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Climate change model as a decision support tool for water resources management in northern Iraq: a case study of Greater Zab River

Y. Osman, N. Al-Ansari and M. Abdellatif

ABSTRACT

The northern region of Iraq heavily depends on rivers, such as the Greater Zab, for water supply and irrigation. Thus, river water management in light of future climate change is of paramount importance in the region. In this study, daily rainfall and temperature obtained from the Greater Zab catchment, for 1961–2008, were used in building rainfall and evapotranspiration models using LARS-WG and multiple linear regressions, respectively. A rainfall–runoff model, in the form of autoregressive model with exogenous factors, has been developed using observed flow, rainfall and evapotranspiration data. The calibrated rainfall–runoff model was subsequently used to investigate the impacts of climate change on the Greater Zab flows for the near (2011–2030), medium (2046–2065), and far (2080–2099) futures. Results from the impacts model showed that the catchment is projected to suffer a significant reduction in total annual flow in the far future; with more severe drop during the winter and spring seasons in the range of 25 to 65%. This would have serious ramifications for the current agricultural activities in the catchment. The results could be of significant benefits for water management planners in the catchment as they can be used in allocating water for different users in the catchment.

Key words | ARX (*p*), climate change, Greater Zab River, LARS-WG, rainfall–runoff model

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INTRODUCTION

Greenhouse gases contributed a global mean surface warming likely to be in the range of 0.5 °C to 1.3 °C over the period 1951 to 2010, with the contributions from other anthropogenic forcings, including the cooling effect of aerosols, likely to be in the range of −0.6 °C to 0.1 °C. The contribution from natural forcings is likely to be in the range of −0.1 °C to 0.1 °C, and from natural internal variability is likely to be in the range of −0.1 °C to 0.1 °C. Together these assessed contributions are consistent with the observed warming of approximately 0.6 °C to 0.7 °C over this period (IPCC 2013). Global surface temperature will continue to change by the end of the 21st century and is likely to exceed 1.5 °C relative to 1850 to 1900 for most climate model scenarios.

Unlike temperature, which has increased almost everywhere on the planet, precipitation has increased in some parts of the world and decreased in others (Archer & Rahmstorf 2010). Changes in precipitation and temperature lead to changes in runoff and water availability. Runoff is projected with high confidence to decrease by 10 to 30% over some dry regions, due to decreases in rainfall and higher rates of evapotranspiration (IPCC 2007). Precipitation has indeed decreased in Middle East countries which has caused problems of water shortage (Biswas

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1994; Roger & Lydon 1994; Al-Ansari 1998, 2013; Allan 2001), where at least 12 countries have acute water scarcity problems with less than 500 m^3 of renewable water resources per capita available (Barr *et al.* 2012; Cherfane & Kim 2012). The supply of water is essential to life, socioeconomic development, and political stability in this region. In 1985, UN Secretary General Boutros Boutrous-Ghali said that the next war in the Near East would not be about politics, but over water (Venter 2008). In view of this situation, a number of research works has been conducted on water scarcity in the region. Most of the work was based on future water demand which in turn was based on population growth rate and water projects in the region (Barton 2015; Osman 2015; Strategic Foresight Group 2015; Türkeş *et al.* 2015; Hydropolitic Academy 2016). In addition, the Middle East seems to be one of the areas in the world most vulnerable to the potential impacts of climate change (Bazzaz 1994; AFED 2009; Hamdy 2013; Yildiz 2015). Moreover, the Mediterranean has been identified as one of the hot spots of climate change (Giorgi 2006). Cudennec *et al.* (2007) have shown that the Mediterranean region is particularly sensitive to changes brought about by human pressure on hydrological processes. Collet *et al.* (2014) found that the annual water balance at a studied catchment scale showed that the decrease in runoff was due primarily to lower annual precipitation and increased AET. The seasonal analysis identified the causes of the annual hydrological changes at the catchment scale. The substantial decrease in winter precipitation (−45%) seems to explain most of the reduction in discharge at the catchment outlet. Moreover, the joint rise in summer temperature and summer withdrawals is the main factor explaining the decrease in low-flow period discharge (−50%). These changes in winter precipitation and summer temperatures were also observed in this region by Stahl *et al.* (2010). In South and East Asia, climate change will increase runoff, although these increases may not be very beneficial because they tend to occur during the wet season and so the excess water may not be available during the dry season when it is most needed (Arnell 2004). There are a great number of studies and investigations on climate change effects for water resources which have shown that regions with decreasing runoff (by 10 to 30%), and a rather strong agreement between climate models, include the Mediterranean, southern Africa, and western USA/northern Mexico (IPCC 2007).

Specifically, rivers in Iraq face a severe risk that has an effect on Iraqi water resources, and this risk mainly comes from global warming. Rainfall occurs between October and May with the highest precipitation levels between December and February reaching 1,000 mm in the north-eastern part of Iraq. The winters are cool and the coldest month is January, with temperatures ranging from 5 °C to 10 °C; summers are hot resulting in a high rate of evaporation in the southern plains (UNDP 2012). Daily temperatures can be very hot; on some days temperatures can reach easily 45 °C or more, especially in the Iraqi desert areas and this causes a danger of heat exhaustion. The IAU Report (2010) indicated that the water level in the Tigris and Euphrates – Iraq's main sources of surface water – have fallen to less than a third of normal capacity. The critical issue is that this trend is expected to continue in the future.

