The impacts of climate variability and human activities on streamflow change at basin scale

Farshid Zolfagharpour, Bahram Saghafian and Majid Delavar

ABSTRACT

Human activities (HA) and/or climate variability (CV) may be two major factors impacting natural flow regime (NFR). This study was conducted following two objectives. The first was to develop scenario-based hydrological modeling (SBHM) to disentangle the natural and human-induced impacts on flow regime. The second objective was to quantify the interaction between temperature and precipitation for the assessment of CV. To do so, six scenarios were defined to evaluate either the impact of HA, CV or both. Four major results were achieved: (1) the interaction between temperature and precipitation was more prominent in basin upstream areas, which reduced the streamflow by 9% in the entire simulation period; (2) when separating the effects of climatic and human factors, SBHM results in comparison with those of the climate elasticity analysis showed no significant differences; (3) HA were the main force driving the streamflow reduction in the study basin; (4) a 5 °C increase in air temperature in the future would lead to an increase of 1.6% in average annual streamflow, and 41% in peak runoff.

Key words | climate elasticity, climate variability, human activity, natural flow, trend analysis

Farshid Zolfagharpour
Bahram Saghafian (corresponding author)
Civil Engineering Department, Science and Research Branch,
Islamic Azad University,
Tehran,
Iran
E-mail: *b.saghafian@gmail.com*

Majid Delavar
Department of Water Resources Engineering,
Tarbiat Modares University,
Tehran,
Iran

INTRODUCTION

In recent decades, with intensifying water shortage in light of increasing water demand, water resources management strategies that in turn are affected by regional and global environmental changes have become more important (Morid *et al.* 2016). Climate variability (CV) and human activity (HA) impacts are two main hydrological driving forces for environment changes and worsening of water shortage problems (Wang *et al.* 2010; Liu *et al.* 2015). Consideration of these impacts and their corresponding compound contribution to streamflow has been a severe challenge for water managers. Study of CV and HA impacts is essential for integrated water resources and promoting local ecological protection and economic development (Sun *et al.* 2019). Even though HA distinctly result in runoff reduction, CV could lead to runoff decrease or increase (Hao *et al.* 2008).

Methodologically, in comparison with other approaches, hydrological modeling is the most common and effective method which can conceptualize hydrological processes and analyze the effects of different variables on flow variations over a basin, while requiring more inputs and computational efforts (Chang *et al.* 2015; Zhang *et al.* 2015). Ren *et al.* (2007) used a hydrological model to study streamflow variations in Laohahe basin, in northeast China, and reported that an average of 48% runoff reduction was associated with HA contribution. Ashofteh *et al.* (2016) used a hydrological model in the Aidoghmoush River basin and found that HA were the primary force driving the reduction in streamflow. Azari *et al.* (2016) applied the Soil and Water Assessment Tool (SWAT) to simulate the impacts of climate change on streamflow and sediment yield in northern Iran. Yan *et al.* (2018), using a SWAT model, showed that HA had the edge on streamflow reduction during 1980–1998, while CV had the upper hand in the 1999–2012 period.

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When available information is not sufficient to calibrate a hydrological model, statistical approaches, such as climate elasticity, are preferred. The climate elasticity method is a simple and efficient approach to disentangle the impacts of HA and CV on streamflow on a yearly time-scale and it represents the sensitivity of streamflow to CV (Sun *et al.* 2016). Zhao *et al.* (2014) applied climate elasticity in the Yellow River basin and found that CV had a greater effect on the streamflow reduction in two out of 12 studied stations (5–56%), while HA accounted for more of the streamflow changes in other tributaries, especially in northern catchments (ranging from 43% up to 93%). Long (2019), using the climate elasticity method and a hydrological model, assessed the impact of CV on streamflow and showed that using the former, CV was responsible for 44% of the reduction in streamflow whereas the latter resulted in 48.8% reduction.

However, only a few studies have focused on isolating the impact and magnitude of hydraulic structures (Sun *et al.* 2016). Moreover, a limited number of studies in the context of streamflow impact attribution have assumed that precipitation and temperature are dependent and considered their interaction (Li *et al.* 2017). Furthermore, no study was found to have applied scenario-based hydrological modeling (SBHM) while Wang *et al.* (2010) recommended employing a scenario-based hydrological model for the study of HA and CV. This study has two objectives. The first is to assess individual contributions of CV, HA and a reservoir to changes in streamflow employing SBHM. The second objective is to evaluate the individual effects of precipitation (Q_P) and temperature (Q_T) as well as their combined impact (C1) on basin streamflow.

STUDY AREA AND METHODOLOGY

Study area

The Zayandeh-Rud River basin (ZRRB) was selected as the study area (Figure 1). Several studies have been reported using the SWAT model to monitor the hydrology of the ZRRB (Faramarzi *et al.* 2017). The ZRRB with an area of 41,500 km^2, maximum river elevation of 2,800 metres above sea level and length of main river of 400 km drains into the Gavkhuni marsh in eastern Isfahan province.

