented through a reduction of the CN values which consequently decreases the amount of surface runoff and increases the amount of infiltration. Based on previous studies, this surface runoff reduction varies from 28% (Adimassu et al., 2014) to 50%–80% (Taye et al., 2013) for all respective sub-basins and HRUs. In our model, 50% of the CN values were reduced in the HRUs with the artificial structures (Table 2, 3).

Table 2.3 Characteristics of the soil and water conservation measures (SWCMs) in the study area

SWCMs	Number of sub-basins	SWAT-variables affected	Hydrological components and processes affected
Semi-circular bunds	17	Curve number (CN)	Surface runoff, infiltration
Soil bunds	53	Curve number (CN)	Surface runoff, infiltration

2.2.3.4 Calibration

In this study, we reviewed previously published SWAT model studies in Wadi systems to depict the hydrological components of the model, and carried out a manual sensitivity analysis to select the most important hydrological parameters. The properties and variables governing water movement into the soil and consequently into or out of the shallow aquifer were the most important parameters to sufficiently represent the WUSs in the model. The selected eight parameters and their ranges were based on previous studies in arid and semi-arid areas (Shrestha et al., 2016; Qi et al., 2017; Zettam et al., 2017) and the manual sensitivity analysis (Table 2.4).

Latin hypercube sampling (LHS) from the R package FME was used to generate a set of variations for the calibration parameters (Soetaert and Petzoldt, 2010; Pfannerstill et al., 2014; Haas et al., 2016) for 3000 model runs. The same set of LHS was used for the two setups. For each calibration run, the SWAT model input files were rewritten in R software (Pfannerstill et al., 2013; R Core Team, 2013).

Table 2.4 Selected parameters for calibration

Parameter	Description	Unit	Calibration range		Type
			Minimum	Maximum	
CN2	Initial soil conservation service (SCS) runoff curve number for moisture condition II	–	–30	–15	Add
SOL_AWC	Available water capacity of soil layer	mm H_2O/mm soil	–0.5	0.5	Add
ESCO	Soil evaporation compensation factor	–	0.90	0.96	Range
GW_DELAY	Ground water delay time	d	4	10	Range
RCHRG_DP	Deep aquifer percolation fraction	–	0.5	0.9	Range
ALPHA_BF	Base flow alpha factor	per day	0.08	0.20	Range
SOL_K	Saturated hydraulic conductivity	mm/hr	30	40	Add
EVRCH	Reach evaporation adjustment factor	–	0.5	0.8	Range

2.2.3.5 Model evaluation

The Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), percent bias (PBIAS; Gupta et al., 1999), root mean squared error (RMSE) and the ratio of standard deviation (RSR; Moriasi et al., 2007) are several quantitative criteria that are frequently used to evaluate the performance of hydrological models. In addition, the Kling–Gupta efficiency (KGE) is a statistical performance metric that considers bias, correlation and variability separately (Gupta et al., 2009). Kling et al. (2012) published a modified version of the KGE, in which bias and variability ratios were not crosscorrelated.

Since each of the aforementioned criteria has a specific hydrological focus (Guse et al., 2019), SWAT model parameters were calibrated using a multi-metric approach which has been proven efficient to balance model performance (Pfannerstill et al., 2014; Haas et al., 2016; Tigabu et al., 2019). Accordingly, 3000 model runs were carried out with the SWAT model. To assess model performance, we used NSE, PBIAS, RSR and the modified KGE as the performance measures on a daily basis. To identify the best model runs for both model setups and to enable a comparison, we defined thresholds for NSE, PBIAS and RSR so that at least 5% of the total model runs are remaining. To this end, a hierarchical selection of model runs was conducted. Firstly, the model runs with NSE values greater than or equal to 0.68 were selected. Secondly, the model runs with PBIAS between –25 and 25 were selected. Thirdly, model runs with RSR greater than or equal to 0.56 were identified. After the application of these thresholds on the 3000 model runs, we sorted the selected model runs according to the KGE. Finally, we selected 5% of the total model runs (150 model runs) as the best calibration runs based on the KGE for both model setups.

In this study, we used the segmentation of the flow duration curve (FDC; Yilmaz et al., 2008) and performance criteria for every segment (Pfannerstill et al., 2014) to distinguish the impact of WUSs and SWCMs on different parts of the hydrograph. The segments were split at different exceedance probabilities of the FDC: 0–5%, 5%–20%, 20%–70%, 70%–95% and 95%–100%, which were associated to very high, high, middle, low and very low flows, respectively. Equal ranges were considered for the very low and very high flows in the FDC as described in Pfannerstill et al. (2014). The RSR was applied on each of the five segments, which enabled a tailored evaluation of the model performance for the 150 best model runs (Haas et al., 2016). Since the WUSs (qanats, wells and springs) extract water from the shallow aquifer and SWCMs increase the infiltration rate, impacts will likely be highest on the base flow. Therefore, RSR in combination with different parts of the FDC is a suitable measure to evaluate the effects of WUSs and SWCMs on the model performance.

2.2.3.6 Water balance components

To assess via which pathways streamflow is affected by implementing WUSs and SWCMs in the model, we compared the hydrological components water yield (WYLD) and actual evapotranspiration (ET) of the 150 best model runs. WYLD represents the total amount of water leaving the sub-basin and entering the main channel, which is evaluated by the model as follows (Neitsch et al., 2011):

$$WYLD = SURFQ + LATQ + GWQ - TLOSS, \quad (1)$$

Where WYLD is the water yield (mm); SURFQ is the surface runoff (mm); LATQ is the lateral flow contribution to stream (mm); GWQ is the groundwater contribution to streamflow (mm); and TLOSS is the transmission losses (mm), i.e., water loss via transmission through the bed of the channels. Since the parameter combinations of the best model runs may not be the same, the parameter combinations of the best model runs were used for both model setups separately and the average changes for the aforementioned hydrological components were compared for all the selected runs.

2.3 Results and discussion

2.3.1 Calibration

Figure 2.2 shows the results of the performance metrics selection of both model setups for the Calibration period of 1995–2003. In Figure 2.2, the 3000 model runs are shown as a relationship between each performance metric and KGE as the main performance criteria. For each performance metric, the acceptable calibration runs are identified. For the Default model, the KGE values of the 3000 model runs range from –0.1 to 0.8 as compared to a narrower range of the KGE values for the WUS-SWCM model, in which the KGE values are mostly greater than 0.3 and 97% of the model runs have KGE values higher than 0.5. The number of acceptable calibration runs (n) for each metric is defined and highlighted in black for both model setups. For the Default model, the number of acceptable calibration runs with NSE≥ 0.68 is 243. The application of the PBIAS threshold reduces the number of total model runs from 3000 to 2358 acceptable calibration runs. Moreover, the number of acceptable calibration runs is even smaller (182) when the defined threshold of RSR is set. However, for the WUS-SWCM model, a higher number of simulation runs remains for each performance metric when the threshold is applied. The number of acceptable calibration runs with NSE≥0.68 is 2486. The PBIAS threshold leads to a high number of acceptable calibration runs (2437). When applying the RSR threshold, only 737 runs are rejected.

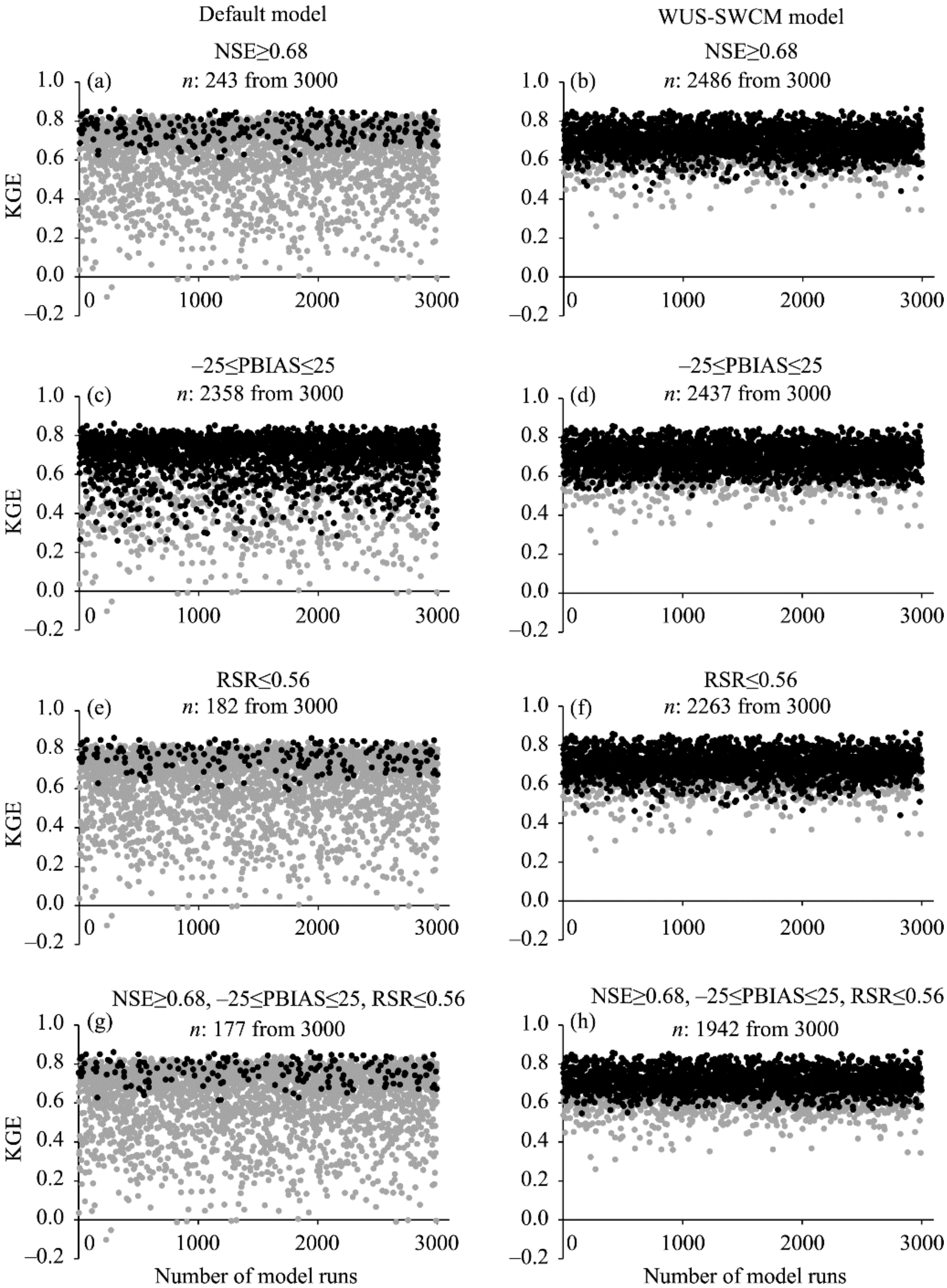

Figure 2.2 Number (*n*) of acceptable calibration runs for each performance metric (black points) for the Default model in the left column and the WUS-SWCM model in the right column. Default model, a model setup without water use systems and water conservation measures; WUS-SWCM model, a model setup with water use systems and water conservation measures. The gray points represent the range of the KGE (Kling-Gupta efficiency) for

the complete dataset of the 3000 model runs. The last row of both columns shows the selection of acceptable calibration runs after the application of all thresholds for the different performance metrics. NSE, Nash-Sutcliffe efficiency; PBIAS, percent bias; RSR, ratio of standard deviation.

Since the thresholds were applied based on performance metrics of the multi-metric framework (NSE, PBIAS and RSR), 177 model runs are remaining for the Default model, while this number is higher for the WUS-SWCM model, with 1942 model runs.

The acceptable calibration runs of the Default model and WUS-SWCM model setups are sorted in increasing order of the KGE values for both model setups and finally 150 best calibration runs are selected and plotted in Figure 2.3. The curves of the KGE clearly show the characteristics of the two model setups. In both model setups, a good performance is achieved for the first 20 runs, in which the KGE value in the calibration period is approximately 0.9. However, the KGE value of the 150th Default model run drops below 0.7. In contrast, the minimum KGE value is higher than 0.8, even for the 150th WUS-SWCM model run (Figure 2.3).

Although the KGE values are lower in the validation period when compared to the calibration period, a similar pattern is found for the validation and calibration periods (Figure 2.3). While the first eight runs of the Default model setup reach higher KGE values, the KGE values of the Default model setup declines more rapidly as compared to the WUS-SWCM model setup. In general, Figure 2.3 shows that better model parameterizations are found for the model with WUSs and SWCMs than for the one without.

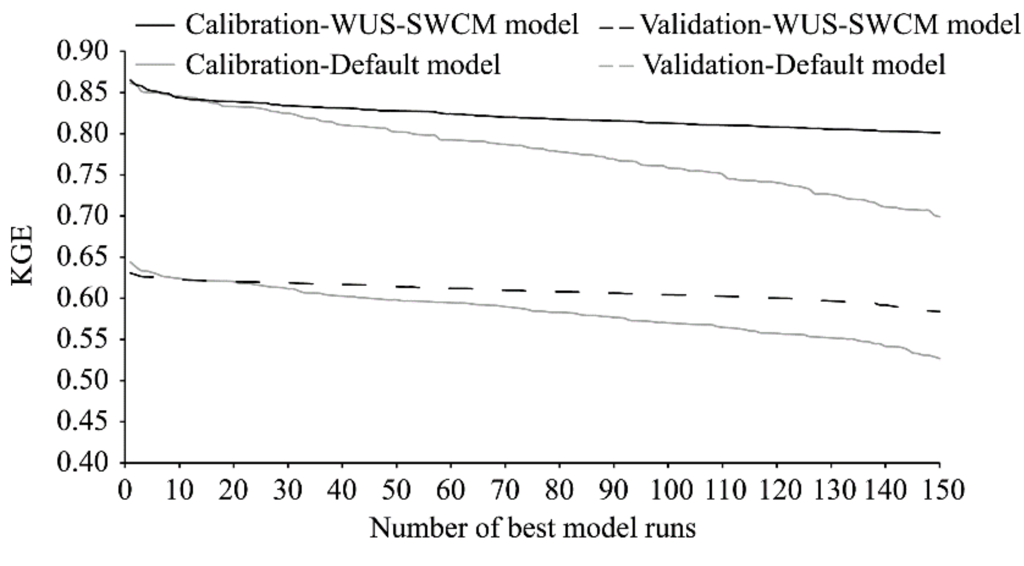

Figure 2.3 Comparison of the 150 best calibration runs for the KGE values of the Default model and WUS-SWCM model setups in calibration (solid lines) and validation (dashed lines) periods

The results show that the overall KGE significantly increases when WUSs and SWCMs are included. To show the effect of WUSs and SWCMs on different segments of the hydrograph and possible improvement, we plotted the ranges of the flow duration curves (FDCs) of the selected 150 best calibration runs for both model setups together with the observed FDC (Figure 2.4). We also calculated and summarized the average RSR value over the 150 best calibration runs to quantify the difference of both model setups for each FDC segment. The results are shown in Table 2.5. For the calibration period, although a high goodness of fit is achieved for very high flow for both model setups (Figure 2.4b), the Default model performs better with an average RSR value of 0.22. High flow is underestimated by the Default model. This is improved when the WUSs and SWCMs are included in the SWAT model (Figure 2.4c), which is confirmed by the comparison of the averaged RSR values for the high flow segment in Table 2.5, where RSR values decrease from 0.42 to 0.22. Flow in the middle segment is overestimated when the WUSs and SWCMs are implemented in the SWAT model (Figure 2.4d), which results in higher RSR values. The averaged RSR value decreases from 3.10 to 2.60 (Table 2.5) for the low flow segment.

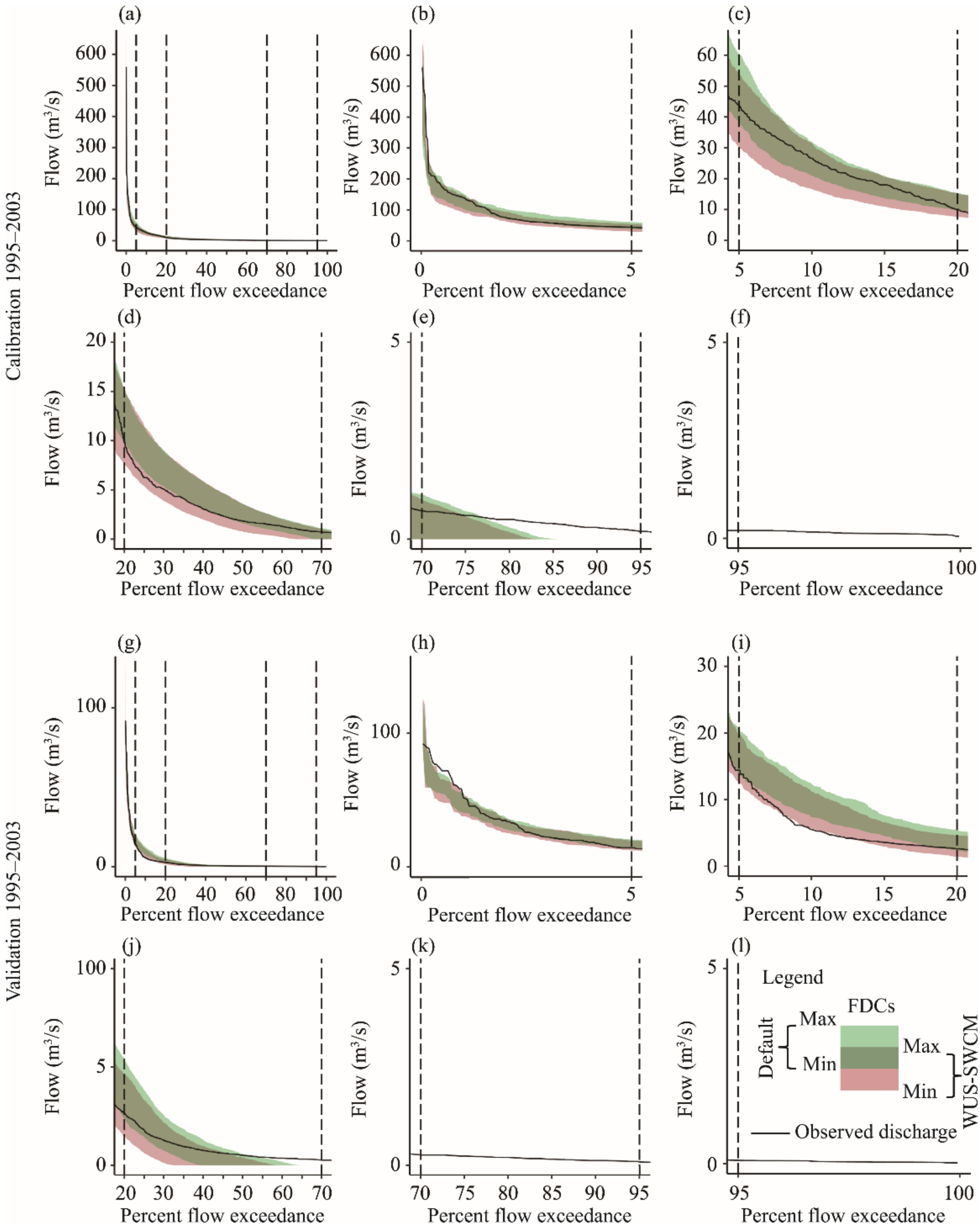

Figure 2.4 Flow duration curves (FDCs) of the selected 150 best calibration runs for the WUS-SWCM model (light green) and Default model (pink) in calibration (1995–2003; a–f) and validation (2004–2009; g–l) periods. The common FDCs between the two model setups are shown in dark green. Different segments of the hydrograph are separated by dotted vertical lines.

In contrast, for the validation period, when the WUSs and SWCMs are implemented, the model is improved for very high and middle flows (Figures 2.4h and j), with RSR values reducing from 0.32 to 0.28 and from 0.87 to 0.81, respectively (Table 2.5). The comparison of the averaged RSR value for the high flow segment reveals a worse model performance for the WUS-SWCM model (Table 2.5), with an overestimation in the high flow segment (Figure 2.4i).

In both model setups, the model is not capable of estimating low and very low flows close to zero (Figures 2.4e, f, k and l). This means that low and very low flows are simulated as zero, while these values are only close to zero in the observed data. This leads to the same RSR value for very low flow segment in both calibration and validation periods. Some qanats have a pool at the end of the channel that allows for a slower release of the water. As this has not been included in the model implementation of qanats, which might explain the incoherencies in low and very low flows.

Table 2.5 Summary of the application of the ratio of standard deviation (RSR) for each flow duration curve (FDC) segment for the average of the 150 best calibration runs of each model setup in calibration (1995–2003) and validation (2004–2009) periods

	Calibration period (1995–2003)						Validation period (2004–2009)					
	Performance metrics						Performance metrics					
	KGE	RSR very high	RSR high	RSR middle	RSR low	RSR very low	KGE	RSR very high	RSR High	RSR Middle	RSR Low	RSR very low
Without WUSs and SWCMs (Default model)	0.77	0.22	0.42	0.38	3.10	3.71	0.58	0.32	0.53	0.87	3.44	0.99
With WUSs and SWCMs (WUS-SWCM model)	0.82	0.29	0.22	0.70	2.60	3.71	0.61	0.28	1.04	0.81	3.44	0.99
Relative changes	+	–	+	–	+	*	+	+	–	+	*	*

Note: + means better performance in the WUS-SWCM model; – means worse performance in the WUS-SWCM model; * means no change in the model performance.

The parameters and their values which lead to the best model performance for both model setups are represented in Table 2.6. While the values of some parameters such as the soil evaporation compensation factor (ESCO) and deep aquifer percolation factor (RCHRG_DP) are almost the same in both model setups, other parameters differ considerably. For instance, CN value and reach evaporation adjustment factor (EVRCH) are higher in the WUS-SWCM model, i.e., more surface runoff and less infiltration as well as more evaporation from the reach are possible in the WUS-SWCM model. In those areas where SWCMs are present, the CN value is further reduced in the WUS-SWCM model setup prior to calibration. This explains the slightly lower overall reduction in the WUS-SWCM model setup compared to the Default model during calibration, as shown by the parameter set. Moreover, groundwater flows are faster in the WUS-SWCM model with higher ground water delay time (GW_DELAY) value.

Table 2.6 Parameter sets that lead to the best model performance for each model setup

Model setup	Number of model runs (1–3000)	Parameters							
		CN2 (add)	SOL_AWC (add)	ESCO (replace)	GW_DELAY (replace)	RCHRG_DP (replace)	ALPHA_BF (replace)	SOL_K (add)	EVRCH (replace)
Default	292	–24.610	0.005	0.956	8.345	0.527	0.143	32.359	0.655
WUS-SWCM	2868	–20.917	–0.008	0.954	4.791	0.508	0.191	36.070	0.798

To understand how the WUSs and SWCMs affect the hydrograph, we compare the hydrographs of the two model setups using the parameter sets of the best WUS-SWCM model (Figure 2.5). Streamflow and particularly streamflow peaks are overestimated by the Default model (Figure 2.5a). We compared the observed and simulated streamflow for a shorter period (from January 2001 to June 2001) from both model setups to assess differences between the two model setups in more detail (Figure 2.6). The Default model overestimates the peak flows considerably, while implementing WUSs and SWCMs results in decreased peak flows and a more reasonable performance in mid-January and at the end of February. Low flow is considerably underestimated by the Default model and a higher goodness of fit is obtained when the WUSs and SWCMs are implemented, e.g., in February and March. Also, the falling limb of the hydrograph is better represented by the WUS-SWCM model. This might be due to the higher infiltration rate and a slower release of water to the reach in the WUS-SWCM model. From the beginning of the dry period (May), both model setups perform similarly.

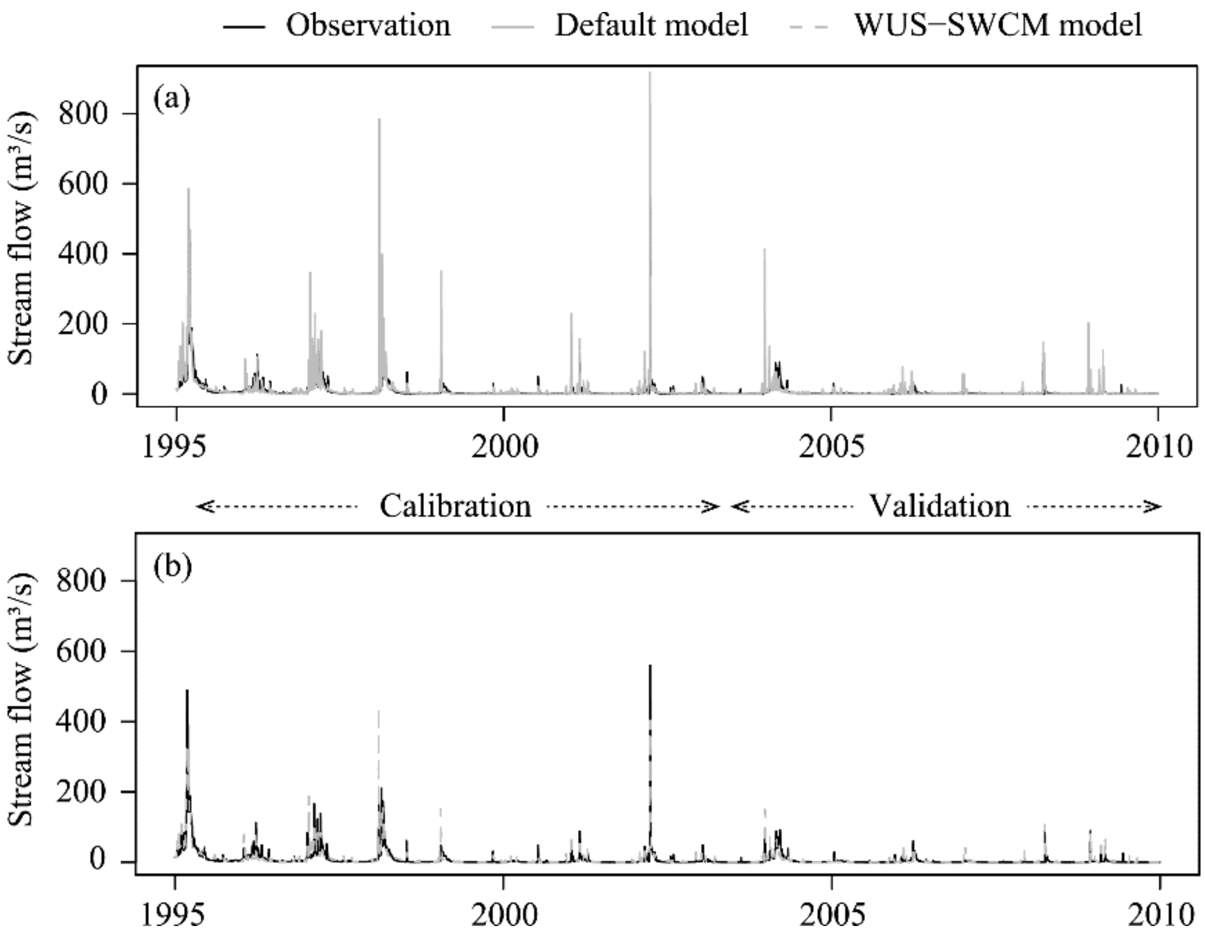

Figure 2.5 Comparison of observed and simulated streamflow from both Default model (a) and WUS-SWCM model (b) setups in calibration (1995–2003) and validation (2004–2009) periods

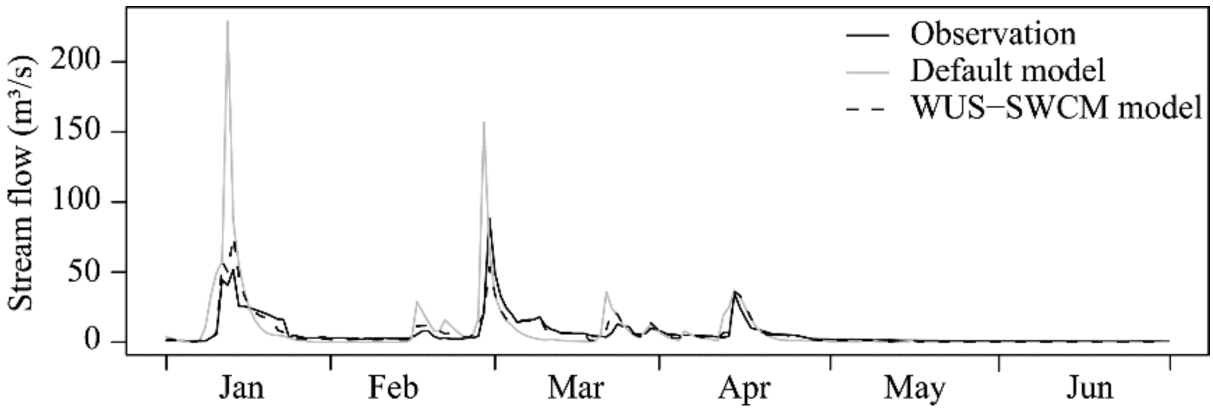

Figure 2.6 Detailed comparison of observed and simulated streamflow from both model setups for the period from January to June, 2001

2.3.2 Hydrological components

The comparison of hydrological components of the model setups shows that aggregated basin value changes are small (changes in ET and WYLD are lower than 3%), because they probably compensate for each other on the large scale. Therefore, the change of hydrological components is evaluated at the sub-basin scale by comparing the WUS-SWCM model with the Default model (Figure 2.7a). WYLD is decreasing in all sub-basins with WUSs and SWCMs, varying from no change to –18% (Figure 2.7b). The change in runoff components is split in surface runoff and groundwater flow (Figures. 2.7c and d). It should be noted that evapotranspiration and lateral flow changes vary less than 1% and therefore are not shown in this paper. The contribution of surface runoff to the stream decreases in sub-basins with WUSs and SWCMs, ranging from –30% to –99%. Moreover, a higher contribution of groundwater to the streams in most sub-basins with SWCMs and on the contrary less groundwater contribution in sub-basins with WUSs (qanats, wells and springs) is shown, but in sub-basins with both WUSs and SWCMs, groundwater contribution increases (maximum 46%) or does not show any change. This indicates that SWCMs counterbalance the impact of WUSs on groundwater flows. Although WUSs are taking water from the shallow aquifer and change groundwater flows, the implementation of SWCMs in the basin compensates for the extracted water from the shallow aquifer by decreasing the surface runoff and by increasing the infiltration rate and ground water recharge. This finding is in agreement with the studies by Abouabdillah et al., (2014) and Khelifa et al., (2017).