Despite all these problems, very little work has been done (Issa *et al.* 2014) to determine detailed future expectations of river flows in the region. In this paper, an attempt has been made to predict the future flow of one of the main tributaries of the River Tigris in Iraq. The objective is to investigate the impacts of climate change on future flows of the Greater Zab River and its implications on the water use in the catchment. It is believed that such work will help decision-makers to take prudent measures to minimize or overcome the water shortage problems in the studied catchment and perhaps the Middle East at large.

Estimation of the magnitude of future flows in a river catchment is always required for efficient design, planning, and management of projects that deal with conservation and utilization of water for various purposes. In order to accurately determine the quantity of surface runoff that takes place in any river catchment, it is necessary to understand the complex relationship between rainfall and runoff processes, which depends upon many geomorphological and climatic factors (Beven 2001). Thus, in the present paper, a rainfall–runoff model in the shape of AutoRegressive with eXogeneours factors was used. The model was developed using observed rainfall and evapotranspiration data for the purpose of calibration and projection of future river flow.

The paper is organized as follows. In the next section, a description of the catchment and data used are given. This is followed by a methodology section, in which all models used are described. Results and a discussion of the model applications and future impact follows, and finally, concluding remarks from the study are presented.

MATERIAL AND DATA

The major water resources in Iraq are the Tigris and the Euphrates rivers. The Greater Zab is a tributary of the Tigris River located in northern Iraq (Figure 1) between latitudes 36° N, 38° N and longitudes 43°18′ E, 44°18′ E. The river originates from the mountainous area in Turkey at an altitude of about 4,168 m a.m.s.l (ESCWA 2013) with 34.8% of this catchment being located in Turkey (Mohammed 1989; Al-Ansari & Knutsson 2011; Al-Ansari 2013; ESCWA 2013). The catchment area of the Greater Zab and its tributaries is 26,473 km^2. Most of the precipitation in the river basin occurs in winter and spring with annual rainfall ranging from 350 to 1,000 mm. A typical distribution for the precipitation over a year in the catchment is as follows: 48.9% in winter as snowfall, 37.5% in spring, 12.9% in autumn, and 0.57% in summer (Abdulla & Al-Badranih 2000). The discharge of this river is about 70% relative to that of the River Tigris before they join together about 49 km south of Mosul towards Sharkat city.

Climatological data (rainfall, evaporation, maximum and minimum temperature) were obtained for Salahaddin weather station in the Greater Zab catchment from the Ministry of Irrigation for the period 1961–2013. Daily river discharge data measured at Eski-Kelek gauging station in the Greater Zab for the period 1961–2013 were used, together with the climatological data, to build to the rainfall–runoff model of the river.

METHODOLOGY

The usual methodology followed to study impacts of climate change on river flow is first, establish a relationship (rainfall–runoff model) between the causes of flow (rainfall and evapotranspiration) and the effect (flows) for a baseline condition, assuming that this relationship is constant in the future. Second, future forecasts of the causes are obtained by means of models and then used to obtain the corresponding future effects (flows) using the established relationship. In the present research two separate models have been used to estimate each of the future rainfall and evapotranspiration in the catchment, and a third model was developed to relate them to the river flow.

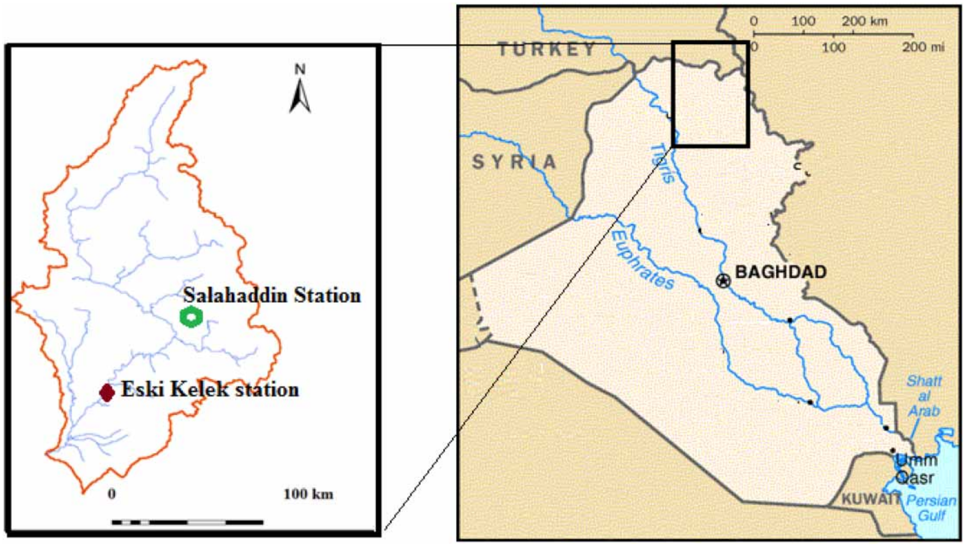

Figure 1 | Location of studied catchment.

Rainfall and temperature downscaling model

The downscale model used in this study for future projections is LARS-WG (version 5.5). LARS-WG model is one of the most popular stochastic weather generators, which is useful for producing daily precipitation, radiation, and maximum and minimum daily temperatures at a station under the present and future climate conditions. The first version of LARS-WG was created as a tool for statistical downscaling method in Budapest in 1990 (Racsko *et al.* 1991; Semenov & Barrow 2002). A study by Semenov (2008) has tested LARS-WG for different sites across the world, including one site in New Zealand's South Island, and has shown its ability to model rainfall extremes with reasonable skill. The LARS-WG model employs complex statistical distribution model for the purpose of modeling meteorological variables. The basis for modeling is the duration of dry and wet periods, daily precipitation, and semi-empirical radiation distribution series.