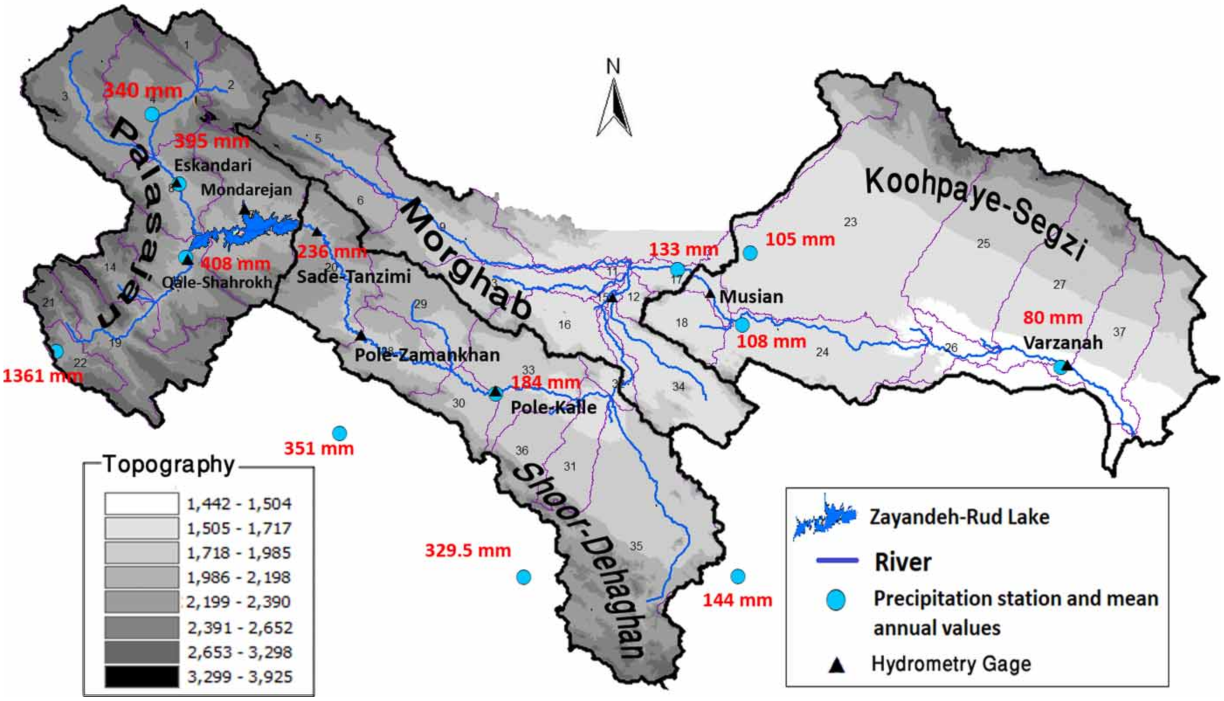

Figure 1 | Topographic map of the study basin (circles show average long-term precipitation).

Since 1971, Zayandeh-Rud reservoir has regulated the downstream in order to supply drinking, industrial, and irrigation water to about 297,000 hectares of agricultural land (see Supplementary Information for agricultural land use). Plasajan subbasin with the area of about 4,246 km^2 is the main unregulated western subbasin of the ZRRB.

The average annual maximum temperature, minimum temperature and precipitation in the basin are 20.57 °C, 5.19 °C and 297.1 mm, respectively. Mean annual precipitation varies from about 90.6 mm in the east to over 1,361.2 mm in the western tributaries. Several interbasin water transfers from Karoon, Dez and Cheshmeh-Langan basins carry water to ZRRB for supplying additional water needed to satisfy the demands in central Iran. The region has had significant population growth in the last six decades. The Khushk-Rud subbasin was excluded from the study because it provides no significant flow to the Zayandeh-Rud River. The water intake from the river to the Meimah, Alavichah, Murcheh-Khort, Barkhoar, Ghomsheh and Dasht-Aseman basins was considered in the form of water use in the SWAT model.

Hydrological and meteorological data

The meteorological data used in the present study including daily wind speed, humidity, maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (PCP) were obtained from the Iranian Meteorological Organization (IRIMO) for the 1985–2013 periods. Daily streamflow data were taken from the Isfahan Regional Water Company, Iran. Digital elevation model (DEM), land-use and soil maps with a spatial resolution of 90, 2,000 and 5,000 metres, respectively, was also obtained from the Isfahan Regional Water Company.

Hydrological model

The SWAT model was used to simulate daily runoff and to disentangle climate and anthropogenic effects in the ZRRB. SWAT is a conceptual semi-distributed model developed to simulate the hydrological cycle of a basin (including different management practices within the basin) on daily, monthly or annual time steps (Arnold *et al.* 1998). The model requires discretization of the basin into homogeneous hydrologic response units (HRUs) based on topography, land use and soil type. In SWAT, the user is offered several alternatives based on accessible data. For instance, surface runoff may be simulated using curve number or Green–Ampt infiltration models while potential evapotranspiration (PET) may be computed via Priestley–Taylor, Penman–Monteith, or Hargreaves techniques. SWAT also allows water to be removed from a shallow aquifer, deep aquifer, river reach, pond or reservoir within any subbasin.