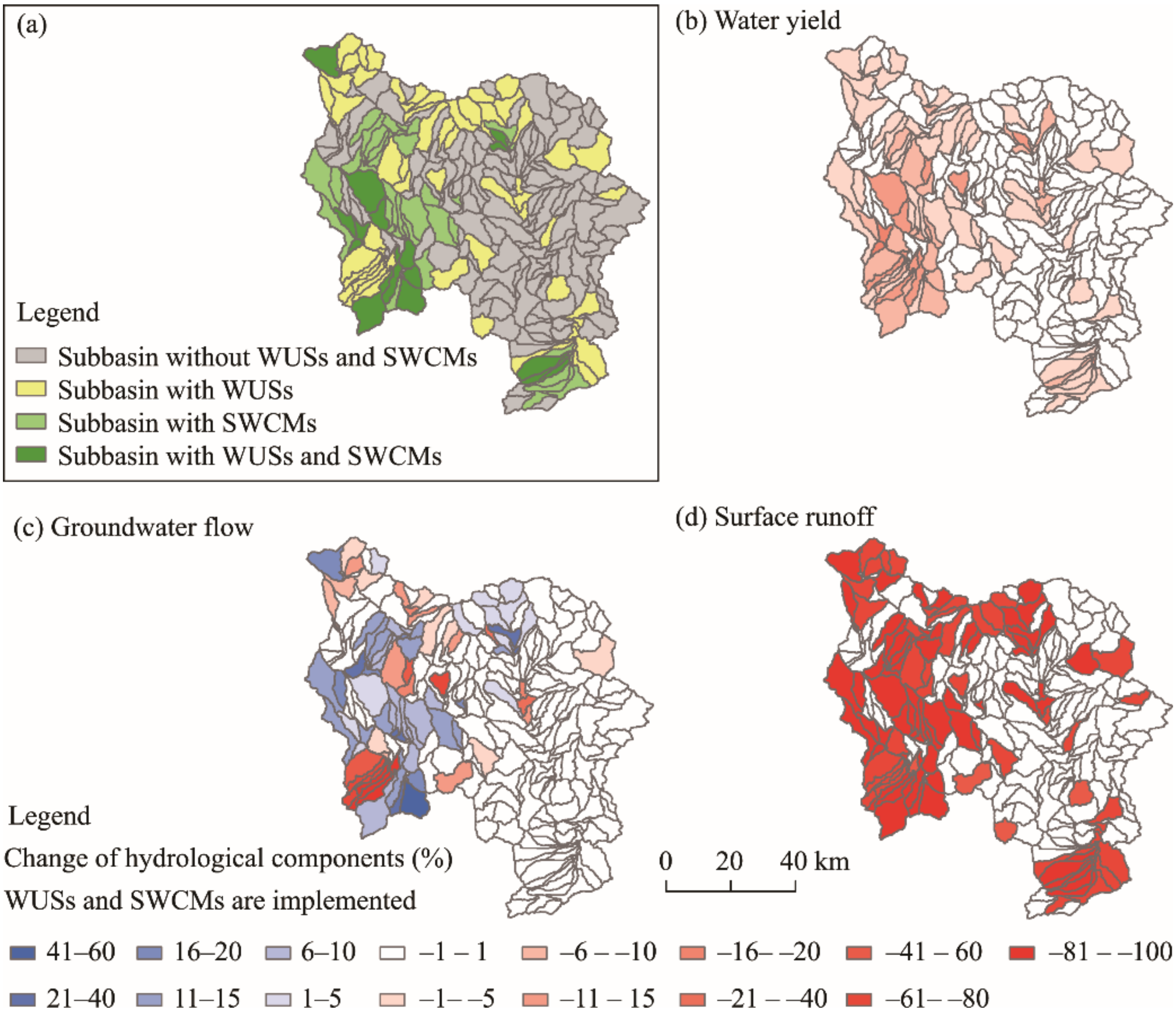

Figure 2.7 Distribution of sub-basins with or without WUSs and SWCMs (a) and changes of hydrological components when WUSs and SWCMs are implemented (b–d). (b), water yield; (c), groundwater flow; (d), surface runoff. Decreasing change is shown as negative values (red) while increasing change is shown as positive values (blue).

2.4 Conclusions

WUSs and SWCMs were successfully implemented into a hydrological model of the Halilrood Basin. Our results clearly show that there are differences in both model setups (Default model and WUS-SWCM model), which can be related to the implementation of the different measures. Model performance improved when WUSs and SWCMs are included in the model. However, this improvement is not similarly observed in all segments of the hydrograph. The model is capable of simulating the hydrological processes more realistically when more details of water usage systems are considered. The comparison of the hydrological components illustrates that the contribution of surface runoff to the stream is decreased pronouncedly when WUSs and SWCMs are implemented. The presentation of SWCMs leads to a higher contribution of groundwater to the streamflow by increasing the infiltration rate and groundwater recharge and by decreasing the surface runoff. Therefore, in the sub-basins with both WUSs and SWCMs, the implementation of SWCMs compensates for the impact of the WUSs. Furthermore, the amount of water leaving the basin is decreased due to the implementation of WUSs and SWCMs in the model, leading to a higher water use in the basin. Implementing WUSs and SWCMs in the model is recommended to accurately simulate the hydrological processes, particularly in Wadis, where water availability is limited, these measures have a pronounced effect. Moreover, with regard to scenario assessments in these arid and semi-arid regions, hydrological models that include these measures are needed to yield reliable results and for being able to evaluate the actual impact of e.g., climate change.

Chapter 3 Modeling the impact of climate change on streamflow and major hydrological components of an Iranian Wadi system

Nariman Mahmoodi[1*], Paul D. Wagner[1], Jens Kiesel[1,2], Nicola Fohrer[1]

[1]Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel 24118, Germany

[2]Department of Ecosystem Research, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin 12489, Germany

[*]Corresponding author. Nariman Mahmoodi (E-mail: nmahmoodi@hydrology.uni-kiel.de)

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Abstract

Climate change has pronounced impacts on water resources, especially in arid regions. This study aims at assessing the impacts of climate change on streamflow of the Wadi Halilrood Basin which feeds the Jazmorian wetland in southeastern Iran. To simulate streamflow and hydrological components in the future periods (2030–2059 and 2070–2099), projections for the emission scenarios RCP4.5 and RCP8.5 from 11 global-regional climate models and two bias correction methods are used as input data for a hydrologic model that represents the daily streamflow with good accuracy (NSE: 0.76, PBIAS: 4.7, KGE: 0.87). The results indicate a slight increase of streamflow in January and March, due to the higher intensity of precipitation. However, according to the predicted flow duration curves, a decrease for high and very high flow and no remarkable changes for middle, low and very low flow is found under both emission scenarios for both future periods. Compared to the simulated hydrological components for the baseline, a slight increase of evapotranspiration of around 6 mm (4%) and 2 mm (<2%) for the mid and end of the century is estimated respectively. Moreover, a substantial drop of water yield of around 36 mm (63%) at mid-century and 39 mm (69%) at the end of the century are projected.

Key words: climate change, hydrological components, streamflow, Wadi

Highlights

- Assess the impacts of climate change on streamflow of a Wadi system.
- Evaluate the variation of major hydrological components to gain insights into the variation of streamflow.
- Apply a set of different bias correction methods and climate models under two emission scenarios to deal with the potential uncertainties.
- Provide valuable information on possible future changes in streamflow and major hydrological components, important for sustainable management of water resources within the basin and maintaining the downstream wetland ecosystem.

3.1 Introduction

Changes in precipitation and the average surface temperature that have been undergone a long-term overall warming trend since the late 19th century, are globally reported (IPCC 2014). The impact of climate change on hydrological processes is an issue of high priority for hydrological research (Blöschl et al. 2019). The effect of climate changes on streamflow condition has been revealed in different parts of the world (Saharia and Sarma 2018; Oeurng et al. 2019). These effects will be particularly severe in regions where the climate becomes drier (Chen et al. 2005; Wang et al. 2012). In the Iranian Wadis such as Halilrood Basin, only sporadic precipitation occurs and potential evapotranspiration is high (Amiri and Eslamian 2010), making them more vulnerable to a drier climate. At the same time, demands for drinking and irrigation water are high (Faramarzi et al. 2009; Emam et al. 2015). Therefore, changes in streamflow caused by climate change have become the most important topic for future water resources management in these regions.

The impact of climate change on streamflow has been assessed in many parts of the world (e.g. Piao et al. (2010) in China, Gizaw et al. (2017) in Ethiopia, and Patil et al. (2018) in India or on the global scale, Asadieh and Krakauer (2017)). The studies are conducted using different hydrological models (e.g. Artificial Neural Networks (ANN), Hydrologic Simulation Program-FORTRAN (HSPF), and Water Balance Model (WBM)). The Soil and Water Assessment Tool (SWAT, Arnold et al. 1998) is a modeling tool for simulating streamflow and other hydrological variables at catchment scale (Praskievicz and Chang 2009) and is frequently used in climate change studies (e.g. Wagner et al. 2015; Wang et al. 2018; Kiesel et al. 2019). In

Iran, although few studies are carried out using different hydrological models (Zarghami et al. (2011), artificial neural networks (ANN); Hajian et al. (2016), HEC-HMS and Sanikhani et al. (2018), gene expression programming (GEP)), most studies that address climate change impacts on water resources have been carried out using the SWAT model. For instance, Abbaspour et al. (2009) conducted a SWAT simulation of Iran to study the impact of future climate change on the water resources. The results indicated more precipitation and more frequent and larger-intensity floods in the wet regions and less precipitation and more prolonged droughts in the dry regions. Moreover, the effect of climate change on streamflow of Karkheh Basin in Iran was assessed using the SWAT model (Vaghefi et al. 2013). They found variability in the impact of climate change in the region, as an increase in both frequency and length of dry periods was predicted in the southern part, and increasing flood events in the northern and the western parts of the Karkheh Basin. Another study by Emami and Koch (2019) on the impact of climate change on water availability in Zarrine River Basin using the SWAT model indicates a water shortage in the period 2012–2029 as the water yield significantly decreases. Although several climate change studies are carried out in Iran, the impact of climate change on the water resources of Wadis in the center of the country has not been studied so far due to the specific hydrologic processes and climatic conditions and limited data availability.

The results of climate change impact assessments are subject to uncertainty. To deal with these uncertainties it is recommended to apply a set of different bias correction methods and climate models (Clark et al. 2007; Kiesel et al. 2019).

Often climate change assessment studies focus on only one hydrological component such as streamflow. However, to gain insights into the variation of streamflow of the basin in the future, all relevant hydrological components should be considered (Uniyal et al. 2015). The long-term evaluation of the impacts of climate change on hydrological components such as streamflow, evapotranspiration, and water yield are necessary to support long-term water resources management and planning (Serrat-Capdevila et al. 2007; Uniyal et al. 2015). To achieve this goal, the specific objectives of this study are: (i) to assess the impact of climate change on streamflow, and (ii) to evaluate the variation of major hydrological components such as evapotranspiration and water yield in a Wadi system.

3.2 Materials and methods

3.2.1 Study area

The Halilrood Basin is located in Kerman Province, Iran. It has an area of 7224 km^2 (Figure 1). Halilrood River is a major river in the province in terms of discharge, which feeds the Jazmorian Wetland. The water released from Halilrood River to the wetland is controlled by the Jiroft Dam. The Jazmorian Wetland is a particularly valuable natural ecosystem. Recently, the wetland suffered from wind erosion, especially during the time of the year when the soil moisture is very low and potential evapotranspiration is high (more than 2800 $mm.y^{-1}$) (Abbasi et al. 2019). The maximum and minimum annual average discharge were 33 $m^3 s^{-1}$ in 1995 and 0.71 $m^3 s^{-1}$ in 2007 respectively during the period 1993–2009. Mean annual temperature averaged over the basin amounts to 13 ºC and the mean annual precipitation is about 295 mm, of which more than half (64%, 189 mm) falls during the winter months, 37 mm (13%) during spring, 16 mm (5%) during summer, and 53 mm (18%) during autumn in the period of 1979–2011. Annual potential evaporation (PE) ranges from 2039 to 2569 mm at the synoptic station Baft, contributing to a low runoff coefficient of 0.12. Limited rainfed agriculture and irrigated farming are found mainly in proximity to rivers, qanats, and springs. Approximately 75% of the basin is covered by bare land (ESA 2010). The southern part of the basin is a mountainous area and the elevation ranges from approximately 1391 to 4359 m above sea level (Jarvis et al. 2008). Lithosol, Calcaric Regosol and Calcic Yermosols are three dominant soil types in the basin (Harmonized World Soil Database v 1.2, 2008), which are classified into soil hydrologic group C with slow infiltration rate and high runoff potential.

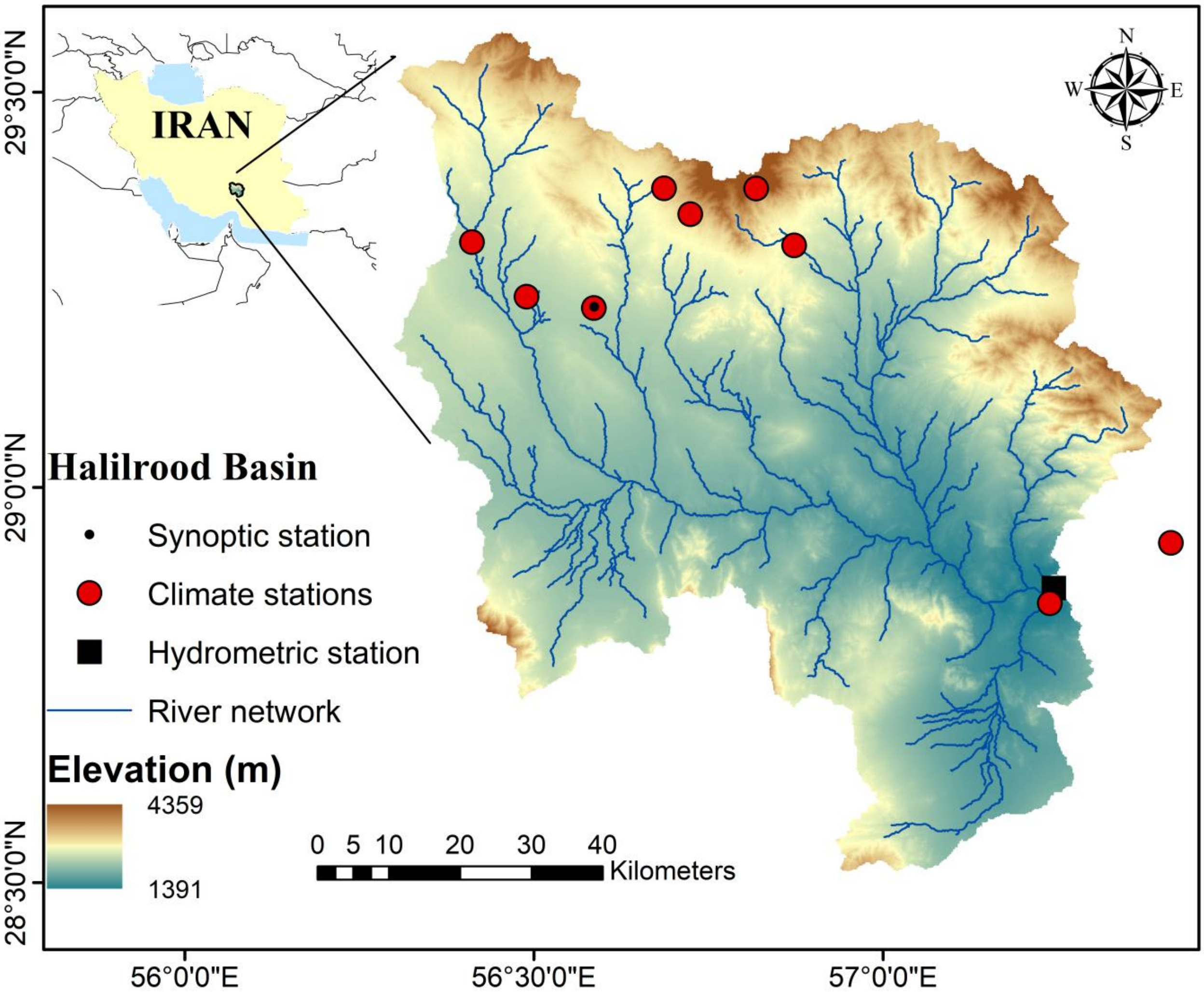

Figure 3.1 Map of the Halilrood Basin with hydrometric and climate stations.

3.2.2 Measured climate and hydrologic data

The climate variables required to run the hydrologic model are daily precipitation (PCP) and temperature (TMP), solar radiation (SLR), humidity (HMD) and wind speed (WND) which are provided from nine climate stations and a synoptic station for the period 1979–2011. This period is defined as the baseline against which all future changes are compared. Observed streamflow data were available from 1993 to 2009. A five-year moving average is applied to visually show the temporal changes in PCP and TMP (as an average over all nine climatic stations) and streamflow (Supplementary Material, Figure A1). TMP is increasing constantly from 1982, except for the last few years that show a slight decrease. There is a remarkable decrease in observed streamflow which correlates well with a decrease of PCP during the same period.

3.2.3 Global and regional climate model data

An ensemble of climate models is used to consider the model related biases and the natural climate variability as two main sources of differences in the climate projections (Christensen and Lettenmaier 2006; Kling et al. 2012; Velázquez et al. 2013). For climate change impact assessment, we used 11 datasets of global and regional climate models (G-RCMs) from the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Jacob et al. 2014), providing data in 50×50 km resolution for Asia. Two emission scenarios, namely RCP4.5 and RCP8.5, are considered (Table 3.1). To obtain a homogeneous dataset, we did not use RCP2.6 and RCP6.0 due to differing climate model availability within the CORDEX dataset.

The root-mean-square error (RMSE) was used to compare the hindcasted precipitation to the measurements on the long-term average monthly values for the period 1979-2005 (Table 3.1). A high RMSE implies a strong deviation of the modeled and measured precipitation data. Therefore, we only used models that had an RMSE below 10% of the mean annual precipitation, i.e. 29.5 mm per month (Table 3.1).

3.2.4 Bias correction of climate model data

Several different bias correction methods are applicable to account for differences between the climate model data and the measured data (e.g. Piani et al. 2010; Teutschbein et al. 2011). In many climate change impact studies, two groups of bias correction methods, simple (e.g. linear scaling, delta-change approach, etc.) and sophisticated (e.g. distribution mapping, power transformation), are applied (Teutschbein and Seibert 2012; Troin et al. 2015). However, individual bias correction methods reduce the deviations between model and measurements in unique ways, resulting in different absolute values as well as a different variability (Teutschbein and Seibert 2013). Therefore, to cope with the considerable deviation from the observed data shown in Table 3.1 for the RCMs simulations, two bias correction methods, mean-based: linear scaling (LS) and distribution-based: distribution mapping (DM), are applied which have already been used in other arid regions (e.g. Fang et al. 2015, 2018; Luo et al. 2018). The linear-scaling approach (Lenderink et al. 2007) corrects the long-term monthly differences between observed and hindcasted values. Distribution mapping is an approach creating a transfer function to shift the occurrence distributions of hindcasted values to agree with the observed values (Sennikovs and Bethers 2009). The bias correction methods are applied on a 32 year period (1979–2011) to remove the error linked to the decadal variability (Berg et al. 2012). The climate models corrected with LS and DM are henceforth referred to as LS-M and DM-M, respectively. Although using bias correction method leads to a better agreement between simulated data and observations, it does not provide a satisfactory physical explanation (Ehret et al. 2012). Bias correction methods are significantly changing the climate model output and alter the climate change signals (Dosio et al. 2012). Moreover, they may hide rather than narrow down uncertainty (Ehret et al. 2012). Hence, we also use the models without bias correction (raw-M) for hydrologic impact analysis.

Table 3.1 shows all combinations of GCM, RCM, emission scenarios, and bias correction methods. The raw-M data was evaluated against the threshold criterion of an RMSE < 29.5 mm per month for the baseline precipitation seasonality. The accepted models are bias corrected, which led to the acceptance of 66 combinations (from the theoretical maximum of 102) which are used for the climate change impact analysis.

Table 3.1 List of climate models used in this study and RMSE values (mm) associated with monthly projected and measured precipitation (climate models with RMSE less than 29.5 are highlighted in bold)

GCMs	*RCMs*	*RMSE (mm)*	*Bias-correction methods*	*Emission scenarios*	*Available models*	*Plausible models*
CCCma	IITM* **SMHI**	40.91 29.49	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	12	6
CNRM	IITM* **SMHI**	31.78 18.57	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	12	6
CSIRO	**IITM** **SMHI**	25.32 25.44	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	12	12
ICHEC	**SMHI**	20.51	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	6	6
IPSL	IITM* SMHI*	37.72 33.18	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	12	0
MIROC	**SMHI**	16.39	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	6	6
MOHC	**SMHI**	24.71	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	6	6
MPI	**MPI** **IITM** SMHI*	23.32 23.03 32.25	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	18	12
NCC	**SMHI**	25.03	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	6	6
NOAA	IITM* **SMHI**	38.19 28.03	Distribution mapping Linear scaling No correction	RCP4.5 RCP8.5	12	6
		17	**3**	**2**	**102**	**<u>66</u>**

*Eliminated regional climate models.

3.2.5 Future weather data

The Soil and Water Assessment Tool (SWAT, Arnold et al. (1998)) of the Halilrood Basin uses the Penman–Monteith equation to calculate potential evapotranspiration. Therefore, besides precipitation (PCP) for the runoff processes, it requires maximum and minimum air temperature (TMP), wind speed (WND), relative humidity (HMD) and solar radiation (SLR). However, only PCP and TMP are consistently provided by all climate models. We used a simple statistical approach to add the other climate components (WND, HMD, and SLR). For every day in the future climate projection, we randomly sampled a day from the same month in the baseline period based on rain occurrence but excluded sampling from the same day. From this day, we used the WND, HMD, and SLR record and used it for the future projection. The method was successfully tested for the calibration period from 1995 to 2003 (KGE = 0.86). It should be noted that the method is superior to the SWAT weather generator, which was less successful when applied to the baseline period (KGE = 0.71). We attribute the better performance of our approach to the fact that the variables are more consistently represented, as WND, HMD, and SLR are taken from the days with same weather conditions (in terms of precipitation occurrence) in the same month over the long-term period, and they represent valid values for a rainy or dry day (precipitation occurrence criterion) and for that time of the year (same month criterion).

3.2.6 Hydrologic model

The SWAT model has been applied to simulate the hydrological processes and assess the impact of climate change on hydrological conditions in the Halilrood Basin. To delineate the basin and set up the model, the SRTM digital elevation model (Jarvis et al. 2008), soil data from the harmonized world soil database (FAO 2009), and the GlobCover 2009 (ESA 2010) land use data were used. We delineated the Halilrood Basin into 285 sub-basins and 6091 hydrologic response units (HRUs). Different Water Use Systems and Soil and Water Conservation Measures have been integrated in the model (Mahmoodi et al.2020). The model showed a good performance for the simulation of daily streamflow between 1993 and 2009 based on Kling-Gupta-Efficiencies (KGE, Kling et al. (2012)) of 0.87 (calibration) and 0.62 (validation). Further details on model parameterization and performance are available in Mahmoodi et al. (2020).

3.2.7 Hydrologic impact assessment

To investigate the hydrologic response of the basin to climate change, the precipitation and temperature projections obtained from the 11 G-RCMs under the scenarios RCP4.5 and

RCP8.5 are used. A particular focus is set on impacts on seasonality and variability. We use flow duration curves (FDCs) that illustrate streamflow values against their exceedance time, to evaluate changes of the variability and magnitude of flows.

