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Evaluation of the Impacts of Climate Variability and Human Activity on Streamflow at the Basin Scale

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Abstract: This paper analyzes long-term trends and sudden changes in hydro-climatic variables (i.e., runoff) in Iran's Aidoghmoush basin during 1971–2000 using the nonparametric Mann-Kendall test and curves of cumulative runoff versus rainfall and cumulative runoff versus temperature The use of the Mann-Kendall test with a 99% confidence level revealed a decreasing trend in annual rainfall and total runoff and an increasing trend in temperature. A sudden change in the gradient of the cumulative curves in 1988 indicated that the relation between climatic variables and runoff is influenced by human activities (agricultural water use). The interval 1971–2000 was separated into a baseline interval (1971–1988) and an impact interval (1989–2000), during which human activities affected runoff. The five-parameter hydrologic model of IHACRES (Identification of unit Hydrographs and Component flows from Rainfall, Evaporation, and Streamflow data) was calibrated and verified over the baseline interval to determine the contribution of human activities and climatic variability to the change in runoff. Runoff was simulated with the hydrologic model for the interval 1989–2000, during which human activities reduced runoff. Results show that climate variability and human activities decreased the runoff in the Aidoghmoush river basin by 79 and 21%, respectively. **DOI: 10.1061/(ASCE)IR.1943-4774.0001038.** *© 2016 American Society of Civil Engineers.*

Author keywords: Climatic variability; Human activities; Runoff; Hydrologic models.

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Introduction

Many previous works in water resources systems dealing with reservoir operation (Ahmadi et al. 2014; Bolouri-Yazdeli et al. 2014), groundwater resources (Bozorg-Haddad et al. 2013; Fallah-Mehdipour et al. 2013b), conjunctive use operation (Fallah-Mehdipour et al. 2013a), design-operation of pumped-storage and hydropower systems (Bozorg-Haddad et al. 2014), flood management (Bozorg-Haddad et al. 2015b), water project management (Orouji et al. 2014), qualitative management of water resources systems, (Orouji et al. 2013; Shokri et al. 2014; Bozorg-Haddad et al. 2015a), water distribution systems (Seifollahi-Aghmiuni et al. 2013; Soltanjalili et al. 2013; Beygi et al. 2014), sedimentation (Shokri et al. 2013), and irrigation water allocation (Ashofteh et al. 2015b) have commonly focused on historical data for analysis purposes. Climatic variability and human activities, such as change in land use and construction of water resources projects, add to the complexity of hydrological processes. Recent investigations (Ashofteh et al. 2013a, b) have evaluated the effects of climate change on hydrology and water resources. Yet, most studies have disregarded changes in land use and land cover, even though rapid population growth, agricultural development, and land use changes are important factors that contribute to modifications in the hydrological regime (Cong et al. 2009). It is, therefore, essential to consider the effects of climate variability and human activities on hydrologic processes to achieve sustainable water management strategies.

Various approaches have been reported in the literature that have dealt with climate-change effects on water supply. Several of those studies analyzed the effects of climate variability and human activities on hydrologic processes. For example, Lørup et al. (1998) assessed long-term impacts of land use change on catchment runoff in semiarid Zimbabwe. A methodology combining common statistical methods with hydrological modeling was adopted to separate between the effects of climate variability and the effects of land use change. For this purpose the hydrological model (NAM) was applied to simulate the observed hydrographs and to provide a means to account for the effects of climate variability. In the test period, the validated model was used to provide the runoff record, which would have occurred in the absence of land use change. Their results showed a decrease in the annual runoff, with the largest changes occurring for catchments located within communal land, where large increases in population and agricultural intensity had taken place.

Motondo et al. (2004) evaluated the impact of climate change on hydrology and water resources in three U.K. catchments by using the geophysical fluid dynamics laboratory (GFDL), the United Kingdom transient resilient (UKTR) model, and the Canadian climate change equilibrium (CCC-EQ) general circulation models (GCMs) as inputs to a WatBall rainfall-runoff model. Kirono et al. (2006) investigated impacts of climate change on water resources in Australia. The rate of global warming was extracted from six atmosphere-ocean global circulation models (AOGCM), in the 2010s, 2020s, and 2030s. Gunawardhana et al. (2011) evaluated the impacts of urbanization and climate change on groundwater, especially aquifer temperature in the Sendai plain, Japan. Harma

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et al. (2012) assessed water supply and demand in the Okanagan basin of British Columbia, Canada, on the basis of scenario-based analysis. The water evaluation and planning (WEAP) model was used to analyze future scenarios for water supply and demand in unregulated and reservoir-supported streams. Their results indicated that streamflow would reduce compared to projected uses (social demand and ecological flow requirements). Also, the present storage system would not be able to meet municipal and instream flow needs during normal precipitation in future periods. Results also showed that the use of modeling tools for the integration of knowledge in the fields of climate change, hydrology, and water systems management will assist in making decisions in surface water and groundwater management. Zhang et al. (2012) evaluated the impacts of climate change and human activities on the Huifa River runoff in northeast China. They used a soil and water assessment tool (SWAT) for runoff simulation. A similar study was conducted by Huang et al. (2013), who explored the hydrologic sensitivity to climate change and human activities in the Jiulong River Basin (China) with coupled Mann-Kendall, wavelet, geospatial analyses and El Niño southern oscillation (ENSO), flashiness, and baseflow indices.

