A Scenario-Based Approach for Assessing the Hydrological Impacts of Land Use and Climate Change in the Marboreh Watershed, Iran

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Abstract

In separate analyses of the impacts of land use change and climate change, a scenario-based approach using remote sensing and hydro-climatological data was developed to assess changes in hydrological indices. The data comprised three Landsat TM images (1988, 1998, 2008) and meteorological and hydrological data (1983–2012) for the Aligudarz and Doroud stations in the Marboreh watershed, Iran. The QUAC module and supervised classification maximum likelihood (ML) algorithm in ENVI 5.1 were used for remote sensing, the SWAT model for hydrological modelling and the Mann-Kendall and *t* test methods for statistical analysis. To create scenarios, the study period was divided into three decades (1983–1992, 1993–2002, 2003–2012) with clearly different land use/land cover (LULC). After hydrological modelling, 10 hydrological indices related to high and low flow indices (HDI and LDI) were analysed for seven scenarios developed by combining pre-defined climate periods and LULC maps. The major changes in land use were degradation of natural rangeland (– 18.49%) and increasing raid-fed farm area (+ 16.70%) and residential area (+ 0.80%). The Mann-Kendall test results showed a statistically significant ($p < 0.05$) decreasing trend in rainfall and flow during 1983–2012. In the scenarios evaluated, hydrological index trends were more sensitive to climate change than to LULC changes in the study area. Low flow indices were more affected than high flow indices in both land use and climate change scenarios. The results show little impact of land use change and indicate that climate change is the main driver of hydrological variations in the catchment. This is useful information in outlining future strategies for sustainable water resources management and policy decision-making in the Marboreh watershed.

Keywords Land use/land cover · Climate variability · Scenario · Hydrological indices

1 Introduction

An increasing amount of water is required to meet the growing human demand for food world-wide, causing conflicts between water supply and demand in water-scarce regions [77]. Climate change and changes in land use/land cover (LULC) are the main factors influencing water availability, as they can alter hydrological processes (e.g. flood frequency, severity and annual mean discharge). Thus, assessing the impacts of LULC change (LULCC) and climate change on hydrological conditions has become one of the greatest

challenges in hydrological research [29, 77]. Moreover, LULCC and climate change/variability (i.e. anthropogenic and natural) are both likely to affect the hydrological cycle and consequently water resources in many river basins (e.g. [26, 76]; Pervez and Henebry 2015; [18, 36, 77]). It is important to assess such changes and a number of studies have already demonstrated that human activities such as LULCC can lead to changes in the hydrological response of watersheds (e.g. [71, 77, 78]) and that climate change/variability can affect precipitation, runoff and flood frequency (e.g. [5, 8, 9, 24, 28, 42, 56, 58, 61, 63, 73]).

Changes in LULC affect partitioning of precipitation through vegetation and soil into the main water balance components of interception, infiltration, evapotranspiration, surface runoff and groundwater recharge [66, 74]. In arid and semi-arid regions, the climate and LULC are closely linked and these links must be understood when seeking to assess climate change impacts on hydrology, water resources and associated ecosystem services [74]. Moreover, climate change/variability is expected to affect precipitation and

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evapotranspiration patterns, a process which is not well understood, but will affect regional and local water availability, river hydrology and the seasonal availability of water supply [3, 8, 27, 65]. Many studies have examined the impacts of LULC change and climate change on watershed hydrology (e.g. [2, 6, 23, 25, 32, 34, 37, 39, 54, 64, 68, 72, 77, 79]). Others have assessed the combined effect of LULC change and climate change on the quantity and quality of water resources (e.g. [12, 26, 55, 60, 69, 75]). Most of those studies have analysed the effects of LULCC and climate change using hydrological models ranging from very simple water balance models to complex models such as the Annualized Agricultural Non-Point Source model (AnnAGNPS) and Soil Water Assessment Tool (SWAT), which are able to simulate a variety of water resource components [12, 79].

