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## Quantifying the contributions of climate change and direct human interventions on streamflow alteration using the GSFLOW hydrological model

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### ABSTRACT

**Background and Objectives:** Climate variations and human activities are two major factors influencing the trends of hydrological cycle components in watersheds. It is essential to understand how flow behavior is separately affected by climate change and human activities in order to formulate effective adaptation policies and strategies for water resource planning and management. In recent years, the reduction in the discharge of the Hablehroud River has led to tensions among stakeholders of the basin's water resources in Semnan and Tehran provinces, as well as between upstream and downstream farmers. Therefore, the aim of this research is to quantify the impacts of climate change and human interventions on the discharge of the Hablehroud River and to determine the relative contribution of each influencing factor. Additionally, this study investigates objectives such as identifying trends in climatic variables and the status of surface water resources, quantifying the effects of various natural and anthropogenic factors on these trends, predicting the future status of water resources in the study area under the continuation of current policies and strategies, and forecasting water resource conditions under different climate change scenario. The study area encompasses the upstream section of the Hablehroud watershed, extending to the Bonekouh hydrometric station, which is situated at the administrative boundary between Tehran and Semnan provinces. The Hablehroud River, serving as the main drainage of the watershed, has been increasingly affected in recent years by human activities and climate change, resulting in significant alterations to its hydrological status over the past decades.

**Materials and Methods:** In this study, long-term statistics from hydrometric stations were collected and pre-processed. A significant change point in the annual discharge time series was then identified. The GSFLOW hydrologic model was applied to distinguish the effects of climate change and human interventions on the declining discharge of the Hablehroud River. In addition to analyzing the impact of influencing factors during the observed period, the region's future climate conditions were projected using the Canadian Earth System Model (CanESM2) under

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RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. Land-use changes and their dynamics in the study area were simulated using the Markov chain and CA-Markov models within the MOLUSCE module, an extension of the QGIS spatial information system. Future flow regime modeling under the combined influence of climate change and human activities was conducted using the GSFLOW model. Ultimately, the study provides a long-term perspective on the impacts of climate change and anthropogenic factors on the discharge of the Hablehroud River.

**Results:** The results indicate that land-use changes in the Hablehroud basin have generally shifted toward an increase in agricultural lands, gardens, and residential areas, accompanied by a decline in pasture quality and continued degradation of natural vegetation. Climatic indicators also reveal an upward trend in the average temperature of the basin, along with changes in several precipitation indices. According to the findings, a significant abrupt change occurred in the annual discharge time series of the Bonekouh hydrometric station in the mid-1990s, leading to a decline in most hydrological indices of the Hablehroud River. The separation of climate change and human intervention effects showed that human activities have had a greater impact on the reduction of discharge in the basin than climate change. Hydrological modeling using the GSFLOW model suggests that climate change and human interventions contributed approximately -50.2% and 150.2%, respectively, to changes in the discharge of the Hablehroud basin. Climate projections for the basin indicate that, for most stations and months in future periods, total monthly precipitation will show a slight increasing trend, while temperature variations will exhibit a significant rise in both average monthly maximum and minimum temperatures. Furthermore, land-use map predictions suggest an expansion of irrigated agricultural lands and a reduction in pasture vegetation cover in the future. Based on climate projections and hydrological modeling with GSFLOW, future hydrological changes in the rivers of the Hablehroud basin are expected to follow the same trends observed in the past.

**Conclusion:** Human intervention plays the most significant and influential role in the decline of the Hablehroud River's flow, primarily due to land-use changes, which serve as key indicators of such interventions. These changes are largely driven by inappropriate administrative policies implemented across the basin. Therefore, reforming management practices and implementing appropriate policies to prevent unsustainable land-use changes can have a substantial impact on stabilizing the river's discharge rate. Given the consequences of human interventions in the Hablehroud watershed such as the sharp decline in discharge rates in its tributaries and the intensification of conflicts among stakeholders it is recommended that management policies and interventions prioritize effective planning. This includes the regulation and optimization of human activities through the development and implementation of land preparation programs, as well as water consumption optimization and conservation strategies. The findings of this study can serve as a valuable reference for the future development, utilization, and management of water resources throughout the study area.

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## Introduction

Climate change and human interventions are the most important factors that in combination influence the hydrological response of a watershed system (Yao et al., 2015). The human beings, in order to increase the level of their social and economic welfare, have made serious and significant interventions in the nature and directly caused several changes in its functions and processes, particularly the hydrological cycle (Milly et al., 2005). On the other hand, the global climate change imposes several impacts on the natural hydrological cycle (Sorokin & Mondello, 2017). Therefore, separation of the effects of direct human intervention and climate change on the hydrological processes is of great importance for land use planning, water resources management, and the socio-economic development policy-making. The hydrological cycle is one of the most important natural processes that has been subjected to human interventions and climate change, whereas its various aspects and components get altered. One of these hydrological components is the river flow discharge, which is jointly affected by climate change and human interventions, and it will have dire consequences on different aspects of human life (Dey & Mishra, 2017). The human activities indirectly (through the emission of greenhouse gases) and directly (through activities such as construction of dams, water diversion structures, water consumption for agricultural activities and land use change) affect the hydrological cycle and the natural regime of river flows (Arrigoni et al., 2010). Quantification of climate change and direct human interventions contributions to streamflow alteration is a prerequisite for developing adaptation strategies and policies for regional water resources planning and management. To this end, various approaches and methods have been developed and proposed during the last decades in order to separate the contribution of natural and human-induced factors on rivers flow regime conditions.

Recent studies have extensively examined the relative impacts of climate change and human activities on streamflow reduction across various river basins. In China, Wang et al. (2013) and Guo et al. (2014) reported that while climate change contributed significantly to runoff decline (23–72%), human activities often played a dominant role, accounting for up to 77% of the reduction. Lv et al. (2018) and Xin et al. (2019) similarly emphasized the stronger influence of anthropogenic factors, with Xin et al. attributing 68% of streamflow changes in the Huifa basin to direct human actions.

In Iran, Ghasemi and Mahjuri Majid (2021), Dariane & Pouryafar (2021), and Sharifi et al. (2021) highlighted the predominance of human interventions over climatic drivers in altering discharge patterns. Rezaei et al. (2022) found rainfall variability to be more impactful than land use changes in the Kiyar watershed. Shah et al. (2022) demonstrated that climate variability was the primary driver in the Buk Han and Nam Han rivers, whereas anthropogenic activity had greater influence in the Lower Han River.

Jiang et al. (2022) and Shi et al. (2023) reinforced the dominant role of human activities in ecohydrological changes and streamflow reduction in the Weihe and Bahe river basins, respectively. Hou et al. (2023) concluded that human interventions outweighed climatic effects in the Amu Darya basin. Finally, Forootan & Sadeghi (2023) quantified the contributions to runoff changes as 21.25% from climate change and 78.75% from human activities, underscoring the prevailing influence of anthropogenic factors.

The reviewed literature highlights considerable regional variability in the influence of climate change and human activities on hydrological components, underscoring the critical need to quantify these contributions for effective land and water resource management. In this context, the present study focuses on the Hableroud watershed, a key subbasin within Iran's

central desert river basin, which has experienced notable hydrological alterations over recent decades. These changes-widely attributed by local communities and authorities to climate change-have intensified concerns regarding the sustainability of water resources. However, the relative impact of direct human interventions remains insufficiently explored. To address this gap, this research employs the integrated GSFLOW hydrological model, which combines the Precipitation Runoff Modeling System (PRMS) and MODFLOW, to disentangle and quantify the respective roles of climate variability and anthropogenic pressures in the observed discharge decline of the Hableroud watershed.

### Data and Methods

The long-term (1987-2017) recorded data of three hydrometric stations of

Namroud, Simindasht and Bonekouh across the Hableroud watershed were collected and subjected to pre-processing. Then, using the Pettit test, the significant change points in the annual discharge timeseries were identified and using the Indicators of Hydrologic Alteration (IHA) and daily discharge timeseries, the alterations in the hydrological condition were analyzed. Furthermore, land use changes and climate changes across the study area were investigated using remotely sensed images and observed climate data, respectively. The GSFLOW hydrologic model was applied to separate the effect of climate change and human interventions on discharge of the Hableroud river Figure 1 illustrates the step-by-step process of the present study in the form of a flowchart.

