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Prediction of Climate Change Impacts on Groundwater Storage by Analysis and Modeling of Hydrograph Recession Curves: Application to the Bar Watershed, Iran

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ABSTRACT: The term climate change denotes any long-term and often irreversible changes in weather conditions occurring on the long time-scale that may range from decades to thousands of years. There are different factors causing climate change and there have been numerous debates about them in recent decades, however, there is now the unequivocal consensus that its main cause is the increase in anthropogenic greenhouse gases. Climate change has strong impacts on the various components of the hydrological cycle, like runoff and groundwater resources. The aim of this study is to investigate climate change impacts on the groundwater stored above the discharge level by using groundwater depletion analysis in the Bar Watershed, Iran. To that avail, two of the GCM-models used in the various analyses of the IPCC, HADCM3 and CGCM, have been used in conjunction with the LARS- WG downscaling method to project the regional climate in the study regions under different future SRES- emission scenarios. The results show that for SRES A2 the HADCM3/LARS-WG - predicted mean annual maximum and minimum temperatures will be increased equally by 1.1, 3.2 and 4.6 °C and precipitation will be decreased by 16.4, 17.6 and 31.4 % during the projected periods 2010- 2039, 2040- 2069 and 2070- 2099, respectively, when compared to the past 1970-2010 reference period. In the subsequent step these 21th -century climate projection are used as input drivers in the rainfall- runoff model IHACRAS model to predict the future discharge of the Bar river. Annual future hydrographs are constructed which indicate that, compared to the 1970- 2010 reference period, the Bar river streamflow will be abated by 9, 44 and 66 %, during the projected periods 2010-2039, 2040- 2069 and 2070- 2099, respectively. Finally, using annual hydrograph recession curve analyses, the future climate change impacts on the groundwater reserve above the discharge level are predicted. The results show that the groundwater storage will drop by 36.9, 52 and 61%, for the three named projected periods, respectively.

Keywords: Climate change, Recession curve analysis, Groundwater reserve, Bar watershed, Iran

1 INTRODUCTION

Water is indispensable for life, but its availability at a sustainable quality and quantity is threatened by many factors, of which climate plays a leading role. The Intergovernmental Panel on Climate Change (IPCC) defines climate as “the average weather in terms of the mean and its variability over a certain time-span and a certain area”, and a statistically significant variation of the mean state of the climate or of its variability lasting for decades or longer, is referred to as climate change. Nowadays, evidence is mounting that we are in a period of climate change brought about by increasing atmospheric concentrations of greenhouse gases, namely, carbon dioxide whose levels have continually increased since the 1950s. The continuation of this phenomenon may significantly alter global and local climate characteristics, including temperature and precipitation. Climate change can have profound effects on the hydrologic cycle through changes in precipitation, evapotranspiration, soil moisture, etc., all of which intractably connected to changing, i.e. rising temperatures. Thus, the hydrologic cycle will be intensified, leading to more evaporation and more precipitation. However, the extra precipitation will be unequally distributed around the globe and some parts of the world may even see significant reductions in precipitation or major alterations in the timing of wet and dry seasons (IPCC, 2007). Information on the local or regional im-

pacts of climate change on hydrological processes and water resources are thus becoming more and more important (Kumar, 2012). Observational data and climate predictions provide abundant evidence that freshwater resources (both surface- and groundwater) are vulnerable and may be strongly affected by climate change, with wide-ranging consequences for society and ecosystems (Bates *et al.*, 2008).

The challenges of understanding climate-change effects on groundwater are unprecedented, because climate change may affect hydrogeological processes and groundwater resources directly and indirectly, in ways that have not been explored sufficiently (Dettinger and Earman, 2007, Koch, 2008). The IPCC (2007) stated that a lack of necessary data has made it impossible so far to determine the effects of climate change on the magnitude and direction of groundwater change (Kundzewicz *et al.*, 2007). According to Jorgensen and Yasin al-Tikiriti (2003) the effects of historical climate change on groundwater resources, which once supported irrigation and economic development in parts of the Middle East, is likely the primary cause of the declining of several cultures there during the Stone Age.