In this study, curve-number for excess rainfall simulation, variable storage for channel routing and Penman–Monteith method for estimation of evapotranspiration were used. The model was calibrated against observed daily runoff at a number of hydrometric stations along the ZRRB mainstream over the 1985–2005 period and validated over the 2006–2013 period. To evaluate the performance of SWAT, Nash–Sutcliffe coefficient (NS) (Nash & Sutcliffe 1970) and coefficient of determination (R^2) were used as follows:

$$NS = 1 - \frac{\sum_i (Q_{\mathrm{m}} - Q_{\mathrm{s}})_i^2}{\sum_i (Q_{\mathrm{m},i} - \bar{Q}_{\mathrm{m}})^2} \tag{1}$$

$$R^2 = \frac{\left[\sum_i (Q_{\mathrm{m},i} - \bar{Q}_{\mathrm{m}})(Q_{\mathrm{s},i} - \bar{Q}_{\mathrm{s}})\right]^2}{\sum_i (Q_{\mathrm{m},i} - \bar{Q}_{\mathrm{m}})^2 \sum_i (Q_{\mathrm{s},i} - \bar{Q}_{\mathrm{s}})^2} \tag{2}$$

where Q_{m} and Q_{s} are measured and simulated streamflow, respectively. A value of unity indicates perfect model performance.

Trend analysis

There are several statistical methods to detect a trend in climatic data series, among which the Mann–Kendall trend test is one of the most commonly practiced (Hamed & Rao 1998; Liu *et al.* 2015). The test is based on non-parametric data properties which can be used in assessing if there is a monotonic upward or downward trend in the streamflow, temperature and precipitation time-series for the assessment period. The MK statistic S of a series x is determined by (Hamed & Rao 1998):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{3}$$

$$sgn(x_j - x_i) = f(x) = \begin{cases} 1 & if\ (x_j > x_i) \\ 0 & if\ (x_j = x_i) \\ -1 & if\ (x_j < x_i) \end{cases} \tag{4}$$

$$Var(s) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k - 1)(2t_k + 5)}{18} \tag{5}$$

$$Z_{\mathrm{MK}} = \begin{cases} \dfrac{s-1}{\sqrt{Var(s)}} & if\quad S > 0 \\ 0 & if\quad S = 0 \\ \dfrac{s+1}{\sqrt{Var(s)}} & if\quad S < 0 \end{cases} \tag{6}$$

where m is the number of tied groups and t_k is the number of data points in group k. A trend is considered significant if $|Z_{\mathrm{MK}}| > (Z_{(1-\alpha/2)})$, where α is the significance level of the test. If the trend in the series was significant, the Pettitt test was used to detect the change point of the time series. The Pettitt test is a non-parametric rank test which is widely used to reveal the abrupt changes in a continuous temporal data series and can be used even when there are some missing values in the time series (Pettitt 1979). The null hypothesis of this test (H_0) states that there is no change point and the alternative hypothesis (H_1) reveals the existence of a change point. The statistics U_k and K are estimated from the ranks of the data series of $(X_i)_{i=1}^{n}$:

$$U_k = 2\sum_{i=1}^{k} r_i - k(n+1) \qquad k = 1, 2, \ \ldots, \ n \tag{7}$$

$$K = \max|U_k|_{1 \le k \le N} \tag{8}$$

$$K_\alpha = \left[\frac{-1}{6}\ln\alpha(n^3 + n^2)\right]^{\frac{1}{2}} \tag{9}$$

where r_i is the rank of X_i in the sample of N observations. When the statistics are maximum or minimum in year k, a break has occurred in year k. To accept the detected change point as a shift in the data series, the calculated value of K (Equation (8)) must be greater than its theoretical value at α significance level (Equation (9)).

The average removing method, a simple yet effective method for detrending the data series (Zhang *et al.* 2014), was employed to detrend the streamflow, precipitation and temperature data series. This method is usually used for series with a relatively regular periodic cycle. Suppose $\{x_i\}_{i=1}^{N}$ is a temporal data series and the MK test suggested a trend in the series. Then, if the Pettitt test diagnoses k as a breakpoint in the data records, the departure $\varphi_k = x_k - \bar{x}_k$ may be considered as the detrended series, where:

$$\bar{x}_k = \frac{1}{(N-K+1)}\sum_{i=k}^{N} x_i - \frac{1}{(k-1)}\sum_{i=1}^{k-1} x_i$$

Impact attribution of climate variability and human activity impacts

Understanding the complex nature of streamflow affected by the intermingled CV and HA impacts is important in the management of water resources in large basins. To quantify the streamflow variation in response to CV and HA, the natural flow regime (NFR) was reconstructed via SBHM. In this study, six scenarios were defined to separate the contributions of CV and HA in streamflow change during the simulation periods: (B1) the base scenario as current basin condition, (H1) the same as B1 scenario plus dam removal, (H2) the same as B1 plus constant land use, (H3) the same as H2 with dam removal, (C1) the same as B1 while observed precipitation and temperature series were replaced by the corresponding detrended time-series, and (N1) the same as C1 with dam removal and constant land use. For HA removal, the validated model was used to simulate the runoff under scenario H3 for the 1985–2013 period. Dooge *et al.* (1999) used the following relationships to separate the impacts of HA and CV:

$$\Delta Q^{\mathrm{tot}} = \bar{Q}_2^{\mathrm{obs}} - \bar{Q}_1^{\mathrm{obs}} \tag{10}$$

$$\Delta Q^{\mathrm{tot}} = \Delta\bar{Q}^{\mathrm{CV}} + \Delta\bar{Q}^{\mathrm{HA}} \tag{11}$$

$$\Delta\bar{Q}^{\mathrm{HA}} = \Delta\bar{Q}^{\mathrm{D}} + \Delta\bar{Q}^{\mathrm{LU}} = |Q_{\mathrm{S}}^{\mathrm{CV}} - \bar{Q}_2^{\mathrm{obs}}| \tag{12}$$