Much of the research has addressed the effects of climate change on basin streamflow (Loáiciga et al. 1996; Abbaspour et al. 2009; Zahabiyoun et al. 2013; Ashofteh et al. 2015a, c), but few have separated the effects of climate change and human activities, which lead to changes in river streamflow (Garcia and Loáiciga 2013). This paper's objectives are (1) detection of temporal trends and sudden changes of hydro-climatic variables, such as temperature, rainfall, and total runoff in the Aidoghmoush river basin of Iran, and (2) determination of the effects of climatic variability and human activities on the basin's runoff. This research employs the five-parameter hydrologic model of Jakeman and Hornberger (1993) (IHACRES) to assess the effects of climate change in a river basin. This model inputs are climatic variables (i.e., temperature and rainfall) and its output is streamflow (i.e., runoff). The study separates the effects of climatic variability and human activities on streamflow in the Aidoghmush River and provides new information for decision makers and policy makers who facilitate the sustainable development of water resources in river basins.

Methodology

This section presents methodology for the separation of the effects of climate variability and human activities on runoff. Fig. 1 depicts the flowchart of the methodology.

Trends in precipitation and temperature are analyzed, and the main driving forces for changes in hydrologic systems are determined. Any change in the gradient of the cumulative curve of runoff indicates that the relations between runoff and climatic variables and between runoff and human activities might have changed also. The effects of human activities on runoff are determined by comparing simulated runoff in the interval associated with human activities with the observed runoff in the same interval.

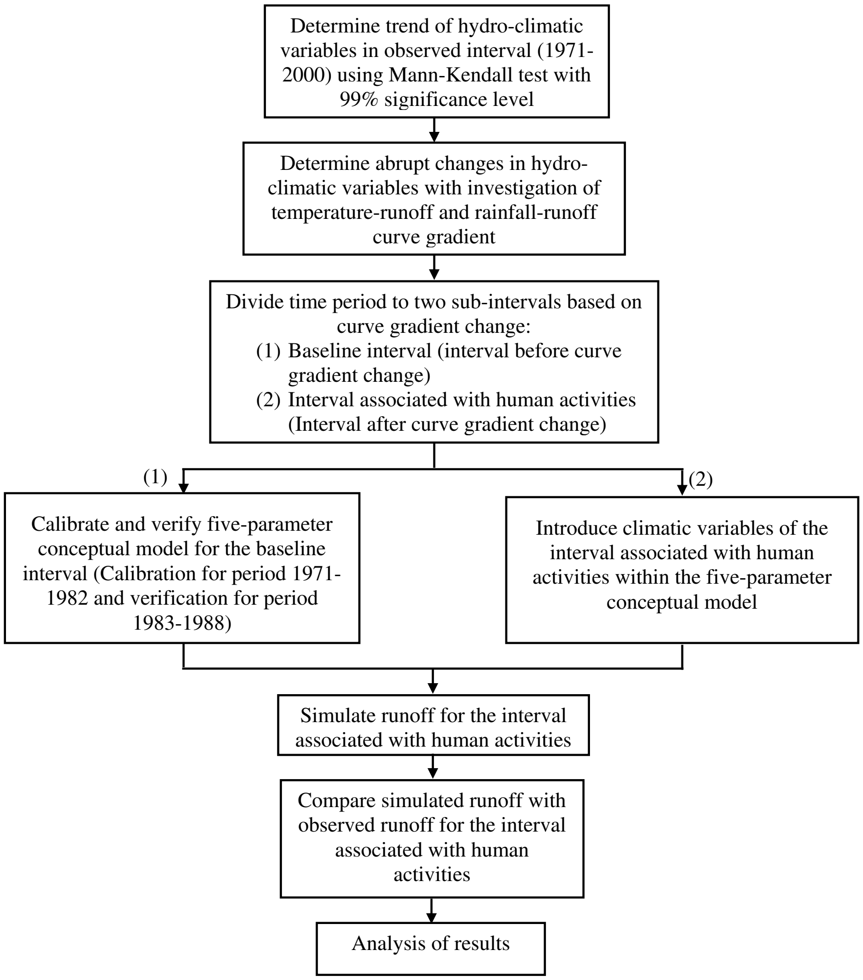

Fig. 1. Flowchart of the methodology

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Case Study and Data

The Aidoghmoush River is one of the main rivers in the Ghezel-Ozan basin in East Azerbaijan, Iran, with a catchment area of about $1,802\ \text{km}^2$ (Fig. 2). The annual discharge of the river and average annual rainfall in the basin are $190 \times 10^6\ \text{m}^3$ and 340 mm, respectively. The Aidoghmoush River basin's climate type is semiarid, and its land use is agricultural. Data of hydro-climatic variables for the observation interval (1971–2000) were obtained from meteorological and hydrometric stations (from Iran's Ministry of Power) (10 stations were used) whose locations are shown in Fig. 2 (Ashofteh et al. 2013b). The time step of the data series was monthly, over a 30-year period. Climatic data include temperature and precipitation, and the observed hydrological data was monthly runoff.