Today, climate change may account for approximately 20% of projected increases in water scarcity globally (Sophocleous, 2004). As groundwater plays an increasingly important role in regional water supply, there is an urgent need to evaluate and understand climatic variability over the long term to better manage future groundwater resources, while taking into consideration the increasing stresses on those resources from population growth and industrial, agricultural, and ecological needs (Warner, 2007).

Up to now, most studies of the assessment and prediction of climate change impacts on groundwater resources are based on recharge estimations under many ensemble of climate projections. In this case, since, climate change directly impacts the recharge and, indirectly, the groundwater head, the availability of sufficient piezometers is a prerequisite for carrying out such a research, but in many less developed countries, widespread measurements of the groundwater levels have not been financially and technically possible. Therefore, in the present research, a new technique is introduced to assess and predict climate change impacts on groundwater storage which consists in the use of historical stream flow records, i.e. data which is usually available for most catchments, even in a developing country like Iran. The other noteworthy point of this study is that with this approach impacts of climate change on both surface- and sub-surface hydrology on the watershed scale are investigated. More specifically, hydrograph recession curves generated for the Bar river, Iran, during the past (observed) reference period 1970- 2010 are compared with those simulated with the rainfall- runoff model IHACRAS driven with future downscaled climate change predictions of the HadCM3- and/or CGCM- global climate models, in order to analyze the impacts of climate change on the future groundwater storage in that basin.

2 STUDY REGION

The study region is the Bar watershed, located in northeastern Iran, southwest of the Binalood Mountains, between $36^{\circ} 27'$ to $36^{\circ} 36'$ N latitude and $58^{\circ} 40'$ to $58^{\circ} 49'$ E longitude (Fig. 1). The basin covers a surface area of 113.88 km^2 . Its landform is a typically mountainous landscape with an average elevation of 2226 m above sea level (MSL) and an average slope gradient of 4.2 %.

The climate of the watershed is of continental dry nature, with strong temperature variations between summer and winter and a mean annual precipitation of 330.4 mm, wherefore 80% of this amount falls in the fall and winter seasons (Tavasoli *et al.*, 2010).

3 MATERIAL AND METHODS

3.1 GCM-downscaled climate change predictions for the study region

Climate models are numerical tools for studying global, regional or local climate and its variability due to changing conditions on the Earth. They come in different forms, ranging from simple climate models (SCMs) of the energy-balance type to Earth-system models of intermediate complexity (EMICs) to comprehensive three-dimensional (atmosphere–ocean) general circulation models or global climate models



Figure 1. Geographical location of the Bar watershed on the map of Iran.

(GCMs). GCMs are nowadays the most sophisticated tools available for the simulation of the current global climate and future climate scenario projections. Their physical and mathematical formulation usually takes into account the behavior and interaction of the different compartments of the climate system in the biosphere, hydrosphere, cryosphere, atmosphere and geosphere.

Since the development of the very early GCMs in the 1960s and 1970s, there has been considerable growth in the knowledge of climate processes and in the complexity of climate research. Over the last decades, not only has the spatial resolution of GCMs increased, but the physical processes incorporated into these models have been refined from simple precipitation rain and CO₂- emissions to complex biogeochemical (including water vapor) feedbacks (Le Treut *et al.*, 2007). Although such broad generalizations of projected climate change may be useful for comparing responses at a global scale, GCMs cannot provide information at scales finer than their computational grid (typically of the order of 100-200 km), and processes at these unresolved scales are important for local climate impact studies. Thus, the usefulness of the raw output from a GCM for climate change assessment in specific regions is limited.

To bridge the spatial resolution gaps for GCMs to produce realistic local climate projections, downscaling techniques are usually applied to the GCM output. Different dynamic and statistical models have been developed in recent decades to downscale GCM outputs. The downscaling method that used in this study is the statistical LARS-WG model (Semenov *et al.*, 1998) that uses the lengths of wet and dry day series, daily precipitation and daily solar radiation as inputs to generate stochastic realizations of the climate time series that represent the basic distributional properties of the observed or GCM-simulated - here the HadCM3- GCM has been used - time series in a reference (baseline) period. The similarity of these stochastic realizations with the reference series is then tested by various statistical tests, namely, the *t*-test for the monthly means and Chi-squared- and F-test for the distributional properties for solar radiation, precipitation, minimum and maximum temperature.