ΔQ^{tot} indicates a total change in mean annual streamflow, $\bar{Q}_1^{\mathrm{obs}}$ is the average annual streamflow during the baseline period and $\bar{Q}_2^{\mathrm{obs}}$ is the average annual streamflow during the change period. $\Delta\bar{Q}^{\mathrm{CV}}$ and $\Delta\bar{Q}^{\mathrm{HA}}$ are the changes in mean annual streamflow due to CV and HA impacts, respectively. $\Delta\bar{Q}^{D}$ and $\Delta\bar{Q}^{\mathrm{LU}}$ represent the change in mean annual streamflow due to dam operation and land-use change, respectively. $Q_{\mathrm{S}}^{\mathrm{CV}}$ is the runoff time-series simulated by the SWAT model only due to CV in the interval along with HA. HA may be classified into direct ($\mathrm{HA_d}$) and indirect HA ($\mathrm{HA_{ind}}$) (Yan *et al.* 2018). The indirect part of HA may be due to the change in basin characteristics, interwoven impacts of HA and CV, afforestation and soil and water conservation projects. $\mathrm{HA_{ind}}$ is defined as the difference between $\mathrm{Q_{H3}}$ and $\mathrm{Q_{C1}}$ where $\mathrm{Q_{H3}}$ and $\mathrm{Q_{C1}}$ are simulated runoff under scenarios H3 and C1, respectively.

Sensitivity analysis

McCuen (1974) stated that the sensitivity of system output O to variation of a system parameter P in systems analysis may be defined by dividing the derivative of O by the derivative of P. In this study, precipitation elasticity (ε) and temperature sensitivity (S) were used to probe the runoff and actual evapotranspiration (ET) response to precipitation (P) and temperature (T) change (Equations (13)–(16)). The precipitation elasticity of streamflow (ε_Q) and actual evapotranspiration (ε_{ET}) show how an incremental change in precipitation (ΔP) results in a percentage change in streamflow (Q) or actual evapotranspiration. Temperature sensitivity is defined as the percentage change in annual average Q per 1 °C temperature change or as an indication of percentage change in Q by incremental temperature change (ΔT) (Vano & Lettenmaier 2014):

$$\varepsilon_{(Q,P)} = \frac{\bar{P}}{\bar{Q}}\frac{\partial Q}{\partial P} = \frac{\frac{\left(Q_{\mathrm{Hist}+\Delta p} - Q_{\mathrm{Hist}}\right)}{Q_{\mathrm{Hist}}}}{\Delta P\%} \tag{13}$$

$$S_{(Q,T)} = \frac{1}{\bar{Q}}\frac{\partial Q}{\partial T} = \frac{\frac{\left(Q_{\mathrm{Hist}+\Delta T} - Q_{\mathrm{Hist}}\right)}{Q_{\mathrm{Hist}}}}{\Delta T} \tag{14}$$

$$\varepsilon_{(E,P)} = \frac{\bar{P}}{\bar{\bar{E}}}\frac{\partial E}{\partial P} = \frac{\frac{\left(E_{\mathrm{ref}+\Delta p} - E_{\mathrm{ref}}\right)}{E_{\mathrm{ref}}}}{\Delta P\%} \tag{15}$$

$$(E,T) = \frac{1}{\bar{\bar{E}}}\frac{\partial E}{\partial T} = \frac{\frac{\left(E_{\mathrm{ref}+\Delta T} - E_{\mathrm{ref}}\right)}{E_{\mathrm{ref}}}}{\Delta T} \tag{16}$$

The elasticity of runoff ($\mathcal{E}$) to a climate variable (X) is defined as (Schaake & Liu 1989):

$$\varepsilon_x(X,Q) = \frac{\partial Q/Q}{\partial X/X} \tag{17}$$

Following Equation (17), changes in streamflow due to CV can be approximated as (Dooge *et al.* 1999):

$$\Delta Q_C = \left(\varepsilon_P \frac{\Delta p}{p} + \varepsilon_{E_0}\frac{\Delta ET_0}{ET_0}\right)Q \tag{18}$$

where ΔQ, ΔP, and ΔET_0 are the changes in streamflow, precipitation, and PET, respectively, and $\mathcal{E}_p$ and $\mathcal{E}_{E_0}$ are precipitation and PET elasticity of streamflow. To estimate the streamflow sensitivity (ε, S) and elasticity $\mathcal{E}_x(X,Q)$, the SWAT model was executed. To determine the effect of changing different climate variables such as precipitation and temperature on the streamflow, the fields from variables related to climate change within the SWAT model were altered, since SWAT allows climatic conditions to vary from month to month. The simulation was carried out for 1985–2013 using initial conditions (scenario B1: present water resources management and land use) and hydrologic sensitivity was quantified during the simulation period.