Trend-Determination by Using Mann-Kendall Test

The Mann-Kendall test is a nonparametric method commonly used to analyze trends in hydrological and meteorological time series (Wang et al. 2011, 2012). The advantage of this test, compared to other trend-determination tests, is the use of data ranks of the time series instead of the values of variables. The test can also be used for assessing the skewness data that do not follow a specific distribution (Turgay and Ercan 2005). The calculation of the Mann-Kendall statistic is as follows:

1. Calculate the difference between each observation, use the sign function, and extract the parameter S by using the expression

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{Sgn}(x_j - x_k) \tag{1}$$

where n = number of time series data; x_j and x_k = data j and k of series, respectively; and Sgn() = sign function that is computed as follows:

$$\mathrm{Sgn}(x_j - x_k) = \begin{cases} +1 & (x_j - x_k) > 0 \\ 0 & (x_j - x_k) = 0 \\ -1 & (x_j - x_k) < 0 \end{cases} \tag{2}$$

2. Calculate the variance with one of the following equations:

$$\mathrm{Var}(S) = \begin{cases} \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} & n > 10 \\ \frac{n(n-1)(2n+5)}{18} & n < 10 \end{cases} \tag{3}$$

where m = number of classes in observed data time series (class means that if the frequency of a given value is greater than one, the identical values form a class); and t = number of identical values in class m.

3. The Mann-Kendall statistic Z is determined with one of the following equations:

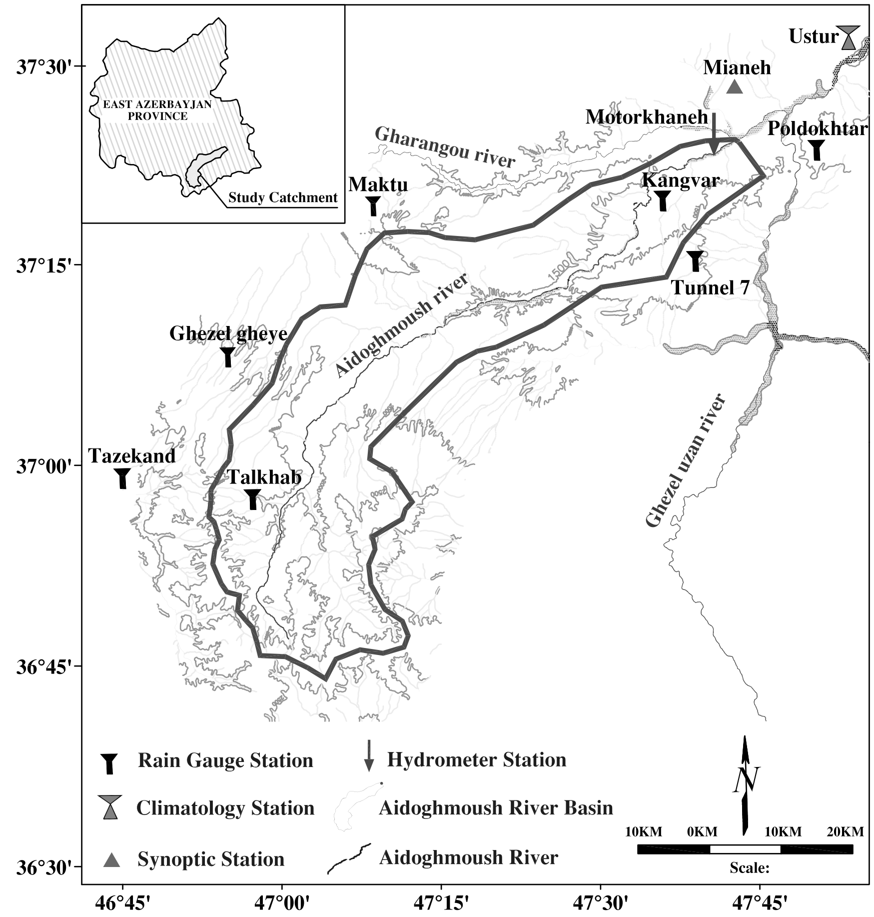

Fig. 2. Location of the river basin and monitoring stations

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & S < 0 \end{cases} \tag{4}$$

In a two-tailed test for routing of data series, the null hypothesis is accepted if Eq. (5) is satisfied

$$|Z| \leq Z_{\alpha/2} \tag{5}$$

where α = significance level of the test; and Z_α = statistic of the standard normal distribution at significance level α.

The Mann-Kendall test with a 99% significance level is used. If statistic Z is positive, an upward trend in the data series is considered. Otherwise, a downward trend is considered.