Based on the downscaled HadCM3/LARS-WG climate for the observed reference period (1970-2010), 21th- century downscaled climate predictions for the study region using under SRES- (emission) scenarios A2 and B2 in the HadCM3 and A1 in the CGCM are carried out.

3.2 Streamflow modeling using the IHACRES- watershed model

The selection of an appropriate hydrological model depends on the objective and the data available. As more complex questions are asked, more complex models are needed. However, with increasing model complexity comes the cost of increasing uncertainty in the model predictions. The IHACRES model (Jakeman and Hornberger, 1993) is a hybrid conceptual-metric model, using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models, while at the same time attempting to represent more details of the internal processes than is possible for a metric model alone.

Figure 2 shows the generic structure of the IHACRES model. It contains a non-linear loss module which converts rainfall into effective rainfall (that portion of the rainfall that directly contributes to the stream hydrograph, i.e. after subtraction of interception, infiltration and surface storage) and a linear

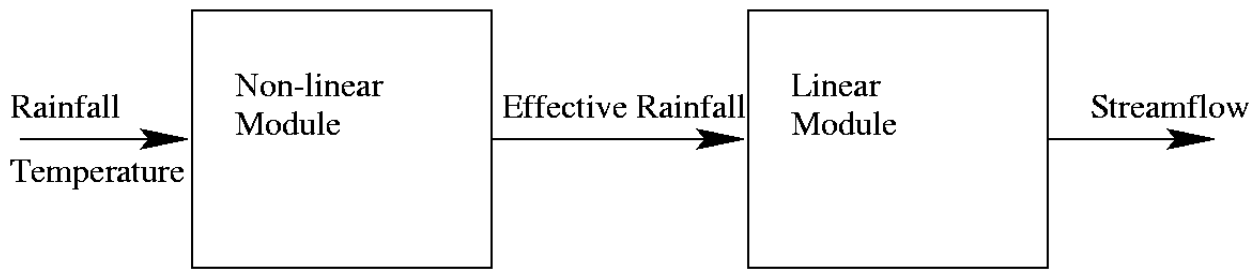


Figure 2. Generic structure of the IHACRES model, showing the conversion rainfall to streamflow.

module which transfers the effective rainfall to stream discharge. Further modules can be added, including one that allows the computation of groundwater recharge. The inclusion of a range of non-linear loss modules within IHACRES increases its flexibility to evaluate the effects of climate- and/or land use changes. The linear module routes effective rainfall to a stream through any configuration of stores in parallel and/or in series. Typically either one store only, representing ephemeral streams, or two in parallel, allowing baseflow as well as quick flow to be represented, are used. Only rarely does a more complex configuration than this improve the fit to discharge measurements (Jakeman and Hornberger, 1993).

In this study, a 41- year long record of daily rainfall and temperature were imported into the IHACRES- model wherefore 34 years were used for the calibration and the remainder (7 years) for the validation of the Bar river streamflow. Finally, the downscaled future climate projections under different SRES are incorporated into the verified model, to predict future streamflow changes.

3.3 Calculation of groundwater storage from hydrograph recession curves

Recession analysis of the falling limb – often after a major rain event - of the hydrograph of a stream or a spring that is in hydraulic connection with an aquifer is known as a simple but reliable technique to determine relevant aquifer parameters, namely groundwater storage (Brutsaert and Niebert, 1977; Kresic, and Stevanovic, 2010). Recession analysis is based on an appropriate mathematical relationship between spring discharge Q and time t , which then allows to predict the discharge rate after a given period without precipitation and, so to calculate the volume of discharged water. However, ideal recession conditions require a long period of several months without precipitation that is rare in moderate, humid climates. Consequently, frequent precipitation events can cause various disturbances in the recession curve that may not be removed unambiguously during the analysis. It is therefore desirable to analyze as many recession curves from different years as possible. Larger samples then allow for a derivation of an average recession curve as well as the envelope of the minima which enables a more accurate quantification of the expected long-term minimum discharge (Tallaksen, 1995).