In addition to streamflow, other major hydrological components such as actual evapotranspiration (ET) and water yield (WYLD) are considered to provide beneficial information for sustainable water resources management in the future. To describe the changes of water yield in detail, surface runoff (SURQ), groundwater flow (GWQ) and lateral flow (LATQ) are also evaluated. In addition, the climate change impact assessment is individually specified for each bias correction methods (LS and DM) and raw-M. The changes in average annual values of the hydrological components are compared to the baseline period simulation (1979–2011) for two future scenario periods (2030–2059 and 2070–2099).

3.3 Results

3.3.1 Climate model ensemble

The hindcasted and projected changes of annual temperature (Supplementary Material, Figure A2) and precipitation (Supplementary Material, Figure A3) in the 21st century have been assessed by comparing the bias-corrected climate models (BCCMs) data to the mean value of the measured data from the baseline (1979–2011). Moreover, the projected changes are shown for both emission scenarios, RCP4.5 and RCP8.5.

The climate model ensemble shows a steady temperature increase in the 21st century. Obviously, the temperature increase under RCP8.5 is larger than under RCP4.5. The median temperature change is approximately doubled by the 2090s. This results in a maximum temperature increase between 1.8 and 5.3 ºC (RCP4.5) and 3.9 and 10.3 ºC (RCP8.5) by the 2090s. LS leads to a slower warming as compared to DM for both emission scenarios. Although, the medians of DM and LS are showing similar increasing trends, the change in temperature driven by DM is always greater than LS, resulting in a difference of the medians by ~1 ºC for RCP4.5 and ~2 ºC for RCP8.5 by the 2090s.

In the case of precipitation, the changes are not as distinctive between the bias correction methods as for temperature. Overall, precipitation decreases and becomes more variable (Supplementary Material, Figure A3). More pronounced decreases are visible in the second half of the century, when the 10-year moving average shows a decrease of up to –21% in 2092 for RCP4.5 and up to –30% in the 2080s and 2090s for RCP8.5. The maximum precipitation is higher in the RCP4.5 scenario (up to 141 mm) and outlines the increased probability of extreme precipitation events. A higher range of change is estimated for models driven by LS under both RCPs when compared to DM. The medians of DM and LS show a very similar development.

Two future time periods of 30 years are defined for further analysis, mid-century (2030–2059) and end of century (2070–2099). The maximum, minimum and median of projected changes in temperature and precipitation for both periods are shown in Supplementary Material, Table A1. The near future period shows a median increase of around 2–2.5 ºC for RCP4.5 and of around 2.4–3.4 ºC for RCP8.5. The end of century period indicates a median increase of around 2.8–4 ºC for RCP4.5 and of around 4–7.1 ºC for RCP8.5. For precipitation, only minor changes are projected for the near future in both scenarios (absolute change of the median <5%, Supplementary Material, Table A1). At the end of the century, the changes of the median are still small in RCP4.5 (DM: –2.5%, LS: –2.7%, Supplementary Material, Table A1) but a pronounced decrease of about –18% (LS) to –21% (DM) is estimated for RCP8.5.

3.3.2 Projected seasonal temperature and precipitation

Since indicators such as timing and seasonality are known to show a more robust response to climate change compared to magnitude (Addor et al. 2014; Melsen et al. 2018), the seasonality of climate data as an important characteristic should be taken into consideration. The seasonality of the projected climate variables in comparison with observed data is shown in Figures 3.2 and 3.3. All BCCMs are projecting higher temperatures and the same seasonal pattern. Change of temperature in summer is slightly higher than in the other seasons. Throughout the year, not only predicted medians are always higher than the mean monthly observation, but the projected minimum temperature is also greater, i.e. even more conservative projections of temperature result in warmer weather conditions in the study area. Furthermore, the applied bias correction methods lead to different results. The medians indicate that DM results in higher temperatures. June is the hottest month for the historical data. While June is still the hottest month in the LS projections, it is shifted to July in the DM projections.

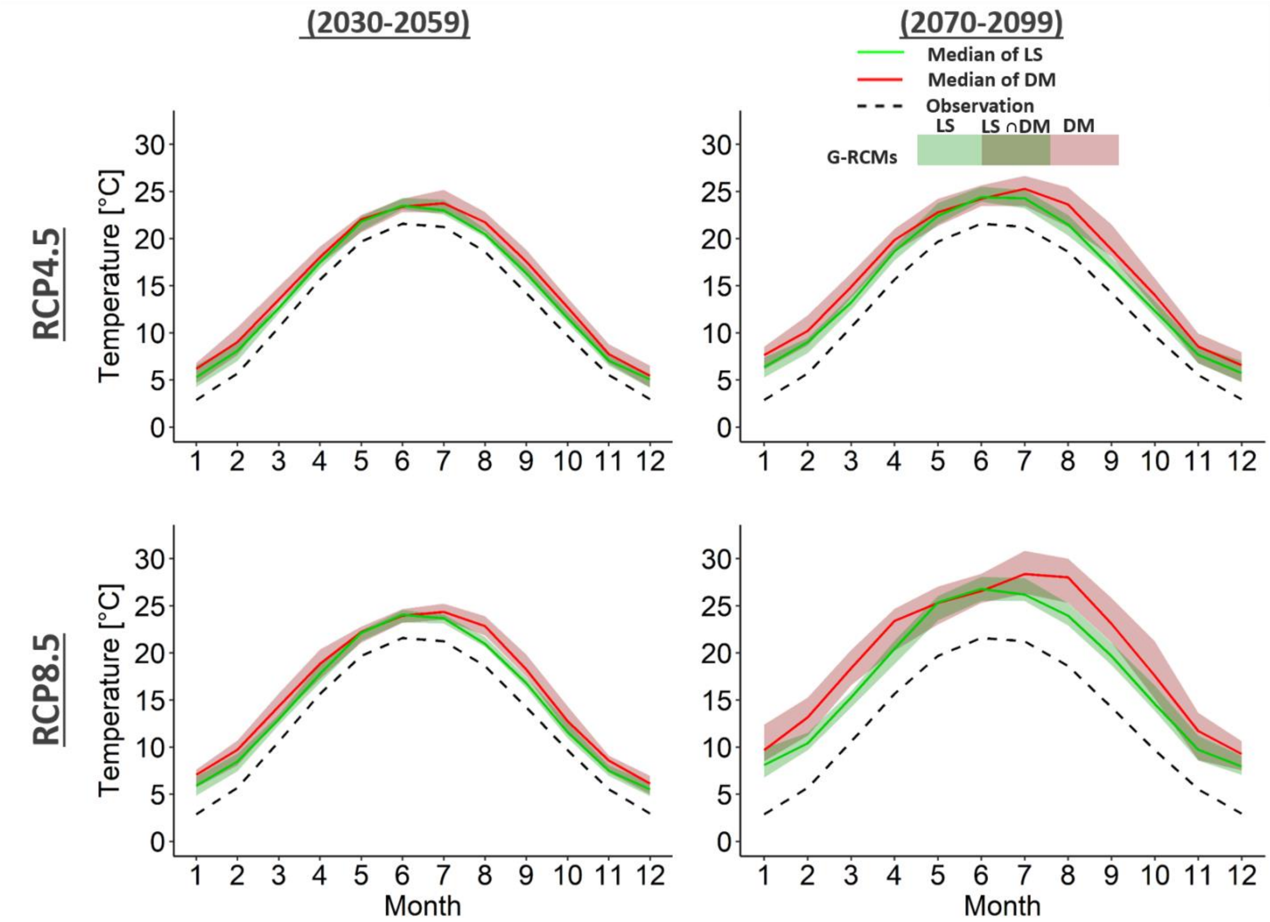

Figure 3.2 Seasonal comparison of G-RCM data with historical measured temperature (dashed line) for both future periods (2030–2059 and 2070–2099) and both RCPs (4.5 and 8.5). Green solid line: median of projected temperature corrected by Linear Scaling (LS). Red solid line: median of projected temperature corrected by Distribution Mapping (DM). Light green and light red shading: full range of projected temperature (minimum to maximum) for both bias correction methods. Dark green: the common range of temperature between both bias correction methods.

Projected bias-corrected monthly precipitation vs. mean monthly observation is shown in Figure 3.3. Precipitation changes are of primary importance regarding the hydrologic assessment. The main precipitation events occur in winter season while minor rain falls in summer (less than 10 mm). The precipitation varies from 2.5 mm in the driest month (September) to 68.3 mm in the wettest month (March). This seasonality is also represented in the bias corrected projected precipitation data. Most of the climate models simulated less precipitation mainly in the winter season, when the medians are smaller than historical data. The range of projected precipitation by LS is wider, predicting higher precipitation for the first three and the last month of the year. Precipitation particularly decreased in March by comparing the medians of modelled data to the mean of observed data. This leads to a shift of the precipitation peak from March to February at the end of the century under RCP4.5 and in the near future for RCP8.5. This shift may have significant impacts on human activities, particularly in agriculture, as the following months are generally exceptionally dry.

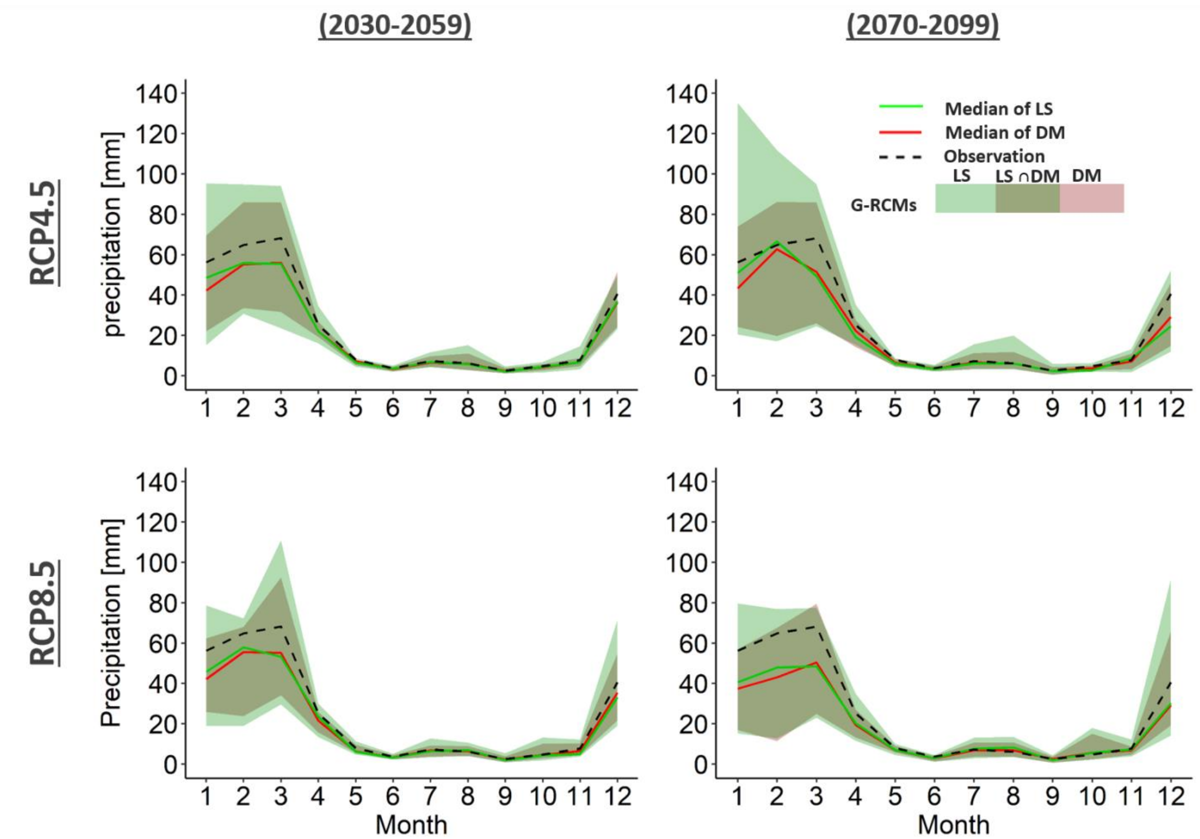

Figure 3.3 Seasonal comparison of G-RCM data with historical measured precipitation (dashed line) for both future periods (2030–2059 and 2070–2099) and both RCPs (4.5 and 8.5). Green solid line: median of projected precipitation corrected by Linear Scaling (LS). Red solid line: median of projected precipitation corrected by Distribution Mapping (DM). Light green and light red shading: full range of projected precipitation (minimum to maximum) for both bias correction methods. Dark green: the common range of precipitation between both bias correction methods.

3.3.3 Impacts on streamflow

The results from the SWAT model simulations in comparison with monthly mean observed streamflow (1993–2009) are illustrated in Figure 3.4. Mostly, the climate models under RCP4.5 predict an increase in streamflow during winter time. In January and February, the medians are higher than the observed streamflow in all periods and scenarios except for the end of the century in RCP8.5. The same three periods and scenarios show a shift in the timing and occurrence of the peak streamflow from March to February by comparing the medians of modelled data to observed data. However, an increase in streamflow in December is also simulated, pointing to a general backward shift of the seasonality of streamflow. A slight increase of streamflow is shown during the hottest month of the year (July), particularly for the LS-M.

The total changes in simulated streamflow are predicted to be smaller under RCP8.5. For the end of the century period, the median predicted streamflow decreased in all months except for January and December. As can be expected, most of the changes in seasonality of streamflow are related to the changes in precipitation (Figure 3.3). This also applies to the comparison of the bias correction methods, which shows that the models corrected by LS resulted in a wider range of simulated streamflow as compared to the models corrected by DM. To explain how less precipitation in winter led to higher streamflow, the number of rainy days per month as an index for precipitation intensity have been determined for both future periods and baseline (Figure 3.5). The number of rainy days during winter season is predicted to decrease in the future from 11 days/month (baseline period) to 5 days/month for LS and to 7 days/month for DM, while the simulated streamflow increased in winter. This indicates that precipitation intensities are expected to increase in the winter season, leading to higher runoff ratios and therefore streamflow values.

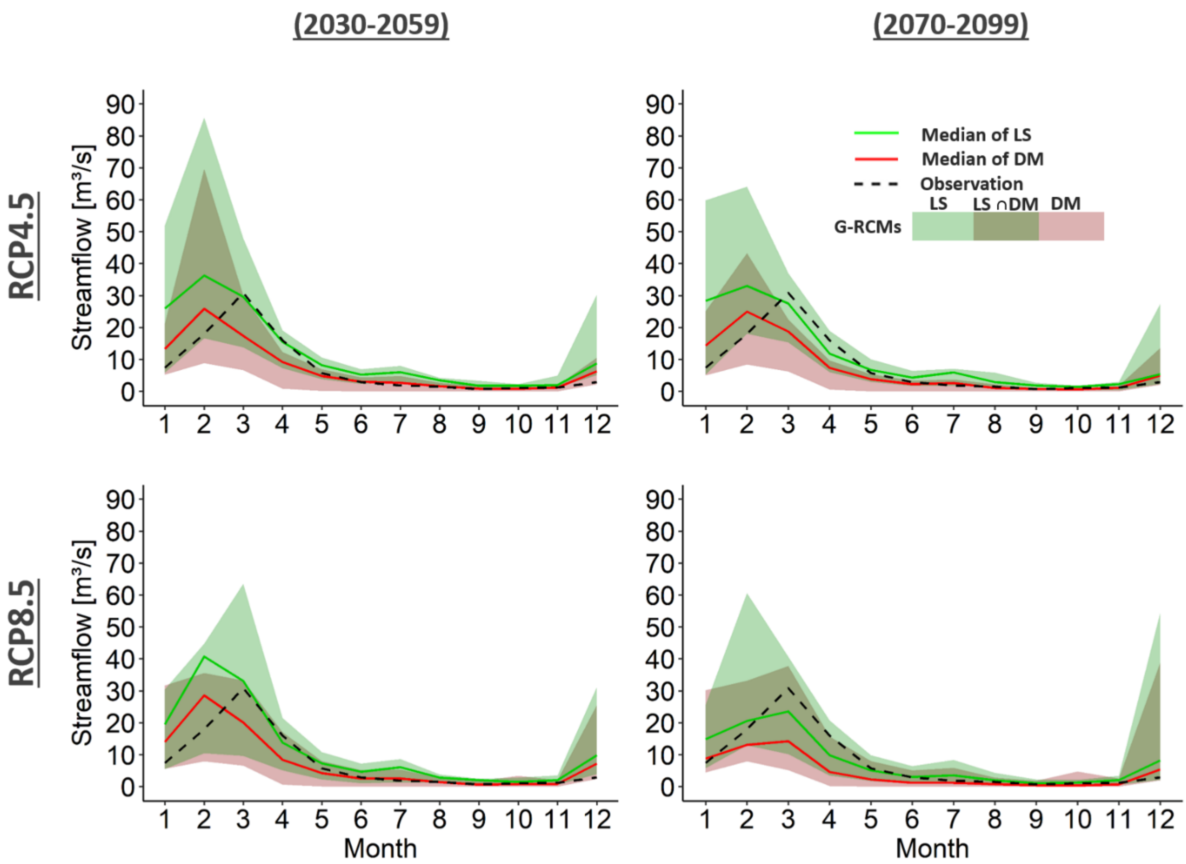

Figure 3.4 Seasonal comparison of simulated and measured streamflow (dashed line) for both future periods (2030-2059 and 2070-2099) and both RCPs (4.5 and 8.5). Green solid line: median of simulated monthly streamflow with data corrected by Linear Scaling (LS). Red solid line: median of simulated monthly streamflow with data corrected by Distribution Mapping (DM). Light green and light red shading: full range of simulated streamflow (minimum to maximum) for both bias correction methods. Dark green: the common rang of simulated streamflow between both bias correction methods.

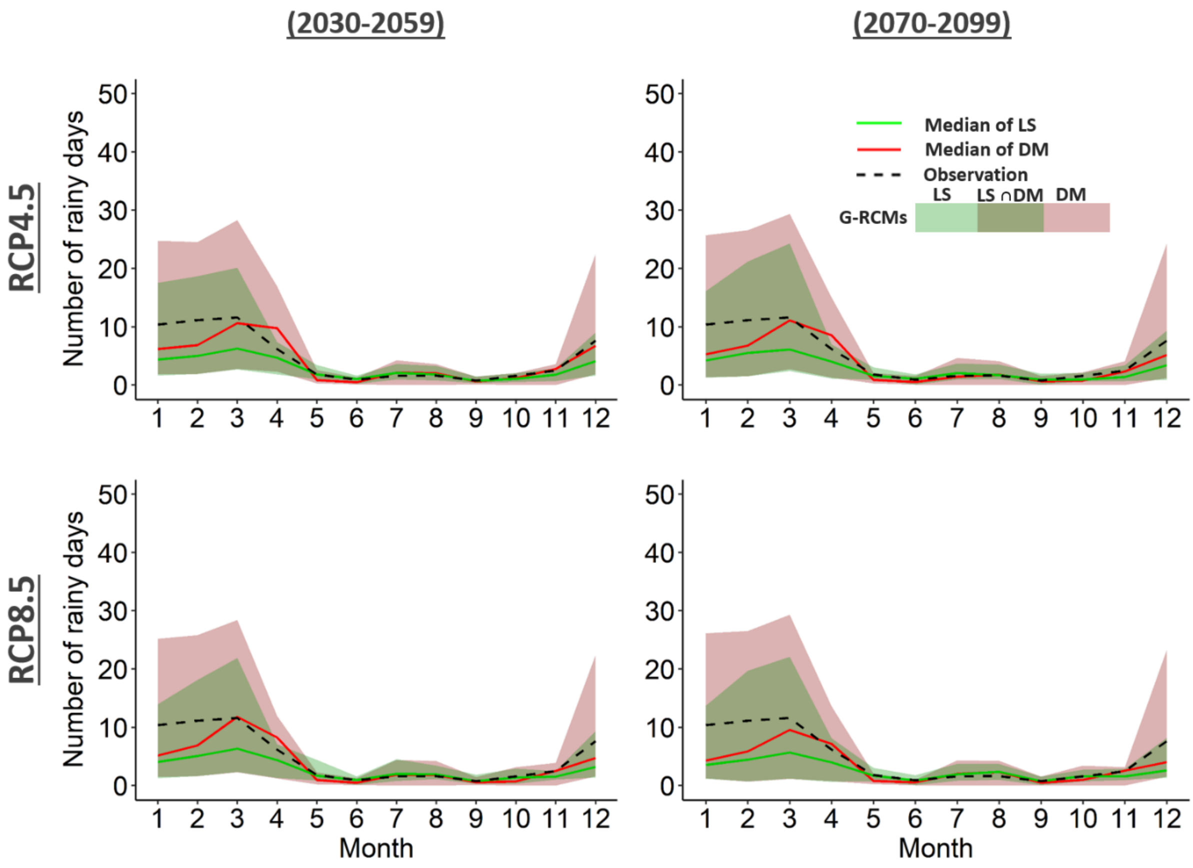

Figure 3.5 Comparison of the number of rainy days for both future periods (2030–2059 and 2070–2099) and both RCPs (4.5 and 8.5).

3.3.4 Simulated flow duration curve

We used monthly flow duration curves (FDCs) to assess the effects of the climate model ensemble on different segments of the hydrograph. The full range of FDCs simulated by the hydrologic model with both bias correction methods (LS and DM) are represented in different colors (light green for LS and light red for DM) for both emission scenarios in Figure 3.6(a)–(d). The common ranges of FDCs are shown in dark green. To distinguish the changes in simulated FDCs in comparison with observed FDC, we focused on different segments of the hydrograph, very high: percent flow exceedance between 0 and 5% (Figure 3.6(e)–(h)), high: percent flow exceedance between 5 and 20% (Figure 3.6(i)–(l)), middle: percent flow exceedance between 20 and 70% (Figure 3.6(m)–(p)), low: percent flow exceedance between 70 and 95% (Figure 3.6(q)–(t)) and very low flow: percent flow exceedance between 95 and 100% (Figure 3.6(u)–(x)). Equal ranges were considered for the very low and very high flows in the FDC as described in Pfannerstill et al. (2014). Generally, a higher variability is estimated for very high and high flow in comparison to the middle, low and very low flow. This variability increases for very high flow toward the end of the century, when the maximum and minimum estimated very high flow nearly ranges from 0 to 650 and 850 m^3 s^{-1} respectively under RCP4.5 (Figure 3.6(f)) and RCP8.5 (Figure 3.6(h)). Hence, the wide range implies that extreme values like floods and droughts are also expected in the Halilrood Basin, particularly for the end of the century. A higher variability in very high, high, middle, low, and very low flow is expected for LS-M under both emission scenarios at mid-century (Figure 3.6(e), (i), (m), (q), (u), (g), (k), (o), (s), and (w)) and under RCP4.5 at the end of the century (Figure 3.6(h), (l), (p), (t), and (x)), while, the variability of flow in all segments of the FDC is higher for DM-M under RCP4.5 at the end of the century (Figure 3.6(f), (j), (n), (r), and (v)). The simulated median curve of LS-M is always greater than the one for DM-M in all segments especially for the very high and high flow components (Figure 3.6(e)–(l)). However, both medians for LS and DM are smaller than the observed median, except for the middle flow segment where LS-M under both RCPs is slightly higher (Figure 3.6(q) and (r)). The most evident discrepancies can be noticed when the medians in high flow segments are compared to the observed FDC, especially for the end of the century, when high flow drops from 38 to 12 m^3 s^{-1} (5% of time flow exceeded) under emission scenario RCP8.5 (Figure 3.6(l)). This denotes a considerable reduction of streamflow over the entire duration of the end of the century period. This can be explained by the remarkable reduction in precipitation projected by climate models for the end of the century (Figure 3.3). The maximum and minimum estimated for low and very low flows nearly range from 0–30 and 20 m^3 s^{-1} respectively under both RCPs (Figure 3.6(q)–(x)). The comparison in low flow segments shows that the median curves remain almost unaltered (Figure 3.6(q)–(t)), where simulated FDC for both bias correction methods are similar to the observed FDC. Also, this behavior is found for the median curves in very low flow (Figure 3.6(u)–(x)) because of the negligible changes in mean monthly streamflow during dry seasons in the future scenarios (Figure 3.4).

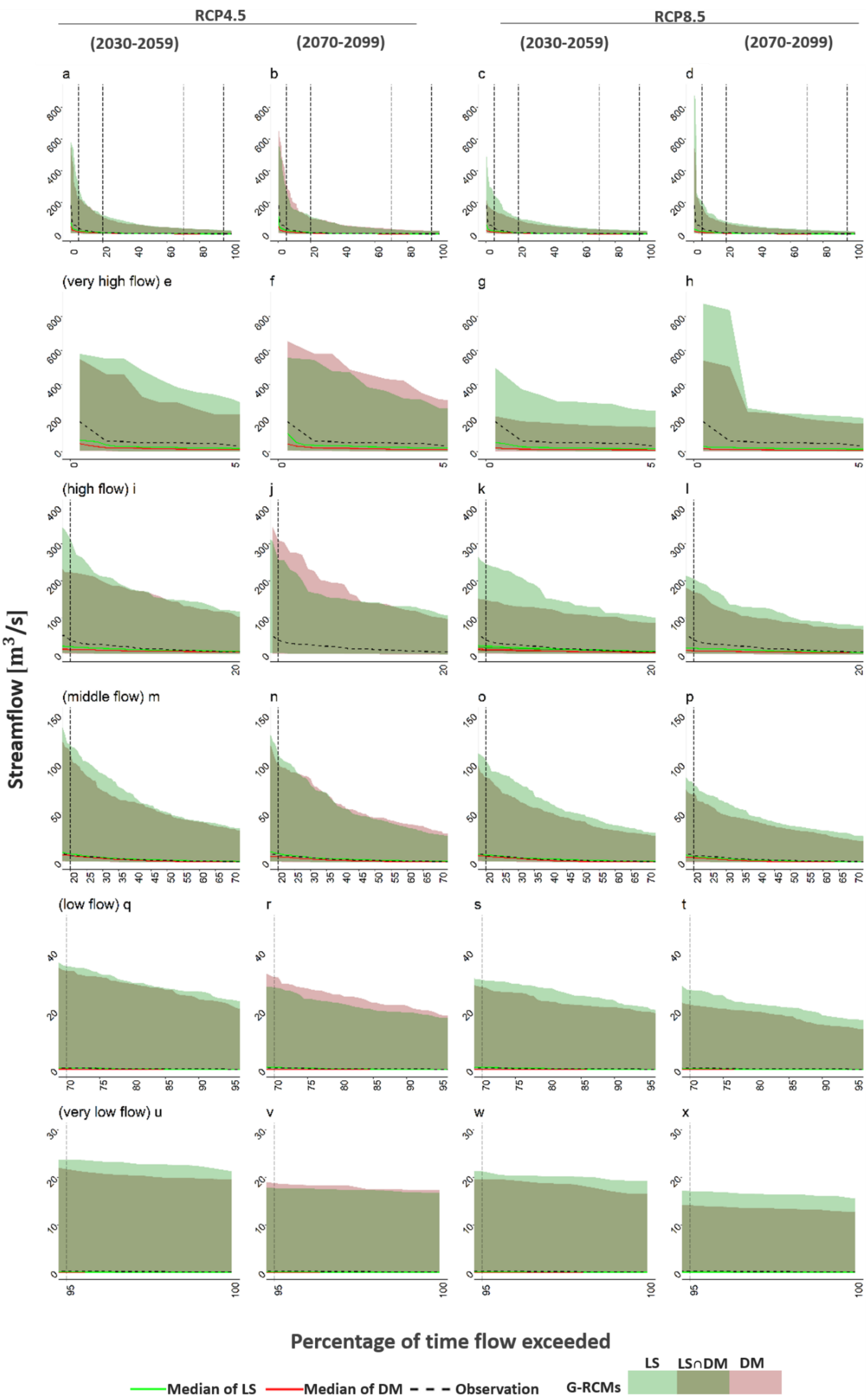
RCP4.5
RCP8.5
(2030-2059)
(2070-2099)
(2030-2059)
(2070-2099)
(very high flow)
(high flow)
(middle flow)
(low flow)
(very low flow)
Streamflow [m³/s]
Percentage of time flow exceeded
Median of LS
Median of DM
Observation
G-RCMs
LS
LS∩DM
DM

Figure 3.6 Comparison of measured and simulated monthly flow duration curves (FDCs). Dashed line: observed FDC. Green solid line: median of climate models corrected by Linear Scaling (LS). Red solid line: median of climate models corrected by Distribution Mapping (DM). Light green and light red shading: full range of FDCs (minimum to maximum) for both bias correction methods. Dark green: the common range of FDCs between both bias correction methods.