The weather generator uses observed daily data for a given site to compute a set of parameters for probability distributions of the variables as well as the correlations between them. The underlining method used to approximate the probability distributions is a semi-empirical distribution calculated on a monthly basis. The computed set of 25 parameters is used to generate synthetic time series of arbitrary length by randomly selecting values from the appropriate distributions. Afterwards, the parameters of the distributions are perturbed for a site with the predicted monthly changes derived from global climate model runs to finally generate a daily climate scenario of the future for the specific site. The monthly changes are calculated as relative changes for precipitation and radiation and absolute changes for minimum and maximum temperatures. No adjustments for distributions of dry and wet series and temperature variability are made (Semenov & Stratonovitch 2010). This model is composed of three main parts: calibration of the model, assessment of the model, and production of meteorological data.

For the purpose of this study, the WG has been used to generate future projections of rainfall, maximum and minimum temperatures for three periods (2020s, 2050s, and 2080s). For more information on LARS-WG and how the model works readers can refer to materials in Semenov & Stratonovitch (2010).

Evaporation model

As LARS-WG simulates future minimum and maximum temperature based on observed time series, the model developed to estimate future evaporation in this study is a temperature-based one. A multiple linear regression (MLR) model for daily evaporation (ET_0) is developed using daily minimum (T_{min}) and maximum (T_{max}) temperatures as predictors, which takes the form:

$$ET_0 = \beta_0 + \beta_1 T_{min} + \beta_2 T_{max} + \varepsilon \tag{1}$$

where $\beta_{0,1,2}$ are model parameters estimated using SPSS software and $\varepsilon \sim \mathrm{N}(0, \sigma^2)$ is a Gaussian error term with variance σ^2.

Rainfall–runoff model

Different rainfall–runoff models have been used before to study the impacts of climate change on stream flows. Among them are conceptual rainfall–runoff models (e.g., Whyte *et al.* 2011) and different forms of time series models (e.g., Pekarova & Pekar 2006; Sveinsson *et al.* 2008; Whyte *et al.* 2011; Mukudan *et al.* 2012). Choice of a model to use in an impact study depends on the type of mode, availability of data required by the model, and the physical conditions in the modeled catchment itself. In the present study, the model AutoRegressive with eXogenous input (ARX), also known as transfer function model (e.g., Beven 2001) and Box–Jenkins model (Castellano-Méndez *et al.* 2004) has been employed. The exogenous factors here are the rainfall and evapotranspiration. The reasons for choosing this model are its availability, ease of use, and lack of data demanded by conceptual models. However, the main drive for choosing this particular autoregressive model (AR) is the positive correlation between the observed rainfalls with the lagging of observed flows in the catchment. The form of ARX (p) model used is described in Equation (2):

$$Q_t = \sum_{i=1}^{p} \theta_i Q_{t-i} + \beta_1 R_t + \beta_2 ET_{0t} + \varepsilon_t \tag{2}$$

where Q_t, R_t, ET_{0t}, and ε_t represents the river flow, the rainfall, the evapotranspiration, and the noise, respectively, at time t. Θ_i and $\beta_{1,2}$ are model parameters estimated using SPSS software.

Fitting measures of models

Fitting measures for LARS-WG are related to tests carried within the model to select the best fitting of rainfall and temperature distributions. LARS-WG uses the Kolmogorov–Smirnov test and distribution of dry and wet spells to test the rainfall and heatwave/frost conditions for the temperature.

Fitting measures for linear regression models are often based on the residual variance of the model fit. If ε_t is the model residual at time t, then assuming that the residuals are normally distributed with zero mean, the maximum likelihood estimate of the residual variance of a model fit to n observations is:

$$\sigma_\varepsilon^2 = \frac{1}{n}\sum_{t=1}^{n}\varepsilon_t^2 \tag{3}$$

To use the most possible parsimonious model and penalize the number of parameters used in the model, the corrected Akaike information criterion (AIC_c) is used in the form given by Shumway & Stoffer (2000):

$$AIC_c = ln\sigma_\varepsilon^2 + \frac{n+k}{n-k-2} \tag{4}$$

where k is number of regression parameters excluding constant terms used to fit the model. The residual variance in Equation (3) is referred to as the mean-squared-error of the model.

Other fitting measures used in the present study for linear regression models are coefficient of determination R^2 and for rainfall–runoff model the Nash & Sutcliffe (1970) efficiency criteria, E_f, defined as:

$$E_f = \frac{F_0 - F}{F_0} \tag{5}$$

where $\boldsymbol{F} = \sum (Q_i - q_i)^2$ where Q_i is the observed flow and q_i is the corresponding simulated flow and $\boldsymbol{F_o}$ is the initial sum squares of differences given by $\boldsymbol{F_o} = \sum (Q_i - Q_o)^2$ with Q_o being the average of the observed flow of the chosen calibration/verification period.

RESULTS AND DISCUSSION

Calibration of the rainfall and temperature models

The daily rainfall, T_{max} and T_{min} data from Salahaddin weather station for the period 1961–2000 (40 years) were used to calibrate and validate the rainfall model of the catchment. To assess the ability of LARS-WG, in addition to the graphic comparison, some statistical tests were also performed. The Kolmogorov–Smirnov (K-S) test is performed on testing equality of the seasonal distributions of wet and dry series (WDSeries) and distributions of daily rainfall (RainD) calculated from observed and downscaled data. The test calculates a p-value, which is used to accept or reject the hypotheses that the two sets of data could have come from the same distribution (i.e., when there is no difference between the observed and simulated climate for that variable). A very low p-value, and a corresponding high K-S value, means the simulated climate is unlikely to be the same as the observed climate; and hence must be rejected. Table 1 shows the statistical analyses results of the model's performance in simulating the seasonal observed data and Table 2 shows the model performance for simulating the daily rain in each month. In both tables, the letter 'N' represents the number of tests carried out.