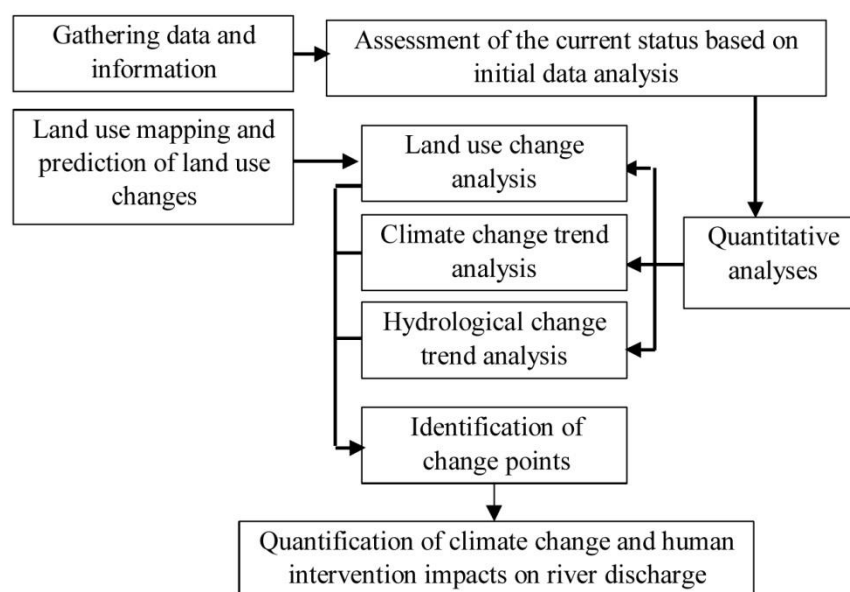


Figure 1. Research flowchart.

### Study area description

The study area of this research is upstream area of the Hableroud watershed in the north central region of Iran. This watershed is one of the important sub-basins of the central desert river basin of Iran in south of the Alborz mountain chain.

It covers an area of nearly 3200 km<sup>2</sup> between northern latitudes from 35°17'54" to 35°57'29" and eastern longitudes from 52°11'19" to 53°8'40" (Figure 2). The topography is mountainous with rugged and steep terrain and turbulent streams in deep valleys. There is a significant elevation variation from 4030 m in the northern

ridges to 1010 m at the outlet in south. The long-term mean annual precipitation of the watershed is 400 mm and mean annual temperature is 11 °C. The watershed has a rain–snow melt hydrological regime, with remarkable inter-annual and intra-annual

flow variations due to arid and semi-arid climate. The dominant land use type of the study area is rangelands (~95%), with dispersed croplands and residential area mainly located on valleys and foothills.

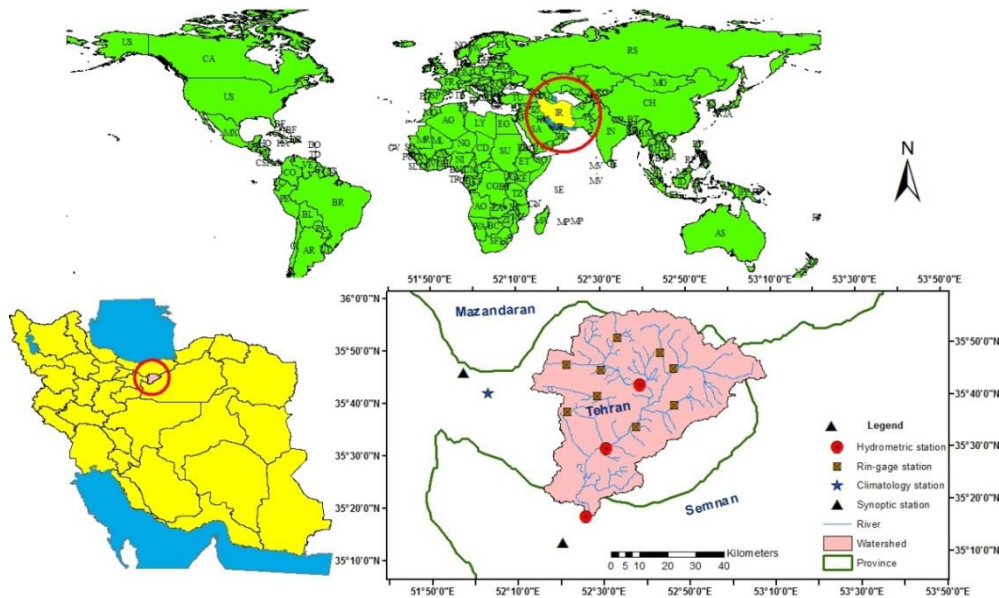


Figure 2. Geographical location of Hableroud watershed in Iran.

### Change point analysis test

The approach after Pettitt (1979) is commonly applied to detect a single change-point in hydrological series or climate series with continuous data. It uses the Mann–Whitney statistic  $U_{t,T}$ , which tests whether two samples  $x_1, \dots, x_i$  and  $x_{i+1}, \dots, x_n$  are from the same population.

$$U_{t,T} = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sgn}(x_{ji} - x_{ij}) \quad (1)$$

$$\text{sgn}(x_i - x_j) = \begin{cases} +1 & \text{if } (x_{ji} - x_{ij}) > 0 \\ 0 & \text{if } (x_{ji} - x_{ij}) = 0 \\ -1 & \text{if } (x_{ji} - x_{ij}) < 0 \end{cases} \quad (2)$$

The non-parametric test statistic (KT) and the approximate significance probability (p) for a change-point is described as (Pettitt 1979):

$$K_T = \max |U_{t,T}| \quad (3)$$

$$p \cong 2 \exp\left(\frac{-6K_T^2}{T^3 + T^2}\right) \quad (4)$$

The change-point of the series is located at  $K_T$ , provided that the statistic is significant ( $p \leq 0.05$ ) at this point.

### Hydrologic change indicators

The Indicators of Hydrologic Alteration (IHA) developed by The Nature Conservancy (TNC) as a tool to calculate the characteristics of natural and altered hydrologic regimes in the USA (Richter et al., 1996) is the most widely used index system (Xue et al. (2017)) which represents most of the important facets of the flow regime (Principato and Viggiani, 2012).

The IHA version 7.1, developed by Richter et al. (1996), includes a total of 67 statistical parameters. These parameters are divided into two groups: the parameters of hydrological change indicators (IHA parameters) and the parameters of environmental flow components. The IHA parameters consist of 33 statistical parameters that quantify various aspects of hydrological alterations, such as magnitude, duration, frequency, timing, and rate of change of flow conditions. These parameters help assess the extent to which natural flow patterns have been altered. On the other hand, the Environmental Flow Components (EFC) parameters include 34 statistical parameters that focus on characterizing the components of environmental flows, such as low flows, high flows, and flow variability. These parameters are useful for evaluating the ecological impacts of hydrological alterations (Richter et al., 1996). By calculating these 67 statistical parameters, the IHA provides a comprehensive assessment of the characteristics of natural and altered hydrologic regimes, allowing for a better understanding of the impacts of human activities on water resources and ecosystems. In this study, the parameters of hydrological change indicators were investigated. In the method of hydrological change indices, the classification of Range of Variability Approach (RVA) into low RVA, medium RVA, and high RVA is used to evaluate the degree of hydrological changes (Richter et al., 1997).

The RVA represents the natural flow regime, which serves as a reference for evaluating the alteration of flow conditions. It is based on the long-term historical flow data from a specific location or region. The RVA is characterized by its variability, including low flows, high flows, and their temporal patterns (Richter et al., 1997).

- Low RVA: This category indicates that the observed flow conditions have experienced significant alterations compared to the reference RVA. It suggests that there is a substantial reduction in flow variability,

including reduced low flows and high flows. This classification often denotes water resource systems that have been heavily regulated or impacted by water management practices.

- Middle RVA: This category suggests a moderate level of hydrological alteration. It indicates that some changes have occurred in the flow conditions, but the overall flow variability is still relatively intact compared to the reference RVA. The Middle RVA category may indicate a combination of natural and human-induced changes in the hydrological regime.

- High RVA: This category indicates a minimal level of hydrological alteration. It suggests that the observed flow conditions closely resemble the reference RVA, with minimal changes in flow variability. This classification often denotes water resource systems that have experienced minimal human intervention and retain a relatively natural flow regime.

#### Land use change assessment

In order to identify the land use types of the Hableroud watershed, a supervised object-oriented classification of the Landsat images for years 1987, 2002 and 2019 was performed within the Google Earth Engine software. To determine the classification performance, several ground truth points is required. In this study the ground truths were acquired through field visits and consultation of the high-resolution images of the Google map. The Markov chain and CA-Markov models within the QGIS extension of MOLUSCE module were used to simulate land use changes and analyze their dynamics over three decades in the study area. The Markov Chain (MC) method was selected for land-use change projection due to its ability to model transitions based on the probability of past land-use patterns. This approach is particularly suitable for regions with limited socio-economic data, as it relies on historical land-use trends rather than requiring extensive future assumptions. By

capturing the temporal dynamics of land-use changes, the MC method provides a practical and data-efficient framework for scenario development, aligning well with the study's objective of assessing the hydrological impacts of land-use transitions under different future conditions.