3.3.5 Hydrological components

Figure 3.7 shows the changes in average annual values of the hydrological components under climate scenarios for the bias corrected and the raw data compared to the historical period (1979–2011). Wider ranges of PCP are projected for both future periods. With respect to the medians, less precipitation is projected to occur in the future. This reduction in PCP is higher at the end of the century when medians are reduced to almost 200 mm under the RCP8.5 scenario (24% reduction) (Figure 3.7(g)). Actual ET slightly increases in the future. Although a substantial increase was expected for actual ET due to an increasing trend projected for TMP over the 21st century (Supplementary Material, Figure A2) and an associated increase of potential ET, the smaller amount of precipitation causes a water limitation and counter balances this effect. The highest amount of average annual water loss by actual ET is simulated for DM under RCP8.5 (more than 10% increase compared to the baseline) at the mid-century (Figure 7(e)), when the increase of actual ET is less than 1% for LS-M. Due to the higher ET and less PCP in future, the amount of water leaving the catchment (WYLD) is projected to considerably decrease. This reduction increases at the end of the century when WYLD falls below 30 mm, around 73 and 56% reduction respectively for DM and LS (Figure 3.7(g)). The results of the historical simulation indicates that, almost half of the total amount of water entering the main channel originates from the lateral flow (30 mm), around 10 mm from surface runoff, and 5 mm from groundwater (Figure 3.7(b)). Therefore, LATQ and GWQ have the highest and smallest contribution to the stream. The remarkable reduction in WYLD is mainly mirrored in SURQ and GWQ in the future. While a zero contribution (from 5 mm in the baseline to zero, 100% reduction) is simulated for GW in future for both bias corrected methods (Figure 3.7(b), (d), (f), and (h)), surface runoff is also estimated to be negligible (from 10 mm in the baseline to 1.1 mm, 90% reduction). Lateral flow, with 30 mm originally being the main contributor, is less than 20 mm for LS (more than 30% reduction) and less than 15 mm for DM (more than 50% reduction) in both future periods (Figure 3.7(b), (d), (h), and (f)). As expected, the reduction of LATQ is higher at the end of the century under RCP8.5 (more than 50% reduction for both LS and DM) (Figure 3.7(g)). In summary, the availability of water is lower when applying DM as compared to LS.

Different changes in hydrological components are simulated for LS, DM and raw climate model data. There are remarkable differences in the magnitude of changes in hydrological components between corrected and raw climate model data. Change signals in hydrological components are smaller when the bias correction methods are applied. Nevertheless, higher reduction in precipitation, water yield and consequently in surface runoff, groundwater flow and lateral flow is projected by raw models under both emission scenarios, followed by DM. For instance, the reduction of WYLD for the raw data is about 79%, which is 6 and 23% higher than DM and LS respectively (Figure 3.7(g)). The simulated ET is generally similar for LS, DM and raw models, while there are a few differences, especially in Figure 3.7(e), where the highest difference between LS and DM is simulated. Therefore, it is noticeable that LS is altering the original climate change signals more than DM.

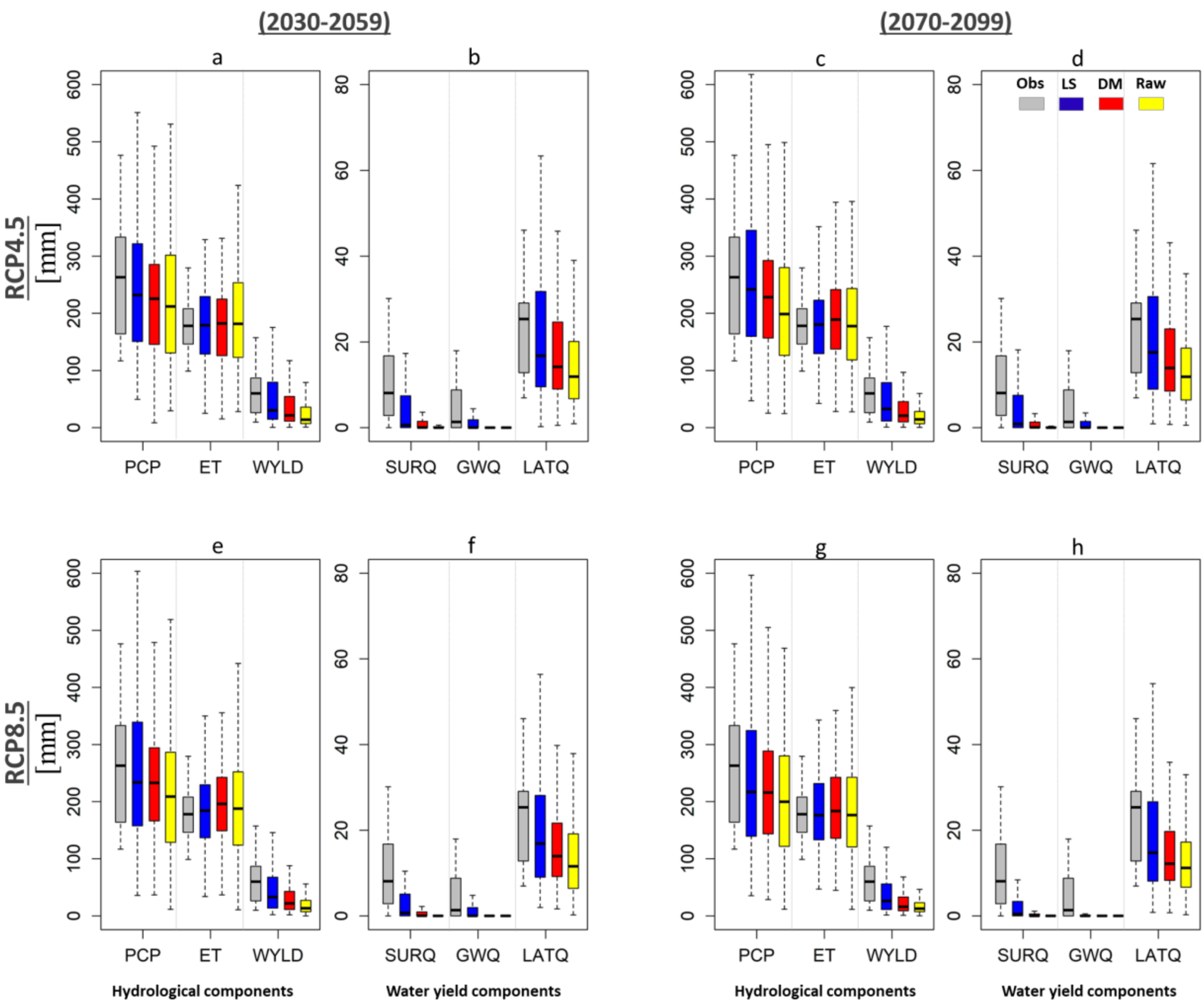

Figure 3.7 Annual average hydrological components simulated for the base-line period and future periods (2030–2059 and 2070–2099) under two emission scenarios (RCP4.5 and RCP8.5). PCP: precipitation, ET: actual evapotranspiration, WYLD: water yield, SURQ: surface runoff, GWQ: groundwater flow, LATQ: lateral flow.

3.4 Discussion

According to the results, climate change is projected to have important implications for streamflow regimes of the Halilrood Basin. Besides other impacts, a shift is simulated in the timing of the seasonal peak-flow. This complements well several previous climate assessment studies in arid and semi-arid regions such as Gan et al. (2015) in central Asia, Mahmood et al. (2016) in Pakistan, Javan et al. (2015), Mousavi et al. (2018), and Shahvari et al. (2019) in Iran. Such seasonal shifts in streamflow in the Halilrood Basin may be due to the change in precipitation pattern, the increase in temperature, and consequently an earlier snowmelt timing in mountainous areas which is similarly reported in other arid and semi-arid basins in Iran such as in the Gharehsoo River Basin (Javan et al. 2015) and in the Varamin Plain Basin (Shahvari et al. 2019). In addition to the seasonality, magnitude of streamflow is projected to change in the future, particularly, a strong reduction is expected for the very-high and high flow. This is confirmed by other climate change assessment studies in arid and semi-arid basins in Iran (Karkheh Basin: Samadi et al. (2012) and Lake Urmia Basin: Sanikhani et al. (2018)) and other arid countries (Lower Zab River Basin located in northern Iraq, Mohammed and Scholz (2018)). However, in some arid regions, such as in the Shiyang River basin, China, streamflow is projected to increase in the future (Wang et al. 2012). The wide range of FDCs simulated for very high, high and middle flow in the Halilrood Basin can be interpreted as an alternation of the future extremes of flood and drought, particularly emphasizing the vulnerability of the Halilrood Basin to climate change. The considerable change in streamflow in the Halilrood Basin, where the main agriculturally used land is found in proximity to rivers, will probably have a significant influence on farming practices. This consequence of climate change was also reported by Fiebig-Wittmaack et al. (2012) in an arid Andean valley in Chile. Also, the Halilrood Basin is mainly covered by bare land and soils with low available water capacity, where the reduction in rainy days is problematic for these types of soils, especially for rainfed agriculture. Therefore, more intense precipitation events are expected to intensify the consequences of floods estimated for the future.

The similar seasonality of precipitation and streamflow shows a water-limited system where flow conditions are strongly linked to the precipitation regime, which is typical for torrential rivers in dry regions (Pumo et al. 2016), such as the Iranian Wadis. In the Halilrood Basin, climate change is projected to result in a decrease in precipitation and a pronounced increase of temperature, which leads to a slight increase in evapotranspiration and less available water for infiltration and percolation. This causes a reduction of groundwater recharge which eventually results in a zero contribution of groundwater to the main channel. Since the water use systems (well, qanat and spring) existing in the area are extracting water from the shallow aquifer, the projected change of groundwater recharge may cause a future increase in the number of dry and deactivated wells, qanats and springs.

As shown in the results, different emission scenarios led to a wide range of projections for the future. Although the predicted climate change for both RCPs will lead to a reduction in streamflow and water yield of the Halilrood Basin, this reduction is greater for RCP8.5, which is in agreement with Emami and Koch (2019). Moreover, using different bias correction methods leads to different outcomes for the climate change studies and the choice of bias correction is an additional source of uncertainty, which is confirmed by previous studies (Graham et al. 2007; Teutschbein and Seibert 2012, 2013; Fang et al. 2015). They also found that the quality of adjusted temperature and precipitation mainly rely upon the choice of the correction algorithm for predicting future climate conditions. Different changes are predicted for climatic and hydrological parameters under both bias correction methods and raw climate model data in the Halilrood Basin. The results showed different variability ranges for raw models as compared to the models corrected by LS and DM. Also, the two bias correction methods differ strongly. This result is in agreement with previous studies (Hagemann et al. 2011; Dosio et al. 2012), which have shown that the bias correction alters the climate change signals. The different results obtained from different bias correction methods can be explained by considering the fact that LS multiplies precipitation with a correction factor. Moreover, LS only accounts for a bias in the mean and is not able to adjust biases in the wet-day frequency, whereas DM results in a narrower range of the variability of hydrological parameters by taking the probability of extreme events (defining scale parameter of Gamma distribution (β)) into account and by controlling the occurrence distributions of precipitation and temperature (defining shape parameter of Gamma distribution (α)). Furthermore, DM not only considers the mean, but also uses the standard deviation to create the transfer function to correct biases in precipitation and temperature data.

3.5 Conclusions

In this study, a hydrological model (SWAT) has been applied to assess the potential impacts of climate change on streamflow conditions and major hydrological components in two different time slices (2030–2059 and 2070–2099) in the Halilrood Basin, Iran.

Our findings have shown that climate change has substantial effects on streamflow. For the two future periods, climate change scenarios projected a pronounced reduction in the mean annual water yield, which mainly reflects the changes in precipitation. The alteration of streamflow is mainly occurring in very high and high flow segments of the flow duration curve. The reduction in streamflow becomes larger towards the end of the 21st century. Besides future precipitation and streamflow reductions, which is a common outcome for dry regions of Iran, actual evapotranspiration is expected to slightly increase in the future while the amount of water leaving the basin (water yield) is expected to strongly decline. According to our simulations, surface runoff, groundwater, and lateral flow are predicted to decrease substantially at mid-, and end of the century. These strong reductions are due to both the effects of climate change and the unchanged water withdrawal assumed in our modeling approach, which is likely to further increase in the future and exacerbate the impacts of climate change.

The remarkable reduction in water yield and consequently in streamflow coincide with a slight increase in evapotranspiration which will lead to a decrease of the water being released to the wetland. Therefore, a decrease of the surface area of the Jazmorian wetland and an increase of wind erosion rates are expected.

This study has demonstrated that the hydrological response of the basin to climate change is strongly dependent on the considered emission scenarios and bias correction methods. The reduction in water yield is 10% more under RCP8.5 in comparison to RCP4.5 at the end of the century. Also, a different response to climate change is found for the different bias correction methods, where the reduction in water yield is higher for raw and DM models compared to LS models. Therefore, we recommend to include multiple bias correction methods for climate change studies in arid regions. The future reduction in water yield is robust since it is observed under both RCP4.5 and RCP8.5, both bias correction methods and the raw data. Therefore, a sustainable strategy needs to be developed to mitigate the negative impact of climate change on future water resources.

Chapter 4 Spatially distributed impacts of climate change and groundwater demand on the water resources in a Wadi system

Nariman Mahmoodi[1], Jens Kiesel[1,2], Paul D. Wagner[1], Nicola Fohrer[1]

[1]Kiel University, Department of Hydrology and Water Resources Management, Kiel 24118, Germany

[2]Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Department of Ecosystem Research, Berlin 12489, Germany

[*]Correspondence to: Nariman Mahmoodi (nmahmoodi@hydrology.uni-kiel.de)

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Abstract

Understanding current and possible future alterations of water resources under climate change and increased water demand allows for better water and environmental management decisions in arid regions. This study aims at analyzing the impact of groundwater demand and climate change on groundwater sustainability and hydrologic regime alterations in a Wadi system in central Iran. A hydrologic model is used to assess streamflow and groundwater recharge of the Halilrood Basin on a daily time step under five different scenarios over baseline period (1979-2009) and for two future scenario periods (near future: 2030–2059 and far future: 2070-2099). The Indicators of Hydrologic Alteration (IHA) with a set of 32 parameters are used in conjunction with the Range of Variability Approach (RVA) to evaluate hydrologic regime change in the river. The results show that groundwater recharge is expected to decrease, and is not able to fulfil the increasing water demand in the far future scenario. The Halilrood River will undergo low and moderate streamflow alteration under both stressors during the near future as RVA alteration is classified as "high" for only three indicators, whereas stronger alteration is expected in the far future with 11 indicators in the "high" range. Absolute changes in hydrologic indicators are stronger when both climate change and groundwater demands are considered in the far future simulations, since 27 indicators show significant changes and RVA show high and moderate levels of changes for 18 indicators. Considering the evaluated RVA changes, future impacts on the freshwater ecosystems in the Halilrood Basin will be severe. The developed approach can be transferred to other Wadi regions for a spatially-distributed assessment of water resources sustainability.

Key words: Climate change impact, Groundwater withdrawals, Groundwater sustainability, Indicator of Hydrologic Alteration (IHA), Wadis, Iran

4.1 Introduction

Water resources are important in arid regions and any alteration caused by anthropogenic activities might have strong environmental and socio-economic impacts. This poses a serious threat to the sustainable development of water resources in different sectors (Oki and Kanae, 2006 and Panahi et al., 2020). Hence, sustainable management of water resources is vital especially in arid regions with limited water availability (Wu et al., 2013; Davijani et al., 2016; Yu et al., 2019).

Sustainable use of water resources should be jointly assessed with regard to surface water and groundwater. Groundwater is not only a valuable source of high-quality freshwater and plays a central role in sustaining water supplies and rural livelihoods in arid regions (Giordano, 2009; Cuthbert et al., 2019), but also contributes to base flow and the functioning of freshwater ecosystems (Boulton and Hancock, 2006; Kath et al., 2018). Excessive groundwater withdrawal for a wide variety of activities, is causing aquifers to rapidly deplete worldwide (Gleeson and Wada, 2013). Groundwater withdrawal has more severe consequences in arid and semi-arid regions, where surface water is insufficient to meet human water demand especially in times of droughts and natural groundwater recharge is low (Long et al., 2016; Taylor, 2014). Moreover, the existence of different and effective groundwater withdrawal systems such as qanats and wells in arid regions can lead to pronounced groundwater depletion (Eissa et al., 2016; Perrone and Jasechko, 2019). Substantial and persistent drops in groundwater levels are expected when the ratio of groundwater demand exceed recharge from infiltration and river transmission losses over the basin (de Graff et al., 2019; Acero Triana et al., 2020). Therefore, the ratio of groundwater demand to the recharge rate is a potential indicator of regional water security (Richey et al., 2015) and sustainability. Little and sporadic precipitation, very high evaporation, little percolation and groundwater recharge are peculiar characteristics of Wadi regions (Pahlevani Majdabady et al., 2020; Messerschmid et al., 2020). In Iran, groundwater extraction rates increased over the last decades due to the scarcity of precipitation, combined with climate change and population growth (Izady et al., 2015; Rafiei Emam et al., 2015; Mahmoudpour et al., 2016). While climate change impacts on groundwater resources are well understood, the combined effects of climate change and population growth (water demand) on groundwater resources are rarely analyzed in a spatially distributed manner. Therefore, estimating the current and future amount of average annual groundwater recharge and storage under climate change conditions and by incorporating growing water demands due to development and population growth is critical and fundamental for a sustainable management of groundwater and surface water (Dash et al., 2019).

Moreover, hydrological changes caused by climate change and population growth are not limited to groundwater, but also extend to surface water resources, where changes in runoff timing, seasonality, peak rates and volumes of surface water have been reported for different arid parts of Iran (Ashraf et al., 2019) and other countries e.g., in the United States (Caldwell et al., 2012), Algeria (Achite and Ouillon 2016), China (Xue et al., 2017), and Jordan (Al Qatarneh et al., 2018). Alterations of the streamflow regime can result in negative environmental consequences, as e.g., in China, where decreases in water resources had a negative effect on the semi-arid wetland ecosystem of Western Jilin (Moiwo et al., 2010). Wen et al., (2013) reported that reduction in streamflow is the principal cause of the decrease in ecological values of a semi-arid wetland in Australia. Similarly in the northwest of Iran, a dramatic reduction of the water level of Urmia Lake has been reported by Khazaei et al., (2019) due to the reduced inflow to the lake from the entire basin. Moreover, the Bakhtegan and Tashk lakes in southern Iran started to disappear due to hydrologic regime changes in Kore River, which altered the inflow to the lakes (Haghighi and Kløve 2017). The fluctuation of streamflow in Hirmand basin caused several hydrologic and environmental effects such as a decrease in water level of Hamoun wetland, increasing wildlife death rates, and increasing air pollution and consequently health problems, in southwestern Iran (Sharifikia, 2012). In addition, Nielsen and Brock (2009) found a shift in species distribution in wetlands of southern Australia due to streamflow regime alteration and salinity induced by climatic changes. According to Qaderi Nasab and Rahnema (2020), the Jazmorian wetland, which is fed by Wadis in central Iran, has undergone significant changes in area and seasonal availability of water between 1987 and 2017. In addition, they report very low soil moisture in the wetland area due to decreasing inflows and high potential evapotranspiration (more than 2800 mm yr^{-1}), which increases vulnerability of the wetland to wind erosion. Modarres and Sadeghi (2018) showed that the dust from the wetland increased the number of dusty days in Iranshahr city, which is almost 180 km away from the wetland. Vulnerability of wetlands to wind erosion has also been found in other arid regions e.g., the dried-up Ebinur Lake region in northwestern China has become one of the main dust sources as a consequence of the change of inflow to the lake (Bao et al., 2006). Further aggravation of climate change will put increasing pressure on the already threatened natural ecosystem of Wadi regions. Therefore, future susceptibility of Wadis to climate change and growing groundwater demand is important to understand.

Recognizing the above concerns, this study aims to: (1) assess the sustainability of groundwater in the future by modeling the recharge rate under climate change and predicted withdrawals, (2) explore possible future hydrologic alterations of rivers in Wadi regions and evaluate their ecological implications.

4.2 Materials and methods

4.2.1 Study area

The Halilrood Basin (7224 km^2) is located in central Iran (Figure 4.1a). It is a major river in the Kerman province in terms of discharge, and provides various ecosystem services, as the water is used for domestic, industrial, energy (Jiroft Dam, Figure 4.1b), and agricultural (small scale farming) purposes, and it provides water to the Jazmorian wetland (Figure 4.1b), mainly from February to April (Figure 4.1c). Annual average precipitation in Halilrood Basin varies between 121 mm to 511 mm with an average of 295 mm from 1979 to 2011 (IWPCO, 2015). The annual potential evaporation is more than 2500 mm and the mean annual discharge (7.68 m^3 s^{-1}) is about one tenth of the precipitation (IWPCO, 2015). Within the period 1979-2011 streamflow intermittency at the outlet of the basin has increased most significantly in 2005 and 2007. Regarding land cover, bare land areas occupy about 75% of the basin. According to Mahmoodi et al., (2020), shrubland and grassland areas can be found in the highlands, whereas irrigated agriculture is existing only in proximity to the rivers and water use systems (WUSs: qanats, wells, springs). Three cities, i.e. Baft, Bazanjan, Rabor are located in the northern part of the basin (Figure 4.1d). Water from shallow aquifer extracted through springs, qanats, and wells drilled in different parts of the basin (Figure 4.1e), is used to supply water to the cities and villages mainly for drinking and washing and to small-scale farming for irrigation.

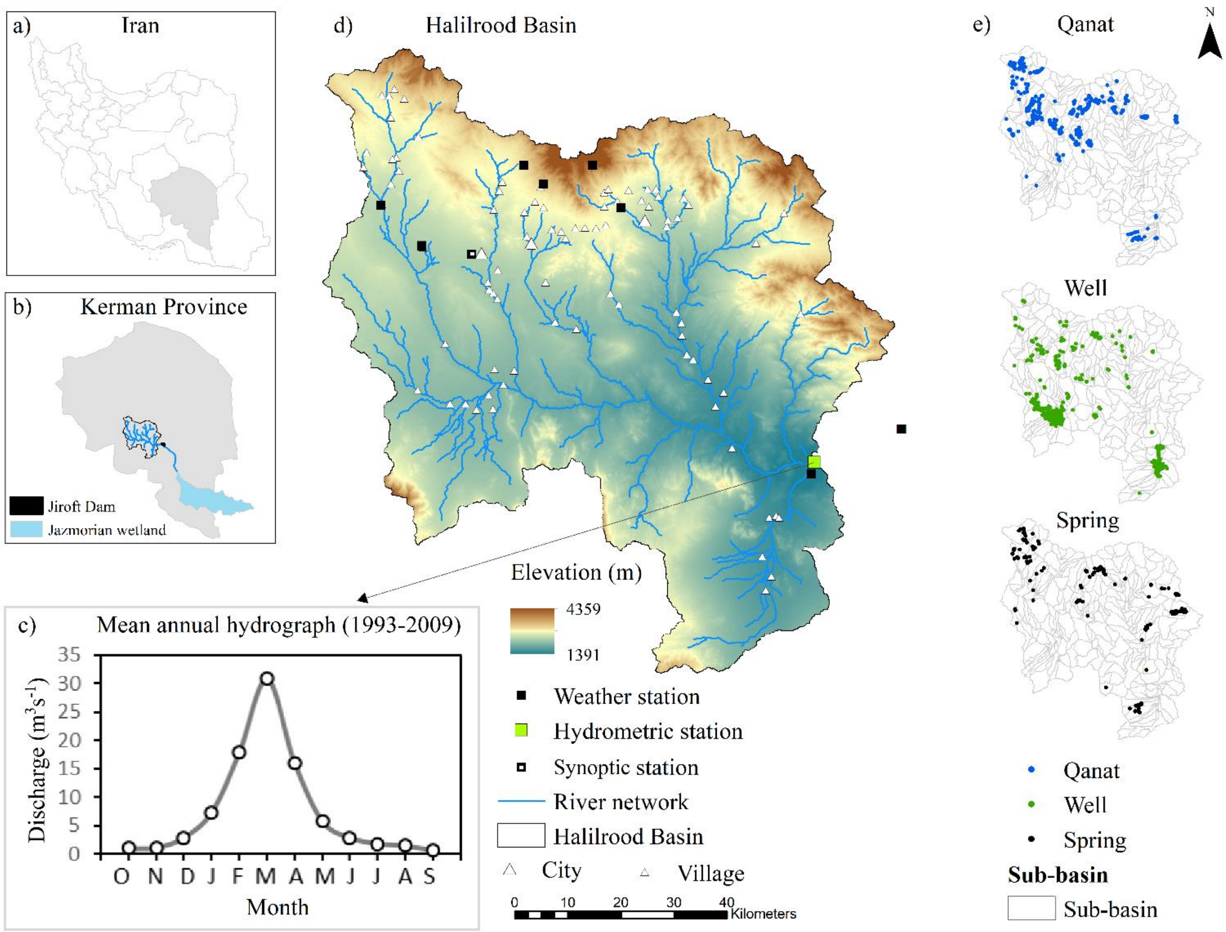

Figure 4.1 Location of the Halilrood Basin, water use systems, and monitoring stations considered in this study. Average monthly flows derived from the observed data at the outlet of the basin.