Hydrologic Model

This study employs the five-parameter hydrologic model of Jakeman and Hornberger (1993) (IHACRES) to study the effects of climate change in a basin. Model inputs are low (i.e., temperature and rainfall), so consequently relevant uncertainties will be less. The model output is the calculated river flow (i.e., runoff). The five IHACRES parameters τ_w, f, α, β, and c are calibrated based on observed data for the basin (Ashofteh et al. 2013b). This model contains two modules: (1) non-linear module of hydrologic losses, and (2) unit hydrograph linear module. The loss non-linear module transforms rainfall and temperature into effective rainfall in each time step, and unit hydrograph linear module transforms effective rainfall into surface runoff in the same time step. The parameters τ_w, f, and c belong to the loss nonlinear module, and the parameters α and β belong to the unit hydrograph linear module, all of which are calculated in the calibration phase. The parameters f and τ_w are the temperature modulation factor and the catchment drying time constant, respectively. The parameters α, β, and c are constant factors.

Estimation of the Separate Effects of Climate Variability and Human Activities on Runoff

Changes in climatic variability and human activities can affect runoff. Generally, the effects of these factors on hydrological processes are considered to be independent (Wang et al. 2010). Therefore, the runoff time series can be divided into two intervals: (1) baseline interval, which is influenced by climatic variability; and (2) interval affected by human activities. The following equation expresses the total changes in runoff as the sum of the changes caused by climatic variability and by human activities

$$\Delta R_T = \Delta R_C + \Delta R_H \tag{6}$$

where ΔR_T = total change in runoff; ΔR_C = changes in runoff due to climate variability; and ΔR_H = changes in runoff due to human activities, such as land use change, construction of water resources projects, and the like.

The hydrological model was calibrated on the baseline interval with monthly rainfall and temperature input to estimate the effect of climate variability on runoff alone during the interval affected by human activities (ΔR_H). Thereafter, the hydro-climatic variables of the interval affected by human activities are input to the calibrated model to simulate runoff related to climate variability, only in that interval. The effect of human activities can then be estimated by the difference between observed runoff and simulated runoff estimated on this interval. In sum, the effects of human activities on runoff are calculated as follows:

$$\Delta R_H = |R_P^{(H)} - R_O^{(H)}| \tag{7}$$

where $R_P^{|H|}$ = runoff time series simulated only due to climate variability; and $R_O^{|H|}$ = runoff time series observed in interval associated with human activities.

Performance Criteria

The following criteria are used to evaluate the performance of the five-parameter IHACRES hydrological model: correlation coefficient (r), root mean square error (RMSE) (Lin et al. 2006), mean absolute error (MAE) (Hu et al. 2001), and Nash-Sutcliffe efficiency (NSE) (Moriasi et al. 2007). The correlation coefficient r ranges from 0 to 1. If $r = 0$, there is no linear statistical relation between observed and simulated data. If $r = 1$, there is a perfect positive linear statistical relation. The RMSE and MAE equal to 0 means a perfect fit. The NSE values between 0.0 and 1.0 indicate acceptable levels of performance (Moriasi et al. 2007).

Results

Analysis of Trends of Hydro-Climatic Variables

Knowledge of the trends of observed climatic variables can help determine the driving forces causing changes in hydrologic systems and water resources (Huo et al. 2008). Figs. 3(a–c) show time series of temperature trends, rainfall, and total runoff for the Aidoghmoush basin during 1971–2000. In addition, the trend slope and statistic of the Mann-Kendall test for these time series are listed in Table 1.

As indicated in Figs. 3(b and c), the rainfall and runoff time series exhibited declining trends with slopes equal to 24.1 and 3.66%, respectively, which is confirmed by the computed Mann-Kendall statistic listed in Table 1 (−0.2 and −0.071, respectively). The time series of mean temperature of all stations indicated an increasing trend with a slope of 5.51% and a Z-statistic of 0.246 [Fig. 3(a)]. Therefore, the reduction in runoff may be attributed to a decreasing trend in the rainfall and an increasing trend in the temperature or both [similar findings were reported by Peng et al. (2013) for studies in China]. However, changes in hydrological variables may be caused by changing land use and human activities. The curves of cumulative runoff versus cumulative rainfall and cumulative runoff versus cumulative temperature were calculated and are depicted in Fig. 4. If hydrologic processes in the basin are stable, these two cumulative curves would be linear (Raghunath et al. 2006). A change in the gradient of the cumulative curve indicates that the existing relation between runoff and climatic variables varied. Yet, a change in runoff could also be caused by other factors, such as human activities (Raghunath et al. 2006). It is seen in Fig. 4 that the cumulative curves are nearly straight lines but display changes in slope in year 1988. The cumulative curves have different slopes before and after the change point. The slope before and after year 1988 equal 0.5 and 0.39 for the curve of cumulative runoff versus temperature, and the slope before and after year 1988 equal 0.2 and 0.15 for the curve of cumulative runoff versus rainfall. This is evidence that runoff changed in year 1988. Similar results were reported by Raghunath et al. (2006). In general, a change in climatic or hydrologic variables occurs when the related gradient of the cumulative curve changes. The years after the occurrence of change (1988) may be indicative of the impact of human activities (i.e., agricultural development) on runoff (similar

