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

Nariman Mahmoodi, Paul D. Wagner, Jens Kiesel and Nicola Fohrer

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 Halliroid 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.
INTRODUCTION

Changes in precipitation and the average surface temperature, that have 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 change on streamflow conditions has been revealed in different parts of the world (Saharia & 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 & 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 & 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. 2011) is a modeling tool for simulating streamflow and other hydrological variables at catchment scale (Praskievicz & Chang 2009) and is frequently used in climate change studies (e.g. Wagner et al. 2015; Wang et al. 2016; Kiesel et al. 2019). In Iran, although few studies are carried out using different hydrological models (Zarghami et al. 2014, 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 (Ashraf Vaghefi et al. 2014). 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 & 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. 2016; 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.

MATERIALS AND METHODS

Study area

The Halilrood Basin is located in Kerman Province, Iran. It has an area of 7,224 km² (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

Figure 1 | Map of the Halilrood Basin with hydrometric and climate stations.
high (more than 2,800 mm·y$^{-1}$) (Abbasi et al. 2019). The maximum and minimum annual average discharge were 33 m$^3$/s in 1995 and 0.71 m$^3$/s in 2007 respectively during the period 1993–2009. Mean annual temperature averaged over the basin amounts to 13 °C 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 2,039 to 2,569 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 1,391–4,359 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 v1.2, 2008), which are classified into soil hydrologic group C with slow infiltration rate and high runoff potential.

**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 has been increasing constantly since 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.

**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 & 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 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 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 1).

**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 & 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 & Seibert 2013). Therefore, to cope with the considerable deviation from the observed data shown in Table 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 & 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. 2015). The climate models corrected with LS and DM are henceforth referred to as LS-M and DM-M, respectively. Although using bias correction methods leads to a better agreement between simulated data and observations, it does not provide a satisfactory physical explanation (Ehret et al. 2015). 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 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 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).

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

*Eliminated regional climate models.

17 3 2 102 66
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).

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).

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 method (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).

RESULTS

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 °C (RCP4.5) and 3.9 and 10.3 °C (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 °C for RCP4.5 and ~2 °C 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 2.8–4.4 °C for RCP4.5 and of around 2.4–3.4 °C for RCP8.5. The end of century period indicates a median increase of around 2.8–4 °C for RCP4.5 and of around 4–7.1 °C 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.

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 2 and 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 are predicted medians 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.

Projected bias-corrected monthly precipitation vs. mean monthly observation is shown in Figure 3. Precipitation changes are of primary importance regarding the hydrologic assessment. The main precipitation events occur in winter 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.

Impacts on streamflow

The results from the SWAT model simulations in comparison with monthly mean observed streamflow (1993–2009) are illustrated in Figure 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). 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 rainfall intensity have been determined for both future periods and baseline (Figure 5). The number of rainy days during winter 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 rainfall intensities are expected to increase in the winter season, leading to higher runoff ratios and therefore streamflow values.
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 6(a)–6(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 6(e)–6(h)), high: percent flow exceedance between 5 and 20% (Figure 6(i)–6(l)), middle: percent flow exceedance between 20 and 70% (Figure 6(m)–6(p)), low: percent flow exceedance between 70 and 95% (Figure 6(q)–6(t)) and very low flow: percent flow exceedance between 95 and 100% (Figure 6(u)–6(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 respectively under RCP4.5 (Figure 6(f)) and RCP8.5 (Figure 6(h)). Hence, the wide range implies that extreme values like floods and droughts are also to be expected in the Hallirrood 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 6(e), 6(i), 6(m), 6(q), 6(u), 6(g), 6(k), 6(o), 6(s), and 6(w)) and under RCP4.5 at the end of the century (Figure 6(h), 6(l), 6(p), 6(t), and 6(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 6(f), 6(j), 6(n), 6(r), and 6(y)). 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 6(e)–6(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 6(q) and 6(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 (5% of time flow exceeded) under emission scenario RCP8.5 (Figure 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). The maximum and minimum estimated for low and very low flows nearly range from 0–30 and 20 m$^3$/s respectively under both RCPs (Figure 6(q)–6(x)). The comparison in low flow segments shows that the median curves remain almost unaltered (Figure 6(q)–6(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 6(u)–6(x)) because of the negligible changes in mean monthly streamflow during dry seasons in the future scenarios (Figure 4).

**Hydrological components**

Figure 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 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 counterbalances 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 75 and 56% reduction respectively for DM and LS (Figure 7(g)). The results of the historical simulation indicate 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 7(b)). Therefore, LATQ
Figure 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. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2020.098.
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 7(b), 7(d), 7(f), and 7(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 7(b), 7(d), 7(h), and 7(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 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 7(g)). The simulated ET is generally similar for LS, DM and raw models, while there are a few differences, especially in Figure 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.

**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. (2013) 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, in particular, 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 & 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 in future, 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 is 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 & 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 & 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 ($\beta$)) into account and by controlling the occurrence distributions of precipitation and temperature (defining shape parameter of Gamma distribution ($\alpha$)). 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.
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.

ACKNOWLEDGEMENTS

The financial support was provided for Nariman Mahmoodi as a scholarship holder by the German Academic Exchange Service (DAAD), Germany. JK acknowledges funding through the ‘GLANCE’ project (Global change effects in river ecosystems; 01LN1320A) supported by the German Federal Ministry of Education and Research (BMBF). We are sincerely grateful to Iran Water Resource Management Company (IWPCO) and Iran Metrological Organization (IRIMO) for providing the data.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


ESA 2010 *GlobeCover 2009* (Global Land Cover Map). Version 2.3, 300 m resolution. Available from: www.esa.int/ESA.


Mahmoodi, N., Kiesel, J., Wagner, D. P. & Fohrer, N. 2020 Integrating water use systems and soil and water
conservation measures into a hydrological model of an Iran Wadi system. *J. Arid Land.* **12** (4), 545–560.


In *Paper Presented at the Proceedings of the 18th World IMACS/MODSIM Congress*, Cairns, Australia.


First received 20 April 2020; accepted in revised form 20 August 2020. Available online 13 October 2020.