The CA-Markov model was employed to simulate future land-use scenarios based on historical transition probabilities derived from classified land-use maps. The underlying assumption is that past land-use change trends will persist into the future under similar socio-economic, environmental, and policy conditions. This approach assumes no major shifts in land management practices, population growth, or regulatory frameworks during the projection period. These assumptions provide a baseline for assessing potential hydrological impacts under a business-as-usual scenario.

### **Climate Change assessment**

To project future temperature and precipitation, it is essential to first identify the most suitable Atmosphere-Ocean General Circulation Model (AOGCM) and base the analysis on its outputs. This approach requires accounting for model-related uncertainties, as the variability among different AOGCMs is significantly greater than that associated with greenhouse gas emission scenarios (Massah Bavani et al., 2006). In this study, to select an appropriate model and methodology, outputs from three AOGCMs-including the American model (GFDL-CM3), the Canadian model (CanESM2), and the Russian model (Inmcm4ncml)-were evaluated. The downscaled outputs of GFDL-CM3 and Inmcm4ncml, along with the statistically downscaled results of CanESM2, were analyzed at four synoptic stations within the study area. Simulated precipitation from these models was compared with observed data over the same period, and correlation coefficients between observed and modeled precipitation were calculated. For

downscaling the CanESM2 outputs, the Statistical Downscaling Model (SDSM) was employed. Among the evaluated AOGCMs, the CanESM2 model was selected for further analysis based on its superior performance in simulating historical climate variables-particularly precipitation and temperature-over the study area. Comparative assessments at four synoptic stations showed that CanESM2 outputs, after statistical downscaling and bias correction, exhibited stronger agreement with observed data compared to the other models (GFDL-CM3 and Inmcm4ncml). Additionally, CanESM2 has been widely used in regional climate studies and is recognized for its ability to capture large-scale atmospheric circulation patterns relevant to the region. These factors, along with its compatibility with the SDSM downscaling tool, made CanESM2 a suitable choice for projecting future climate conditions in this study.

### **Separating the impact of climate variability/change and human activities on streamflow**

There are indeed numerous methods available to isolate the exclusive effects of climate change and human activities on water flow. These methods can be broadly categorized as experimental approaches, hydrological modeling, conceptual approaches, and analytical approaches.

Empirical approaches involve analyzing the time trend of observations and conducting paired basin analysis. Time trend analysis examines long-term observations of streamflow to identify any significant changes. Zhang et al. (2012) have employed the time trend method in their study. Paired watershed analysis compares the flow characteristics of two similar basins, one impacted by human activities and the other unaffected. Huang et al. (2003) and Liu et al. (2004) have utilized this method in their research.

Hydrological modeling approach involves the use of computer-based models

to simulate water flow under different scenarios, including natural conditions and altered conditions due to human activities. Examples of studies using hydrological modeling approach include Li et al. (2009), Liu et al. (2013), Farinosi et al. (2019) and Andrade et al. (2021).

Conceptual approaches include various hypotheses, frameworks, and sensitivity analysis methods. Examples include Budyko hypothesis, which suggests that changes in vegetation due to land use change can affect water flow. Liang et al. (2013), Zhang et al. (2013) and He et al (2023) have used the elasticity approach in conjunction with the Budyko hypothesis.

Analytical techniques, such as climate elasticity and hydrological sensitivity methods, are used to quantify the relative contributions of climate change and human activities to water flow. Climate elasticity measures the responsiveness of water flow to changes in climate variables. Studies by Yang and Yang (2011) and Li et al. (2018) have utilized this approach.

The methods mentioned, including those cited in the article by Dey et al. (2017), provide a comprehensive overview of the different approaches used to isolate the exclusive effects of climate change and human activities on water flow. In the current research, the hydrological modelling approach has been applied.

### Hydrological modeling approach

The methodology for distinguishing the effects of climate variability from human-induced changes in hydrological systems can be expressed through a set of mathematical formulations, as proposed by Dey et al. (2017). This approach enables researchers to quantify the relative contributions of natural climatic factors and anthropogenic interventions to observed changes in water resources, particularly river discharge. By simulating different scenarios—baseline, natural, and climate-driven—using hydrological models, the method isolates the impact of each factor.

The equations used in this framework are as follows:

$$WT = WN - WL$$

$$WC = WM - WN$$

$$WH = WT - WC$$

$$QC = \frac{WC}{WT} \times 100$$

$$QH = \frac{WH}{WT} \times 100$$

where, WT is the difference between average streamflow during the natural period (WN) and the impacted period (WL); WM, is the simulated natural streamflow of the impacted period; WC, is the streamflow variation attributed to climate change; WH, is the streamflow variation attributed to human activities; QC and QH are proportions of streamflow variation attributed to climate variability and human activities, respectively. Since, there is no operational built large hydro-structure across the river basin, the land use changes have been assumed the dominant direct human intervention affecting the hydrological regime of the study area. The hydrologic model of GSFLOW has been used to quantify the contribution of climate change and human interventions.

### GSFLOW

Over several decades, hydrologists have worked to develop an integrated view of processes and parameters important in controlling the behavior of water through the land-based portion of the hydrologic cycle. With the development of GSFLOW, a coupled groundwater/surface water model, the USGS has created a coupled hydrological modeling system for simultaneously simulating flow across the land surface, within subsurface saturated and unsaturated materials, and within streams and lakes at a watershed scale (Markstrom et al., 2008). The GSFLOW

model coupled the Precipitation Runoff Modeling System (PRMS) with the Modular Groundwater Flow Model (MODFLOW). The GSFLOW model can run either PRMS only or MODFLOW only or both. There are three conceptual regions involved in the GSFLOW model (Figure 3). The first region is between the plant canopy on the top and the soil zone on the bottom. The second region consists of streams and lakes. The third region is beneath the soil zone. In the GSFLOW model, the responses of the hydrologic processes in the first region are simulated by the PRMS model. However, the processes in two other regions are simulated with the MODFLOW model. Because the GSFLOW model integrates many simulation modules, the formats, contents, and module communications must be defined in the input files for both PRMS and MODFLOW models. All the formats of input files in the GSFLOW model had been organized based on modular modeling system files (Leavesley et al., 1996) and followed the standard MODFLOW input requirements (Harbaugh, 2005). The GSFLOW model is a physically-based model developed by the U.S. Geological Survey (USGS). The advantages of the GSFLOW model are the efficiency of PRMS modules and the well-developed MODFLOW-2005 packages that can provide detailed dynamics of the

surface and groundwater flows. The model uses a flexible and adaptive modular design framework and allows simulations to be performed by only PRMS MODFLOW-2005 or both. In the GSFLOW model, the coupling process employs iterative techniques to solve interdependent governing equations for surface water and groundwater flow. The calculations of detailed water balances in time and space are available in the models. The model also allows flexible spatial discretization of the hydrologic response units (HRUs) used for PRMS and the finite difference grid used for MODFLOW-2005 (Markstrom, 2008).

While GSFLOW provides a robust framework for simulating coupled surface and groundwater processes, several limitations and sources of uncertainty should be acknowledged. These include potential inaccuracies in input data (e.g., land use maps, climate records), sensitivity of key model parameters, and structural assumptions within the model that may not fully capture local heterogeneity. Additionally, scenario-based simulations rely on assumptions about future climate and land use conditions, which introduce further uncertainty into the attribution of hydrological changes. Despite these constraints, calibration and validation procedures were carefully conducted to minimize model bias and improve reliability.

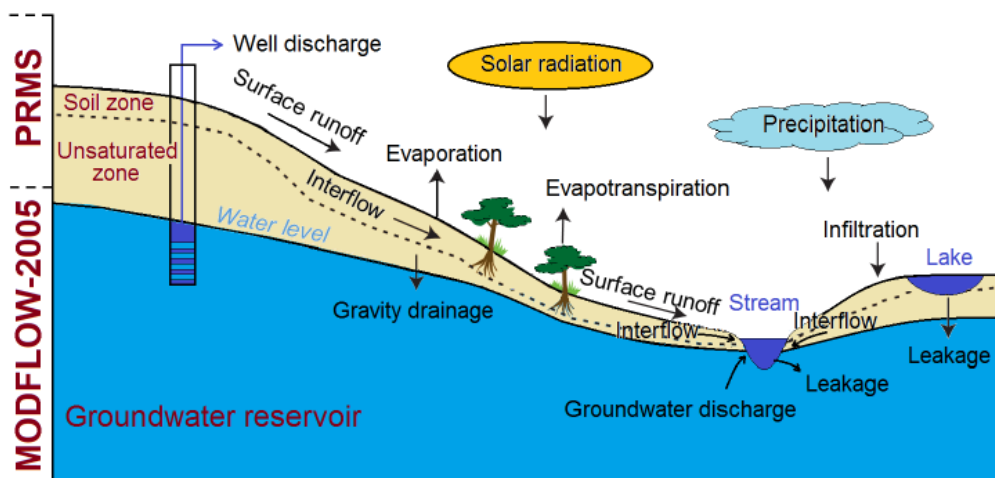


Figure 3. The three regions for the GSFLOW model, including the plant canopy and the soil zone, the streams and lakes, and the unsaturated zone and the aquifer system (Tran et al., 2020).