Research to date has improved understanding of the impacts of climate change and LULCC on hydrology and water resources and water availability, especially at large scales. However, determining how climate change and LULCC might affect hydrological conditions regionally and locally is a challenge, as the extent of climate change and LULCC at regional level is uncertain, especially in developing countries where there is a lack of data. For efficient hydrology and water resource management, there is a clear need to understand flow variability over time and extreme endpoints. Therefore, the aim of this study was to develop and refine a framework for analysis of extreme hydrological responses to LULCC and climate change in terms of daily flow regime. The novel contribution of this framework is generation of data on potential hydrological changes based on observed hydrological, land use and climate data. In addition, the focus is mainly on extreme data, through indices related to low flow (LDI) and high flow (HDI), whereas in most previous studies on hydrological changes, the major emphasis has been on mean values (e.g. [26, 46, 54, 81]). Identifying any hydrological changes that occur, especially in low-flow conditions, would help in devising a solution to protect ecological processes through environmental flow allocation [80]. It would also assist in the development of adaptation and mitigation strategies regarding climate change and land use change for critical natural habitats. In this study, the framework was tested by applying it to the case of the Marboreh River (located in the semi-arid region of Iran), which is a very important habitat for many aquatic species. The analysis was based on data from three Landsat TM images (1988, 1998, 2008) and on meteorological and hydrological data (1983–2012) recorded at the Aligudarz and Doroud stations in the Marboreh watershed. The SWAT model and statistical analysis were also used in analysis of scenarios, to distinguish the impacts of LULCC from those of climate change/variability. The aim was to achieve a better understanding of the impacts of LULCC and climate change on water resources, information which is needed by planners and decision makers.

2 Methods and Materials

2.1 Case Study and Data

The Marboreh watershed (2710 km²) extends between 49° 03' 51" to 49° 58' 22" East and 33° 11' 05" to 33° 49' 45" North (Fig. 1). The climate in the region is semi-arid (aridity index 0.326), with 397-mm annual precipitation (mean 1983–2012) and 1215-mm potential evapotranspiration based on the Thornthwaite equation [51]. Mean annual runoff (R) for 1983–2012 was 256 mm/year, resulting in a long-term runoff to precipitation ratio (R/P) of 0.64. Climate data (1983–2012), including daily rainfall, maximum and minimum temperature, wind speed and relative humidity observations for the Aligudarz station, were obtained from the Iranian Meteorological Organisation (IRIMO). Data on observed daily discharge at the Doroud station (located at the outlet of the Marboreh watershed) were obtained from Lorestan Regional Water Authority. The soil in the watershed consists of four types [15]. The digital elevation model (DEM, 30 m) for the area was downloaded from the USGS Server. Land use data in 1988, 1998 and 2008 were prepared from Landsat images.

2.2 Land Use/Land Cover Maps

Landsat multispectral images (from the USGS dataset) were used for preparing the land use map. The Landsat images consisted of Landsat 5 Thematic Mapper images (TM Path/Row: 165/037) acquired on 9 August 1988, 10 June 1998 and 21 June 2008. The images comprised seven spectral bands (from b1 to b5 and b7) with a spatial resolution of 30 m (120 m for thermal band 6). Atmospheric correction is a necessary step in accurately extracting quantitative information from Landsat [30, 38]. In image pre-processing, atmospheric correction of Landsat 5 images was carried out using QUick Atmospheric Correction (QUAC) in ENVI 5.1. The supervised classification and maximum likelihood algorithm in ENVI 5.1 [10, 48] was then employed to process and classify the images. There are seven land use types in the Marboreh watershed: dry farming, irrigation farming, rangeland, bare land, orchard, outcrop and residential area. Accuracy assessment is an essential and most crucial part of image processing [7, 11]. The overall classification accuracy and kappa coefficient were used to determine the accuracy of classification, using the ENVI v.5.1 software [48]. Based on the Landsat images, land use maps were generated for 1988, 1998 and 2008, as illustrated in Fig. 2. Changes in the different land use types (dry farming, irrigation farming, rangeland, bare land, orchard, outcrop and residential area) are listed in Table 1.