Two well-known mathematical formulas that describe the discharge for the falling limb of a hydrograph and the base flow (see Fig. 2) are that of Boussinesq (1904)

$$Q(t) = Q_0 / [1 + \alpha(t - t_0)]^2 \quad (1)$$

and that of Maillet (1905) (more commonly used)

$$Q(t) = Q_0 e^{-\alpha(t-t_0)} \quad (2)$$

where t = time since the beginning of the recession for which the flow rate is calculated and t_0 = time at the beginning of the recession, usually (but not necessarily) set equal to zero, for which $Q = Q_0$ [L^3/T] and α [$1/T$] represents the recession coefficient, which depends on the aquifer's transmissivity and specific yield (Szilagyi *et al.*, 1998). On a semilog-diagram the Maillet Eq. defines a straight line with slope α :

$$\log Q_t = \log Q_0 - 0.4343 * \alpha * (t - t_0) \quad (3)$$

from which α is easily computed (the factor 0.4343 enters when Q is expressed in m^3/s and time in days).

Based on the sketch of Fig. 3, the groundwater storage is estimated as:

$$V = V_1 + V_2 + \dots + V_n = [Q_1 / \alpha_1 + Q_2 / \alpha_2 + Q_n / \alpha_n] \quad (4)$$

All annual hydrographs are then inspected to extract suitable recession curves for both the past, reference period and the future (up to year 2100) period - with hydrographs for the latter being predicted by the IHACRES model with input from the downscaled climate predictions -. Then, using Eqs. 2 and 4, the annual groundwater storages in the Bar basin are estimated for the whole analysis period 1970-2100.

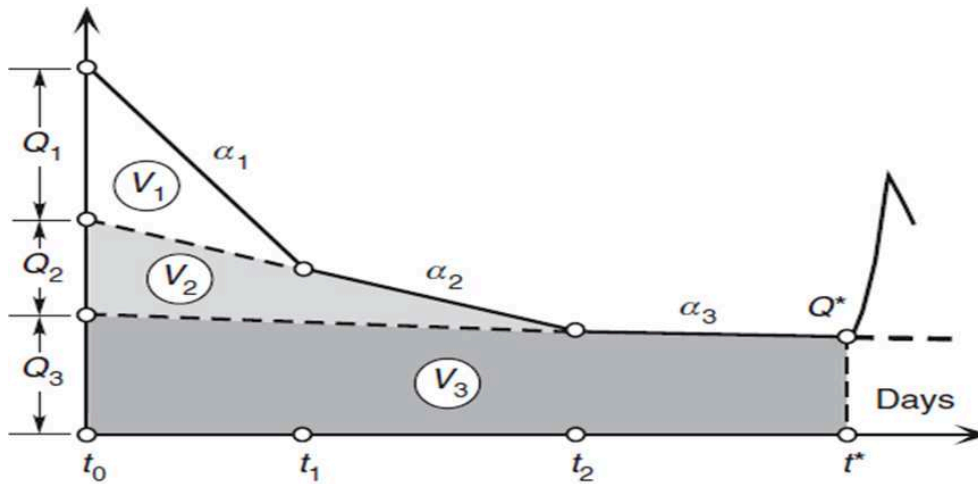


Figure 3. Schematic recession curve showing how to estimate groundwater storage.

4 RESULTS AND DISCUSSION

4.1 Trend analysis of observed hydro-climate predictions

To get an idea on possible recent hydro-climatic changes in the study region, a trend analysis of several observed hydro-climatic variables, i.e. river flow, rainfall, max and min temperatures, and sunlight hours for the reference period has been carried as a first step of the analysis, using the Mann-Kendall test (Hirsch *et al.*, 1982) which tests the hypothesis H_0 : no trend in the time series against the alternative hypothesis H_1 : there is a trend. The results are, together with other relevant statistical parameters of these time series are listed in Table 1. Based on the p -values in the first column of the table, the H_0 – hypothesis must be rejected, i.e. there is a significant trend (on the $\alpha= 0.05$ significance level, i.e. $p < \alpha$) for stream-flow and hours of sunlight, whereas rainfall and, particularly, temperatures do not exhibit trends.