4.2.2 Hydrological model

The Soil and Water Assessment Tool (SWAT, Arnold et al., 1998; Arnold et al., 2012) is used to simulate the streamflow of Halilrood River between 1993 and 2009 on a daily time step. SWAT is a semi-distributed model which is most commonly applied to simulate water fluxes on the catchment scale with diverse agricultural management options and under various hydrologic conditions over long periods of time (Arnold et al., 2012). As a process-based hydrological model SWAT has proven its capability for climate change impact studies (Emami and Koch 2019; Tigabu et al., 2021). The SWAT model of the Halilrood Basin is divided into 285 sub-basins and 6091 hydrologic response units (HRUs) defined by land use (FAO, 2009), slope, and soil type (ESA, 2010). Based on an equal distribution of dry years (total precipitation < 200 mm), wet years (total precipitation > 270 mm) and average years (200–270 mm annual precipitation) in the study area, an eight-year period of observed data provided by Iran Water & Power Resources Development Company (IWPCO, 2015) is used for model calibration (1995-2003) and a six-year period for validation (2004–2009). Both calibration and validation periods are composed of almost 1/3 dry, wet, and normal years, respectively. Water use systems (WUSs) and soil and water conservation measures (SWCMs) scattered within the basin were implemented in the model (Mahmoodi et al., 2020). According to the model performance rating suggested by Moriasi et al. (2007), very good and satisfactory performances for modeling daily streamflow were achieved judged by a multi-metric approach including NSE (0.76 and 0.54), PBIAS (4.7 and 7.1), RSR (0.49 and 0.78), and the modified KGE (0.87 and 0.62) for calibration and validation period, respectively. The calibrated hydrologic model showed also a good performance (NSE = 0.65) for simulating potential evaporation (PE) at the sub-basin scale, where the comparison showed a good agreement between simulated and observed PE at the synoptic station shown in Figure 1d. In addition, modelled annual actual evaporation (AE) for the Halilrood Basin between 1995 and 2009 (min.:100.2 mm yr^{-1}, median: 173.1, max.: 274.2,) is in a similar range as the AE from the Global Land Evaporation Amsterdam Model (GLEAM version 3.5a, https://www.gleam.eu/; Martens et al., 2017; Miralles et al., 2011) (min.: 96.7 mm yr^{-1}, median: 163.1, max.: 255.9). Further, the groundwater recharge of the Halilrood basin estimated by SWAT is around 50 mm yr^{-1}, which is in agreement with the recharge rate reported by Parizi et al. (2020) for most Wadis in central Iran. No observations or estimates of river bed infiltration were available for the Halilrood basin and it generally is one of the most challenging water balance components to be quantified in Wadi regions (Wheater et al., 2008; Neitsch et al., 2011). Given the plausible representation of all other water balance components in the model, it can be inferred that simulated bed infiltration is represented realistically. A more detailed model description and evaluation is available in Mahmoodi et al., (2020).

4.2.3 Future climate change simulation

Mahmoodi et al., (2021) used an ensemble of 17 global and regional climate models (G-RCMs) from the Coordinated Regional Climate Downscaling Experiment‒CORDEX (Jacob et al., 2014) to assess the impact of future climate change on streamflow and major hydrological components of the Halilrood Basin. Climate data of the Representative Concentration Pathway (RCP) 8.5 were bias corrected with two methods (distribution mapping and linear scaling) and evaluated alongside the raw (not bias corrected) data. RCP8.5 is selected since actual green-house gas emissions of the last decade have followed the RCP8.5 trajectory closer than any of the other RCPs (Sanford et al., 2014). Although the projections driven from scenarios with high CO2 emissions (e.g. RCP8.5) have been criticized as mitigation measures are not accounted for (Hausfather and Peters, 2020), the projections from these scenarios can still be valuable (IPCC, 2021) as they not only agree with historical total cumulative CO2 emissions, but are also plausible for future projections given current and stated policies (Schwalm et al., 2020). The climate model (G-RCM CSIRO-SMHI, RCP8.5, bias adjusted with distribution mapping; Figure 2a) is selected according to the ‘model democracy’ or ‘ensemble of opportunity’ approach (IPCC 2013) that represents the median for most of the simulated hydrological components, i.e., evaporation, water yield, surface runoff, lateral flow, and groundwater flow (Mahmoodi et al., 2021). This procedure of analyzing the impacts of all climate models in an ensemble on the target indicator (here: streamflow) and then selecting the median model is one of many possible approaches in climate change impact studies (Kiesel et al., 2021). The climate models leading to min (CSIRO+IITM) and max (CCCma+SMHI) hydrological components are analysed in addition to the median model to quantify the uncertainty range associated with the full climate change ensemble (Figure 4.2a). Similar to the median model, this min and max analysis is carried out for all water use system scenarios (Table 4.5)

The climatic conditions of the selected median climate model are within the range of conditions of the baseline period as the driest and wettest future years are already included in the baseline years. Therefore, it can be assumed that the parameterized SWAT model is sufficiently applicable the future climate conditions.The calibrated and validated SWAT model is run with the selected climate model output to simulate groundwater recharge and streamflow for the baseline period (1979-2009) and two future periods (near future: 2030-2059 and far future: 2070-2099). The choice of the baseline period can alter the depiction of the changes in hydrologic indicators under climate change, but its uncertainty is lower when baseline periods exceed multiple decades (Ruokolainen and Räisänen 2007). Basic statistical analysis of streamflow at the basin outlet for baseline period and future climate conditions (median, min, and max model) are shown in Table 1. The contradiction shown for min annual streamflow simulated for max (the wettest condition) and the median climate models might be due to the distribution of the rain day and the way of min and max climate model selection, which is based on simulated water balanced components.

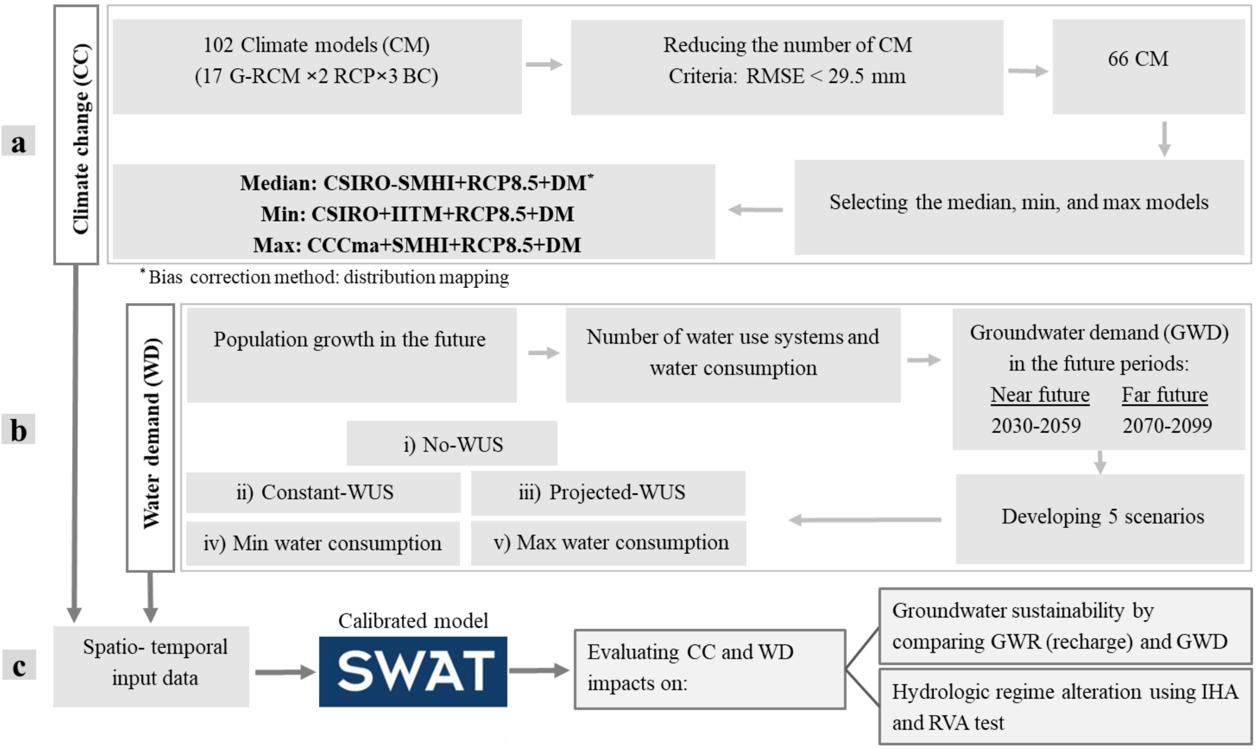

Figure 4.2 Flow chart of the methodology employed.

Table 4.1 Statistical analysis of annual streamflow ($m^3 s^{-1}$) simulated for the baseline (1979-2009) and two future periods (2030-2059 and 2070-2099) for the median, min (driest) and max (wettest) climate models.

			Median climate model		**Max climate model**		**Min climate model**	
	Observations (1993-2009)	Baseline (1979-2009)	Near future (2030-2059)	Far future (2070-2099)	Near future (2030-2059)	Far future (2070-2099)	Near future (2030-2059)	Far future (2070-2099)
Mean	7.66	13.31	9.93	5.84	11.62	15.11	2.85	2.13
Max	33.21	39.79	38.75	20.78	48.59	76.97	6.74	5.72
Min	0.43	1.56	0.53	0.85	0.77	0.3	0.34	0.21
Median	3.42	11.73	6.67	3.74	5.84	10.34	2.34	1.51
STDEV	8.20	10.27	9.77	5.34	13.58	17.20	1.72	1.48
SKEW	1.88	0.98	1.50	1.55	1.52	1.94	0.76	0.99

4.2.4 Future population growth and water demand

Population growth is the main factor governing water consumption in Iran, as Keshavarz et al. (2006) reported a significant correlation between water consumption and population/size of households in Fars province. In addition, the water consumption data reported for three provinces i.e., Azarbaijan, Khuzestan, Isfahan during the period 2001-2010 shows that the consumption rate is increasing linearly with population growth (Mombeni et al., 2013). Based on the data reported by the Statistical Center of Iran (SCI, 2017), Iran has experienced a remarkable population increase within the last few decades (from 33.7 million (M) in 1976 to more than 80 M in 2017 (Dienel et al., 2017)). According to the last census in 2017, the total urban and rural population of Halilrood Basin was 124,000 (Statistical Center of Iran-SCI, 2017). Four population growth rate scenarios are suggested by PBO (2019), i: childbirth rate decreases with a steep slope, ii: childbirth rate decreases with a gentle slope, iii: childbirth rate remains constant, iv: childbirth rate increases. Among these scenarios, a conservative scenario, constant childbirth rate (scenario iii) —i.e. the current trend of population growth will remain constant in the future— is applied on the 2017 population data to estimate the population of the basin for the years 2045 and 2085, representative for the near and far future periods respectively (Table 4.2).

Table 4.2 Population of cities located in the Halilrood Basin according to the last census in 2017 and the future population projected based on the population growth rate suggested by PBO (2019).

Cities	**Population 2011**	**Population 2017**	**Mid. First Period 2045**	**Mid. Second Period 2085**
Bazanjan	4325	4517	5592	7127
Baft	80528	84103	104119	132714
Rabor	33859	35362	43778	55801
Total basin	118712	123982	153489	195643

Future water demand in Halilrood Basin is projected by considering (i) groundwater withdrawal from WUSs and (ii) minimum and maximum water consumption for the estimated population.

(i): To meet the future domestic, agricultural and industrial water demand, increases in the number of wells and qanats are linearly extrapolated with the estimated increases in the population of Halilrood Basin as follows:

$$NWUSj = \frac{Pj}{Pi} * NWUSi, \tag{1}$$

Where *NWUSj* and *NWUSi* are the number of water use systems in the year *j* and *i*, respectively; *Pj* and *Pi* is population in the year *j* and *i*, respectively. The number of springs as a natural WUS is assumed to remain constant in the future. The annual average water withdrawal per WUS recorded for the baseline period is assumed to remain constant in the future and is used to linearly extrapolate the groundwater demand for each sub-basin for the future number of WUS (*NWUSj*) for 2045 and 2085 (Table 4.3). The number of WUSs are reported until 2011. Therefore, the population growth rate between 2011 and 2017 is used to determine the number of WUS in 2017 (Table 4.3).

Table 4.3 Projected water demand from water use systems. Number of water use systems mentioned in parenthesis are estimated based on population growth in 2017 and in the near and far future.

WUS	Mean discharge ($m^3\ s^{-1}$)	Year 2011-reported (Mm^3)	Year 2017 (Mm^3)	Mid. of near future-2045 (Mm^3)	Mid. of far future-2085 (Mm^3)
Well	0.01152	(329) 119.52	(344) 124.83	(425) 154.54	(542) 196.98
Qanat	0.00211	(262) 17.43	(274) 18.21	(338) 22.54	(431) 28.73
Spring	0.00134	(170) 7.16	(170) 7.16	(170) 7.16	(170) 7.16
WUS	0.01497	(761) 144.12	(787) 150.20	(934) 184.24	(1134) 232.87

M: million

(ii): The minimum and maximum amount of water required per person per day in Iran is about 135 and 300 litres, respectively (ISC, 2017-2018). According to these numbers and the estimated population growth (Table 4.2), maximum and minimum water consumption in near and far future are estimated (Table 4.4).

Table 4.4 Minimum and maximum estimated demand for consumptive water use according to the data reported for the water required and population growth currently and in the future.

	Year 2011-reported ($mil.m^3$)	Year 2017 ($mil.m^3$)	Mid. of near future-2045 ($mil.m^3$)	Mid. of far future-2085 ($mil.m^3$)
Min. water consumption: 0.135 m^3/day/person	5.84	6.11	7.56	9.64
Max. water consumption: 0.300 m^3/day/person	12.99	13.58	16.8	21.42

M: million

4.2.5 Scenarios

To disentangle the impacts of climate change and population growth and its combined effects on future aquifer condition and hydrologic regime, five scenarios are developed (Table 4.5, Figure 4.2b). “NO-WUS” scenario is included, to assess the sole impact of climate change on the hydrologic regime under pristine conditions. It therefore represents a scenario where all anthropogenic extractions have ceased. “Constant-WUS” scenario is defined to investigate the impact of climate change on hydrologic regime and groundwater sustainability in the future simulations in comparison to the current condition by keeping the number of WUSs unaltered. The impacts of both climate change and WUSs on groundwater sustainability and hydrologic regime are assessed under "Projected-WUS" scenario. To precisely indicate the impact of the sole water demand by the population on groundwater sustainability in near and far future, the maximum and minimum amount of water required per person is computed and considered under min- and max-consumption scenarios. These two scenarios are considered only on the entire basin scale due to limited availability of information regarding population growth on smaller scales (e.g., villages). Minimum and maximum water consumption is included in the Constant- and Projected-WUS scenarios.

Table 4.5 Scenarios included in near and far future simulations to evaluate groundwater sustainability and hydrologic regime alteration on different spatial scales.

Scenarios	Description	Climate change (median, min, and max)	WUSs including water consumption	Water consumption only	Groundwater sustainability		Hydrologic regime change
					Sub-basin scale	Entire basin scale	
i. No WUS	Water use systems do not exist	✓					✓
ii. Constant-WUS	Currently existing water use systems in the basin remain unaltered	✓	✓		✓		✓
iii. Projected-WUS	The number of water use systems increase linearly with population growth	✓	✓		✓	✓	✓
iv. Min-consumption	Minimum amount of water required per person per day in Iran	✓		✓		✓	
v. Max-consumption	Maximum amount of water required per person per day in Iran	✓		✓		✓	

✓ Addresses the scenario/s considered for each analysis

4.2.6 Groundwater sustainability

Groundwater sustainability is assessed on two different spatial scales: on the sub-basin and on the entire basin scale.

4.2.6.1 Sub-basin scale

Groundwater sustainability (GWS) on the sub-basin scale is defined as the ratio of groundwater demand (GWD) to groundwater recharge (GWR) (Figure 4.2c).

To provide an appropriate estimate and range of the future aquifer condition on the sub-basin scale, groundwater demand for the baseline period and two future periods is estimated for two scenarios: Projected-WUS and Constant-WUS. Moreover, groundwater recharge is averaged for the entire 30-year periods.

4.2.6.2 Entire basin scale

The possible connection of groundwater bodies across sub-basins is considered by treating the Halilrood Basin as one integrated groundwater system. Therefore, groundwater sustainability (GWS) is assessed by comparing the total groundwater recharge (GWR) over the entire basin and entire 30-year periods to (i) the total projected groundwater demand (GWD) from the WUSs under Projected-WUS scenario, (ii) the minimum, and (iii) the maximum water consumptions (min- and max-WC) estimated for the growing population under min- and max-consumption scenarios.

4.2.7 Indicators of Hydrologic Alteration (IHA)

Changes in the hydrologic regime of the Halilrood River that are caused by climate change and growing groundwater demand are not only a challenge for the water sector (e.g., small-scale farming), but also decrease groundwater levels and threaten the Jazmorian wetland ecosystem by reducing its water availability. The hydrologic regime alteration is analyzed for the flow into the wetland under the following scenarios: No-WUS, Constant-WUS, and Projected-WUS (Figure 2c).

Numerous hydrologic indicators have been developed to describe different components of the streamflow regime. A set of 32 hydrologic indicators are used to assess changes in the hydrologic streamflow regime (Richter et al., 1996). The indicators are categorized into five groups; Group1: Magnitude of monthly water conditions, Group2: Magnitude of annual extreme streamflow events with different durations, Group3: Timing of annual extreme water conditions, Group4: Frequency and duration of high and low streamflow pulses, and Group5: Rate and frequency of water condition changes (Table 4.6). The "IHA" software developed by The Nature Conservancy (TNC, 2009) is used to attribute the characteristic of intra- and inter-annual variations in streamflow based on simulated daily discharge for baseline period and future periods (2030-2059 and 2070-2099) under the three different WUS scenarios (No-, Constant-, and Projected-WUS). An ANOVA test is applied with a significance level of 5% (p-value = 0.05) to evaluate the significant differences of IHA in near and far future of each of the aforementioned scenarios compared to the baseline period as suggested in Vu et al. (2019).

The Range of Variability Approach (RVA) established by Richter et al. (1997) is applied to evaluate streamflow regime alteration caused by climate change and groundwater withdrawals (WUSs). The RVA category thresholds are set as the median ±25th percentile of the models setup period data for each hydrologic indicator using non-parametric statistics. The degree of alteration (DA) is calculated as (The Nature Conservancy, 2009):

$$DAi = \frac{Roi - Rei}{Rei} * 100\%, \tag{2}$$

Where *DAi* is the degree of hydrologic alteration of the i^{th} IHA; Roi and Rei are the number of observed and expected repetitions in the scenario period for the i^{th} IHA falling within the RVA target range. *Rei* is defined as:

$$Rei = \gamma Rt, \tag{3}$$

Where γ is the proportion of a single indicator's values falling within the RVA target range in the near and far future, i.e. γ = 0.5 is the suggested RVA target range between the 25^{th} and 75^{th} percentile values. *Rt* is the total number of values for each indicator in the near and far future (30 years period), i.e. *Rt* = 30 (Richter et al., 1997; Zhang et al., 2019).

To evaluate the magnitude of change for each indicator, Richter et al., (1998) divided DAi (absolute value) into three classes: 0–±33% represents no or low alteration (L), ±33%–±67% represents moderate alteration (M), and ±67%–±100% represents high alteration (H). Positive RVA values indicate that the indicator remains stable within the upper and lower bounds (RVA targets) and negative RVA indicates, where the indicator is moving outside the upper or lower bounds to an alternative state.

Table 4.6 The used set of 32 indicators of hydrologic alteration categorized into five groups (Richter et al., 1997).

IHA parameters group	Hydrologic parameters	Unit
Group 1. Magnitude of monthly water conditions	Median flow for each calendar month	$m^3 s^{-1}$
		$m^3 s^{-1}$
Group 2. Magnitude of annual extreme discharge events with different durations	1-day minimum flow (1-day min)	$m^3 s^{-1}$
	3-day minimum flow (3-day min)	$m^3 s^{-1}$
	7-day minimum flow (7-day min)	$m^3 s^{-1}$
	30-day minimum flow (30-day min)	$m^3 s^{-1}$
	90-day minimum flow (90-day min)	$m^3 s^{-1}$
	1-day maximum flow (1-day max)	$m^3 s^{-1}$
	3-day maximum flow (3-day max)	$m^3 s^{-1}$
	7-day maximum flow (7-day max)	$m^3 s^{-1}$
	30-day maximum flow (30-day max)	$m^3 s^{-1}$
	90-day maximum flow (90-day max)	$m^3 s^{-1}$
	Base flow index (Base flow)	$m^3 s^{-1}$
Group 3.Timing of annual extreme water conditions	Date of annual minimum flow (Date min)	day of year
	Date of annual maximum flow (Date max)	day of year
Group 4. Frequency and duration of high and low pulses	Number of low pulses each year (Lo pulse)	dimensionless
	Number of high pulses each year (Hi pulse)	dimensionless
	Duration of low pulses (Lo pulse D)	dimensionless
	Duration of high pulses (Hi pulse D)	dimensionless
	Number of zero flow days (Zero days)	days
Group 5. Rate and frequency of water condition changes	Median rate of positive changes in flow (Rise rate)	$m^3 s^{-1} day^{-1}$
	Median rate of negative changes in flow (Fall rate)	$m^3 s^{-1} day^{-1}$

4.3 Results

4.3.1 Groundwater sustainability

Groundwater sustainability assessment is evaluated on the sub-basin and entire basin scale.

4.3.1.1 Sub-basin scale

The SWAT model of the Halilrood Basin is divided into 285 sub-basins, however, WUSs are located only in 73 sub-basins corresponding to almost 33% (around 2385 km^2) of the total area of the Halilrood Basin. 31 of all 73 sub-basins with WUSs are in a sustainable state (groundwater recharge (GWR) > groundwater demand (GWD)) in the baseline period, however, in 42 sub-basins (17% of the total area) the groundwater demand is higher than GWR. Less than 50% of water demand can be sustainably withdrawn from the groundwater in 22 sub-basins and less than 20% in 8 sub-basins.

The impact of climate change on GWR is assessed in the future periods for Constant-WUS scenario (Figure 4.3b and d). In the near future (Figure 4.3b), the number of sub-basins with a sustainable state (GWR > GWD) decreases from 31 (baseline period) to 26, while the unsustainable sub-basins (GWR < GWD) covering an area of 1211 km^2 (baseline period) increases to 1419 km^2 (20% of the total area). In the far future (Figure 4.3d), 25% of the entire basin (55 sub-basins) reach an unsustainable state, where less than 50% of water demand can be sustainably provided by groundwater in 24 sub-basins and among these, 9 sub-basins can only provide 20% of the water demand.

As shown in Figure 4.3c and e, where the two stressors climate change and growing water demand are considered simultaneously (Projected-WUS), supplying water sustainably is becoming more difficult in the near and far future when compared to the baseline period. Already 25% of the entire basin reach an unsustainable state in the near future (Figure 4.3c), similar to what we estimated to occur in the far future under the Constant-WUS scenario (Figure 4.3d). In the far future, among 73 sub-basin with WUSs, only 8 sub-basins are sustainable and in 56 sub-basins groundwater only provides less than 50% of the water demand (Figure 4.3e). Among these 56 unsustainable sub-basins, groundwater can only satisfy 20% of the water demand in a majority of 42 sub-basins.

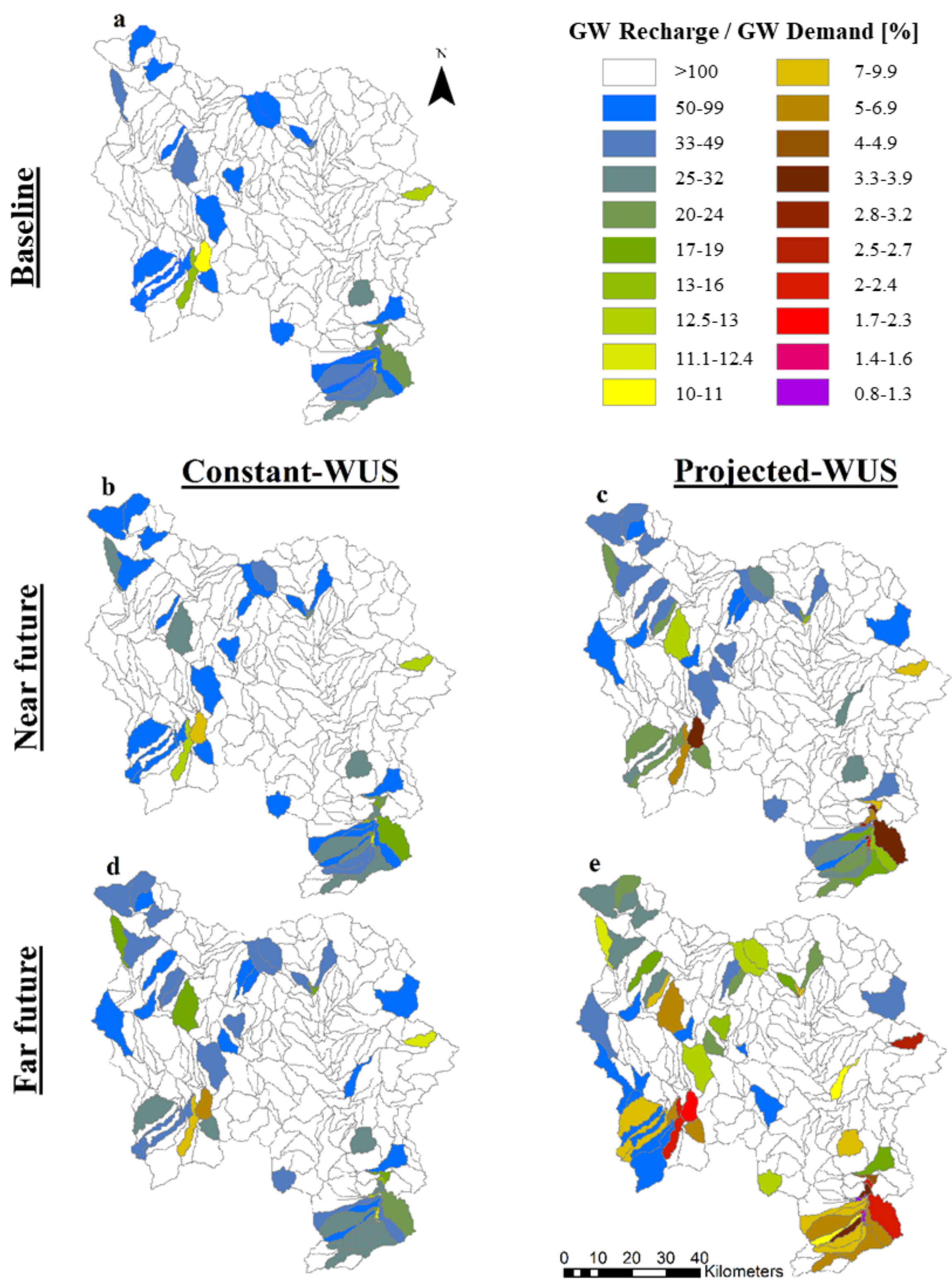

Figure 4.3 The percentage of groundwater demand that can be sustainably met by groundwater recharge at sub-basin scale under two different scenarios: Constant-WUS: the number of water use systems in the basin remain unaltered in the future, and Projected-WUS: the number of water use systems increase linearly with population growth.

4.3.1.2 Entire basin scale

GWR is simulated for the baseline, near, and far future periods (Table 4.7). The GWR is estimated to decrease under future climate change. This reduction is more severe in the far future, when it drops from 385 $Mm^3\ yr^{-1}$ in the baseline period to 172 $Mm^3\ yr^{-1}$. The currently sustainable groundwater situation for the entire Halilrood Basin (total GWD is lower than total GWR) is expected to remain sustainable under future climate conditions, if we only account for the minimum and maximum water consumption for the growing population (min- and max-consumption/GWR < 1). However, if we consider the future increases in the number of WUSs (Projected-WUS), groundwater is only sustainable in the near future (GWD/GWR = 0.59), whereas in the far future GWR is only able to fulfil 75% of the total demand (Table 4.8).