RESULTS AND DISCUSSION

SWAT calibration and validation

The SWAT model was calibrated against daily discharge data observed from 1985 to 2005 and validated for the 2006–2013 period at Qale-Shahrokh, Pole-Zamankhan, Pole-Kalle, Musian and Varzanah hydrometric stations. The model parameters were calibrated via comparison of measured and simulated daily runoff records. The model output is illustrated for Plasajan subbasin at Qale-Shahrokh station as it is the only unregulated subbasin that directly drains into Zayandeh-Rud dam (Figure 2).

The R^2 of the calibration period for daily streamflow at Qale-Shahrokh and Varzanah stations was 0.79 and 0.67 with NS of 0.75 and 0.65, respectively. The results indicating SWAT performance for both calibration and validation

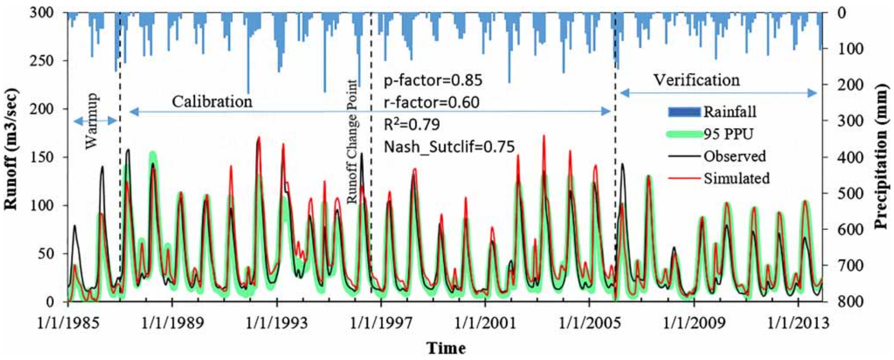

Figure 2 | Comparison of observed and SWAT simulated daily streamflow at Qale-Shahrokh station for calibration (1985–2005) and validation (2006–2013) periods.

periods was satisfactory (see Supplementary Information, Table S2). As far as the results are concerned, SWAT simulation was acceptable in wet periods but poor in dry periods, as well documented in several other studies (e.g. Zhang *et al.* 2015). We found that model weakness was more pronounced at Varzanah terminal station.

Trend analysis

The MK test was used to assess the existence of trends in streamflow, $T_{\max}$, $T_{\min}$ and precipitation time-series (see Supplementary Information). The outlet of the basin exhibited major variation in its streamflow. The Pettitt test with a significance level of 5% in Plasajan and Varzanah subbasins showed an abrupt change point that occurred in the 1996–1998 period. The upper part of the basin showed a slight decreasing trend in precipitation and increasing trend in maximum and minimum temperatures (Figure 3). Spatiotemporal variability of PCP, $T_{\max}$ and $T_{\min}$ resulted in the western part of the basin producing much more streamflow compared with the eastern part. The trend in annual $T_{\max}$ and $T_{\min}$ averaged over all ten basin stations was 0.59 and 0.16 °C per decade, respectively. Urbanization effects under climate change conditions cause an accumulation of a greater rate of CO_2 emission and this is consistent with the positive trend in the temperature (Abbasnia *et al.* 2016).

$T_{\max}$ had a consistent increasing trend over the entire basin that changed in the range of 2.09 °C at Daran to

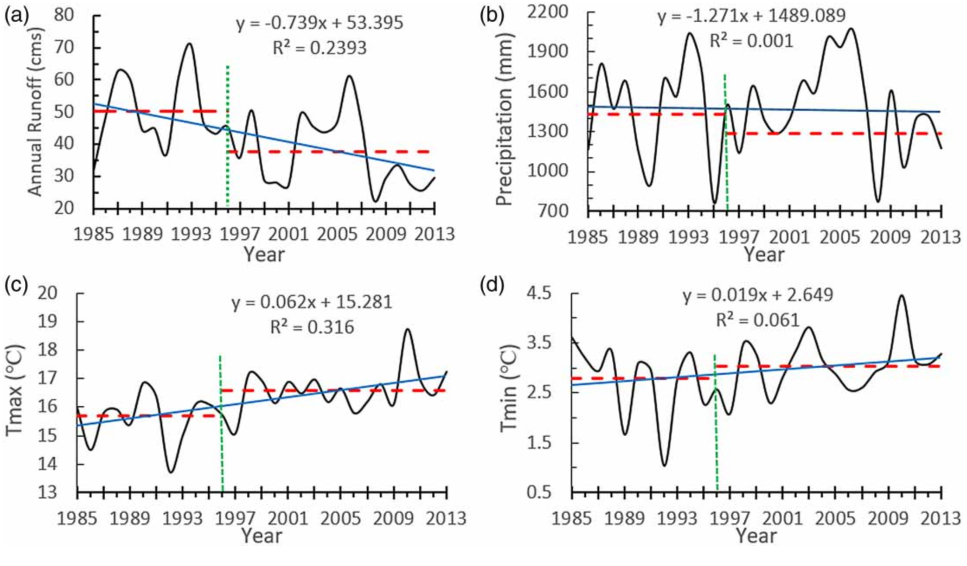

Figure 3 | Variation of hydro-climatological time-series in upstream of Zayandeh-Rud dam at Qale-Shahrokh hydrometric station (the green line): (a) annual runoff, (b) precipitation, (c) maximum temperature and (d) minimum temperature. The blue line is the linear trend and the red horizontal dotted lines represent the averages. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/ws.2020.012.