Table 1. Analysis of trends in observed (1970- 2010) hydro- climate variables and summary of statistics

Variable	p-value	SD	Ave.	Max	Min
River flow (m3/sec)	0.002*	0.32	0.62	1.7	0.12
Rainfall (mm)	0.051	108	319	505	150
Max Temp. (oC)	0.73	1.3	39	42.2	36.7
Min Temp. (oC)	0.94	3.2	-15.2	-23.6	-10.4
Sunlight (hours/yr)	0.005*	226	2850	3196	2130

*Hypothesis of no trend rejected

4.2 Comparison of observed and downscaled climate series in the reference period 1970-2000

In the subsequent step downscaled global climate model “predictions” for temperature and precipitation are compared with observed data for the past baseline period (1970-2010). Note that this reference period extends to - unlike to that used in most climate model predictions , where it is 1970-2000 (IPCC, 2007) - to a “future” year 2010, i.e. covers already 10 years of “future” climate prediction, where the SRES- scenario of a climate model starts to kick in and may become discernable.

Table 2 summarizes the results using various performance indicators, i.e. PBIAS, MAE, NS, R2 and MAE, used commonly in climate and hydrological modeling studies (see Moriasi *et al.*, 2007, for definitions), employing SRES A2 , A1B and B2, in decreasing order of its anticipated future climate impact, in the GCMs. More specifically, for A2 and B2 the HadCM3-, and for A1B the CGCM- model, in conjunction with LARS-WG downscaling, turned out to be the best combinations and are presented here.

Table 2. Comparison of observed and downscaled GCM predictions for the reference period (1970- 2010)

Precipitation			Temperature					SRES/ GCM			
PBIAS	MAE	NS	R ²	RMSE	PBIAS	MAE	NS	R ²	RMSE		
-2.3	0.23	-0.32	0.01	4.11	0.78	0.1	0.94	0.82	4.20	B2	HadCM3
9.44	0.83	0.01	0.02	3.56	-0.24	0.33	0.99	0.84	4.04	A2	
-0.44	0.35	-0.45	0.09	4.13	-0.51	0.06	0.79	0.73	4.52	A1B	CGCM

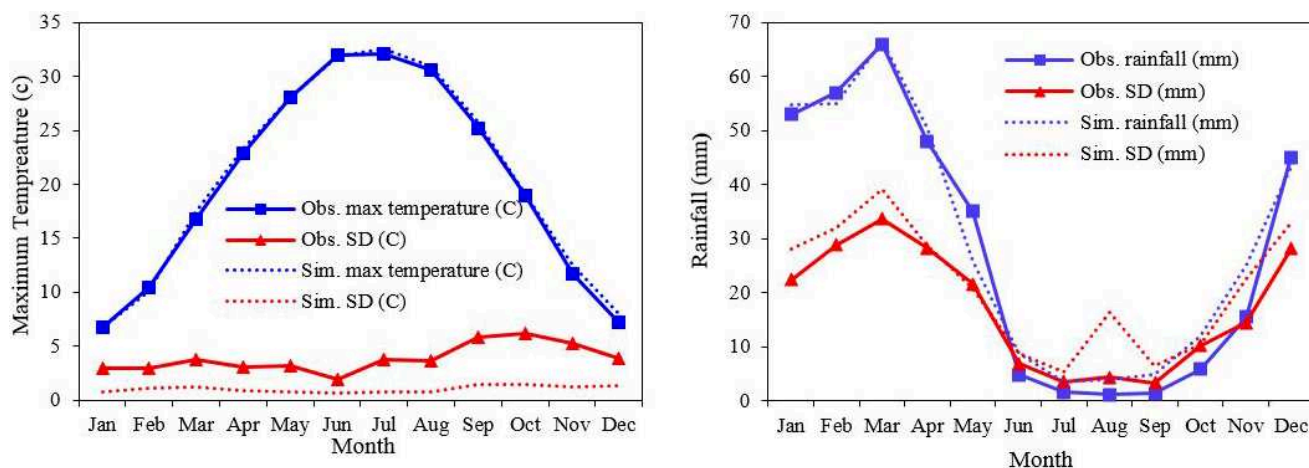


Figure 4. Observed and LARS- WG downscaled monthly rainfall, min. and max. temperatures for the reference period.