Rangeland, the most commonly distributed land use type in the Marboreh watershed, showed a decreasing trend of 9.93, 18.40 and 6.34% during 1988–1998, 1988–2008 and 1998–

Fig. 1 Location of the Marboreh catchment and study area in Iran

2008, respectively (Table 1). Rainfed farmland area, mainly in the plains and lowlands of the study area, increased by 8.32%, 14.66% and 8.47% during 1988–1998, 1988–2008 and 1998–2008, respectively. Orchards, a common land cover on river edges, increased by 0.19, 0.53 and 0.34% during 1988–1998, 1988–2008 and 1998–2008, respectively. Residential area increased by 0.34, 0.80 and 0.46% during 1988–1998, 1988–2008 and 1998–2008, respectively. Irrigated and bare land area also increased from 1988 to 2008 in the Marboreh watershed (Table 1). An accuracy assessment of land use classification, obtained by computing the confusion matrix in ENVI software, showed an overall accuracy value of 79.36% for 1988, 80.38% for 1998 and 81.40% for 2008. The kappa coefficient for 1988, 1998 and 2008 was 0.71, 0.75 and 0.78, respectively.

2.3 Scenario Settings

To evaluate the response of daily flow indices to land use changes and climate change, the daily flows were simulated by changing the land use under specific climate conditions, and vice versa. Different scenarios were developed by combining the different land use maps and climate periods. For this purpose, the available meteorological data from 1983 to 2012 were divided into three decades (climate periods 1983–1992 (hereafter called C1), 1993–2002 (C2) and 2003–2012 (C3)). The land use maps were extracted based on the Landsat TM5 images for the middle year of each period (1988 (hereafter LU1), 1998 (LU2) and 2008 (LU3)). Nine sets of land use and climate conditions were obtained by combining three climate periods (C1–3) and three land use maps (LU1–3), to

Fig. 2 Land use maps of the Marboreh watershed for 1998, 1998 and 2008, based on Landsat TM images

give C1_LU1, C2_LU2 and C3_LU3 as historical conditions, and C1_LU2, C1_LU3, C2_LU1, C2_LU3, C3_LU1 and C3_LU2 as virtual conditions. The values of hydro-climate parameters in the Marboreh watershed for three decades (1983–1992, 1993–2002 and 2003–2012) are presented in

Table 2. As can be seen from the table, the mean values of discharge and precipitation decreased from 1983–1992 to 2003–2012. In addition, the 10th percentile value for discharge decreased from 1983–1992 to 2003–2012 and that for precipitation increased. The 90th percentile of discharge

Table 1 Areal distribution of land use/land cover categories in the Marboreh watershed

Land use	Land use (TM/1988)		Land use (TM/1998)		Land use (TM/2008)	
	Area (km ²)	%	Area (km ²)	%	Area (km ²)	%
Bare land	3.11	0.11	10.32	0.38	12.75	0.47
Rainfed crops	556.10	20.52	781.55	28.84	953.48	35.18
Irrigated crops	164.34	6.06	186.23	6.87	219.66	8.11
Orchard	22.46	0.83	27.57	1.02	36.97	1.36
Outcrop	28.40	1.05	28.40	1.05	28.40	1.05
Rangeland	1895.27	69.94	1626.20	60.01	1396.84	51.54
Residential	40.30	1.49	49.72	1.83	61.98	2.29
Total	2710	100	2710	100	2710	100

Table 2 Statistical parameters on precipitation and discharge in the Marboreh watershed in three decadal climate periods, 1983–1992, 1993–2002 and 2003–2012

	1983–1992		1993–2002		2003–2012	
	Precipitation	Discharge	Precipitation	Discharge	Precipitation	Discharge
Mean	411.286	9.660	404.330	9.066	375.400	5.424
SD	109.401	4.828	121.700	6.778	82.599	2.061
Skewness	−0.089	0.649	−0.356	1.221	−0.732	−0.105
Kurtosis	−0.780	−0.431	0.392	0.191	−0.028	−1.621
10th percentile	292.885	5.166	306.255	4.171	311.285	2.920
25th percentile	339.653	6.437	364.025	4.223	326.500	3.503
Median	413.950	8.430	415.500	5.947	388.400	5.525
75th percentile	480.975	12.275	449.900	11.812	442.050	7.119
90th percentile	544.880	15.958	563.010	19.179	455.420	7.723

also decreased from 1983–1992 to 2003–2012, as did median discharge.