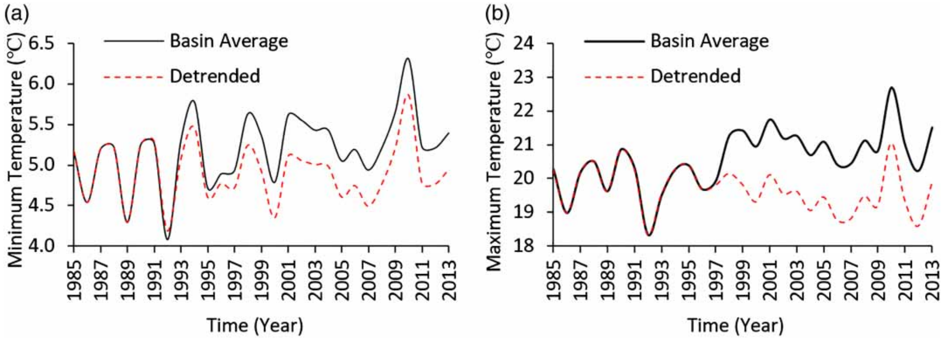

Figure 4 | (a) Detrended basin average minimum temperature series, (b) detrended basin average maximum temperature series.

1.24 °C at Isfahan Airport station, while for $T_{\min}$, six out of ten stations showed an increasing trend (0.82 °C–4.66 °C), three stations showed no significant decreasing trend and one station had a significant decreasing trend (see Supplementary Information). The four stations with decreasing trends are located in the eastern part of the basin. On a daily basis, the highest $T_{\max}$ and $T_{\min}$ increased by 0.75 and 1.66 °C per decade at Daran station located in the eastern part of the basin. The streamflow series at Qaleh-Shahrokh and Varzanah hydrometric stations exhibited remarkable negative trends ($P < 0.05$) of 1.05 and 0.63 cm per decade, respectively.

The observed annual streamflow in these stations was 50.1 and 8.08 cm in the pre-change period (baseline period, 1985–1996), whereas it decreased to 37.54 and 0.52 cm in the post-change period (simulation period, 1997–2013). The simple method of average removing was applied to detrend the series (Figure 4(a) and 4(b)).

Hydrological sensitivity analysis

Knowledge of the sensitivity of streamflow and actual evapotranspiration to precipitation and temperature is helpful for projection of relative shifts in the streamflow due to future climate change. Values of the sensitivity of streamflow to precipitation ($\varepsilon(Q,P)$) and temperature ($S(Q,T)$) larger than 1 indicate streamflow increase with precipitation and temperature. The sensitivity of actual evapotranspiration to precipitation ($\varepsilon(ET,P)$) and temperature ($S(ET,T)$) was modest over the entire basin (Figure 5(a) and 5(b)). The $\varepsilon(Q,P)$ and $S(Q,T)$ for the outlet of the basin were 0.63 and −2.37, respectively (Figure 5(c) and 5(d)). When the

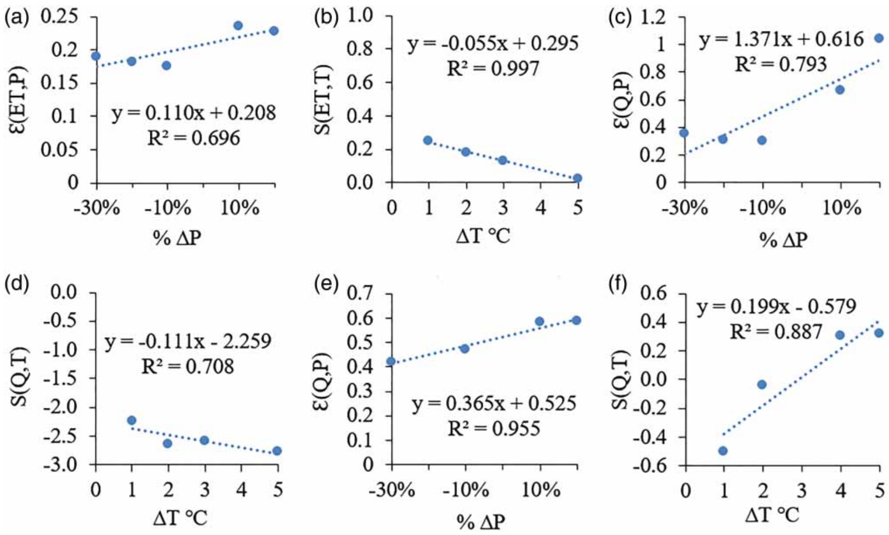

Figure 5 | Sensitivity (ε,S) analysis of change in temperature and precipitation: (a), (b) mean evapotranspiration; (c), (d) in outlet subbasin; (e), (f) in upstream subbasin (Plasajan subbasin).

precipitation changes by −30%, −20%, −10%, 10% and 20%, the runoff changes by −10.63%, −6.22%, −3%, 6.67% and 20.75%, respectively (Figure 5(c)). Precipitation elasticity of runoff in Plasajan subbasin is equal to 0.365, which is lower than in Varzanah (1.37). This may be due to the fact that Plasajan subbasin is located in the western part and Varzanah in the eastern part of the ZRRB, so that the precipitation pattern is quite different. Plasajan subbasin receives high precipitation and is the mainstream draining into the dam. The subbasin receives a large amount of snow, has a low infiltration rate and enjoys steep topography that all lead to a higher runoff coefficient.