## Model calibration and validation

The calibration and validation of the GSFLOW hydrological model to simulate the hydrologic response of the Hableroud watershed was done using PEST software, which is a specialized software for automatic optimization of parameters and sensitivity analysis, calibration and validation (Doherty et al., 2005). The statistical periods of 1986 - 1991 and 1992 - 1997, were used as calibration and validation

periods, respectively. It is noteworthy that due to unavailability of enough temperature data, the simulation period was started from 1986, while for the other analyses, data during 1981 - 2017 were used. The Nash-Sutcliffe coefficients of efficiency, R-squared correlation and root-mean-square error were considered as the model performance criteria. After a sensitivity analysis of the GSFLOW model parameters, the following parameters were selected for calibration (Table 1).

**Table 1. The selected parameters for calibration of the GSFLOW model (Markstrom et al. (2008)).**

Parameter	Description
careax_max	Maximum possible area contributing to surface runoff, expressed as a decimal fraction of HRU area
slowcoef_lin	Linear flow-routing coefficient for slow interflow
slowcoef_sq	Non-linear flow-routing coefficient for slow interflow
gwflow_coef	Linear coefficient to route water in ground-water reservoir to streams
gwsink_coef	Linear coefficient to route water in ground-water reservoir to ground-water sink
ssr2gw_exp	Exponent in the equation used to compute gravity drainage to PRMS ground-water reservoir or MODFLOW finite-difference cell
ssr2gw_rate	Linear coefficient in the equation used to compute gravity drainage to PRMS ground-water reservoir or MODFLOW finite-difference cell
pref_flow_den	Decimal fraction of the soil zone available for preferential flow
smidx_coef	Coefficient in non-linear contributing area algorithm
smidx_exp	Exponent in non-linear contributing area algorithm
rain_adj	Monthly factor as a decimal fraction used to adjust rain at the HRU
snow_adj	Monthly factor as a decimal fraction used to adjust snow at the HRU

## Results

### Descriptive analysis of changes

The statistical analysis of the long-term recorded hydrometry data across the Hableroud watershed indicates a statistically significant change point in mid 1990s (Figure 4). The identification of change points in the streamflow time series is one of the key findings of this study, indicating significant shifts in the

hydrological conditions of the watershed. A closer examination of these points reveals that some coincide with regional climatic changes, such as temperature increases or reduced precipitation during specific periods. Additionally, major land-use changes such as agricultural expansion or urban development and the implementation of certain management policies or water resource regulations may have contributed to the emergence of these change points. Analyzing these connections provides a

deeper understanding of the interactions between natural and human factors in shaping streamflow patterns. As shown in Figure 5, most of the Indicators of Hydrologic Alteration (IHA) reflect a deterioration in the hydrological condition of the study area following the identified change point. For most of the hydrological indicators, the frequency of the low values category has increased and the frequencies of the middle and high values categories have decreased after the mid 1990s. Also, the frequency of low values category of the mean monthly discharge for all months of the year and the base flow of the basin has significantly decreased. Both the frequency and duration of low flow pulses have increased, aggravating the water shortage and tension challenges across the area, particularly conflict rising among the stakeholders in upstream, midstream, and downstream. On the contrary, both the frequency and duration of the high flow

pulses have decreased. For this reason, the frequency and magnitude of high extreme events such as medium and large floods have decreased (Figure 5). The average monthly discharge also decreased in the period after the change point compared to the period before the change point (Figure 6). Also, the mean annual discharge of the watershed at the Bonekouh station at the outlet of the watershed, has declined from 8.83 m<sup>3</sup>/s during the pre-impact period to 5.20 m<sup>3</sup>/s during the post-impact period, which is equivalent to about 41 percent decline in watershed outflow. While, the watershed's mean annual precipitation does not indicate any significant decreasing trend. It even shows a negligible increment after year 2000. However, all the previous climate change studies across this watershed, reported a significant increasing trend for most of the temperature indicators (Naderi et al., 2023, Salehpoor et al., 2019).

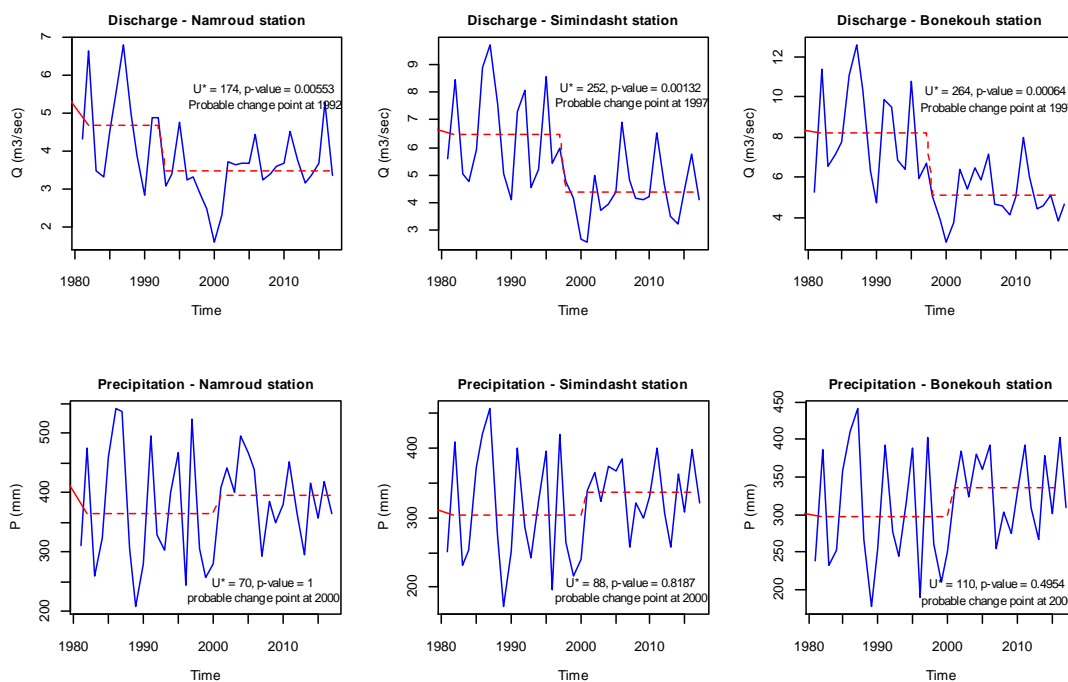


Figure 4. The change point detected for the average annual discharge timeseries at the hydrometric stations of the Hablehroud watershed.

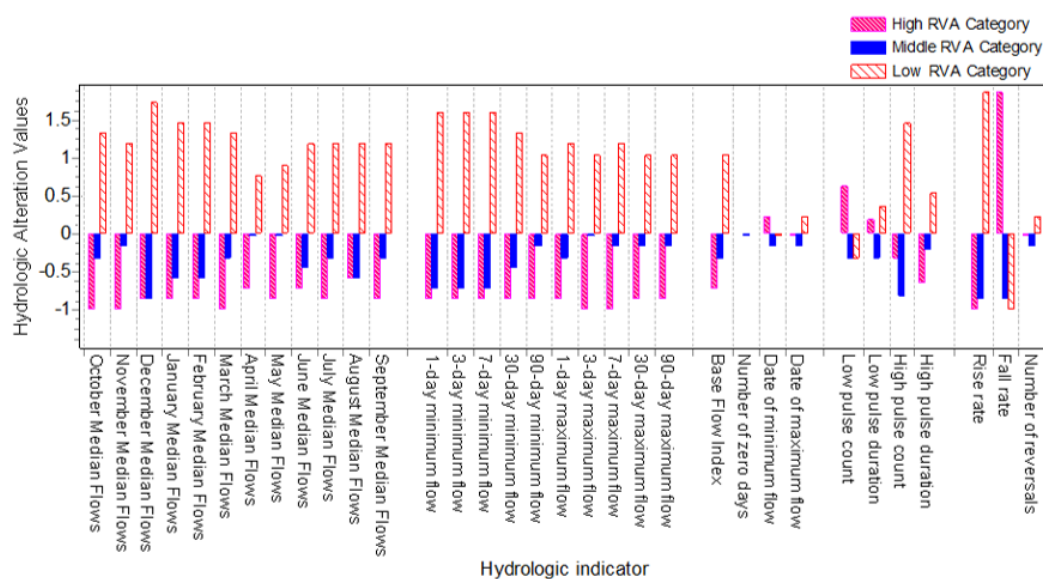


Figure 5. The RVA approach results for the Bonekough station at the outlet of the Hableroud watershed.