By combining different components, seven time series scenarios were created (Table 3). Scenario 1 (SR1) was a time series generated based on the observed climate and land use. Scenarios SR2 to SR4 considered constant land use during three decades combined with the observed climate, e.g. in SR2 the land use for three decades was LU1 (land use during 1988, assuming no land use change) in combination with C1 for 1983–1992, C2 for 1993–2002 and C3 for 2003–2012 (Table 3). The assumption for scenarios SR5–SR7 was to consider the observed climate for different decades and land uses (Table 3).

Components of C1_LU1, C2_LU2 and C3_LU3 as observed conditions. Components of C1_LU2, C1_LU3, C2_LU1, C2_LU3, C3_LU1 and C3_LU2 as virtual conditions.

2.4 Hydrological Modelling

The SWAT model has been widely used for different sizes of watersheds and has been applied to a range of hydrological and/or environmental problems, including assessments of the effects of land use changes and climate change on hydrological conditions (e.g. [13, 49, 54, 46, 14, 77, 79, 44]). SWAT is a conceptual, time-continuous and semi-distributed hydrological and watershed-scale model [59] that was initially developed by the United States Department of Agriculture (USDA) Research Service and Texas A&M University to predict changes in landscape management practices on water, sediment and chemical yield [4, 41, 54]. It operates on daily time steps but can aggregate the results to monthly or annual output [13]. In this study, Arc SWAT 2012 was set up for the periods 1983–1992, 1993–2002 and 2003–2012 and each period was divided into three parts: warm-up, calibration (1984–1989, 1994–1999 and 2004–2009) and validation (1990–1992, 2000–2002 and 2010–2012). For each decade, one hydrological year (1983–1984, 1993–1994 and 2003–2004) was used

to warm up the SWAT model, in order to reduce the effects of the initial conditions. The DEM was used to delimit the drainage area of the watershed, considering the Doroud gauge as an outlet. Based on the DEM, surface slope was classified into five ranges (< 5%, 5–15%, 15–30%, 30–40% and > 40%), as one of the requirements for the SWAT model. The different types of land use were parameterised based on the SWAT land use classes chosen. Spatial parameterisation of the SWAT model was performed by dividing the watershed into a series of six hydrological response units (HRU) based on unique soil, land use and slope characteristics.

SWAT calibration was performed automatically using the SWAT Calibration Uncertainty Procedure (SWAT-CUP). SWAT parameters were calibrated using observed stream flow at the Doroud station for three 6-year periods and then validated using the observed stream flow for 3-year periods. In SWAT-CUP, the Sequential Uncertainty Fitting (SUFI-2) program algorithm was used for calibration parameters. Two factors were used to quantify the uncertainty performance: P-factor, which is the percentage of measured data bracketed by the 95PPU band, and R-factor, the average width of the band divided by the standard deviation of the corresponding measured variable [1, 79]. Nash-Sutcliffe efficiency (NS) was used to assess the accuracy of the goodness of fit between simulation and observation [40]. It was calculated as

$$NS = 1 - \frac{\sum_{t=1}^T (Q_{sim}^t - Q_{obs}^t)^2}{\sum_{t=1}^T (Q_{obs}^t - \bar{Q}_{obs})^2} \quad (1)$$

where Q_{obs} is the mean of observed discharge, Q_{sim} is modelled discharge and Q_{obs}^t is observed discharge at time t . The range of NS lies between $-\infty$ and 1.0 (perfect fit).