From Table 2 it is inferred that, whereas the observed temperatures in the reference period are well predicted by the GCM/LARS-WG downscaling combination, as indicated by the high NS, R² and a low RMSE, this is not the case for the precipitation. In fact, this shows also in the standard deviations (SD) of the simulated time series which are underestimated for temperature and overestimated for the rainfall. This is particularly noticeable from Fig. 4 which shows the observed and simulated variables on a monthly basis. Thus the SDs of the simulated rainfall during the summer months are higher than the rainfall itself, i.e. the summer rainfall is not well predicted. However, as the summer precipitation in the Bar watershed makes up only 2% of the annual sum, this low prediction accuracy of the LARS-WG model for this season should not significantly affect the streamflow modeling and the subsequent recession analysis.

Based on the results of Table 2, the most extreme SRES- scenario A2 will be used in the subsequent GCM/LARS-WG predictions of the 21th –century climate and its effect on the groundwater reserves.+

4.3 Predictions of the 21th –century climate

Fig. 5 shows the average monthly 21th- century LARS-WG downscaled predictions of maximum temperature and rainfall with the HadCM3-model under scenario A2 for the three periods 2010-2039, 2040- 2069 and 2070- 2099, relative to those of the 1970-2010 reference period. In agreement with IPCC (2007) maximum- (and minimum, not shown here) temperatures can be seen to dramatically increase and rainfall to decrease, namely, in the first six months of future years, whereas at the end of a year, in November and December, a slight increase of the precipitation is to be anticipated. Our findings are more extreme than those of Etemadi *et al* (2012) obtained for southeastern Iran where the receiving precipitation is attributed to other hydro-meteorological fronts, namely from the Mediterranean and the Persian Gulf, while the major incoming rainfall in the present Bar watershed originates in Siberia.

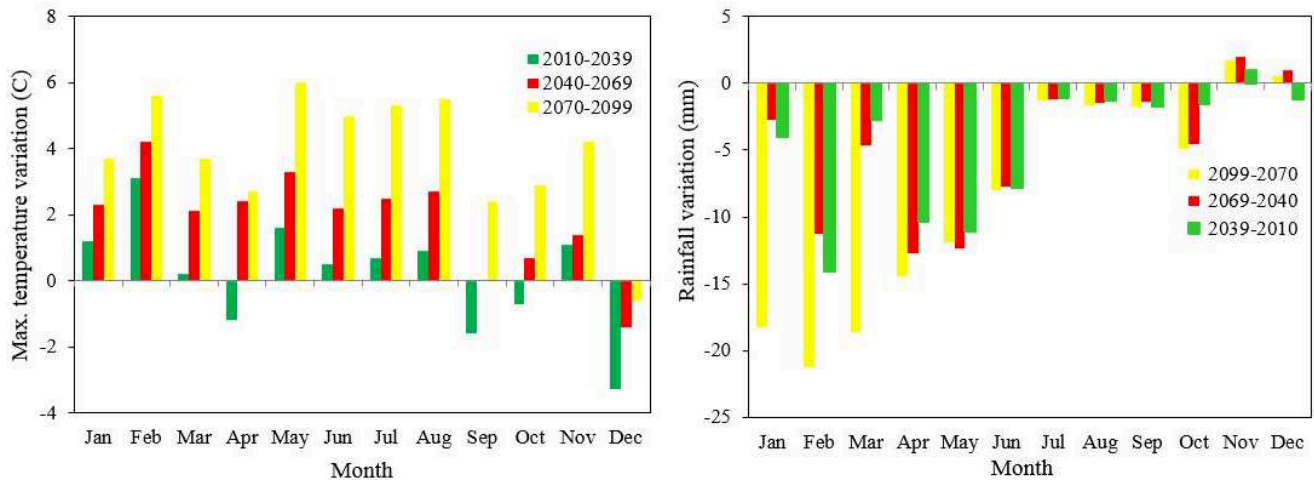


Figure 5. Relative variations - compared with the 1970-2010 reference period - of maximum temperature (left) and rainfall (right) projected by the HadCM3-model under scenario A2 for the future periods 2010-2039, 2040- 2069 and 2070-2099.