Table 4.7 Average annual groundwater recharge on the entire basin scale in different periods.

	Climate scenarios		
	Baseline (1979-2009)	**Near future (2030-2059)**	**Far future (2070-2099)**
Groundwater Recharge ($Mm^3\ yr^{-1}$)	385	311	172

M: million

Table 4.8 Groundwater sustainability on the entire basin scale under three scenarios: Projected-WUS: the number of water use systems increase linearly with population growth, Min- and Max Consumption: the minimum and maximum water demand corresponded to population growth in the future.

Scenarios	Groundwater sustainability		
	Baseline (1979-2009)	**Near future (2030-2059)**	**Far future (2070-2099)**
Projected-WUS	0.4 (250%)	0.59 (170%)	1.35 (75%)
Min-Consumption	0.015 (6600%)	0.024 (4200%)	0.056 (1700%)
Max-Consumption	0.034 (2900%)	0.054 (1850%)	0.124 (800%)

4.3.2 Streamflow sustainability

The alterations in each hydrologic indicator under future climate conditions (median, min, and max climate models) and different WUS scenarios are shown in Figure 4.4.

4.3.2.1 IHA-Group 1

The median monthly streamflows are expected to decrease in the future. This reduction is not significant for all indicators in the near future under No-WUS, although, a moderate RVA change is shown in late spring, summer, and early autumn. Three out of 12 indicators are significantly altered and eight out of 12 indicators have been significantly altered in scenarios Constant-WUS and Projected-WUS, respectively (Table 4.9).

In the far future, in eleven out of 12 months, median streamflows are expected to decrease significantly (Table 4.9), and the streamflow changes in Aug, Sep, and Oct are classified as "high" for all scenarios.

Strongest changes in monthly streamflow are expected for March under the Projected-WUS scenario where the streamflow decreased by 13.2 and 20.2 $m^3\ s^{-1}$ respectively in the near and far future (Table 4.9). This might be due to the higher reduction in projected winter precipitation compared to the observations (Mahmoodi et al., 2021).

The magnitude of changes expected under the three WUS scenarios (No-, Constant-, and Projected-WUS) are different. For instance, for the month of March which is subject to the strongest impact, the expected decrease under No-WUS scenario (corresponding to the singular impact of climate change) is 10.1 $m^3\ s^{-1}$ in the near future, whereas under Constant- and Projected-WUS scenarios (corresponding to the impact of climate change and growing groundwater demand) the expected decreases are 11.6 $m^3\ s^{-1}$ and 13.2 $m^3\ s^{-1}$, respectively.

The uncertainty range of alterations in monthly streamflow under the min and max climate models indicate that uncertainty associated with the climate projections is higher in summer, fall, and winter seasons compared to spring season (i.e. April to June) when the degree of alteration varies between -13 to -100. This shows that the climate models consistently predict future spring streamflows outside the current 25th and 75th percentiles. Moreover, the direction of changes in spring season remains constant under different climate conditions projected by different climate models.

4.3.2.2 IHA-Group 2

In the near future, none of minimum streamflow indicators is expected to change significantly for No-WUS and Constant-WUS, while three out of five indicators will decrease pronouncedly for Projected-WUS (Table 4.9). In the far future scenario, the alteration in all minimum streamflow indicators is classified as "high" and decreases significantly, as the seasonal moving average declines by 1.1 $m^3 s^{-1}$ (87%) under the three scenarios (No-, Constant-, and Projected-WUS; Table 4.9). Although annual extreme streamflows mainly experience a lower degree of change in the near and far future, the change is more significant for all indicators in the far future for the Projected-WUS scenario for which seasonal maximum streamflow decrease 22.4 $m^3 s^{-1}$ (35%) compared to the baseline period (Table 4.9). Also, alteration in the magnitude of base flow is estimated to be moderate and high in the near and far future, respectively. However, this alteration is only significant when WUS are considered. The reduction of base flow during the near future under climate change is 0.01 $m^3 s^{-1}$ (44%), which doubles when both climate change and extraction are considered in the future simulation (Table 4.9).

A wide uncertainty range of alterations (from -100 to +87 %) exists for the low-flow indicators i.e. 1 day min, 3 day min, 7 day min, and 30 day min. This indicates that the direction of alteration is associated with high uncertainties for the lowest streamflow and base flow indicator. The uncertainty is lower for the 30- and 90-day low flow values. In contrast, the annual extreme high streamflow indicators (e.g., 90 day max) consistently move outside the RVA target range, which is predicted for both the min and max climate models.

4.3.2.3 IHA-Group 3

Lowest streamflows are projected to occur earlier in all three scenarios, around three months for the near future (shift from Sep to June) and more than four months for the far future (shift from Sep to April). Also, the date of peak streamflow will shift by around two months and is estimated to happen earlier (shift from March to January) in both the near and far future of all scenarios. The uncertainty range shows that the alteration caused by different climate model projections is more pronounced for the time of occurrence of high flows, as the percentage of alteration varies from +47 to -53, compared to the occurrence of low flows with positive alteration (between +13 and +100) under different climate projections.

4.3.2.4 IHA-Group 4

The number of low streamflow pulses is estimated to increase in the future but this change is not significant in any scenario. The duration of low streamflow pulse is expected to increase significantly in the near future for all scenarios, whereas it is not significant in the far future except for the Projected-WUS scenario. The number of high streamflow pulses decreases significantly only in the near future for Projected-WUS scenario. The duration of high streamflow pulses does not change significantly in the near and far future in all scenarios. Number of days with no streamflow will increase significantly in both the near and far future under the three scenarios. This alteration is more severe for the far future under Projected-WUS scenario with 136 days more no-flow days as compared to the baseline period (Table 4.9).

The alterations in frequency and duration of high and low streamflow pulses under No-WUS in near and far future, are similar to the alterations expected under Constant- and Projected-WUS. For instance, the number of high pulses (Hi Pulse) is estimated to reduce similarly (-2) under all three scenarios. Frequency and duration of high and low pulses do not change under the full range of climate projections and, with the relatively narrow uncertainty band, can therefore be assessed as robust projections.

4.3.2.5 IHA-Group 5

The number of fall and rise rates in streamflow are subject to significant changes only in the far future under No- and Constant-WUS scenarios (Table 4.9). The alteration for these indicators lies in the lower range for the median model. The full range of climate impacts causes a high degree of alteration in fall and rise rates (-47% to +93%).

The Non-parametric IHA scorecard is displayed in the supplementary material (Table A2). This shows a comparison of statistics (e.g., the low and high streamflow thresholds and annual coefficient of variation) for the baseline period and the future period. Moreover, the annual values and total distribution of each hydrologic parameter for the baseline period and two future periods under different WUS scenarios are shown in the supplementary material (Figure A4 and A5).

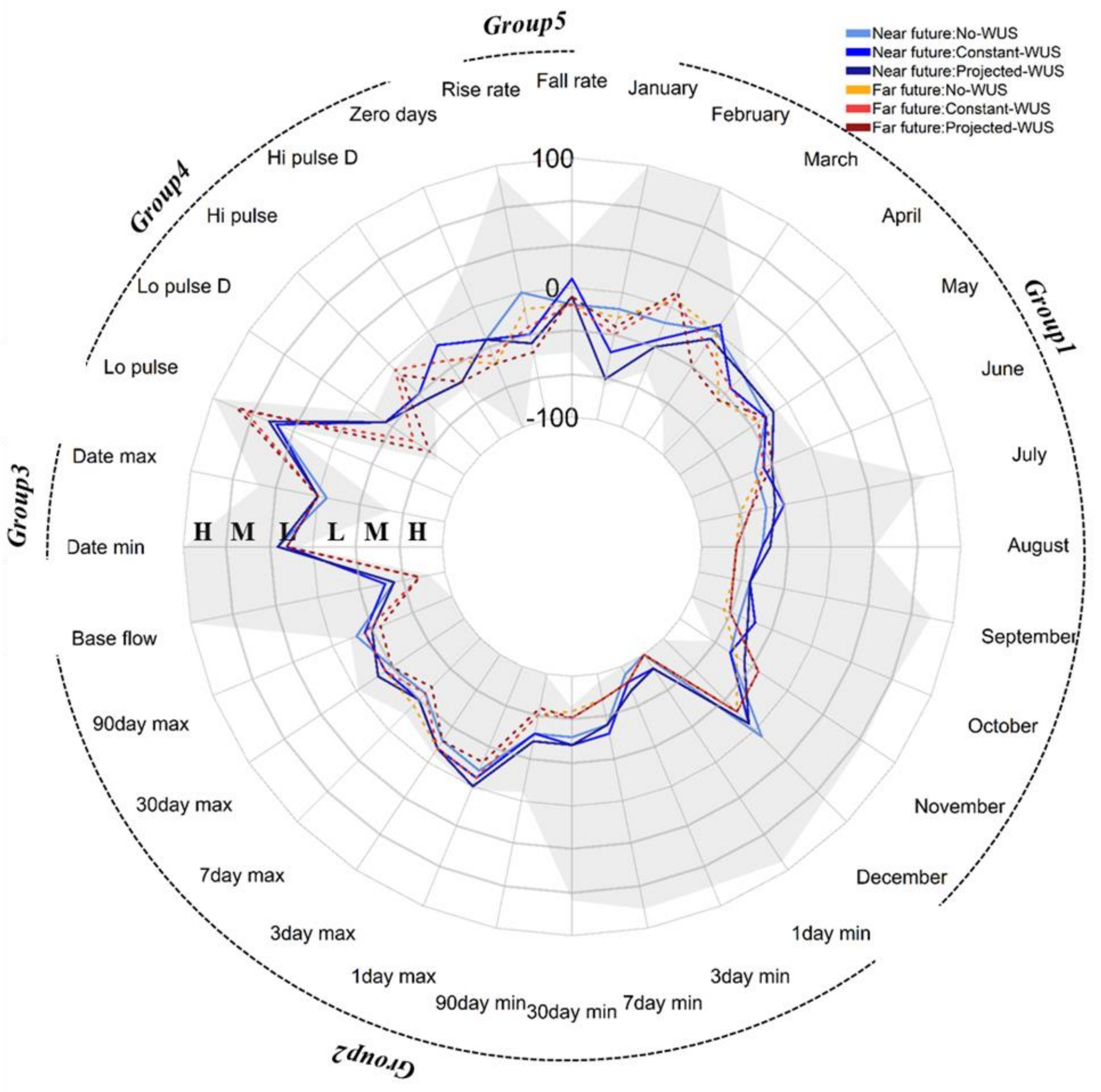

Figure 4.4 RVA (The Range of Variability Approach) deviation and classes of alteration (High (H), Moderate (M), and Low (L)) for each IHA (Indicators of Hydrologic Alteration) indicator in the near and far future under three different scenarios: No-WUS: the water use systems are not considered, Constant-WUS: the number of water use systems in the basin remain unaltered in the future, and Projected-WUS: the number of water use systems increase linearly with population growth. Alteration (uncertainty) band derived from min and max climate models for both near and far future simulations under three WUSs scenarios is shown in grey.

Table 4.9 Absolute change for each Indicators of Hydrologic Alteration (IHA) (significant changes highlighted in gray) in the future under three different scenarios: No-WUS: the water use systems are not considered, Constant-WUS: the number of water use systems in the basin remain unaltered in the future, and Projected-WUS: the number of water use systems increase linearly with population growth. Percentage of RVA (The Range of Variability Approach) deviation is shown in brackets.

IHA groups	IHA	Near future			Far future		
		NO-WUS	Constant-WUS	Projected-WUS	NO-WUS	Constant-WUS	Projected-WUS
Group1	January	-6.3(-13)	-7.0(-47)	-7.8(-68)	-8.8(-20)	-9.4(-33)	-9.9(-27)
	February	-2.8(-13)	-4.2(-27)	-5.8(-33)	-9.6(+7)	-10.7(+7)	-11.9(+13)
	March	-10.1(0)	-11.6(+6)	-13.2(-7)	-18.2(0)	-19.2(-13)	-20.2(-33)
	April	-5.5(-13)	-6.4(-27)	-7.4(-13)	-10.1(-40)	-10.6(-27)	-11.1(-40)
	May	-2.5(-20)	-3.2(-20)	-3.8(-13)	-5.3(-27)	-5.6(-27)	-5.9(-20)
	June	-1.4(-47)	-1.8(-40)	-2.2(-33)	-3.3(-40)	-3.5(-40)	-3.7(-33)
	July	-1.1 (-47)	-1.4(-33)	-1.7(-40)	-2.4(-68)	-2.5(-60)	-2.6(-60)
	August	-1.1(-53)	-1.2(-53)	-1.4(-47)	-1.9(-73)	-2.0(-73)	-2.0(-73)
	September	-0.7(-60)	-0.8(-60)	-1.0(-60)	-1.3(-73)	-1.4(-73)	-1.4(-73)
	October	-0.7(-60)	-0.8(-47)	-0.9(-53)	-1.2(-73)	-1.3(-68)	-1.3(-68)
	November	-0.5(-53)	-0.6(-53)	-0.7(-40)	-0.8(-47)	-0.9(-27)	-0.9(-27)
	December	-2.7(+7)	-3.0(-7)	-3.3(-7)	-3.8(-20)	-3.9(-20)	-4.1(-20)
Group2	1-day min	-0.2(-100)	-0.2(-87)	-0.2(-87)	-0.3(-100)	-0.3(-100)	-0.3(-100)
	3-day min	-0.2(-93)	-0.3(-87)	-0.3(-80)	-0.4(-87)	-0.4(-87)	-0.4(-87)
	7-day min	-0.3(-60)	-0.3(-53)	-0.4(-60)	-0.4(-80)	-0.4(-80)	-0.4(+80)
	30-day min	-0.2(-53)	-0.3(-47)	-0.4(-47)	-0.6(-73)	-0.6(-68)	-0.7(-68)
	90-day min	-0.6(-53)	-0.7(-53)	-0.8(-47)	-1.1(-68)	-1.1(-68)	-1.1(-73)
	1-day max	-110.1(-13)	-122.8(-7)	-135.5(0)	-199.1(-7)	-206.7(-7)	-214.3(-20)
	3-day max	-62.5 (-20)	-71.1(-13)	-79.7(-13)	-115.2(-13)	-120.9(-13)	-126.6(-20)
	7-day max	-40.8(-40)	-46.5(-33)	-52.1(-33)	-72.3(-27)	-76.3(-40)	-80.3(-47)
	30-day max	-22.7(-33)	-25.6(-27)	-28.4(-20)	-36.3(-27)	-38.4(-27)	-40.5(-33)
	90-day max	-10.6(-20)	-12.5(-27)	-14.4(-33)	-19.7(-27)	-21.0(-27)	-22.4(-40)
	Base flow	-0.01(-60)	-0.01(-53)	-0.02(-60)	-0.02(-80)	-0.02(-80)	-0.02(-80)
Group3	Date min	-85(+27)	-84.0(+20)	-85(+27)	-137(+20)	-136.0(+20)	-137(+20)
	Date max	-53(-7)	-52.0(0)	-53(0)	-61(0)	-60.0(0)	-61(0)
Group4	Lo pulse	2.6(+47)	2.6(+47)	2.6(+53)	2.4(+73)	2.4(+73)	2.1(+80)
	Lo pulse D	2.4(-27)	2.3(-27)	2.3(-27)	2.0(-53)	2.1(-53)	2.4(-68)
	Hi pulse	-2.0(-33)	-2.0(-33)	-2.0(-40)	-1.6(-7)	-1.6(-7)	-1.8(-13)
	Hi pulse D	-1.9(-13)	-1.9(-13)	-2.3(-47)	-1.3(-27)	-1.3(-27)	-1.6(-47)
	Zero days	78(-27)	79(-27)	83(-27)	130(-47)	132(-40)	136(-47)
Group5	Rise rate	0.16(0)	0.003(-33)	-0.08(-40)	0.89(-13)	0.6(-27)	0.53(-47)
	Fall rate	-0.16(-13)	-0.01(+7)	0.1(-7)	-0.45(-13)	-0.25(-13)	-0.08(-7)

4.4 Discussion

The spatio-temporal variations of the groundwater demand to groundwater recharge ratio in the Halilrood Basin are compromising groundwater sustainability in the near and far future.

These challenges are expected to be more severe when both climate change and population growth are considered. In addition, groundwater sustainability on the sub-basin scale for the Projected-WUS scenario as compared to Constant-WUS shows that the increases in groundwater demand and consumption exacerbate the negative impact of climate change on groundwater sustainability. To predict future groundwater demand, we used population growth as the main driver. However, increases in number of days with zero streamflow coincide with higher temperature and evapotranspiration rate, and shifts in the precipitation regimes caused by climate change (Mahmoodi et al., 2021). While we considered this reduction in water availability, the changing climate may lead to increasing irrigation requirements and may put the existing water use systems under additional pressure as similarly revealed in Toews and Allen (2009).

The rising water demand and WUSs will cause a decline of groundwater levels, due to the imbalance between the groundwater recharge under climate change and estimated groundwater demand in the future. This is not only resulting in an unsustainable groundwater use on sub-basin level and in the entire basin, but also changes the hydrologic regime and ecosystem condition by reducing the contribution of groundwater to streamflow, as 22 and 27 indicators show significant changes respectively for the near and far future under the Projected-WUS scenario. This is in agreement with findings by Haghighi et al. (2020) who stated robust changes in low streamflow indicators of Marboreh Basin in western Iran under future climate conditions.

The evaluation of indicators defined for monthly streamflows in the near future show that growing groundwater demand strongly affects the hydrologic regime of the Halilrood Basin during the dry season (spring, summer, and autumn) as opposed to the wet season (winter), when the changes of monthly streamflows are not significant under the Projected-WUS scenario. This is in agreement with the findings of Kakaei et al., (2018) which revealed substantial deficits in river discharge during the dry season (summer) of the Eskandari Watershed in central Iran due to human activities (abstraction of groundwater and surface water for irrigation purpose).

The predicted unsustainability of groundwater use could be even more intense if we focus on the changes projected for the magnitude and timing of annual extreme conditions, in which base flows, minimum and maximum streamflows are projected to decrease and a four months shift is expected for minimum streamflows from Sep to June. This could lead to a higher groundwater demand during summer when surface water does not meet the rising demand, which is different in other seasons.

In the near and far future, monthly streamflows and annual extreme streamflows are expected to decrease. However, the different magnitude of changes under the three WUS scenarios (No-, Constant-, and Projected-WUS) indicated that the influence of climate change on the streamflow regime alteration is stronger than growing groundwater demand. This is in agreement with previous studies e.g., Döll and Zhang (2010) and Shahid et al., (2018). In addition, the similar results for timing, frequency and duration of extreme hydrologic parameters under all three scenarios also showed that their changes are mainly caused by climate change.

Since the Halilrood River is the most important source of water in the region, the significant changes in hydrologic alteration indicators may have an impact on the ecosystem of the Wadi and Jazmorian wetland (water presence, area of water body, water depth, and wetland species). We are expecting smaller inundated area and shallower water body in Jazmorian wetland under climate change condition and groundwater withdrawal, as 27 hydrologic regime indicators show substantial alterations since out of 32 RVA 12 are classified as “high” and 15 as “moderate“. Simultaneously, the availability of water for the wetland is reduced since, among 23 IHA considered for the magnitude of monthly streamflows and annual extreme streamflows, 21 IHA indicate significant changes and 15 IHA show high and moderate levels of alteration based on the RVA approach. Moreover, we expect lower water availability in future for the wetland due to increases in the number and duration of low pulses and number of days with zero streamflow as well as decreases estimated for the number and duration of high pulses. The significant alteration in falling rates, coinciding with alteration in the magnitude of streamflows, might influence soil moisture in the wetland and consequently change the distribution of the plants by an intensification of drought stress on plants, preventing wind and water erosion in the Jazmorian wetland. In summary, hydrologic regime alteration caused by climate change and growing groundwater demand, will contribute substantially to the ecological change of the wetland and hence, influence the freshwater ecosystem of Wadis in central Iran according to our RVA analysis.

Assessing the streamflow regime changes using IHA in conjunction with RVA, provide a proxy on initial ecological responses to the hydrologic regime changes without having to explicitly investigate ecological indices or building ecological models. However, in order to understand detailed ecological consequences and to identify hydrological thresholds for sustaining the complete or parts of the wetland ecosystem, an in-depth study involving ecological indicators and species requirements is nevertheless needed. The RVA approach enables researchers to link and track the hydrologic and ecological responses to the desirable implementations or ecosystem research efforts. Since, the RVA targets were set as the median ±25th percentile of the baseline period data for each hydrologic indicator, the high variation of the streamflow data in Wadi systems might lead to a high range of RVA targets. Therefore, we recommend a combination of RVA approach and a statistical method such as ANOVA to test the level of alteration and their significance in different hydrologic indicators.

The range of alteration derived from the min and max climate model projections allows to investigate how the climate models contribute to the uncertainty in projected hydrological changes. The derived uncertainties vary across the hydrological indicators. For instance, the magnitude of extreme streamflow events are highly uncertain for the low streamflow events as opposed to lower uncertainty shown for the high streamflow events. Similarly, Cui et al., (2018) found that the uncertainty for low-flow periods under different climate projections is higher than for high-flow periods in the Yellow river, China. Projections of streamflow alterations in April, May, and June are more robust as opposed to other month of the years, as the uncertainty band of the min and max climate models is relatively narrow. The streamflow for these months is mainly generated from lateral flows and snowmelt, which are both expected to change under the projected seasonal temperature increases for all climate models (Mahmoodi et al., 2021). Temperature increases can cause a transformation in the pattern and type of precipitation, leading to more rain than snow, which is also reported for other arid regions in Iran (e.g., Shahvari et al., 2019). The lower RVA target (25th percentile of the baseline) for the magnitude of low flow extreme events (1-7 day min) and for the base flow indicator is zero and 0.007 respectively. Therefore, these indicators cannot be significantly reduced further and future changes are likely to occur only under wetter climate conditions. The number and duration of low flow pules shows a strong alteration regardless of which climate model is used, which is likely driven by the reduction of groundwater contribution to streamflow under all possible future climate conditions (Mahmoodi et al., 2021). When considering the uncertainty originating from the climate models, it is unrealistic to expect more optimistic conditions for the already threatened Jazmorian wetland. For instance, the degree of alteration and reduction in the magnitude and duration of high streamflow pulses remains constant even under the wettest climate conditions in the future (max climate model). The alterations for different indicators under the median climate model is always within the uncertainty band, while for some indicators the alterations approach the upper or lower bound. This can be explained by the selection method of the median, min and max climate models, which was carried out based on the lumped water balance components and not the individual indicators.

4.5 Conclusions

The spatio-temporal variation of groundwater sustainability and the streamflow alteration in the near and far climate change-impacted future have been assessed under five different scenarios: (i) no groundwater demand (ii) unaltered present-day groundwater demand (iii) an increase in groundwater demand (iv) minimum-, and (v) maximum water consumption. Our findings show that:

1) The significant reduction estimated for groundwater recharge under climate change coincides with rising demand from WUSs and water consumption.

2) The growing groundwater demand in the future exacerbates the impact of climate change on the sustainable use of water resources in the Halilrood Basin.

3) A sustainable state is possible for the entire Halilrood Basin in near and far future if only consumptive water use is considered. However, several sub-basins would still be extremely unsustainable. Hence, water provisioning from sustainable to unsustainable sub-basins would be required.

4) The impacts of climate change and growing groundwater demand on the freshwater ecosystems in the Jazmorian wetland basin are expected to be intensified as considerable hydrologic regime alterations projected in the Halilrood River (27 IHA indicators show significant changes in the far future and among these the RVA is classified as “high” and “moderate” for 18 IHA).

5) Uncertainties originating from the climate model ensemble are higher for the monthly streamflow in summer, fall, and winter season and extreme low flows compared to the streamflow of spring season and the number and duration of low streamflow pulse indicators.

The combined results show that climate change has a stronger impact on hydrologic regime alterations and consequently on the freshwater ecosystem in the near and far future as compared to growing groundwater demand in Halilrood Basin. The presented results are useful for long-term planning which is required for a sustainable water resources management under changing future conditions.

Chapter 5 General discussion

Wadis are regions with arid climate conditions and very limited water resources (Sherif et al., 2012). To sustainably manage these resources, suitable models that are capable of representing these regions are required. In this thesis, the special characteristics of Wadis have been implemented in a hydrologic model. Under consideration of climate change and growing water demand, the sustainability of groundwater, possible alterations in the hydrologic regime, and the vulnerability of Wadis' ecosystem were evaluated to answer the research questions.

5.1 Addressing the research questions

(1) How can Wadi systems be more accurately represented in a hydrologic model?

Hydrological modeling of semi-arid regions is challenging due to the extreme climatic and hydrological conditions and the scarcity of data in combination with a large number of water use systems and soil and water conservation measures.

One of the challenging tasks in hydrological modeling context is how models can provide a higher accuracy in simulation of hydrological processes and reduce the uncertainties in hydrological projections (Renard et al., 2010). One way to improve the model performance is the assimilation of more details and input data in the models (Lahmers et al., 2019). This is supported by our results from the inter-comparison of model setups that showed a more stable performance when WUSs and SWCMs as a specific characteristic of Iranian Wadis are included in the model. The number of model runs with acceptable performance was higher for the model setup in which additional relevant input data are considered. While each performance measure has a specific hydrological focus (Guse et al., 2020), the WUS-SWCM model showed better performances for more model runs under all performance measures. Moreover, when applying a multi-metric framework (KGE, NSE, PBIAS and RSR), less model runs remain as being acceptable for the Default model (177 runs) in comparison to the WUS-SWCM model with 1942 runs. This emphasizes the model's improvement in simulating hydrological processes when specific characteristics of the Wadis were included. E.g. the reduction of the CN value in those areas where SWCMs are present led to a better representation of the rising and falling limbs of the hydrograph by the WUS-SWCM model due to the higher infiltration rate and higher interflow and groundwater contribution as a consequence. This complements well the findings of Woznicki and Pouyan Nejadhashemi (2014) where the water impounded within soil and water conservation measures (e.g., terraces and contour farming) increase water infiltration and alter surface runoff in Tuttle Creek Lake Basin, USA. Khelifa et al. (2017) also reported a decrease in streamflow and sediment yield of a small semi-arid watershed catchment in Tunisia due to SWCMs. Moreover, as previously reported by other researchers (e.g., Boulton and Hancock, 2006; Kath et al., 2018) the existence of groundwater withdrawals (e.g., wells) can alter the contribution of the groundwater to the streamflow by decreasing the level of the water table. Therefore, the implementation of WUSs and SWCMs can resolve the overestimation of peak flows simulated by the default model. In addition, higher contribution of groundwater to the base flow in sub-basins with SWCMs in the enhanced model improved the representation of the middle and low flow segments of the FDC. These results show that the enhanced model better represents both, rising and falling limbs of the hydrograph in Wadi regions, while other studies had difficulties to depict those (e.g., Korichi and Hazzab, 2012).