From the results in Tables 1 and 2, it can be noted that LARS-WG is more capable in simulating the seasonal

Table 1 | KS-test for seasonal wet/dry SERIES distributions

Season	Wet/Dry	N	K-S	P-value	Comment
DJF	Wet	12	0.129	0.985	Perfect fit
	Dry	12	0.053	1	Perfect fit
MAM	Wet	12	0.073	1	Perfect fit
	Dry	12	0.043	1	Perfect fit
JJA	Wet	12	0.174	0.8416	Perfect fit
	Dry	12	0.174	0.8416	Good fit
SON	Wet	12	0.192	0.7436	Good fit
	Dry	12	0.114	0.9968	Perfect fit

Table 2 | K-S test for daily RAIN distributions

Month	N	K-S	P value	Comment
J	12	0.01	1	Perfect fit
F	12	0.063	1	Perfect fit
M	12	0.056	1	Perfect fit
A	12	0.058	1	Perfect fit
M	12	0.058	1	Perfect fit
J	12	0.261	0.3593	Moderate fit
J	12	0.348	0.0955	Poor fit
A	12	0	1	Perfect fit
S	12	0.348	0.0955	Poor fit
O	12	0.151	0.937	Perfect fit
N	12	0.058	1	Perfect fit
D	12	0.057	1	Perfect fit

distributions of the wet/dry spells and the daily precipitation distributions in each month. These two properties are very important when using the model results in impact studies.

To increase confidence in LARS-WG capability for predicting future precipitation, comparisons between statistics calculated from simulated precipitation with the corresponding ones calculated from the observed data are carried out here. Figure 2 shows a comparison between the monthly mean rainfalls yielded by the two series. Graphs of Figure 2 reveal a very good performance of LARS-WG in fitting the mean. Overall, the mean monthly rainfalls are very well modeled by LARS-WG.

The simulation of wet/dry spell lengths is very important, as it can be used for the assessment of drought risk or drainage network efficiency of a region. The simulation results of LARS-WG are shown in Figure 3(a) and 3(b) for wet and dry spell lengths, respectively. Examination of Figure 3(a) and 3(b) shows LARS-WG has remarkable skill in simulating the lengths of wet and dry spells, as the lines representing observed and simulated values are almost overlapping throughout.

As temperature is a well-defined physical variable, it is always easy to model. LARS-WG models T_{min} and T_{max} in the same manner as rainfall by fitting appropriate empirical distributions for the temperature variables in the region. Figures 4 and 5 show comparisons between the mean calculated from simulated T_{min}/T_{max} with the corresponding ones calculated from the observed data. The column plots in Figures 4 and 5 reveal a very good performance of LARS-WG in fitting the mean $\mathrm{T}_{\mathrm{min}}/T_{max}$.

LARS-WG's perfect performance in fitting rainfall and temperature as evidenced by the discussion above, give reasonable confidence in using it to simulate future rainfall and temperature.

Calibration of the evapotranspiration model

A MLR model is developed for evapotranspiration in the Greater Zab catchment using T_{min} and T_{max} as predictors, as per Equation (1). Daily data in the period 1961–2000 were used for calibrating the model and data in the period 2001–2008 were used for verification. The software SPSS was used to estimate model parameters. The model developed is:

$$ET_0 = -0.919 + 0.118T_{min} + 0.681T_{max} \quad (6)$$

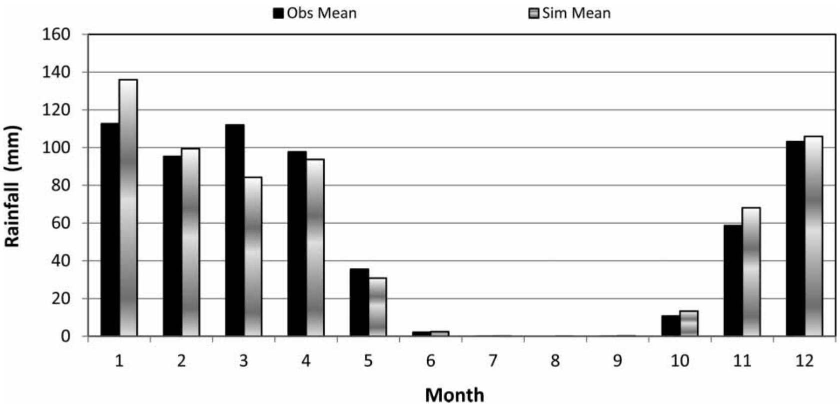

Figure 2 | Comparison of observed and simulated monthly mean rainfall.