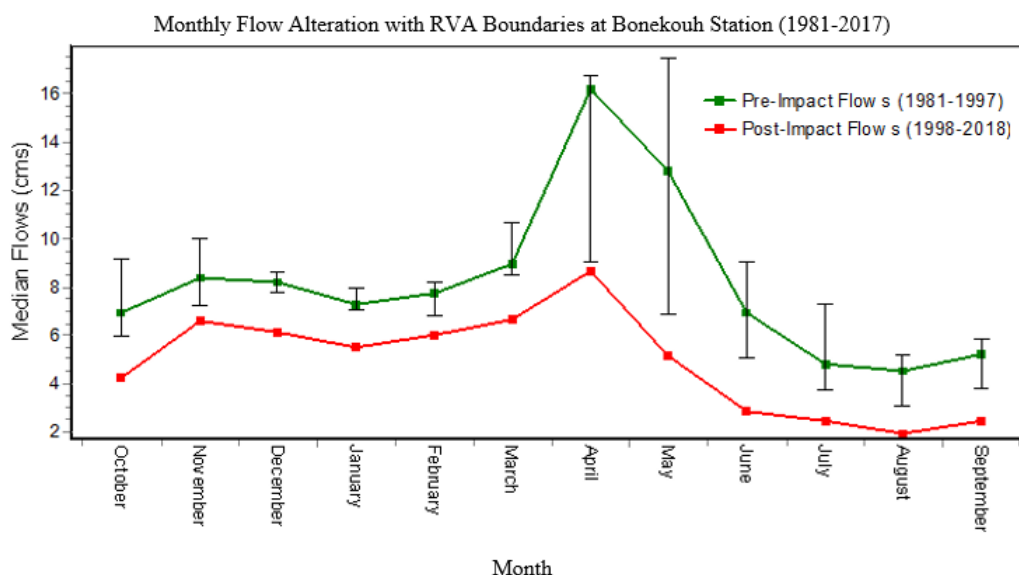


Figure 6. Monthly median discharge at the Bonekough station during the pre-impact and post-impact periods.

Since land use and land cover changes are considered the most important direct drivers of ecosystem changes over the last decades (Millennium Assessment, 2005), land use changes of the study area over the last three decades (1987 - 2019) were modeled using the satellite images and stochastic process models and projected up till 2050 (Figure 7). The overall accuracy percentage of more than 88 and the Kappa coefficient of more than 0.86 indicates a good performance of the applied

classification method in this study (Table 2). The statistics of land use changes during 1987 - 2050 across the Hableroud watershed have been summarized in Table 3. As seen, during 1987 - 2019, the area coverage of the irrigated agriculture, rainfed agriculture, and residential areas have increased by about 67.5, 20, 21 km<sup>2</sup>, respectively. Furthermore, the natural vegetation cover of the watershed has been deteriorated. Whereas, the area coverage of good and moderate rangelands has been

remarkably decreased, while the area coverage of poor rangelands has been escalated during last decades. If this retrograding trend continues, during 2019 - 2050, the extent of the irrigated areas, poor and medium class rangelands will respectively increase by about another 20, 50, and 50 km<sup>2</sup>, while the extent of the

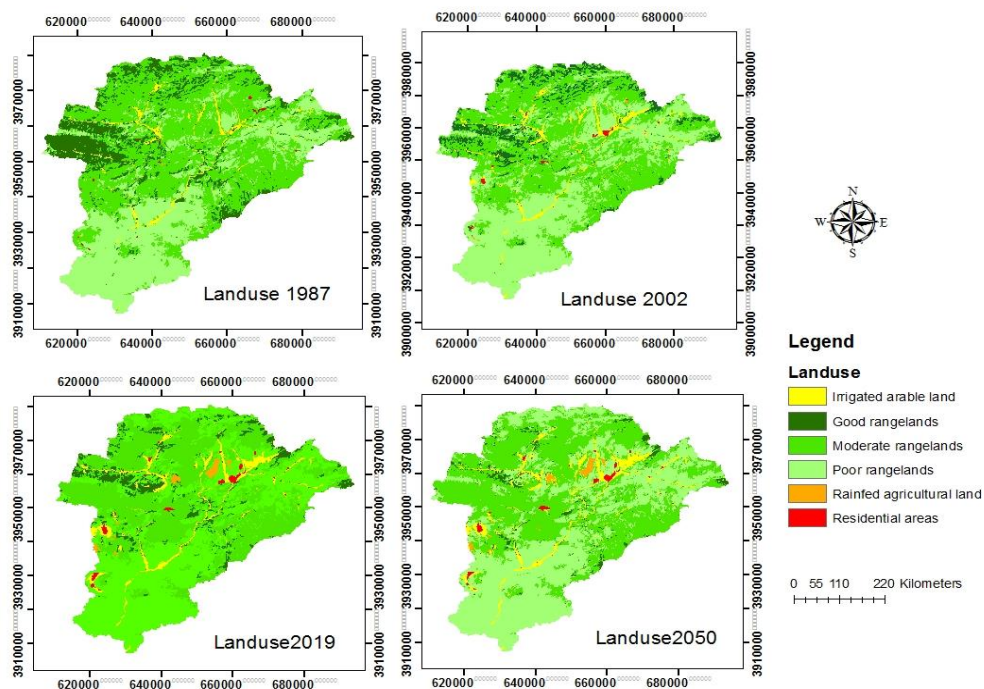
good rangelands will shrink about 127 km<sup>2</sup>. The extent of the residential areas will increase too. It is noteworthy that changes in land use types are dominant in valley beds, plains and piedmonts adjacent to residential areas, while natural vegetation cover changes are dominants on mountains and remote areas (Figure 7).

**Table 2. Accuracy of object-oriented supervised classification in detecting land use types.**

Evaluation criteria	Object-oriented approach		
	1987	2002	2019
Overall accuracy(%)	95.53	91.95	88.48
Kappa coefficient(%)	94.31	90.08	86.06

**Table 3. The summary statistics of land use changes during 1987 – 2050 across the Hableroud watershed.**

Land use	Area (km <sup>2</sup> )				Changes (km <sup>2</sup> )		
	1987	2002	2019	2051	1987-2002	2002-2019	2019-2051
Irrigated arable land	74.96	104.3	142.41	162.32	29.34	38.11	19.88
Rainfed agricultural land	5.03	3.99	25.69	23.55	-1.04	21.71	-2.16
Good rangelands	454.23	429.83	213.56	86.15	-204.44	-36.29	-127.55
Moderate rangelands	1580.38	1482.31	1384.07	1436.83	-97.88	-98.27	52.02
Poor rangelands	1114	1377.59	1441.73	1499.81	263.59	64.04	56.95
Residential areas	2.27	12.69	23.40	24.26	10.43	10.71	0.85



**Figure 7. Land use and land cover maps of 1986, 2002, 2019 and 2050 in the Hableroud watershed.**

### Hydrological modeling analysis

Hydrological modeling is a well-known and most used approach for separating the impact of climate change and direct human interventions on alteration of the hydrological systems in previous studies (Liu et al. (2020), Tang et al. (2021) and Li et al. (2023). In this research, the GSFLOW model was applied to simulate

and quantify the impact of climate change and human intervention on the hydrological response of study area. In Table 4 the initial and optimized values of the model's calibration parameters have been shown. For other parameters of the model that are not included in this table, the default values proposed by Markstrom et al. (2008) were used.

**Table 4. The initial and optimized values of the model parameters selected for calibration of GSFLOW model to the Hableroud watershed.**

Parameter	Initial value	Optimal value
care_max	0.5	0.44
slowcoef_lin	0.015	0.038
slowcoef_sq	0.1	0
gwflow_coef	0.015	0.007
gwsink_coef	0.01	0
ssr2gw_exp	1	1.43
ssr2gw_rate	1	0.30
pref_flow_den	0.2	0.02
smidx_coef	0.01	0.0001
smidx_exp	0.3	0.2
rain_adj	1	0.68
snow_adj	1	1.35

The comparison of observed and simulated hydrographs by GSFLOW model in calibration and validation periods is presented in Figure 8. The model performance statistics including the Nash-Sutcliffe coefficients of efficiency,

R-squared correlation and root-mean-square error at three hydrometric stations of Bonekouh, Simindasht, and Namroud across the Hableroud watershed are summarized in Table 5.