However, both models showed an underestimation of low and very low flows. Especially, very low discharges were simulated as zero discharge by the models. These incoherencies in low and very low flow segments might be explained by the return flows originating from qanats that are not monitored and have therefore not been considered in the model, as the approach is based on the measured monthly discharge. Measurements with a higher precision and a higher temporal resolution would be necessary to overcome this limitation. The hydrological components showed significant changes when WUSs and SWCMs have been implemented. Those changes are more pronounced at smaller sub-basin scales. Therefore, there is a strong need to consider these changes in the present and future water management as SWCMs could be promising options to mitigate climate change impacts (Lal et al., 2011). With the aim of doing that, understanding the spatio-temporal interactions of groundwater and surface water using a coupled SWAT-MODFLOW model is important. Overall, we found that including all available information of Wadis' characteristics such as groundwater consumptions and soil and water conservation practices in the model enhances the model's capability to better represent Wadi hydrology.

(2) How does climate change affect the water resources of a Wadi system?

The impacts of climate change have been the subject of many hydrological studies. Although long-term efforts have been made by the hydrological community to evaluated those impacts, still there are many issues remaining unresolved for hydrologists, especially in arid regions (Blöschl et al., 2019). Hence, the impacts of climate change on streamflow and major hydrological components in the near-(2030-2059) and far-future (2070-2099) have been assessed.

The results demonstrated that climate change impact on the magnitude of streamflow seasonality is considerable. The future model simulations show an increase in streamflow during early winter and middle of summer seasons, when the medians of model projections are slightly greater than the observed streamflow of January, February, and July, which is the hottest month of the year. The highest temperature projected for the middle of summer, will increase the demand for water in Halilrood Basin in all sectors, especially in agriculture as the main consumer of water (Ardakanian 2005) and the most vulnerable sector to climate change and water scarcity in Iran (Karimi et al., 2018), hence increases in future summers' surface streamflow can partially be allocated to irrigation and improve agricultural productivity. However, all bias corrected climate models are projecting smaller precipitation in winter season. These inconsistencies between magnitudes of monthly precipitation and generated streamflow can be explained by the number of rainy days calculated on the monthly basis as an index for precipitation intensity. The number of rainy days during winter is predicted to decrease, which indicates higher intensities for the future precipitation and higher runoff ratios and streamflow as a consequence. Furthermore, a shift in timing and occurrence of the seasonal peak flow from March to February is expected to occur in the future. Increases in December streamflow are also pointing to the predicted backward shift in the seasonality of streamflow in the future. As similarly reported in other arid and semi-arid basins in Iran such as in the Gharehsoo River Basin (Javan et al., 2015) and in the Varamin Plain Basin (Shahvari et al., 2019), these seasonal shifts in streamflow of Iranian Wadis may be due to the changes in precipitation pattern or/and the increases in seasonal temperature leading to an earlier snowmelt in mountainous areas. Since the annual streamflow volume of Wadi systems in Iran is concentrated in the time from December to April, any change in the seasonal pattern and magnitude will have considerable environmental implications, such as significant shrinkages in the lakes' surface areas (e.g., Haghighi and Kløve, 2017), or increases in wildlife death rates and air pollution (e.g., Sharifikia 2012) and socio-economic effects, in particular rising out-migration (Khavarian-Garmsir et al., 2019) and less proceeds for farmers (Mosavi, et al., 2020). Moreover, in this regard, other studies already highlighted that agricultural yields are estimated to decrease significantly under future climate change in arid regions (Bannayan and Rezaei, 2014) and Iran due to a precipitation deficit. The vulnerability to climate change and water shortage is more intense for the areas with higher water demand crops (Kalbali et al., 2021), therefore adapting the crop types to the future climate condition would be a potential solution to sustainably manage the limited water resources in Halilrood.

Assessing the impact of the climate model ensemble on different segments of the hydrograph showed high variabilities for all segments, in particular for very high and high flows. This variability increases toward the end of the century, when the maximum and minimum changes estimated for very high flow nearly ranges from -87 % to +1200 %. The wide ranges of streamflow in different segments of the hydrograph imply that extreme values like floods and droughts are also to be expected in the Halilrood Basin. This confirms the results of a study by Modarres et al. (2016), which indicates significant increasing trends of flood risks for most of the basins in Iran, particularly in arid regions. Moreover, future projections on intensity and frequency of droughts in different parts of Iran indicate a higher probability of severe droughts under future climate conditions (Sayari et al., 2012; Kameli et al., 2017). The comparison of the projected median flow duration curves and FDC derived from the observed data shows that low flow segments are less impacted in Halilrood Basin. This may be due to negligible changes estimated in mean monthly streamflow of dry seasons in future scenarios. While the results of this study showed higher reductions for high flows of Halilrood basin under climate change, Haghighi et al. (2020) reported that the impact of climate change on low flow is stronger than on high flow in Marboreh Basin in western Iran.

To gain a better understanding of the streamflow variation in the future, all relevant hydrological components such as evapotranspiration, surface runoff, lateral flow, and groundwater flow should be considered, as recommended by Uniyal et al. (2015) and Serrat-Capdevila et al. (2007). Substantial increases in temperature and slight increases estimated for evapotranspiration show that reduction in precipitation causes a water limitation and counterbalances the effect of temperature on evapotranspiration. Changes of precipitation and evapotranspiration in the future lead to a considerable decrease in the amount of water leaving the catchment (water yield). The analysis of historical and future simulations show that the main reduction estimated for water yield (more than 50 %) is reflected in surface runoff and groundwater flow with less than 10 percent contribution to the streamflow. While the share of lateral flow as the main contribution is reduced by 50%. As previously reported (Graham et al., 2007; Teutschbein and Seibert 2012, 2013; Fang et al., 2015) a range of projections is generated depending on the selected emission scenario and bias correction methods. The streamflow of Halilrood basin show a greater reduction under the RCP8.5 scenario. This is in agreement with the findings of Emami and Koch (2019), who similarly reported a greater reduction for water yield under RCP8.5 in the Zarrine River Basin, Iran, where the contribution of groundwater and lateral flow is projected to decrease in the future.

Overall, the main future hydrological insight for the region under climate change is lower availability of water in the Halilrood Wadi mainly due to higher precipitation intensity and lower contributions of groundwater, lateral flow, and surface runoff to the streamflow.

(3) How does the combination of climate change and growing water demand affect groundwater sustainability of a Wadi system?

Reduction in surface water in the Halilrood Basin due to climate change (Chapter 3) can lead to more pressure on the groundwater in the future. To provide reliable hydrological projections of the groundwater situation, we evaluated the ratio of groundwater withdrawal to the recharge rate as a potential indicator of regional water security and sustainability on two spatial scales: sub-basin and entire basin scale. The groundwater recharge of the Halilrood basin estimated by our hydrological model is around 50 mm yr^{-1}, which is in agreement with the recharge rate reported by Parizi et al. (2020). The groundwater recharge is estimated to decrease pronouncedly under future climate condition, around 20% for the near future and more than 50% for the far future. Reduction in groundwater recharge is also reported for other arid and semi-arid regions in Iran (e.g., Zamanirad et al., 2018; Jeihouni et al., 2019). Our analysis on the sub-basin scale shows that among 73 sub-basins with WUSs, groundwater extraction is greater than groundwater recharge in 42 sub-basins (17% of the total Halilrood Basin) for the baseline period. In most of these sub-basins with unsustainable water use (i.e. groundwater extraction>groundwater recharge) the rate of groundwater use to groundwater recharge is higher than two, particularly in the southeastern and northern part of the basin. However, this rate can reach 10 in a few sub-basins, in which wells are the main water supplier. The number of unsustainable sub-basins increases to 47 (55), covering 20% (25%) of the total area in the near (far) future, when extraction rates remain at current levels and climate change impact is accounted for. While, including increasing water demand simultaneously with climate change in our projections more sub-basins indicate unsustainable water use and in the far future, among 73 sub-basins with WUSs, only eight sub-basins remain sustainable (around 30% of total area). Evaluation of groundwater sustainability at the smaller sub-basin scale provides effective information on where strategies to mitigate the impact of climate change may need to focus on. Comparison of total groundwater recharge under pressure of climate change and total groundwater withdrawal for the whole basin also shows that groundwater utilization is only sustainable in the near future, whereas in the far future groundwater recharge is not able to fulfill the future increasing demands. The imbalance between water withdrawal rates and natural recharge is reported in most of the Iranian aquifers, as the Ministry of Energy in Iran applied serious restrictions in more than 404 plains from the total 609 plains to reconcile water withdrawal rates with recharge (Samani, 2021). Our results show that the increases in groundwater withdrawal and consumption exacerbate the negative impact of climate change on groundwater sustainability. The impact of groundwater withdrawal on the groundwater sustainability is also discussed by Tizro et al. (2019), who anticipate increases in the water table of a semi-arid aquifer in western Iran under climate change if groundwater withdrawal decrease by 20% in the near future. These future challenges are expected to be even more severe if additional pressures on groundwater withdrawals are considered, such as increasing irrigation requirements caused by changes in temperature, evapotranspiration rate, and hydrologic regime (Toews and Allen, 2009). This is in agreement with findings by Vörösmarty et al. (2000) who report a severe water scarcity under climate change in the regions where industrial and agricultural water demands are increasing, particularly in arid regions. Substantial drop in the levels of groundwater due to consumptive uses leads to a lower contribution of groundwater to the streams, springs, and wetlands and potentially devastating effects on aquatic ecosystems (de Graff et al., 2019, Ahmadi et al., 2017).

(4) How does climate change and growing water demand affect the ecological flow regime of a Wadi system?

Flow regime alteration is regarded as one of the primary threats of river and wetland ecosystems and a challenge for water security in arid regions (Moiwo et al., 2010; Wen et al., 2013). Possible changes in the hydrologic regime were evaluated using 32 indicators, that describe the characteristics of intra- and inter-annual variations in streamflow based on simulated daily discharge for a baseline (1982-2011) and two future periods (2030-2059 and 2070-2099) under the three different WUS scenarios (No-, Constant-, and Projected-WUS). Results show that there are significant changes in the hydrologic regime as the magnitude of alteration for most hydrologic indicators is classified as moderate and high. The indicators representing magnitude of monthly flows and extreme events with different durations are expected to change in the future. The alterations in magnitude of flows in both monthly water conditions and extreme events are most pronounced when WUSs are included in the projection. These alterations are higher in the dry season (spring, summer, and autumn). This is in agreement with the findings of Kakaei et al. (2018) who found more severe water shortages during the dry season in the Eskandari Basin in central Iran due to groundwater and surface water abstractions for irrigation purpose. The comparison between magnitudes of changes under different scenarios show that the sole impact of climate change is the main cause of alterations in the hydrologic regime in comparison to rising water demand and population growth, as similarly reported in Gohari et al. 2017 for Zayandeh-Rud River in central Iran. Moderate and high alterations are estimated for base flow in the near and far future, respectively when only the impact of climate change is considered. Dramatic hydrologic alteration was also demonstrated in other arid basin such as Zab River in Iran and Iraq due to a reduction in base flow as one climate change implication (Mohammed and Scholz, 2016). Moreover, the investigations by Haghighi et al. (2020) indicate that climate change is the main driver of hydrological variations in the Marboreh Basin in western Iran. Including WUSs in our model projections not only changes the magnitude of the base flow significantly in the future, but also leads to an around three months' earlier occurrence of lowest flows for the near future (shift from Sep to June) and more than 4 months for the far future (shift from Sep to April). This may be due to the imbalance between the groundwater recharge under climate change and future groundwater withdrawal, which causes a decline of groundwater levels and reduces groundwater contribution to streamflow, which is in agreement with findings by Arciniega-Esparza et al. (2017) and Mukherjee et al. (2018). The shift and earlier occurrence of minimum flows lead to a higher groundwater withdrawal in summer season when the surface water does not meet the rising demand. Change in magnitude and timing of streamflow are critical to many ecosystems, especially in arid regions (D'Odorico and Bhattachan, 2012), therefore, assessing the alteration in hydrologic regime using IHA indicators provides useful information for hydrologists to develop environmental flow recommendations and to assess hydrological change (Richter et al., 1996; Mathews et al., 2007). Hydrologic regime changes of the Halilrood River might increase the pressure on the already threatened freshwater ecosystem, where Qaderi Nasab and Rahnema (2020) reported low soil moisture and significant changes in water availability towards the end of the 1987-2017 period. The results of the RVA test on IHA indicators indicate that the Jazmorian wetland will be threatened by less inflows, which may lead to a reduction of its size and a shallower water body. Comparative analysis of 23 indicator values, representing the magnitude of flows at the monthly and annual basis, showed that the availability of water for the wetland will be reduced in the future. Among the 23 indicators, 21 IHA are subject to significant changes and 15 IHA show high and moderate levels of alteration based on the RVA approach. This is in agreement with other studies that report an impact of hydrologic regime change on aquatic ecosystems in Iran. For instance, alteration in magnitude of streamflow to the Anzali Lake lead to reductions in wetland volume, area and depth (Naderi and Saatsaz, 2020). Moreover, we expect lower water availability in the future for the wetland due to increases in the number and duration of low streamflow pulses and number of days with zero flow as well as decreases estimated for the number and duration of high streamflow pulses as essential step in wetland restoration worldwide (Middleton, 2002). Soil moisture in the Jazmorian wetland, which depends on inflows more than on precipitation, already showed a decreasing trend (Qaderi Nasab and Rahnema, 2020). This reduction is expected to continue in the future, as significant alterations in the magnitude of flows are projected under future climate conditions. Since soil moisture is one of the major factors for variations in the spatial pattern of vegetation in the arid regions of Iran (Zare et al., 2011), a lower soil moisture is expected to change the plants' presence and absence probabilities in the Jazmorian wetland.

In summary, according to the RVA analysis, climate change and groundwater withdrawal lead to strong hydrologic regime alteration, which is expected to contribute substantially to the ecological change of the wetland and hence, influences the freshwater ecosystem of Wadis in central Iran. Combining the RVA analysis with the IHA is a valuable method to assess the probable ecologic implications of climate change and groundwater withdrawals.

5.2 General conclusion

The research presented in this dissertation provides insights into the current and future water resources of an Iranian Wadi system. Based on the general characteristics of hydrology in Wadi environments and existence of different water use systems and soil and water conservation measures, the SWAT model setup was enhanced for an adequate representation of the hydrology in the study area and was used to assess the susceptibility of major hydrological components to climate change, water withdrawal and soil and water conservation measures. A special focus was given to groundwater sustainability and alteration of the hydrologic regime under pressure of both climate change and increasing water demand in the future. Key results can be summarized as follows:

(1) Implementation of water use systems and soil and water conservation measures into the hydrological model enhances the capability of the model to represent the hydrology of Wadi systems.
(2) Climate change has substantial effects on streamflow and major hydrological components. The Iranian Wadis face conditions of severe water limitation towards the end of the century.
(3) Rising future water demand exacerbates the impact of climate change on limited water resources and results in unsustainable extraction rates of groundwater and high alterations of the hydrologic regime in Iranian Wadis. Generally, combining both the impacts of climate change and growing water demand cause cumulative pressures on the entire ecosystem. Therefore, combining both pressures in the future scenarios ensures a complete picture of hydrological conditions.
(4) Applying the RVA test on IHAs is a suitable approach that explicitly exposes the severity of the changes in the different hydrologic indicators and in parallel their probable implications on the ecosystems.

This work represents an effort to improve our hydrological modeling of Wadi systems and to assess their vulnerabilities to climate change and growing water demand and developments in the future. The hydrological modeling is an appropriate approach for further planning water management aspects, therefore, the applied methodology and approaches should be extended to other Wadi regions with different hydro-meteorological characteristics and conditions.

5.3 Outlook

The following recommendations are given for future work on improving the water resources simulation in Wadi regions:

1) Model improvement in Wadi regions: The hydrologic regime of Wadi systems is mainly characterized by high variability of temporal and spatial precipitation distribution, which leads to flash floods and period of drought in those regions. A better representation of hydrological processes, especially on smaller scales, requires sub-daily data. Hence, measuring data on the sub-daily scale is recommended, particularly for precipitation as a main driver of magnitude and frequency of flash floods and drought events. Moreover, we suggest evaluating the hydrological model performance with respect to the new satellite-based evapotranspiration productions such as MODIS Global Evapotranspiration Project (MOD16).

2) Climate change impact assessment: Due to undeniable uncertainties in modeling chain studies, considering all sources of uncertainty, including, global climate model structures, internal climate variability, climate downscaling and bias correction methods, and hydrological models is suggested (Clark et al., 2016). Therefore, the methodology can be applied using a number of different global climate models, downscaling and bias correction techniques, and hydrological models to identify the uncertainty bounds of the estimates.

3) Assessment of future water scarcity and its ecological consequences: The variability of the ecological indicators in Halilrood River and the wetland area should be directly monitored and compared to the findings of this research. Due to the fragile ecosystems existing in the Iranian Wadis, looking at the species that occur in the wetland and their specific requirements would enable an ecological impact assessment. In addition, evaluating the spatial efficiency of different water harvesting structures such as surface dams, series of sand dams, and SWCMs under future climate change is necessary. To this end, spatial analysis of groundwater and surface water interaction is required that can be conducted using coupled surface- and groundwater models (e.g. SWAT-MODFLOW), which however requires spatio-temporal observations from piezometric wells.

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Supplementary material

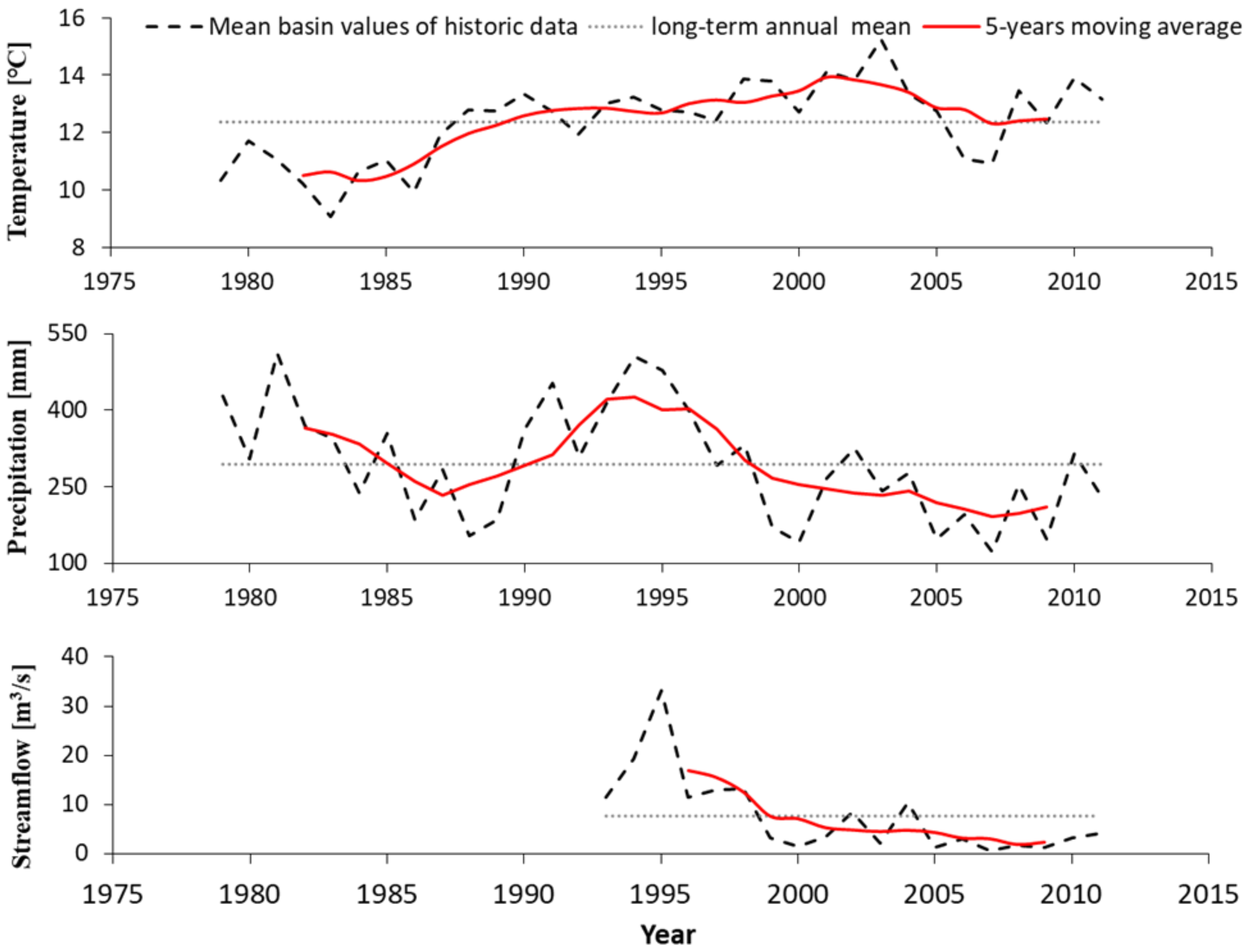


Figure A1 Annual mean values of the measured data.

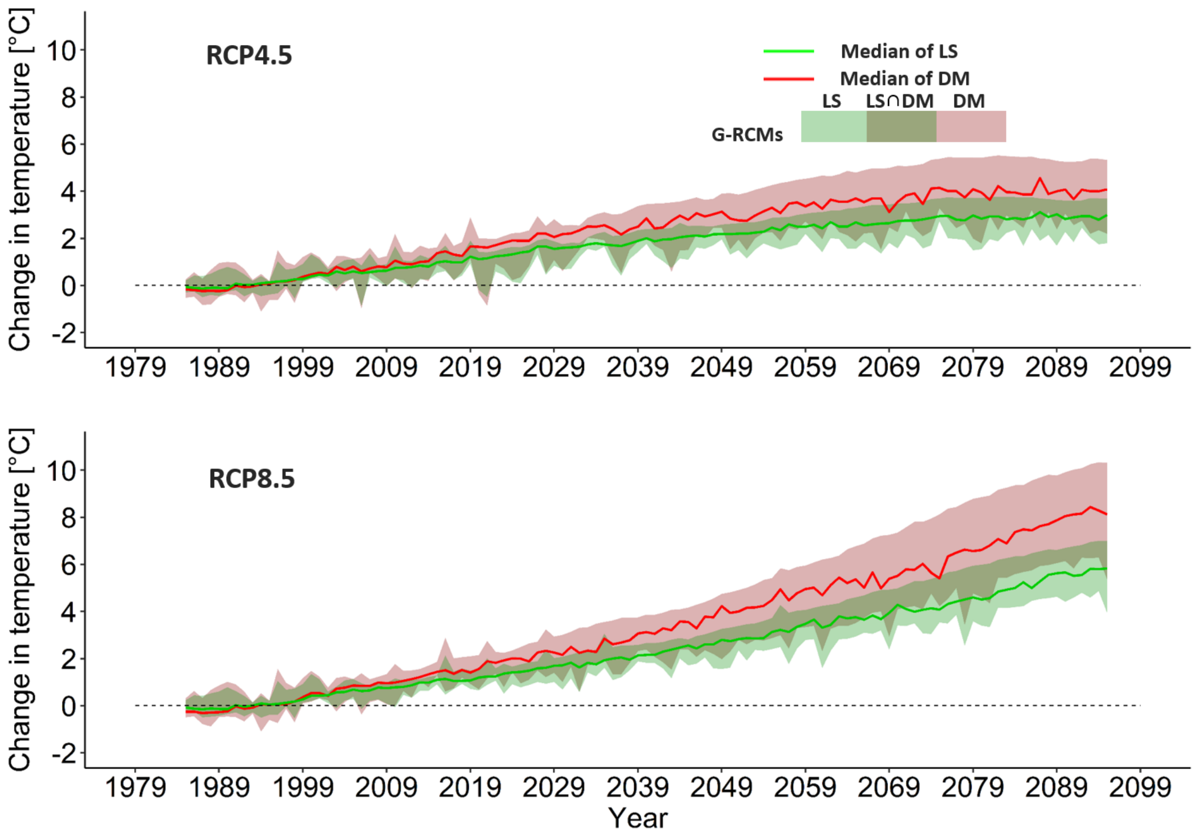


Figure A2 Change in 10-year moving average of projected annual temperature compared to long-term annual mean of baseline data (gray dashed line). Green solid line: median of climate models corrected by Linear Scaling (LS). Red solid line: median of climate models corrected by Distribution Mapping (DM). Light green and light red shading: full range of projected temperature (minimum to maximum) for both bias correction methods. Dark green: the common range of temperature between both bias correction methods.

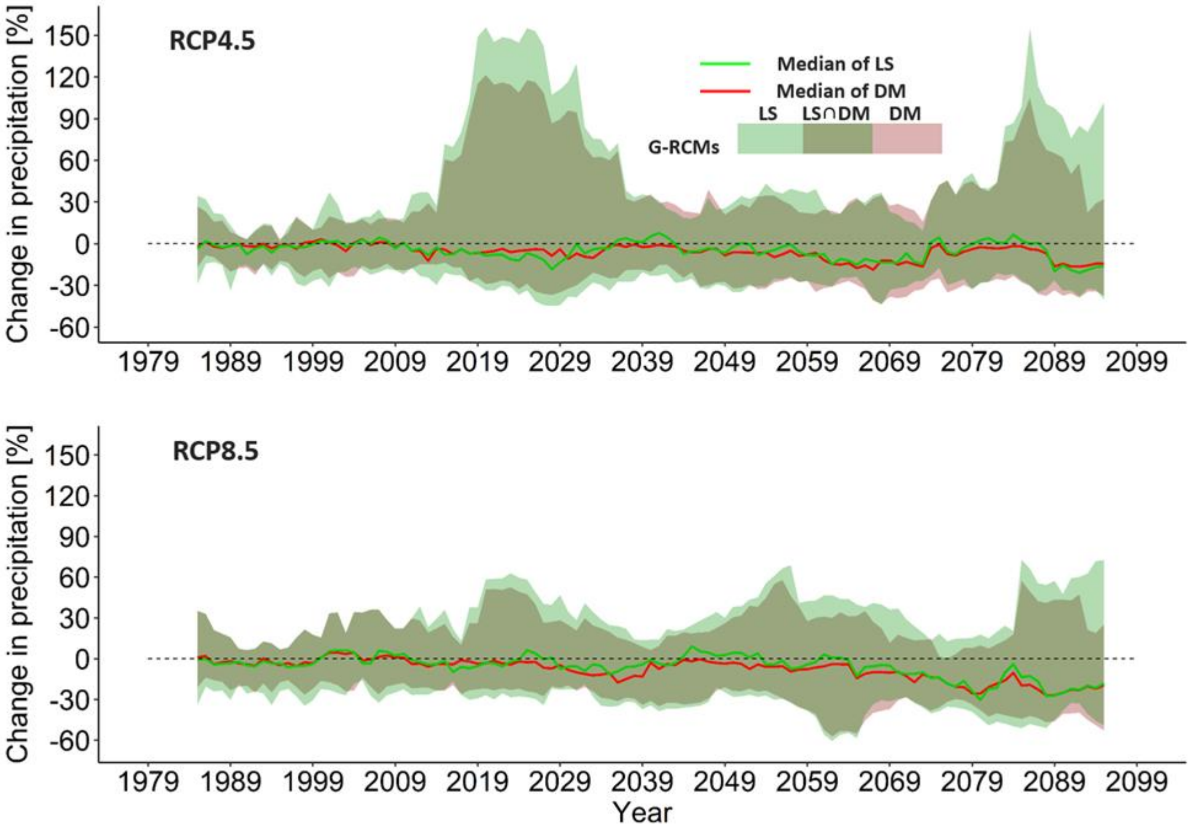


Figure A3 Change in 10-year moving average of projected annual precipitation compared to long-term annual mean of baseline data (gray dashed line). Green solid line: median of climate models corrected by Linear Scaling (LS). Red solid line: median of climate models corrected by Distribution Mapping (DM). Light green and light red shading: full range of projected precipitation (minimum to maximum) for both bias correction methods. Dark green: the common range of precipitation between both bias correction methods.