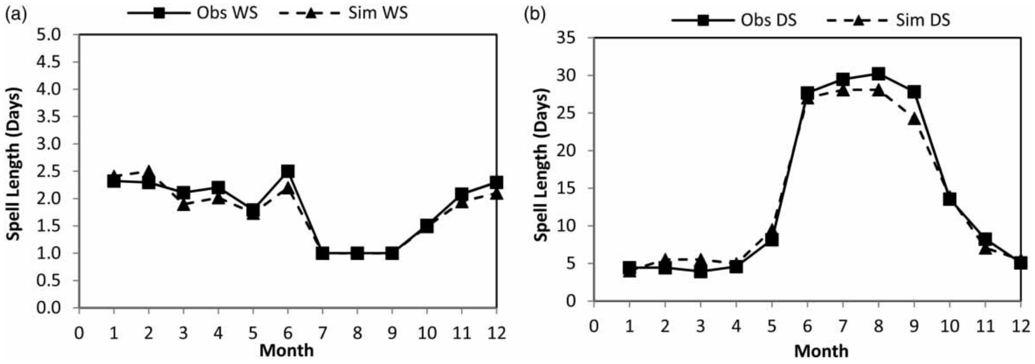

Figure 3 | Comparison of observed and simulated monthly mean wet (a) and dry (b) spell length.

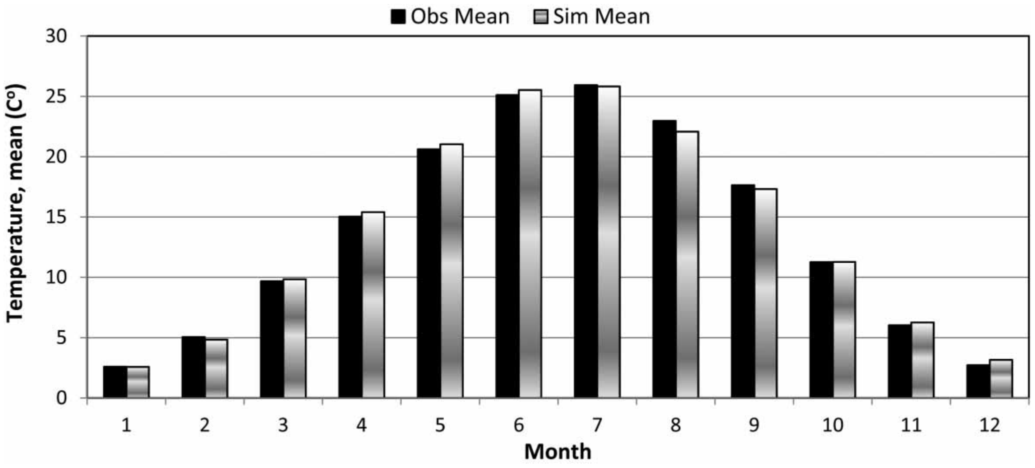

Figure 4 | Comparison of observed and simulated monthly mean T_{min}.

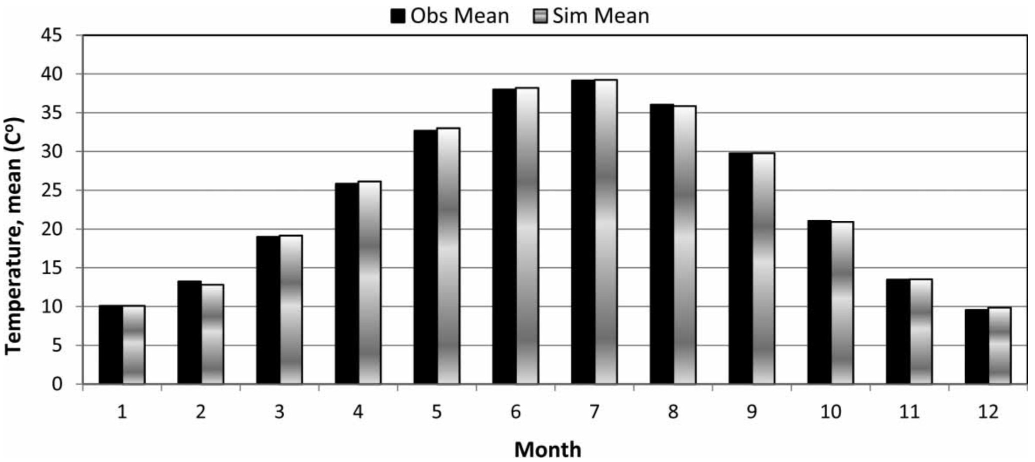

Figure 5 | Comparison of observed and simulated monthly mean T_{max}.

The coefficient of determination, R^2, for the model in Equation (6) was found to be 0.977 for the calibration period and 0.99 for the verification period. These high values of R^2 provide confidence that this model can be used to predict evapotranspiration in the region.

Calibration of the rainfall–runoff model

The ARX (p) model described in Equation (2) is calibrated using daily data in the period 1961–2000 using SPSS software. However, the order of the autoregression (or lagging) was determined first. This involved choosing different order of an AR with the two exogenous factors (rainfall and evapotranspiration) and testing a specific criterion of the fitted model. The corrected Akaike information criterion (AIC_c), described in Equation (3), with $k = p + 2$ was used for this purpose. The corresponding Nash–Sutcliffe efficiency (E_f), described in Equation (5), for each tested model was also calculated.

Figure 6 shows plots of AIC_c and E_f up to $p = 5$ for the AR combined with the exogenous factors. In Figure 6, the minimum AIC_c and highest E_f occurs at $p = 1$, suggesting that an ARX (1) is the most suitable rainfall–runoff model in this case. The ARX (1) model found is then calibrated using the observed flow, rainfall, and evapotranspiration data for the period 1961–2000. The calibrated linear model is:

$$Q_t = 26.172 + 0.891\,Q_{t-1} + 0.815\,R_t + 0.92ET_{0t} \qquad (7)$$

Efficiency (E_f) of the rainfall–runoff model was evaluated for the calibration period as 0.8. The standard error of estimate, representing the noise term in Equation (2) above, was estimated at 3.319 cumec for the calibration period, which is insignificant compared to the river daily mean flow of 397.68 cumec. The calibrated rainfall–runoff model was further verified using data in the period 2001–2008 and efficiency (E_f) for the verification period was found as 0.92. Figures 7 and 8 show comparative plots for the observed and simulated flow at Eski-Kelek gauging station for the calibration and verification periods. The plots in the two figures clearly show that the calibrated ARX (1) model has a good fitting and can reasonably be used in predicting flow at this site.