The temperature sensitivity analysis in the outlet subbasin located in flat lowland shows that while temperature increases from 0 to 5 °C, surface runoff decreases by an average of 14%. As in the eastern part of the ZRRB there is no significant snowfall, and then with increasing the temperature, evapotranspiration consumes most of the precipitation. In contrast, *S* in the upstream subbasin (Figure 5(f)) shows a positive slope. This is because the snow-water equivalent over this snow-dominated subbasin reduces with increase in air temperature. As a result, annual snowmelt runoff and total streamflow increase linearly with increase in temperature in this subbasin. An increase of 5 °C in air temperature enhanced annual snowmelt runoff that resulted in an increase of 1.6% in average total streamflow, and 41% increase in peak runoff.

The impact of human activities on streamflow

The NFR of the basin were reconstructed using SWAT under scenario H3 and its hydrograph was compared with the base scenario (Figure 6(a)). The NFR hydrograph is above that of the base during wet seasons, but falls below during the low flow period due to regulated flow. The average natural annual flow hydrograph was seen to be higher than the regulated annual flow hydrograph, while the actual evapotranspiration (ETa) in scenario N1 is below the other

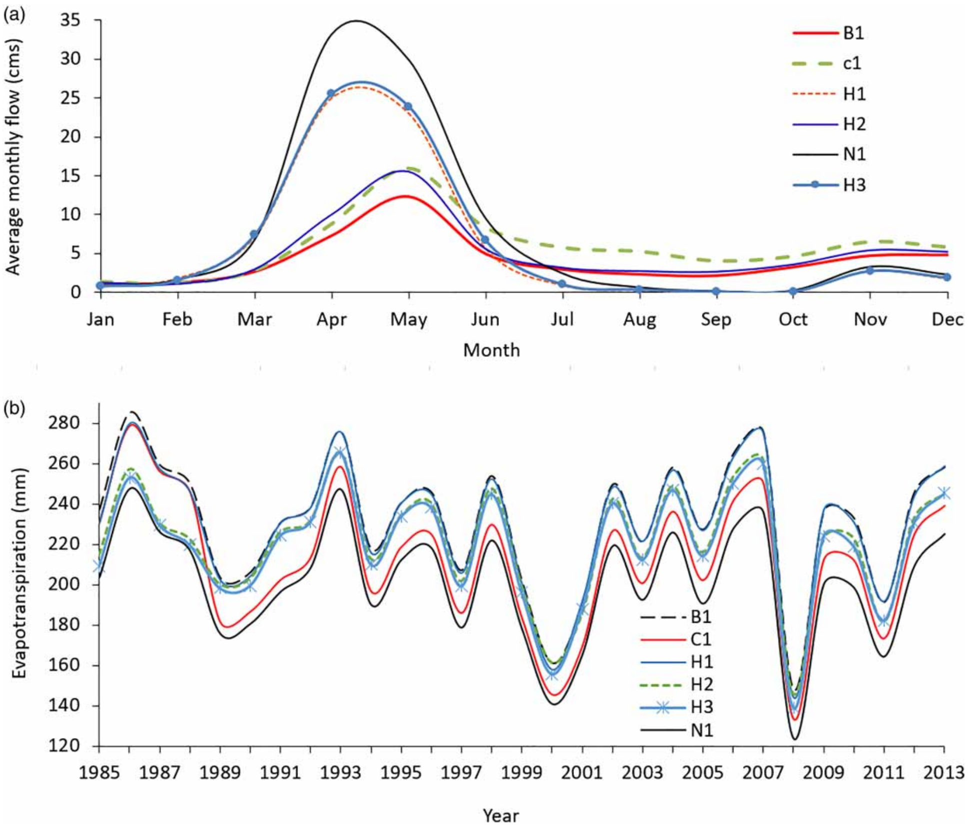

Figure 6 | (a) Effect of different scenarios on the study basin outlet; (b) effect of different scenarios on evapotranspiration.

curves, which indicates the importance of CV in ETa (Figure 6(b)). Following Equation (18), the elasticity of annual streamflow in Plasajan subbasin to precipitation and PET was 0.38 and 0.62 respectively, which indicates that the annual streamflow in this subbasin is more sensitive to the change in evapotranspiration than to the change in precipitation. This is because in the upstream areas of the ZRRB a large amount of the precipitation occurs in the form of snow, leading to no direct response to the outflow.