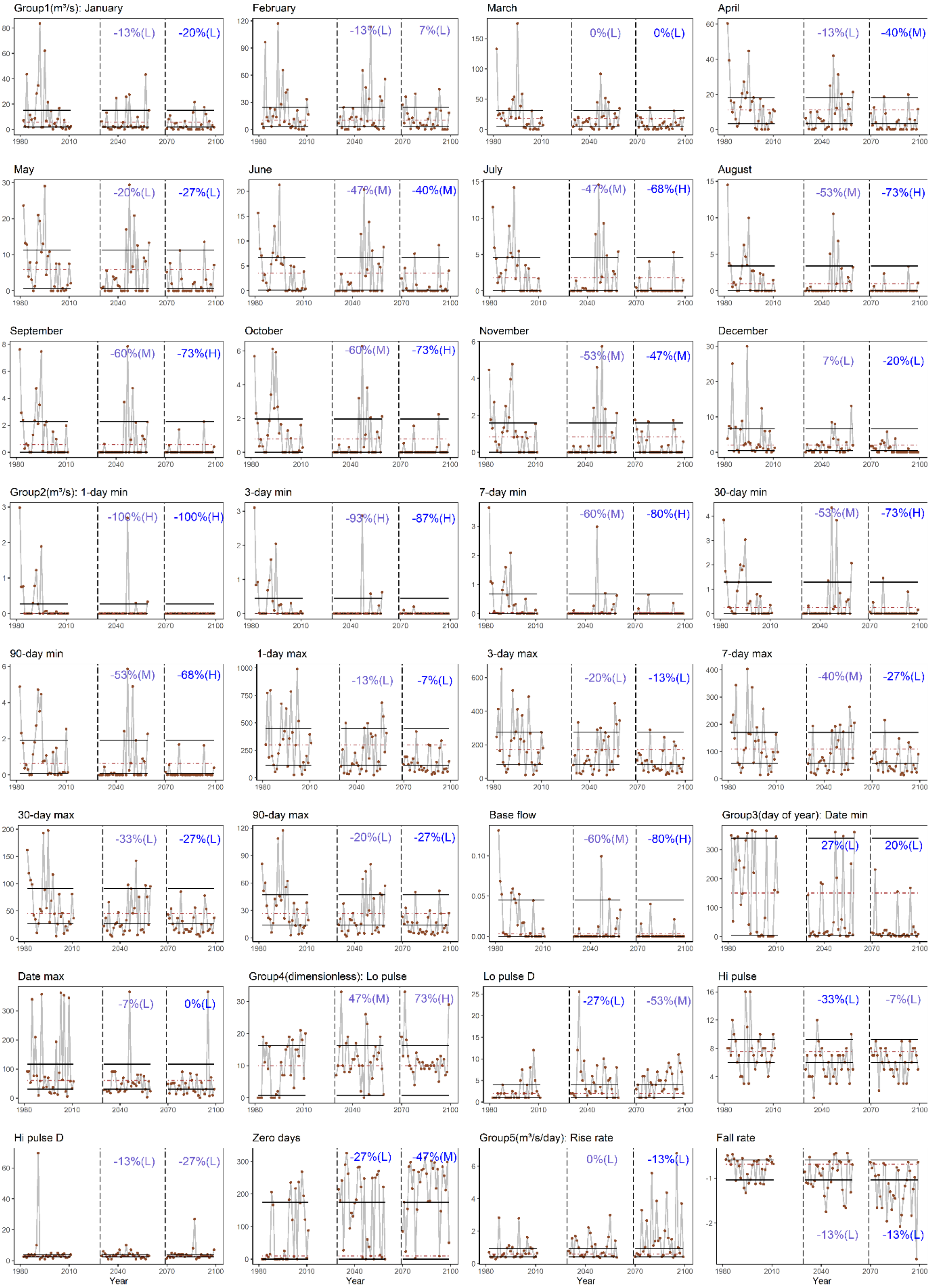
Table A1 Change in projected temperature and precipitation

Bias correction methods		TMP (°C)				PCP (%)			
		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
		2030–2059	2070–2099	2030–2059	2070–2099	2030–2059	2070–2099	2030–2059	2070–2099
LS	Min	+1.63	+2.25	+2.07	+4.24	–24.28	–27.22	–29.38	–40.30
	Max	+2.43	+3.68	+2.98	+6.26	+36.99	+61.48	+19.16	+12.36
	Med	+1.98	+2.78	+2.40	+4.94	–1.73	–2.68	+0.42	–18.3
DM	Min	+2.08	+3.04	+2.56	+5.64	–22.52	–30.59	–26.32	–37.05
	Max	+3.51	+5.35	+4.34	+9.24	+37.32	+44.82	+12.53	+7.13
	Med	+2.50	+3.95	+3.41	+7.12	–4.94	–2.48	–3.59	–20.99

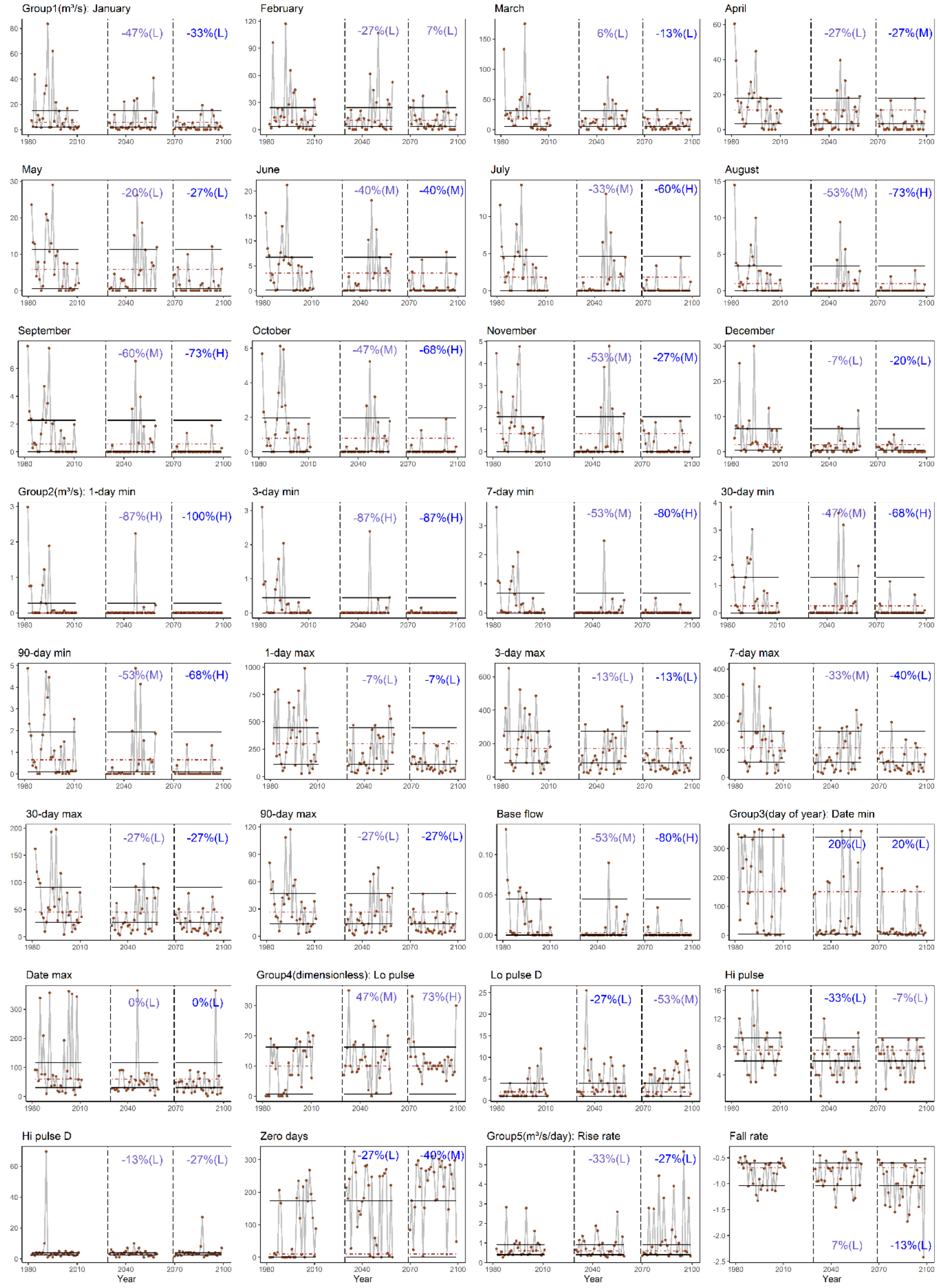
Table A2 Non-parametric IHA scorecard for the model setup and the future periods under the three WUS-scenarios.

	Baseline period (1982-2011)	**Future period 1 (2030-2059)**			**Future period 2 (2070-2099)**		
		No-WUS	Constant -WUS	Projected-WUs	No-WUS	Constant -WUS	Projected-WUs
Normalization Factor	1	1	1	1	1	1	1
Mean annual flow ($m^3\ s^{-1}$)	12.13	10.66	9.94	9.23	6.13	5.84	5.5
Non-Normalized Mean Flow ($m^3\ s^{-1}$)	12.13	10.66	9.94	9.23	6.13	5.84	5.5
Annual Coefficient of Variation (C. V).	2.99	4.39	4.5	4.63	4.76	4.9	5.06
Flow predictability	0.28	0.32	0.34	0.34	0.43	0.44	0.44
Constancy/predictability	0.54	0.60	0.62	0.62	0.71	0.70	0.70
Percent of floods in 60d period	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Duration of flood-free season (day)	10	48	48	48	124	124	124
Low Pulse Threshold ($m^3\ s^{-1}$)	0.28	-	-	-	-	-	-
High Pulse Threshold ($m^3\ s^{-1}$)	9.71	-	-	-	-	-	-

i)NO-WUS Scenario



ii)Constant-WUS Scenario



iii)Projected-WUS Scenario

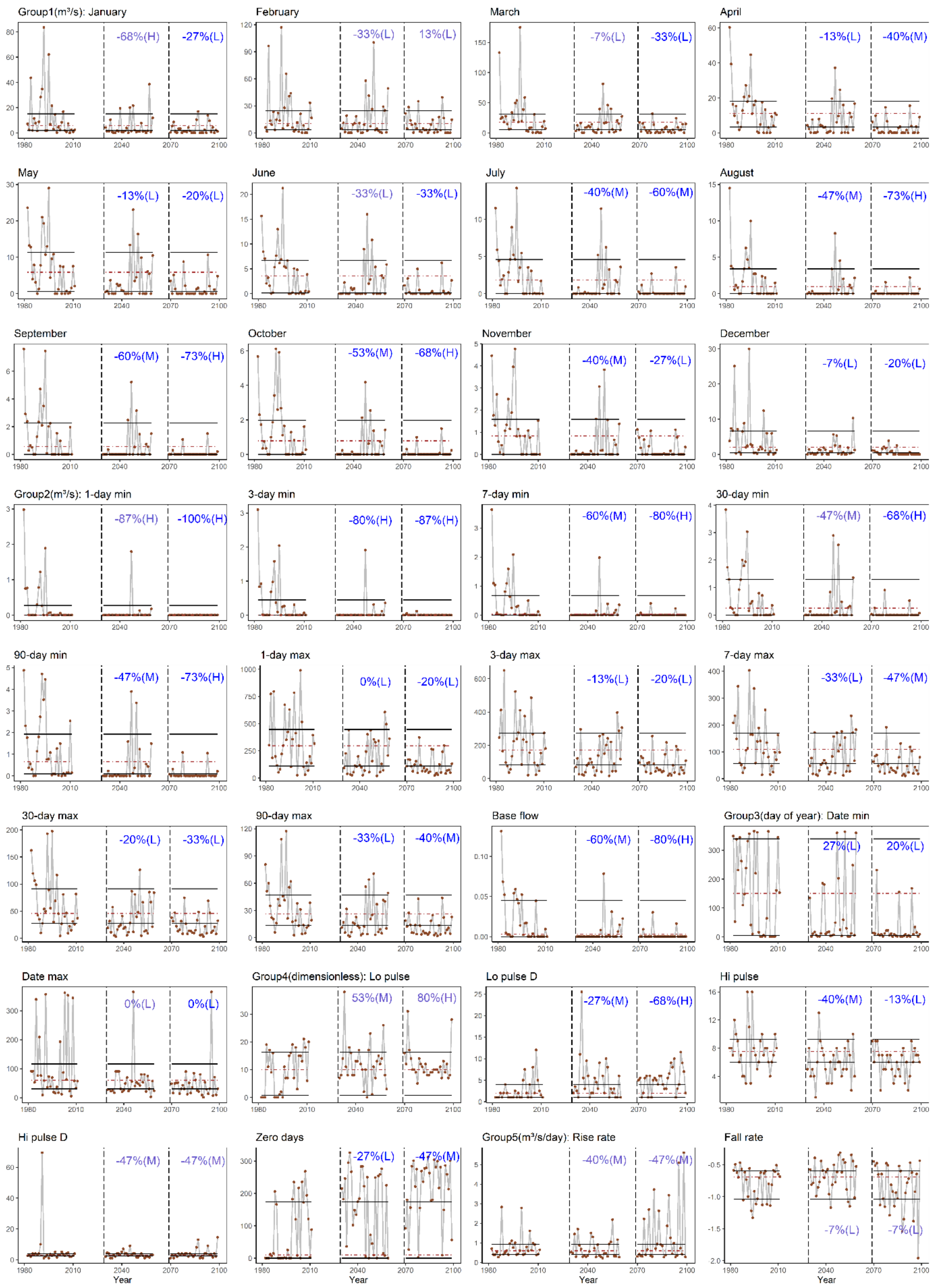
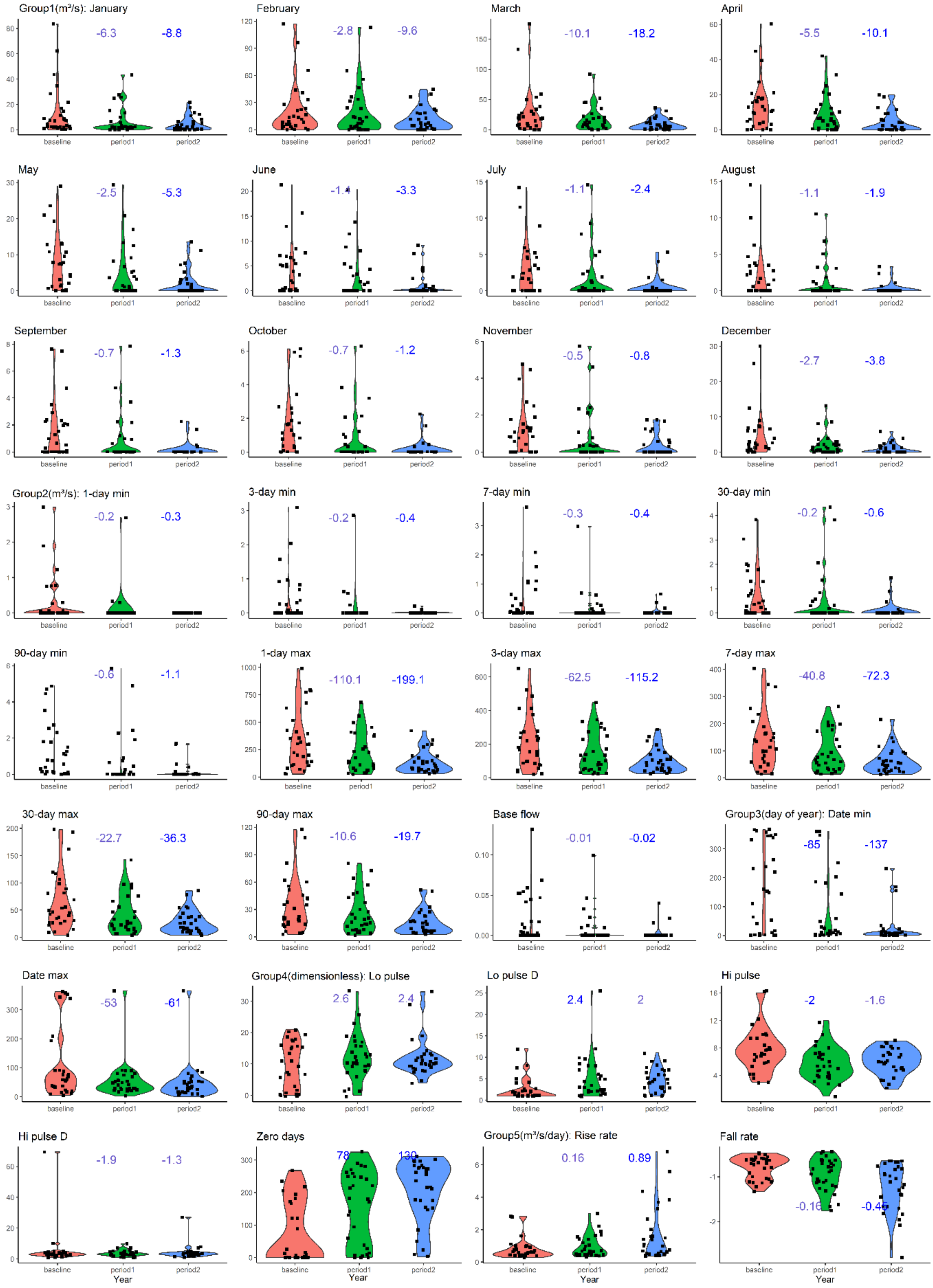
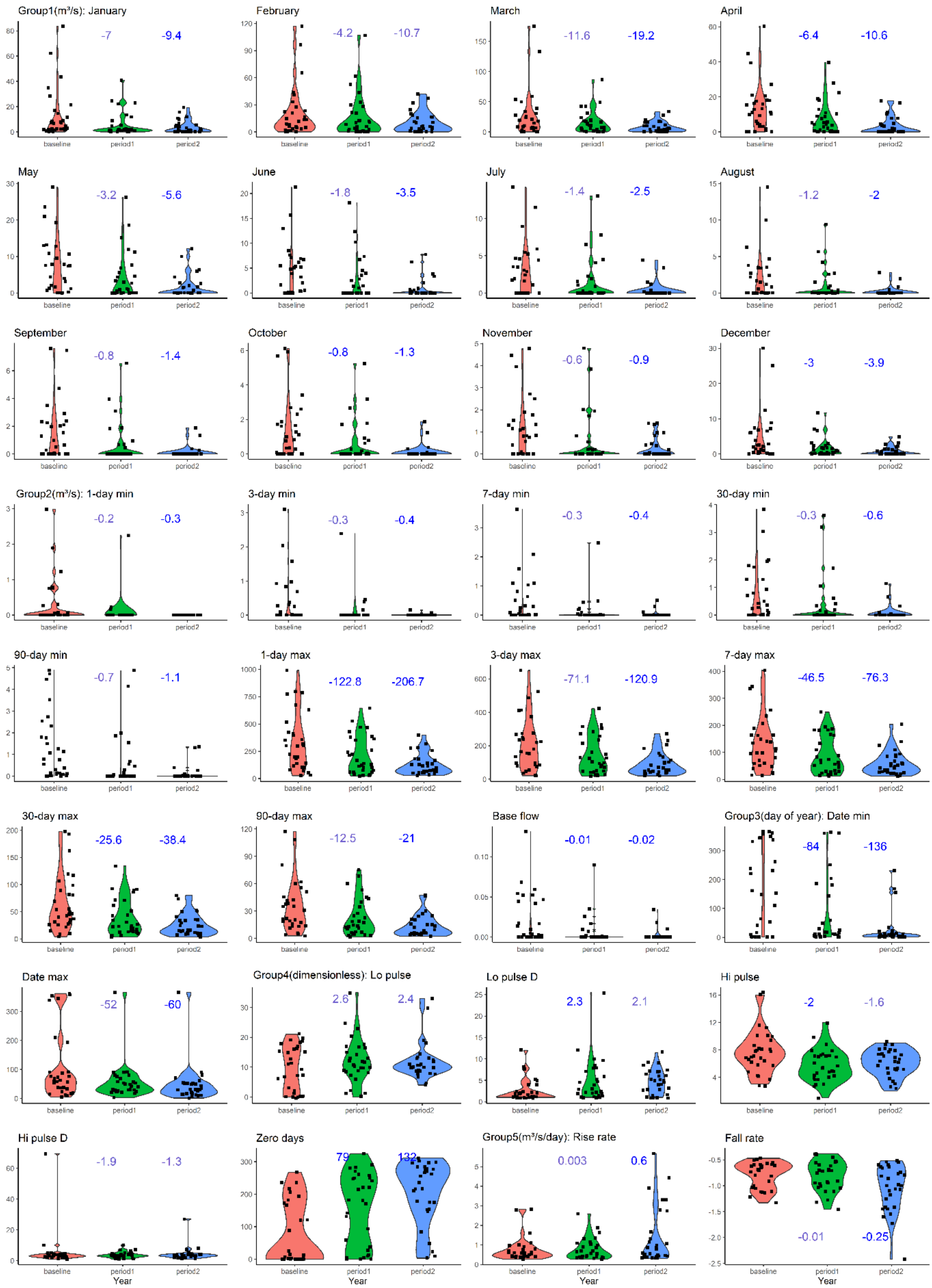


Figure A4 Alteration of 32 IHA (Indicators of Hydrologic Alteration) under three water use system scenarios in the future: No-WUS: the water use systems are not considered, Constant-WUS: the number of water use systems in the basin remain unaltered in the future, and Projected-WUS: the number of water use systems increase linearly with population growth. The red horizontal dashed line shows the median for the model setup period. The black horizontal lines represent the low and high-threshold of RVA (The Range of Variability Approach). The number indicates RVA deviation (%) in light blue and dark blue respectively for insignificant and significant changes.

i)No-WUS Scenario



ii)Constant-WUS Scenario



iii)Projected-WUS Scenario

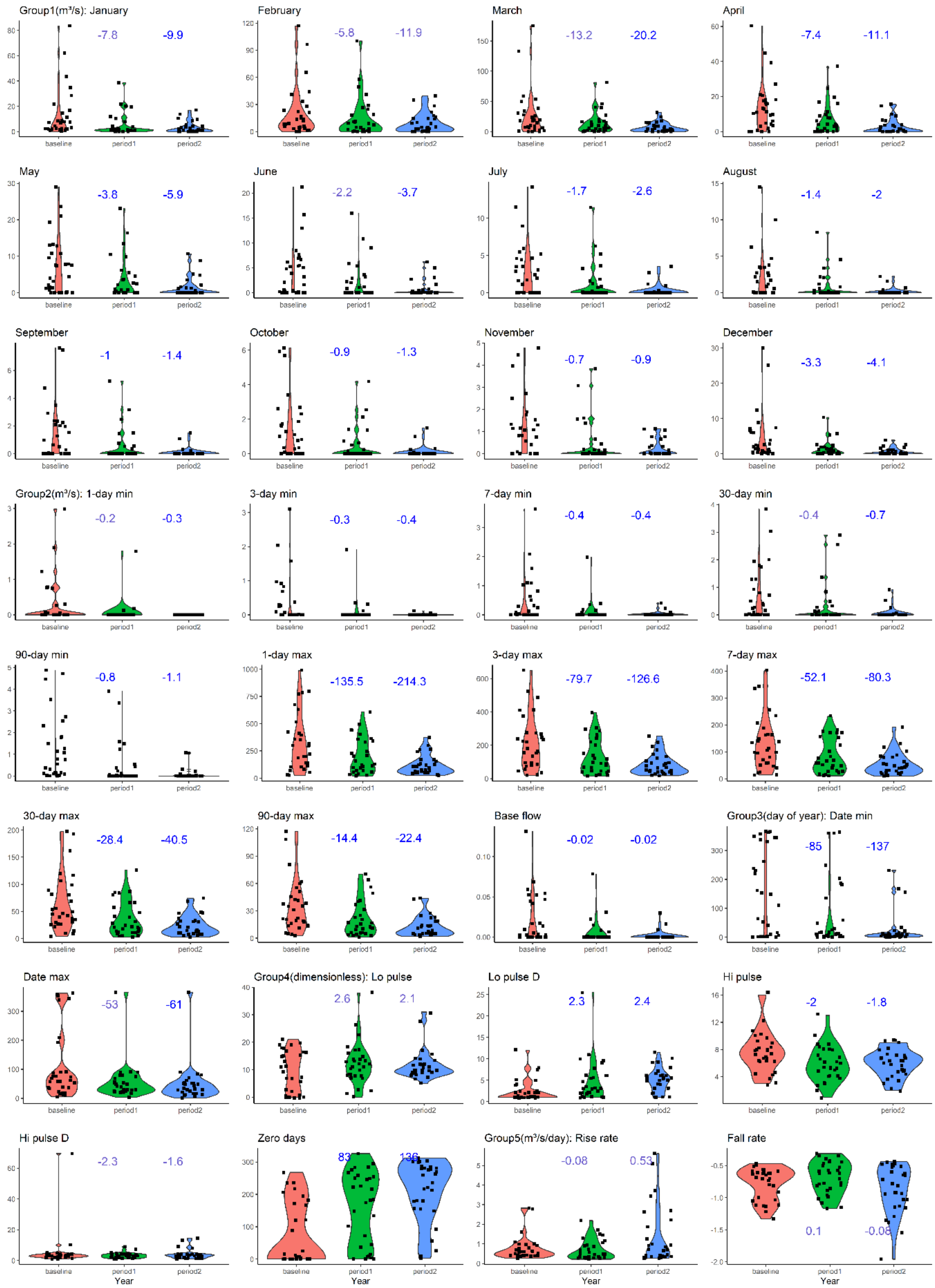


Figure A5 Distribution of annual values for each indicator under three water use system scenarios in the future: No-WUS: the water use systems are not considered, Constant-WUS: the number of water use systems in the basin remain unaltered in the future, and Projected-WUS: the number of water use systems increase linearly with population growth. Each single dot represents the value calculated for a specific indictor e.g., month January, in a year. Absolute changes are highlighted in light and dark blue respectively for insignificant and significant changes.

Declaration

I, Nariman Mahmoodi, hereby declare that the dissertation submitted, entitled “Assessing the integrated water resources development potential of Wadi systems in Iran and their vulnerability to climate change” was written independently by me. The content and design of this thesis, apart from the supervisor’s guidance, is my own work. The thesis has not been submitted either partially or wholly as a part of a doctoral degree to another examining body and is my first and only doctoral procedure. Chapter 2 and 3 of the thesis have been published in peer-reviewed journals and chapter 4 is currently under review. This work has been prepared respecting the Rules of Good Scientific Practice of the German Research Foundation. I have not been deprived of an academic degree.

Kiel, June-2021

Nariman Mahmoodi