The impact model

The rainfall, temperature, evapotranspiration, and rainfall–runoff models developed above were used to study the impacts of climate change on flows of the Greater Zab River. The impact model is developed by establishing the flow conditions in the baseline period 1961–2000 and then estimating future flows in the river to assess differences in the flows. Generation of future flows would be based on considering future rainfall and temperature obtained from climate models.

To generate climate scenarios in the Greater Zab catchment for a certain future period and an emission scenario, the LARS-WG baseline parameters, which are calculated from the observed weather of the region for the baseline

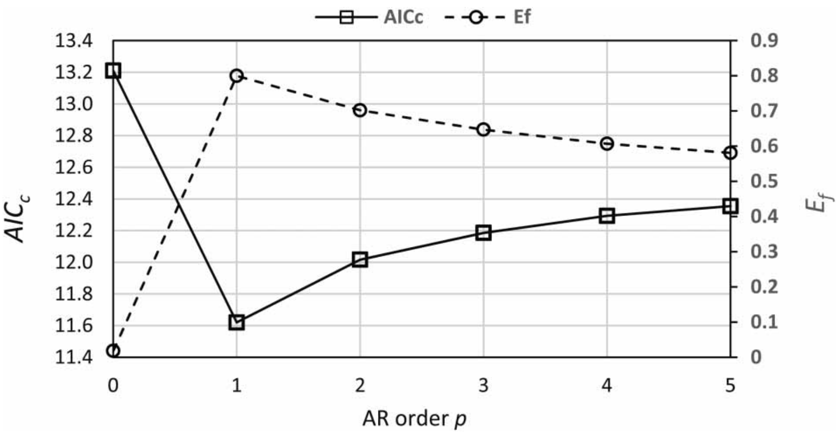

Figure 6 | AIC_c and E_f of an ARX (p) rainfall-runoff model.

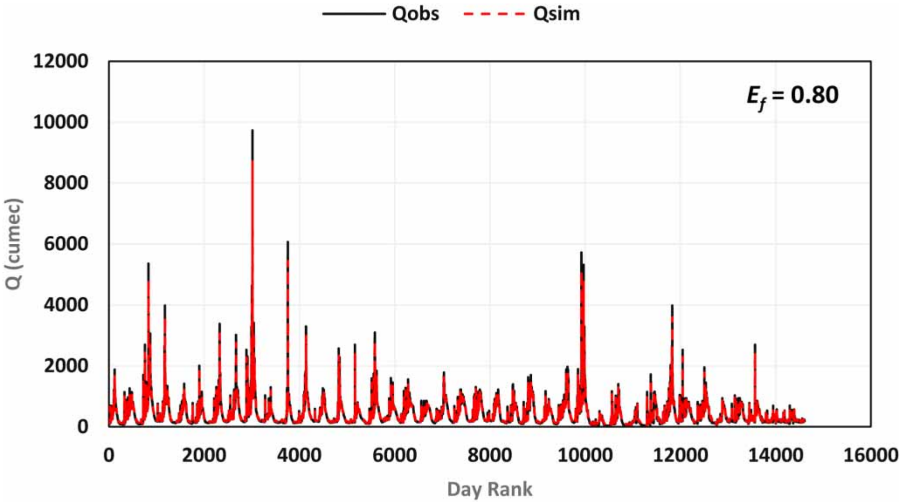

Figure 7 | Comparison of observed and simulated daily flow at Eski-Kelek gauging station for the calibration period (1961–2000).

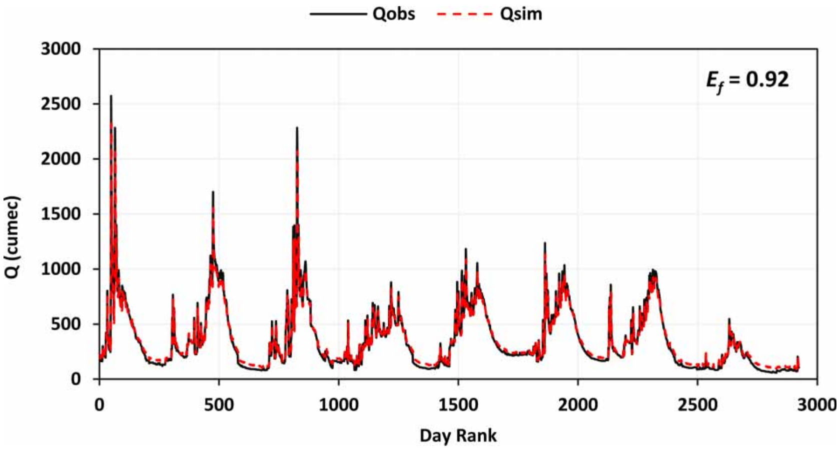

Figure 8 | Comparison of observed and simulated daily flow at Eski-Kelek gauging station for the verification period (2001–2008).

period 1961–2000 are adjusted by the Δ-changes of the future period and the emissions predicted by a GCM for each climatic variable for the grid covering the region. In this study, the local-scale climate scenarios, based on the SRES A2 scenario simulated by seven selected GCMs, shown in Table 3, are generated by using LARS-WG (version 5.5) for the time periods 2011–2030, 2046–2065, and 2080–2099, to predict future change in rainfall and temperature in the region. Semenov & Stratonovitch (2010) and Osman *et al.* (2014) have used this procedure before to generate the local-scale climate scenarios based on the IPCC AR4 multi-model ensemble at several locations in Europe and Iraq, respectively.