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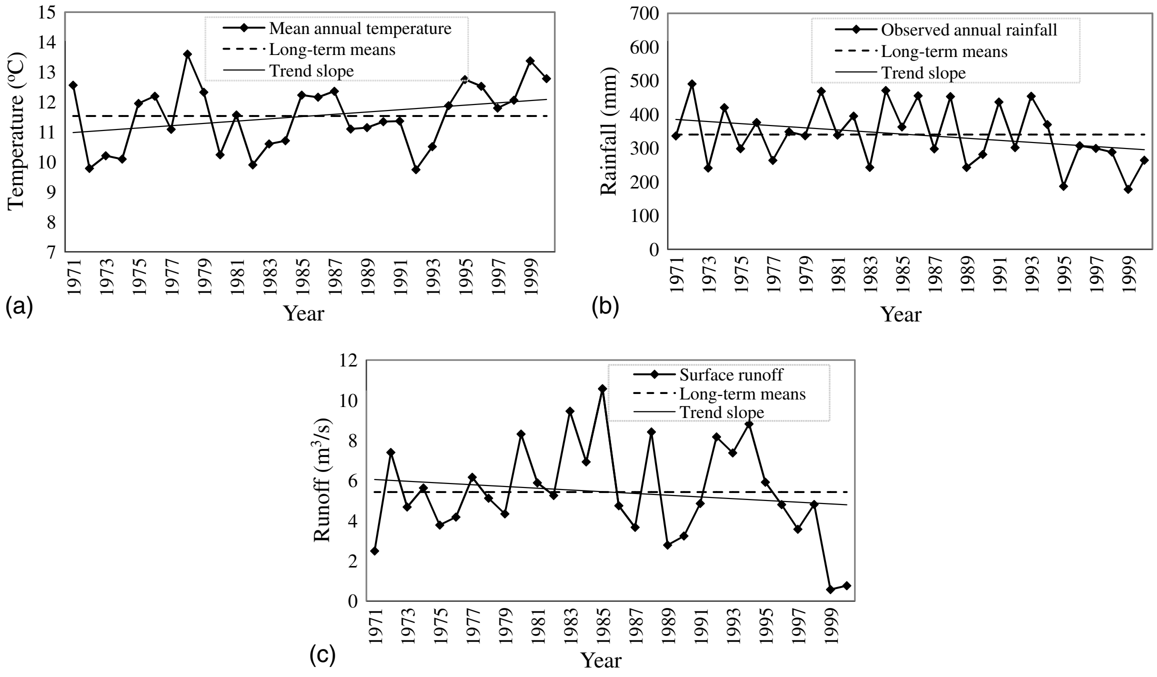

Fig. 3. Time series of hydro-climatic variables (a) temperature; (b) rainfall; (c) runoff in the Aidoghmoush river basin of all stations during the observation interval (long-term means denoted by dashed lines)

Table 1. Calculation of Trend Slope and Mann-Kendall Test Statistic in the Period 1971–2000 for Hydro-Climatic Variables

Variable	Mean value (mm)	Trend slope (%)	Mann-Kendall test	
			Z statistic	Significance level
Temperature	11.53	5.51	0.246	0.99
Rainfall	28.35	−24.10	−0.200	0.99
Runoff	5.43	−3.66	−0.071	0.99

findings were reported by Peng et al. 2013, in China). The interval 1971–1988 is thus considered as the baseline interval and the interval 1989–2000 as that in which runoff is impacted by human activities, hereafter called the impact interval. The next section provides evidence of the contribution of rainfall decline and human activities to runoff reduction.

Comparison of the Average Monthly Hydro-Climatic Variables and Their Joint Correlation within the Baseline and Impact Intervals

Intra-annual changes of rainfall, temperature, and observed runoff were analyzed to discern the effects of climate change and human activities on runoff during the baseline and impact intervals associated with human activities, respectively. Figs. 5(a–c) show average monthly temperatures, rainfall, and observed runoff in 1971–1988 and 1989–2000. It is seen in Fig. 5(a) that the difference between average monthly temperatures for the baseline and impact intervals is of minor importance, and in some months, the average monthly temperatures in the impact interval are higher than in the baseline interval. In contrast, the average monthly rainfall and runoff are less in the impact interval than in the baseline interval in most months [Figs. 5(b and c)]. Also, substantial changes in runoff relative to rainfall are visible so that in May (wet month in the basin) the ratios of runoff to rainfall for baseline and impact intervals are 33 and 42%, respectively. Therefore, in addition to climate variability, human activities (i.e., agricultural water use) affect runoff. In addition, further runoff reductions occur during the wet season (March–May). Notice that there is no significant difference between the average monthly temperatures in the base and impact intervals. Therefore, runoff is influenced by rainfall and by use of river water for irrigation that begins on April 1. Briefly, the ratio of runoff to rainfall in the baseline interval is less than the ratio of runoff to rainfall in the impact interval because the rainfall decreases in the impact interval. This means a possible shortage of