**Table 5. The performance criteria for the GSFLOW model application in the Hableroud watershed.**

	Period	NS	R <sup>2</sup>	RMSE
Bonekouh	Calibration	0.611	0.783	3.81
	Validation	-0.206	0.435	5.85
Simindasht	Calibration	0.690	0.836	2.21
	Validation	0.671	0.838	2.20
Namroud	Calibration	0.496	0.764	1.92
	Validation	0.675	0.844	1.25

Generally speaking, the performance of the GSFLOW model across the study area is satisfactory, except for the validation period at the Bonekouh hydrometric station (McCuen et al., 2006). The weak performance of the model at the Bonekouh station is due to the construction of a diversion structure and water abstraction from the Hableroud river at a point upstream of the Bonekouh hydrometric station. In other words, a portion of the Hableroud river flow during normal and low flow conditions is diverted to a man-made lined channel running parallel to the natural Hableroud river course and transfer water for irrigation purpose in the Garmsar plain at downstream of the Hableroud watershed, within the jurisdiction of the Semnan province. Therefore, it can be concluded that GSFLOW has an acceptable ability to simulate the hydrologic processes of the Hableroud watershed and to be used for separation of the impact of climate variables from the human interventions on

different components of the watershed hydrologic balance. The negative Nash-Sutcliffe Efficiency (NSE) value observed at one of the validation stations indicates that the model's predictions at this location are less accurate than the mean of the observed data. To investigate this issue, we considered several potential contributing factors. First, data quality concerns-such as missing records, measurement errors, or inconsistencies in the observed time series-may have affected model calibration. Second, structural limitations of the model, including its ability to represent localized hydrological processes or anthropogenic modifications, could have influenced performance. Finally, unaccounted human activities such as upstream water diversions, withdrawals for irrigation, or land-use changes may have altered the natural flow regime. These factors are discussed to provide a more comprehensive understanding of the model's limitations and guide future improvements.

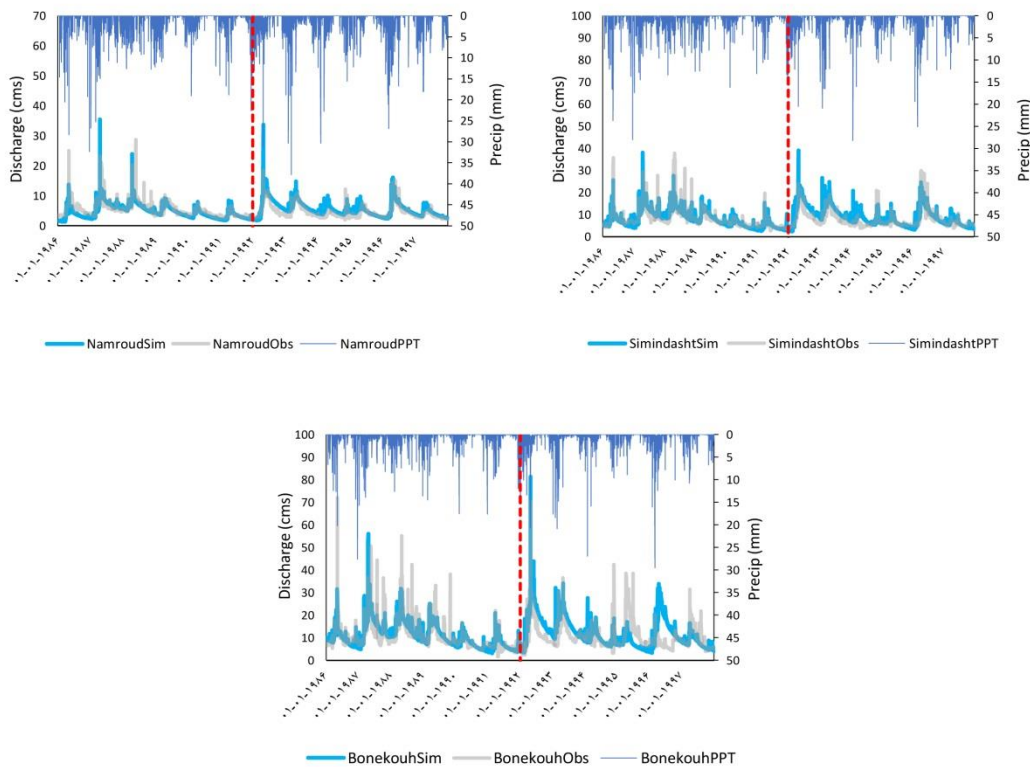


Figure 8. Comparison of the observed and simulated hydrograph with the GSFLOW model, at three hydrometric stations across the Hableroud watershed (red dashed line separates the calibration and validation periods).

### The Water balance components analysis

Compared to the empirical and analytical approaches, it is a privilege of the hydrological modelling approach that provides many important information about the hydrological process components. For example, the content of the output file of the GSFLOW model at the Bonekouh hydrometry station has been depicted in Figure 9. As seen in this figure, the information about direct forcing variables (precipitation, minimum and maximum temperature), the preprocessed intermediate forcing variables (rain, snow, potential evapotranspiration, and actual evapotranspiration), hydrological process components (simulated total discharge, surface runoff, subsurface flow, groundwater flow, and recharge), and some other useful hydrological information (snow cover and snowpack water equivalent) has been produced using the hydrological model. To this end, after calibration and validation of the GSFLOW model during 1986 - 1997, it was used to simulate the hydrological balance of the Hableroud watershed from 1986 to 2017 to quantify the contribution of climate variables change on the hydrologic response of the watershed and separate their impacts from the direct human interventions. Furthermore, the trend in different components of water balance of the watershed was analyzed using the Mann-Kendall test.

In order to separate the impact of climate change and direct human intervention using the hydrological modelling approach, the mean annual flow rates were calculated from the simulated daily discharge data and plotted together with their counterpart observed data at the locations of three hydrometric stations of Namroud, Simindasht, and Bonekouh (Figure 10). As can be seen, in the years before the significant change point (mid 1990s), the simulated and observed discharges are close to each other, but after the change point, the simulated values are higher than the observed values, which can be attributed to human interventions. Interestingly, the disparity of simulated and observed flow rates after the significant change point increases from the upstream station (Namroud) to downstream station (Bonekouh). This indicates that impact of the most direct human intervention such as land use change and water abstraction on the hydrologic response of the watershed is more pronounced than the least direct human intervention such as deteriorating the natural vegetation cover due the overgrazing. As mentioned earlier in the Descriptive analysis of changes section, the most land use type changes have been occurred in the midstream and downstream parts of the watershed on valley beds, plains and piedmonts adjacent to residential areas. In fact, the intensity of changes in land use types is less pronounced in the sub-watershed draining to the Namroud hydrometric station.