Comparing the baseline and simulation periods, 149.05 mm decrease in precipitation led to 1.99 cm decrease in streamflow, whereas the 43.89 mm increase in ET_0 resulted in a decrease in annual streamflow by 1.25 cm. The changes in precipitation and ET_0 led to a decrease in streamflow by 3.24 cm in the 1997–2013 period, accounting for 26% (3.24/12.55) of the total observed reduction in annual streamflow. Correspondingly, HA resulted in a decrease in annual streamflow by 9.32 cm, accounting for 74% of the decrease in streamflow. The values of ε_P and ε_{E_0} for the downstream of Zayandeh-Rud dam were 1.37 and −0.37 respectively, an indication of faster streamflow response to precipitation compared with that of evapotranspiration. This implies that precipitation is the main component of CV that impacts streamflow in the downstream areas of the studied basin.

For further impact assessment, the simulation period was split into two sub-periods: period I (1997–2005) and period II (2006–2013). After 1996, streamflow was reduced by 25% and 92% at Qale-Shahrokh and Varzanah hydrometric stations, respectively (see Supplementary Information, Table S5). At Qale-Shahrokh station, HA varied from 90% (in period I) to 35% (in period II). At Varzanah station, 72%, 27% and 53% of the change is attributed to dam operation in period I, period II and the total simulation period, respectively. Although precipitation in the period 1997–2006 is higher than that in the period 1985–1996, observed runoff in period I is less than that in the baseline period because of extensive HA in period I (33% more cultivated land, according to the registered agricultural data).

In Plasajan subbasin, indirect HA caused change in average annual streamflow by 26%, 10% and 16% in period I, period 2 and the total simulation period, respectively. The corresponding indirect HA at Varzanah station was 3% in all time periods because this station is located downstream of the dam and is affected by dam operation rules. Accordingly, the NFR is about 85% larger than the impacted observed flow. Disentangling the effect of human intervention (H3) and the CV (C1) shows that human impacts alone can account for 67% of the variability in streamflow; such reduction is due, in parts, to differential changes in dam operation (53%) and agricultural land use and management (14%).

The impact of climate variability on streamflow

CV varied from 10% in period I to 65% in period II. CV also accounts for 33% of the streamflow reduction at the basin outlet attributed to temperature (32%) and precipitation (1%). The simulated streamflow with respect to the effect of temperature (Q_T) at Qale-Shahrokh station was 47.2, 36.2 and 42.7 cm in period I, period II and the simulation period, respectively, while it was 5.6, 3.9 and 4.9 cm at Varzanah station. The simulated streamflow under the effect of precipitation (Q_P) at Qale-Shahrokh station was 51.9, 42.3 and 47.9 cm, while it was 2.9, 2.4 and 2.7 cm at Varzanah station in period I, period II and the simulation period, respectively (see Supplementary Information, Table S4). The results indicate that the coupling effect of temperature and precipitation is not identical to the summation of these impacts, separately. The interaction between temperature and precipitation at Qale-Shahrokh station reduced the streamflow by 8%, 11% and 9% in period I, II and the total simulation period. One of the main reasons for this reduction is linked to the lower temperature on rainy days and the association of dry spells with high temperature (Li *et al.* 2017). The corresponding interaction reduced the streamflow up to 1% at Varzanah hydrometric station in all periods, mainly because the streamflow in this station originates in the upstream areas of the basin. The results indicated that the impact of interaction between temperature and precipitation was more pronounced in upstream areas of the basin rather than in downstream areas.

CONCLUSIONS

Attributed to the compound impact of CV and HA on the NFR, an SBHM approach was adopted to investigate potential causes of streamflow changes in the ZRRB. Several conclusions have been drawn from this study:

(1) In the upstream areas of the study basin, the interaction between precipitation and temperature is considerable, while it may be negligible in the downstream areas unless the downstream flow is supported by other major inflows that come from the downstream tributaries of the basin. Therefore, this interaction should be further investigated in future research.
(2) In hydrologic studies, considering the interaction between temperature and precipitation would lead to an increase of the accuracy of hydrologic simulations.
(3) HA were the main force driving the streamflow reduction in the study area. They caused 56% and 67% of the changes in average streamflow during the entire simulation period at Qale-Shahrokh and Varzanah stations, respectively.
(4) Direct HA had the highest influence on the streamflow reduction in both the upstream (Qale-Shahrokh station) and downstream (Varzanah station) of the reservoir, while indirect HA had a considerable share of streamflow reduction only in the upstream of the dam.
(5) Considering the impact of CV and HA, if total surface water withdrawal remains unchanged, then the difference between the simulated streamflow in scenario H3 and the observed runoff ($\bar{Q}_2^{\text{obs}}$) in the impact period implies that there is a need for an additional 7 cm (222 MCM per year) and 4.56 cm (144 MCM per year) of water transfer to the basin to revive the NFR at the Qaleh-Shahrokh and Varzanah hydrometric stations, respectively.

The SBHM approach involves comprehensive physical processes and incorporates uncertainties e.g. hydroclimatological uncertainty that mainly results from instrumental and human errors) while it is time-consuming and requires a large volume of input data. On the other hand, the climate elasticity cannot take the interactions among individual climate variables into account, so that the accuracy of the estimated streamflow response to the variable of interest may be in question. It is hoped that water managers will be inspired to adopt the SBHM framework that involves the interaction of precipitation and temperature in promoting the ecohydrological and economic benefits of a hydrological system.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

SUPPLEMENTARY MATERIAL

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