As autoregressive runoff models of lag $L \geq 1$ in runoff require L runoff data values to predict a runoff value at the $(L+1)th$ time point, runoff data corresponding to this future rainfall are not available. The approach taken here is to use a historical runoff value for the lagged runoff term required to initiate the prediction of runoff. The effect of the initial values is transient for a stable model. To ensure that the runoff predictions are not unduly affected by the choice of initial runoff values, a correction or scaling factor (SF) is applied to the simulated runoff to correct it, as in Equation (8.1). The correction factor is derived from the ratio of the means for the observed mean rainfall in the baseline period 1961–2000 and that simulated by the LARS-WG

Table 3 | Seven selected global climate models from IPCC AR4 incorporated into the LARS-WG 5.5

No.	GCM	Research center	Grid
1	CNCM3	Centre National de Recherches France	1.9 × 1.9°
2	GFCM21	Geophysical Fluid Dynamics Lab USA	2.0 × 2.5°
3	HADCM3	UK Meteorological Office UK	2.5 × 3.75°
4	INCM3	Institute for Numerical Mathematics Russia	4 × 5°
5	IPCM4	Institute Pierre Simon Laplace France	2.5 × 3.75°
6	MPEH5	Max-Planck Institute for Meteorology Germany	1.9 × 1.9°
7	NCCCS	National Centre for Atmospheric USA	1.4 × 1.4°

for the same period as in Equation (8.2). The SF is applied to the simulated runoff at the $(L+1)th$ time point before using it to calculate the runoff at $(L+2)th$ time point.

$$Q_{corrected} = SF \ x \ Q_{sim} \tag{8.1}$$

where

$$SF = \frac{Mean_{Observed\ Rainfall\ period\ 1961-2000}}{Mean_{Simulated\ Rainfall\ period\ 1961-2000}} \tag{8.2}$$

The generated future maximum and minimum temperatures were used as inputs to the calibrated model in Equation (6) to generate future evapotranspiration. The generated future evapotranspiration (ET_0) and rainfall (R) were then used together with a historical value for the runoff to generate a future value of flow for the Greater Zab River. The obtained future daily flows were analyzed to investigate the impact of climate change on the catchment. Seven series of future flows were generated using the seven GCMs in Table 3. Ensemble average of the generated series was then taken to reduce the amount of uncertainty in the results.

Figure 9 shows plots for time series of total annual flow for the first and second 20 years of the baseline period and each of the three 20-year future periods. Comparison of these plots reveals that the Greater Zab River is generally projected to undergo a reduction in its total annual flow in the future. The reduction in annual flow magnitude is projected to be below the current annual average flow.

To investigate which seasons would be most affected by the climate change, a comparative graph for the difference between the average seasonal flow in the baseline period and that of each of the three future periods is presented in Figure 10. The graphs in Figure 10 indicate that the winter and spring seasonal flows are projected to suffer a significant reduction in the future. The reduction is predicted to be in the order of 25 to 65% of their corresponding observed seasonal flow for the three future periods. The seasonal flow of

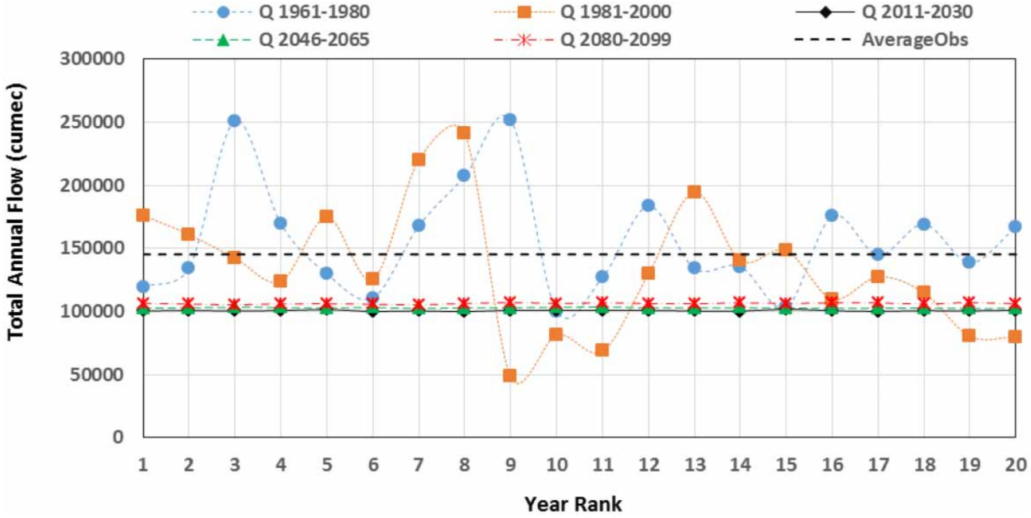

Figure 9 | Comparative plots of annual flow in the baseline and future periods.