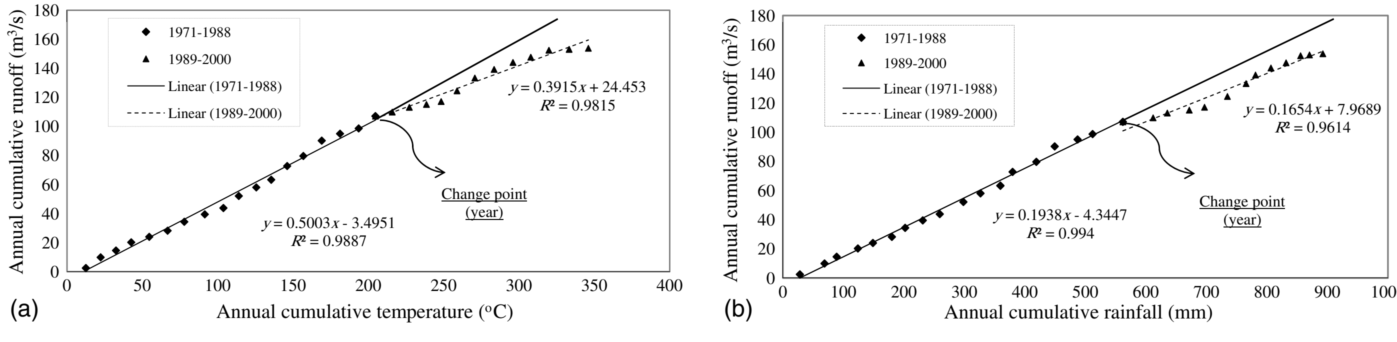

Fig. 4. Annual cumulative runoff curve as a function of (a) cumulative temperature; (b) cumulative rainfall

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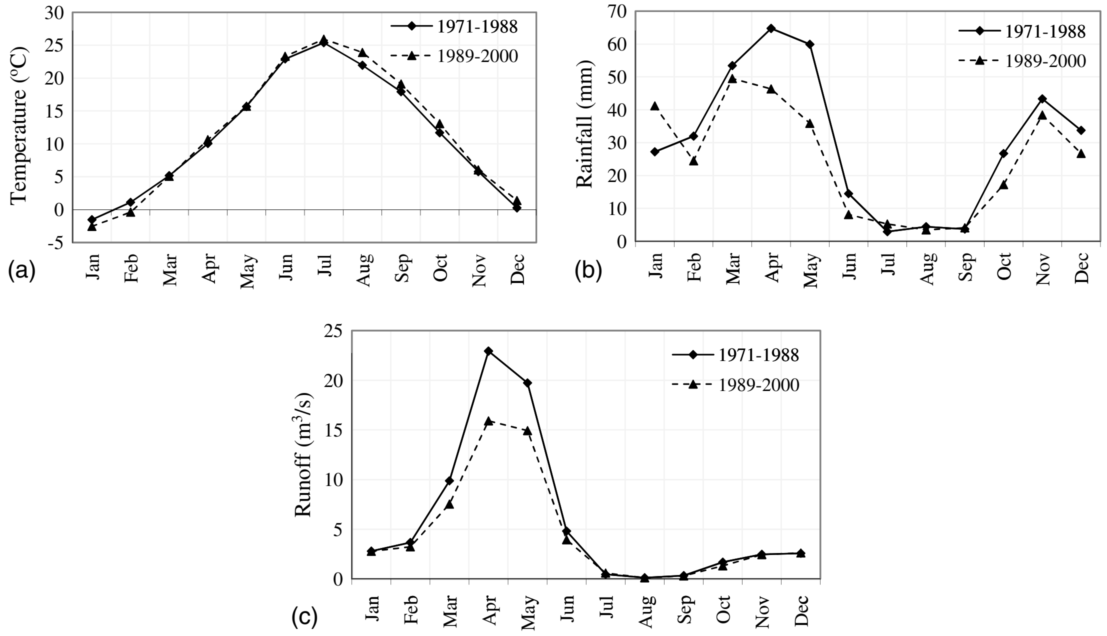

Fig. 5. Monthly temperature, rainfall, and runoff for the baseline and impact intervals: (a) monthly temperature; (b) rainfall; (c) runoff for the baseline and impact intervals