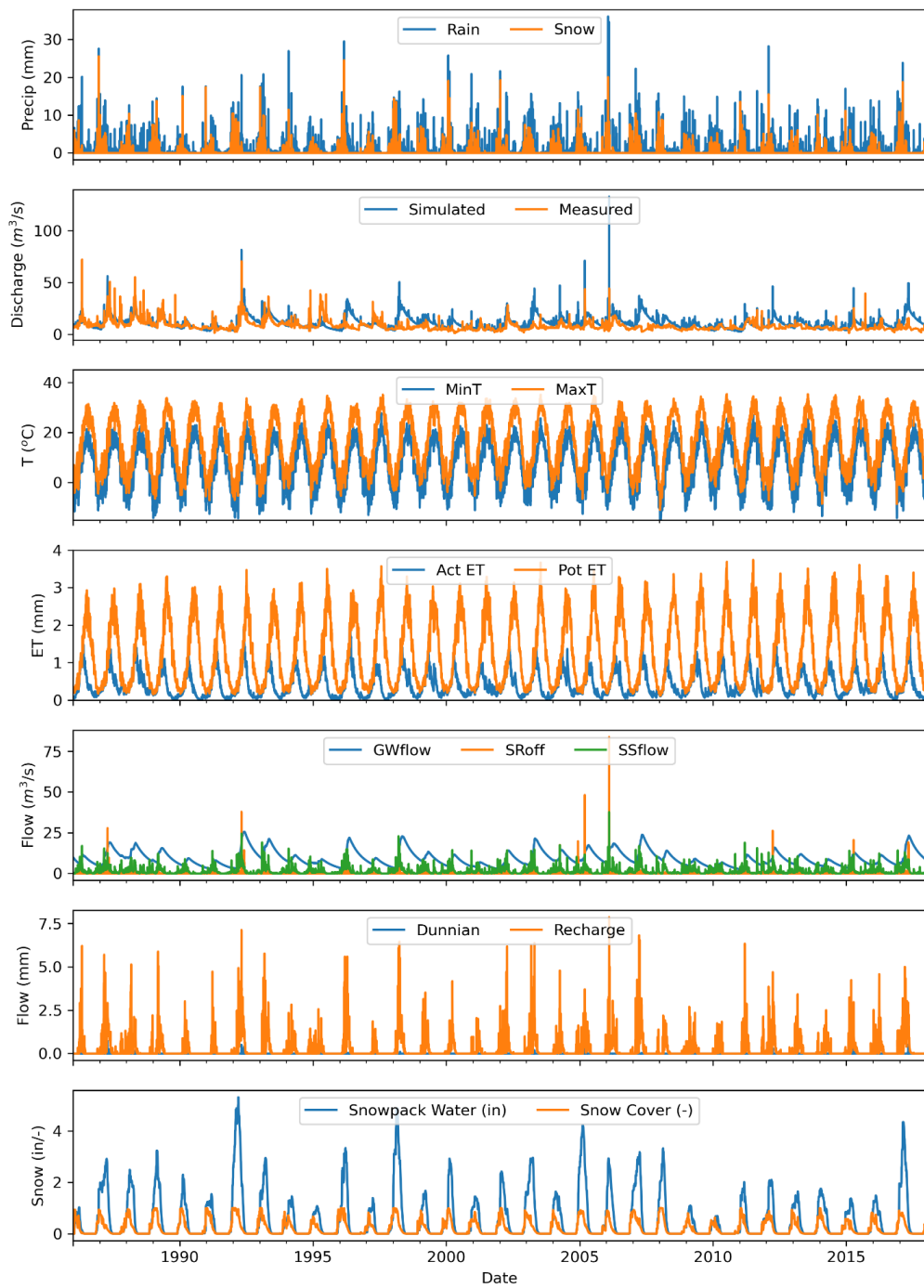


Figure 9. The GSFLOW simulated hydrological balance components at the Bonekouh hydrometry station.

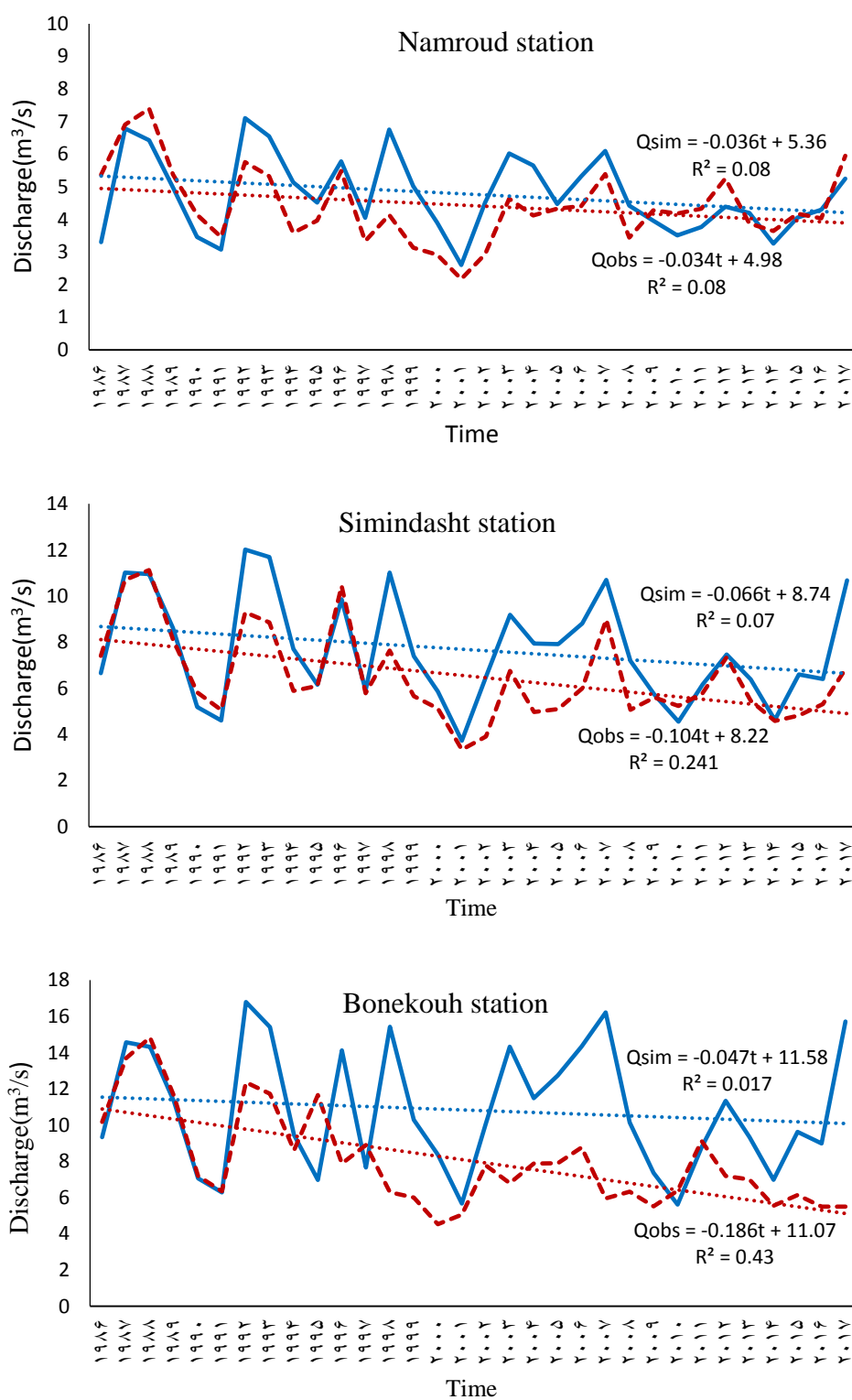


Figure 10. Observed and simulated average annual discharge trend at Hableroud watershed.

The absolute and relative values of changes in stream flow across the Hableroud watershed caused by the climate change and direct human interventions have been summarized in Table 6. As seen, the contribution of human interventions on the hydrologic change is much strongly marked in midstream and downstream section of the watershed. The positive value of streamflow variation attributed to climate change (1.82) for the Bonekouh station denotes that if the climate change is the mere factor driving the hydrological change, we should expect an increase in the observed values of streamflow at the Bonekouh station after the change point in 1997. The formula used to determine the

relative contribution of climate change and human activities to streamflow variations enables a quantitative comparison of their individual impacts. This formulation allows contribution values to exceed 100% or fall below 0% in cases where the effects of climate and human factors interact nonlinearly or offset each other. For instance, a contribution greater than 100% may occur when one factor alone accounts for more than the total observed change due to compensating effects from the other factor. Conversely, a negative contribution indicates that the factor in question influenced streamflow in the opposite direction of the overall observed change.

**Table 6. The contribution of climate change and direct human interventions on stream flow across the Hableroud watershed.**

Variable	Namroud	Simindasht	Bonekouh
Average streamflow in natural period (m <sup>3</sup> /sec)	5.49	7.88	8.83
Average streamflow in impacted period (m <sup>3</sup> /sec)	4.12	5.68	5.20
Absolute change in the streamflow after change point (m <sup>3</sup> /sec)	-1.37	-2.20	-3.63
Simulated natural streamflow during impact period (m <sup>3</sup> /sec)	4.70	7.24	10.66
Absolute streamflow variation attributed to climate change (m <sup>3</sup> /sec)	-0.79	-0.64	1.82
Relative streamflow variation attributed to climate change (%)	57.59	29.07	-50.18
Absolute streamflow variation attributed to human activities (m <sup>3</sup> /sec)	-0.58	-1.56	-5.46
Relative streamflow variation attributed to human activities (%)	42.41	70.93	150.18

As mentioned earlier in this section, the principal advantage of the hydrological modeling approach over empirical and analytical approaches of separating the impacts of climate change and human intervention on hydrological change, is the provision of many useful information on different hydrological process components. We used this detailed information to analyze the long term trend in the directly used observed forcing variables and the indirectly used preprocessed intermediate forcing variables as well as the hydrological process components variables across the

watershed using the Mann-Kendall trend test (Figure 11). As clearly depicted in Figure 11, among the major climate forcing variables, the temperature indices (minimum and maximum temperatures) show statistically significant (P-value < 0.05) increasing trend resulting in an increase in the evapotranspiration loss and a decrease in the snow fall, cover, and equivalent water, particularly in upstream areas. Although not statistically significant, the total precipitation of the watershed shows a decreasing trend. Except the basin surface runoff, all other water balance components

represent a decreasing trend, although not statistically significant. As can be noticed, the magnitude of trend for the water balance components at the Namroud station is higher than the other two stations, whereas it is significant for the groundwater flow component at the significance level of 0.1 ( $P$ -value  $< 0.1$ ). Since, the land use map of 1987 has been used for hydrological

simulation of the watershed with the GSFLOW model, it can be concluded that despite a significant increasing trend for temperature and decreasing trend for snow cover, the impact of changes in climate variables does not suffice to cause a significant change in water balance components in midstream and downstream sections of the Hableroud watershed.