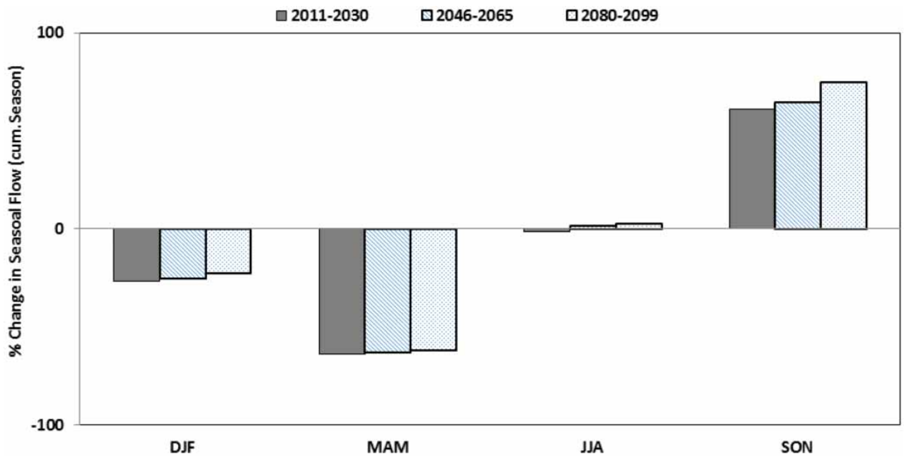

Figure 10 | Percentage difference of future seasonal flow relative to observed seasonal flow.

the summer season is projected to show no significant changes from the corresponding observed summer seasonal flow. Conversely, the autumn seasonal flow is projected to significantly increase, to more than 60%, over the corresponding observed seasonal flow.

Further, Figure 11 shows comparative plots for the average monthly flow in the baseline period and the three future periods. The average monthly flows for the months July to November are projected to increase, whereas those for the months January to June are projected to significantly decrease in all future periods with maximum reduction associated with 2080–2099. The reduction in the flows is much greater than the increase, which ultimately is reflected in the amount of total annual flow as presented in Figure 9.

As agricultural activities in the catchment depend on the winter and spring precipitation, the results obtained above would have significant implications on future agricultural activities in the catchment. Moreover, the projected significant increase in future autumnal flow could lead to flooding (if a flow exceeds river capacity), if the catchment is unprepared for this condition.

CONCLUSIONS

Impacts of future climate change on the Great Zab River are assessed in the present study. The studied catchment is located in Northern Iraq where people heavily depend on

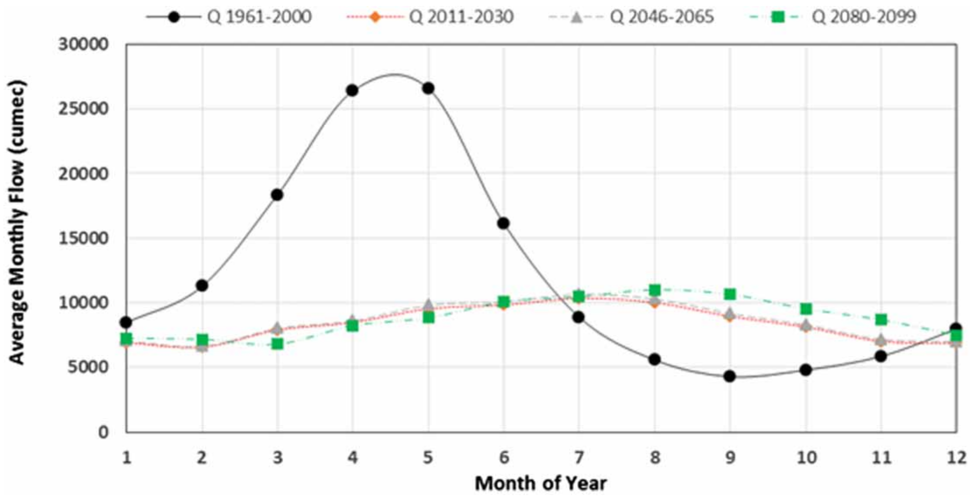

Figure 11 | Average monthly flow in the baseline and future periods,.

the river yield for their agricultural activities. The objective is to assess the impacts of climate change in the near, medium, and future periods to inform the water management authority in the catchment for their future plans. Three models were developed, one for the rainfall and temperature using LARS-WG, another for the evapotranspiration using MLR, and a third for transforming rainfall into runoff using an AR with rainfall and evapotranspiration exogenous factors. Daily rainfall and potential evapotranspiration data from the weather station in the catchment together with flow measurements from a downstream end river gauging station, for the period 1961–2008 were used for calibration and verification of the three models.

The calibrated models were then used to project future flows in the river, using A2 climate scenario emission and three future periods. The results can be summarized as follows:

- LARS-WG was very skillful in describing rainfall and temperature distribution and magnitude in the catchment; this would increase confidence in the current research results.
- The autoregressive, with exogenous factors, model developed for transforming rainfall and evapotranspiration into runoff or river flow was also very efficient. This model could also be used for flow forecasting in the river.
- The impacts' results obtained with the developed models show that climate change would have significant impacts on the Greater Zab River flows. Annual flows are projected to generally decrease below the current average annual flow.
- The negative impacts would be very much apparent in the winter and spring flows as the reduction is predicted to be in the order of 25 to 65%, whereas positive impacts are projected to occur in the autumn seasons with significant increase to more than 60%. The negative impacts could have significant consequences on the agricultural activities in the catchment whereas the positive impacts should be treated with care, depending on the river flow capacity as they could result in significant flooding. The seasonal flow of the summer season is projected to show no significant changes from the corresponding observed summer seasonal flow.
- Results from this study could be beneficial to water management planners in the catchments as they can be used in allocating water for different users.

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