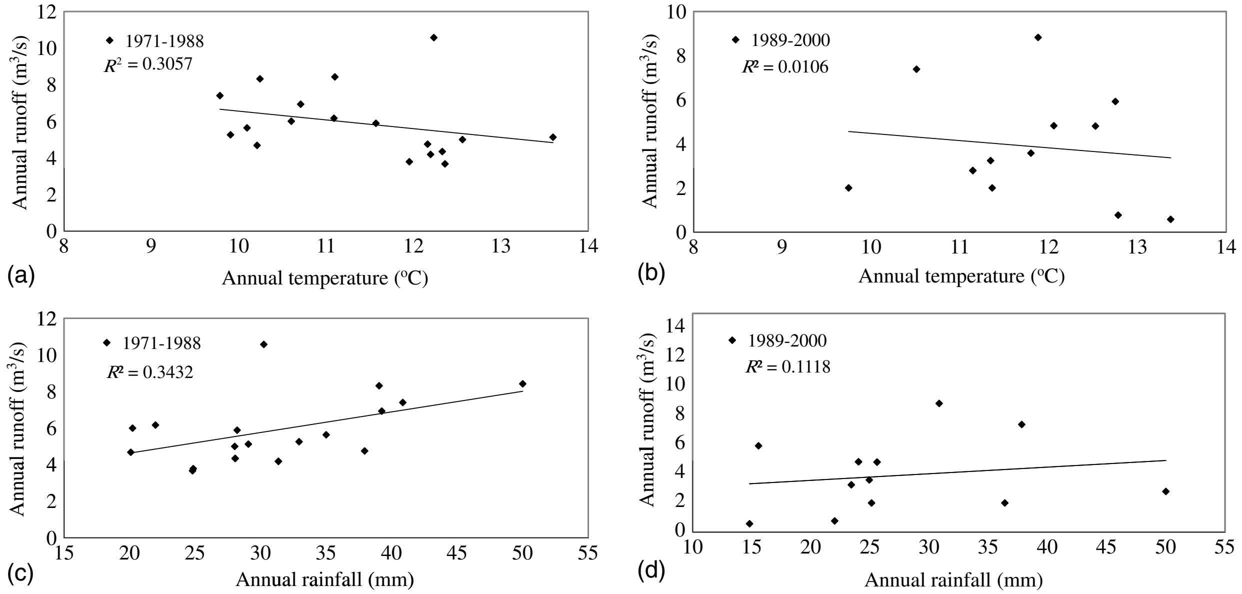

Fig. 6. Correlation between temperature with runoff for the (a) 1971–1988; and (b) 1989–2000 intervals, and correlation between rainfall with runoff for the (c) 1971–1988; and (d) 1989–2000 intervals

water for irrigation in the future. Similar findings were reported by Yang and Tian (2009) and Jiang et al. (2011) for studies in China.

Figs. 6(a–d) show a comparison of the correlations between temperature and runoff and rainfall with runoff for the baseline and impact intervals. Notice that the correlation between temperature and runoff for the baseline interval is higher than that corresponding to the impact interval, indicating that runoff is affected by human activities in the region after 1989 [Figs. 6(a and b)]. Similar findings were reported by Peng et al. (2013) for studies in China. This is also true for the correlation between

Table 2. Parameters of the Calibrated Model

Model parameters	Calibration
Temperature modulation factor (τ_w)	1
Catchment drying time constant (f)	1.7
Constant factors	
α	0.2877
β	0.5016
c	0.00102

Table 3. Goodness-of-Fit Criteria for Calibration and Verification Periods

Period	r (%)	RMSE (m^3/s)	MAE (m^3/s)	NSE (dimensionless)
Calibration (1971–1982)	0.85	3.34	2.05	0.72
Verification (1983–1988)	0.88	4.14	2.54	0.75

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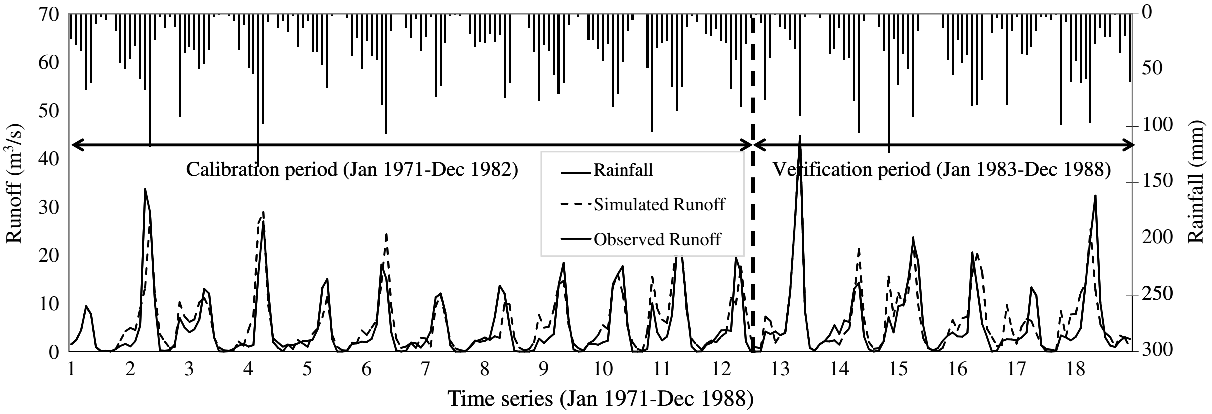

Fig. 7. Monthly runoff for calibration (1971–1982) and verification (1983–1988) periods