4.4 IHACRES- streamflow modeling for the 1970-2010 reference period.

Using the climate forcing of the 1970-2010 reference period the Bar river streamflow have been simulated by the IHACRES model, wherefore the daily data of rainfall and temperature and streamflow during 1970-2004 have been used for calibration and the remaining seven years for validation of the model. From Fig. 6 it is clear that, despite its conceptual simplicity, IHACRES is able to simulate the streamflow with acceptable accuracy, as coefficients of determination R^2 of 0.75 and 0.60 (and corresponding values for the other statistical measures indicated in Table 1) have been obtained for the calibration- and validation periods, respectively.

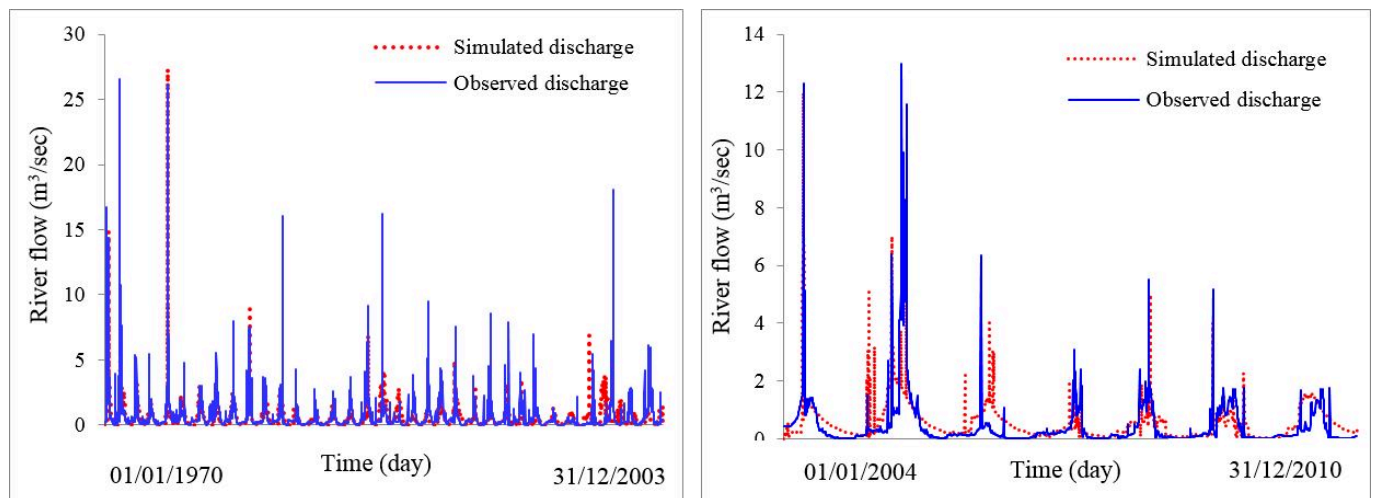


Figure 6. IHACRES- calibrated (left) and validated (right) streamflow of the Bar river for the 1970-2010 reference period.

4.5 Streamflow recession analysis and groundwater storage

Employing the GCM/LARS-WG projected climate variables for the periods 2010- 2039, 2040- 2069 and 2070- 2099 in the calibrated IHACRES- model, future Bar- streamflow during these periods has been predicted. The results are shown in the left panel of Fig. 7, from which one can see that the discharge of that river will be decreased by 50% in the second half of the 21th - century. Moreover, this reduction is more pronounced for the peak flows, such that in the period 2070- 2099 , the former will be lower by up to 1.5 m³/sec. Above all, compared to the baseline period, the volume of the flow will be abated by 9, 44 and 66 % during the aforementioned periods, respectively. As a result, the current stream regime, which is perennial, will be shifted to intermittent during the future months of July, August, September and October after year 2040. This is clearly a consequence of reduced future rainfall, rising temperature and, more importantly, an earlier seasonal spring snow melting which nowadays still sustains the river flow during the dry summer season. These findings are consistent with those of Jamali *et al.* (2012).