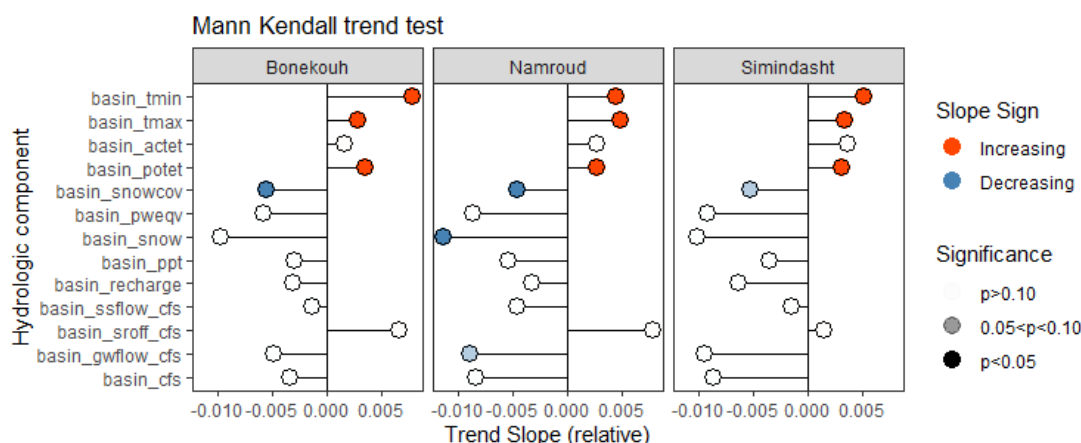


Figure 11. Trend of hydrologic balance components simulated with GSFLOW for hydrometry stations across the Hableroud watershed.

## Discussion and Conclusions

Hydrological regimes play a critical role in shaping the structure and function of ecological processes and river ecosystems. Significant changes in river flow regimes lead to spatial and temporal heterogeneity within river systems, degrade natural ecosystem services, and pose threats to biodiversity. The primary objective of this study is to quantify the respective contributions of climate change and direct human interventions to streamflow alterations in the Hableroud watershed using a hydrological modeling approach. While various methods exist to separate the impacts of climate change and human activities on hydrological changes, hydrological modeling offers distinct advantages due to its ability to generate detailed insights into different components of the hydrologic cycle.

To achieve this goal, the coupled groundwater and surface water flow model GSFLOW was applied to quantify and separate the impacts of climate change and human interventions on hydrological alterations in the inter-provincial Hableroud watershed, which spans upstream areas in Tehran Province and downstream regions in Semnan Province. Conflicts over water distribution and access between these provinces and local communities have intensified in recent years. Climate change, land use changes, and excessive water abstraction in upstream areas are cited as major causes of a roughly 40% decline in the annual discharge of the Hableroud River over the past three decades (Naderi et al., 2023). However, the prevailing perception among provincial and local authorities, as well as the general public, is that climate change is the primary driver of this decline. Although climate change is undeniably occurring in the region,

substantial land use and land cover changes particularly the expansion of irrigated agriculture have significantly influenced the watershed's hydrological response.

Given these dynamics, it is essential to determine the proportion of hydrologic alteration attributable to climate change versus human interventions, in order to develop effective strategies, policies, and sustainable development plans for the watershed. To this end, descriptive analyses and hydrological modeling were conducted. The descriptive analysis revealed a statistically significant change point in the annual discharge time series of the watershed's hydrometric stations in the mid-1990s, with most hydrological indicators showing deterioration in the watershed's condition. The mean annual discharge declined from 8.83 m<sup>3</sup>/s during the pre-impact period (1981–1997) to 5.20 m<sup>3</sup>/s in the post-impact period (1998–2017), accompanied by a significant drop in the baseflow index and a notable increase in low-flow frequency. These severe hydrological changes have triggered various socioeconomic and environmental issues, including escalating tensions between upstream and downstream communities and growing inter-provincial disputes. Moreover, these conditions threaten riparian plant and animal communities, degrade ecosystem services, and increase the vulnerability of floodplain infrastructure to potential flooding—ultimately resulting in substantial damages.

The study of land use changes across the Hablehroud watershed indicates an extensive land use conversion from natural rangelands to irrigated agriculture and residential areas during the last three decades. Furthermore, the quality of natural vegetation cover has undergone a significant retrogression trend. These conditions have certainly impacted the hydrologic status of the watershed and quantification of these impacts is of vital importance. The results of hydrological simulation using the GSFLOW model helped to quantify the impacts of land use

and land cover changes and separate these impacts from the impact caused by climate change on the hydrologic condition of the Hablehroud watershed. According to the results of the hydrological modeling approach, the contribution of climate change and human interventions on discharge decline varies across the watershed. Whereas, the contribution of climate variables on hydrologic alteration in upstream areas is slightly higher and decreases towards the downstream areas. This connotes that the impact of human interventions on hydrologic alteration is more pronounced towards the downstream areas of the watershed. These findings contradict the dominant misconception among the authorities and general public that introduce the climate change as the major or even mere culprit of discharge decline across the Hablehroud watershed. Therefore, management policies and priorities should be focused on managing and optimizing human interventions, promoting public awareness, optimal using of water resources, and preventing over-exploitation of water resources across the watershed. It is suggested that provincial and local policymakers and authorities and water resources managers should develop and enact strategies and policies in order to monitor and improve the human activities influencing the natural water cycle. The results of this study can provide a scientific guide for the development, utilization, and management of regional water resources and ecological environment protection.

Based on the mentioned research study, it can be concluded that human interventions have played a significant role in the decrease in the water flow of the Hablehroud River. This conclusion is consistent with the findings of, Guo et al. (2014), Lv et al. (2018), Xin et al. (2019), Ghasemi and Mehjuri Majd (2021), Sharifi et al. (2021), Liu et al. (2021), Dariane & Pouryafar (2021), Hou et al. (2023) and Forootan & Sadeghi (2023). However, there are also some research studies such as

Wang et al (2013), Rezaei et al (2022), Jiang et al (2022), and Shi et al (2023), that do not align with this conclusion, suggesting other factors or processes impacting river flow. The results of this research can be valuable for stakeholders in the Hableroud watershed, providing insights into the reasons behind the decrease in river flow and encouraging them to reconsider their perspectives and implement appropriate measures to reduce human interventions and mitigate the impacts on river flow. It is important to note that further studies and a comprehensive understanding of the specific factors and processes in the Hableroud watershed are needed to develop effective management strategies and address the conflicts over water distribution and access.

This study demonstrated the effectiveness of integrating the GSFLOW hydrological model with land-use change analysis to disentangle the impacts of climate variability and human interventions on streamflow alterations in the Hableroud watershed. The methodological contribution lies in the ability of this coupled modeling approach to simulate complex surface-groundwater interactions while accounting for dynamic land-use transitions. Applying scenario-based simulations, the study provided a quantitative assessment of the relative influence of climate change and anthropogenic activities, offering a transparent and replicable framework for future watershed management and policy development. Future research could focus on incorporating higher-resolution remote sensing data, exploring the role of groundwater abstraction patterns in more detail, and integrating socio-economic scenarios to assess the long-term implications of land and water management strategies. Such efforts would further refine the understanding of hydrological responses under changing environmental and human pressures and support more adaptive and equitable watershed governance.

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### **Financial Interests**

The authors have no relevant financial or non-financial interests to disclose.

### **Ethical Approval**

We follow the principles of ethics, in conducting and publishing this research.

### **Consent to Participate**

The authors are consented to participate in the research.

### **Consent for Publication**

The authors are contented with the publication of the results.

### **Availability of Data and Materials**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### **Authors' contribution**

The first author: Preparation of data, preparing maps, simulation and statistical analysis, and preparing the manuscript. Second author: guiding and supervising the basics and concepts of the research,

modeling and performing calculations, writing and revising the manuscript.

The third author: providing advice on the basics and concepts of research

The fourth author: providing advice on the basics and concepts of research

Fifth author: Consulting on conducting research and field survey

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