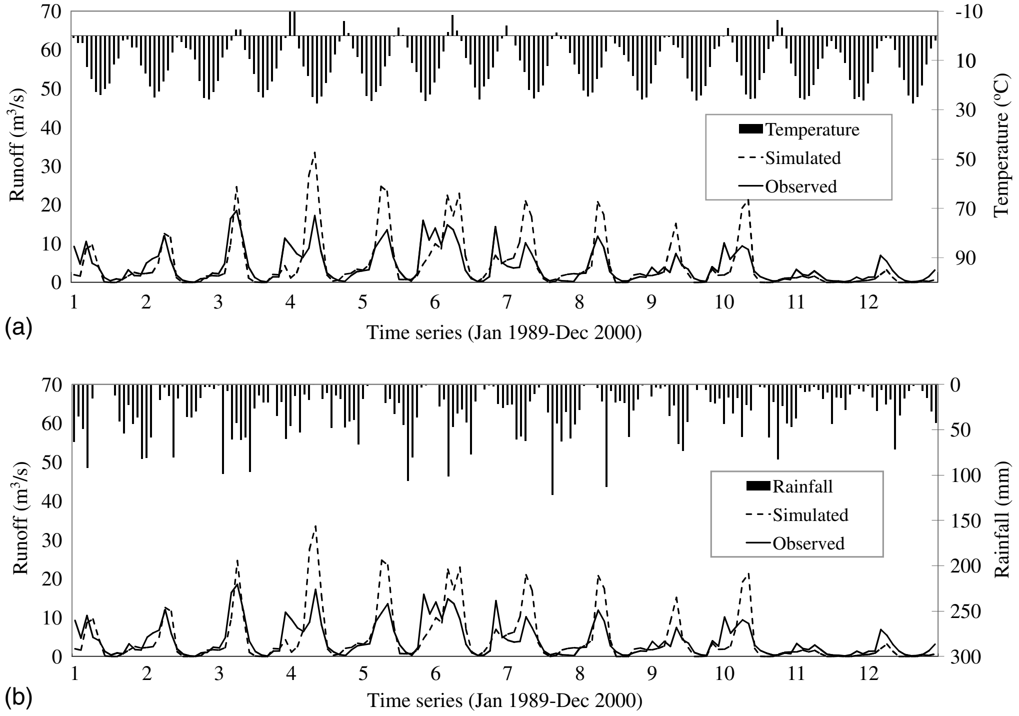

Fig. 8. Comparison of simulated and observed runoff for the impact interval (1989–2000) with changes in (a) temperature; (b) rainfall in the same interval

rainfall and runoff [Figs. 6(c and d)]. In addition, the rainfall-runoff correlation compared to temperature-runoff is higher than the temperature-runoff correlation in both intervals, indicating a greater influence of rainfall on runoff. Similar findings were reported by Guo et al. (2005) for a study in China.

Calibration of the Five-Parameter Conceptual Model and Simulated Runoff

The five parameters of the IHACRES hydrologic model (Jakeman and Hornberger 1993) were calibrated with data from January 1971 to December 1982 and verified with data from January 1983 to December 1988. The calibration and verification periods encompass the baseline period exactly (1971–1988). The optimal parameter values of the calibrated model (Table 2) were determined by using several goodness-of-fit criteria: r, RMSE, MAE, and NSE criteria (Table 3). Fig. 7 shows a comparison of simulated and observed runoff for the calibration and verification periods. Simulated monthly runoff (Fig. 7) is consistent with observed monthly runoff values, except for peak runoff. In general, the results in Fig. 7 and goodness-of-fit criteria in Table 3 indicate an acceptable performance of the five-parameter model in simulating runoff.

Separation of the Effects of Climate Variability and Human Activities

Runoff was simulated during the impact interval using the five-parameter hydrologic model and compared with the observed runoff in the same interval (Fig. 8). Fig. 8 shows that simulated runoff is larger than observed runoff during the impact interval for most of the months, which indicates the effect of human activities decreased runoff in the interval 1989–2000. The difference between simulated runoff and observed runoff reveals a decrease in runoff due to human activities, according to Eq. (7). Also, the percent change in mean annual simulated runoff during the impact interval (1989–2000) was compared with the mean annual observed runoff for the same interval. Results show that climate variability contributed 79% to the decrease in runoff while human activities contributed 21% of the decrease.

Concluding Remarks

Changes in temperature, rainfall, and runoff in the Aidoghmoush River basin during 1971–2000 were analyzed in this study using the nonparametric Mann-Kendall test and curves of cumulative runoff versus cumulative rainfall and cumulative runoff versus cumulative temperature.

The rainfall and runoff data had declining trends with slopes equal to 24.1 and 3.66%, respectively, as confirmed by calculated values of the Mann-Kendall statistic (−0.2 and −0.071, respectively). Temperature followed an increasing trend with a slope of 5.51% and a Z-statistic for this variable of 0.246. Therefore, a reduction of runoff was associated with a decreasing trend of rainfall and an increasing trend of the temperature.

There was an abrupt change in the gradient of the curves of cumulative runoff versus rainfall and cumulative runoff versus temperature in 1988 (change year), indicating the effects of human activities on runoff after 1988. Therefore, the interval 1971–2000 was divided into two subintervals: a baseline interval (1971–1988) and an impact interval (1989–2000) in order to evaluate the contributions of rainfall and human activities (agricultural water use) to the decline in runoff.

Our results established that climate variability contributed 79% of the decrease in runoff while human activities contributed 21% to the decrease in runoff.

Acknowledgments

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