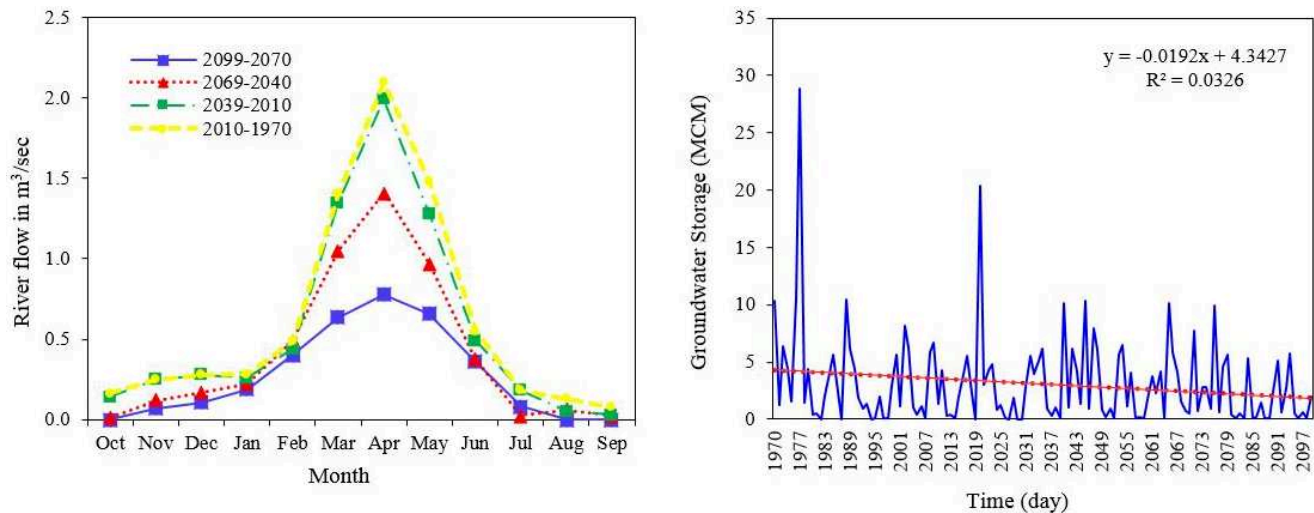


Figure 7. IHACRES-simulated monthly Bar river streamflow (left panel) and annual recession-computed groundwater storage (right panel) for the reference- and projected future periods.

Finally, recession curves for the observed and predicted Bar river hydrographs for each year of the 1970-2099 analysis period have been extracted and, using the Maillet recession model (Eqs. 2-4), the annual groundwater storages computed. These are shown in the right panel of Fig. 7. A linear regression line has been fitted to the storage values which, despite a low R^2 , has a consistent and statistically significant negative slope ($p < 0.05$), i.e. a systematic decreasing trend – which is also supported by a Mann-Kendall trend test ($p < 0.05$) (Hirsch *et al.*, 1982) - of the storage over the whole 21th-century is obtained, so that, compared with the 1970-2010 reference period, the former is reduced by 37, 52 and 61% for the time periods 2010-2039, 2040- 2069 and 2070- 2099, respectively.

5 CONCLUSIONS

There is a need to evaluate and understand climate variability over the long term to better plan and manage groundwater resources well into the future, while taking into the consideration the increasing stresses on those resources from population growth and industrial, agricultural, and ecological needs. To that regard, climate change impacts in the Bar watershed, Iran, have been analyzed with downscaled GCM predictions for the region. Using the predicted hydro-climatic variables in the IHACRES watershed model, past and future Bar streamflow has then been simulated and recession curves of the annual hydrographs analyzed. From this annual groundwater storages have been predicted. The results show that, unlike the hydro-climate variables, the groundwater reserves in the basin are – most likely due to a buffering effect of groundwater (Koch and Markovic, 2007) – less affected by the expected 21th- century climate change in the region. In conclusion, the present study indicates also that in areas where there is a lack of detailed groundwater information, recession analysis of streamflow records which are more readily available, is a viable tool for the assessment of climate change on the groundwater resources.

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