2.5 Hydrological Indices

To assess hydrological changes in different scenarios, 10 different indices (Table 4) were used [33, 35, 43, 57, 62]. These

Table 3 Setup of scenarios SR1 to SR7 and the different land use and climate periods used in simulations

Historical	Land use scenarios (climate constant)			Climate scenarios (land use constant)			
	SR1	SR2	SR3	SR4	SR5	SR6	SR7
Land use	Land use		Climate	Climate	Climate	Land use	Land use
1988, 1998,	1988, 1998,	Land use	1983–2012	1983–2012	1983–2012	1988, 1998,	1988, 1998,
2008	2008					2008	2008
Climate	Climate	Land use	Land use	Land use	Climate	Climate	Climate
1983–2012	1988, 1998,	1988, 1998,	1988, 1998,	1988, 1998,	1983–2012	1983–2012	1983–2012
C1_LU1	C1_LU1	C1_LU1	C1_LU1	C2_LU1	C3_LU1	C1_LU1	C1_LU2
C2_LU2	C2_LU2	C1_LU2	C1_LU2	C2_LU2	C3_LU2	C2_LU1	C2_LU2
C3_LU3	C3_LU3	C1_LU3	C1_LU3	C2_LU3	C3_LU3	C3_LU1	C3_LU2
							C1_LU3
							C2_LU3
							C3_LU3

were classified into two groups, based on their dependency on high or low hydrological conditions, as high dependency indices (HDI) and low dependency indices (LDI). For example, low-flow pulse count was classified as LDI, because the number of low pulses indicated how many times daily flows fell below the lower threshold during the whole period.

The thresholds for low and high flows were taken as the 25th and 75th percentiles [57] of observed daily flow (1983–2012, belong to SR1). These thresholds were also used in all other scenarios (SR2–SR7) to enable uniform comparison. For example, the low-flow pulse count index (LFPC) in SR1 was calculated based on the number of events in which the magnitude of daily flow dropped below a lower threshold (for Marboreh watershed below the 25th percentile of all daily flow, $2.42 \text{ m}^3 \text{ s}^{-1}$).

2.6 Statistical Analyses

The Mann-Kendall test and Sen's slope estimator (two statistical nonparametric methods) are widely used for hydro-climatological purposes (e.g. [17, 19, 21, 31, 47, 50, 53]). They were applied here to observed hydro-climatological data (1983–2012) and used to determine the trends in the hydrological indices in the seven time series scenarios (SR1–SR7). SR1 represented historical data under both land use change and climate variability, SR2, SR3 and SR4 represented scenarios under land use change and SR5, SR6 and SR7 represented scenarios under climate change. The Kolmogorov-Smirnov (K-S) test [20, 45] showed that the time series of selected hydrological indices were normally distributed ($p > 0.05$). Therefore, the t test [20, 70] was used to evaluate differences between the observed scenario (SR1) and other scenarios (SR2–SR7). All statistical analyses were carried out using SPSS 23.v software.

In the land use scenarios, land use map was considered a constant factor in each scenario and Mann-Kendall and Sen's slope estimator methods were used to assess the impact of climate change on hydrological index trends under each land use scenario. In the climate scenarios, each climate decadal period was considered a constant factor and the Mann-Kendall and Sen's slope estimator methods were used to determine the impact of LULCC on hydrological index trends under each climate scenario. The t test method was used to compare mean values of hydrological indices, in order to assess the impact of LULCC in each land use scenario and also to compare the mean values of hydrological indices, in order to assess the impact of climate variability in each climate scenario. The impact of LULCC and of climate change on hydrological indices was assessed from two aspects: (1) the hydrological indices trend for each scenario separately and (2) by comparing mean values of hydrological indices for each scenario with the historical scenario.

Table 4 High and low dependency hydrological indices (HDI, LDI) used to assess river regime changes in the Marboreh watershed

Acronym	HDI	LDI	Description	Units
MLF	✓		Minimum low flow during wettest ¹ month	mm/day
MHF		✓	Maximum high flow during driest ¹ month	mm/day
LPC		✓	Number of low-flow pulse ² counts for each year	–
HPC	✓		Number of high-flow pulse ² counts for each year	–
LPD		✓	Annual low-flow pulse duration (no. of days).	days
HPD	✓		Annual high-flow pulse duration (no. of days)	days
DDC		✓	Annual low-flow pulse days per annual normal flow days or dryness duration coefficient	–
WDC	✓		Annual high-flow pulse days per annual normal flow days or wetness duration coefficient	–
MLPD		✓	Mean low-flow pulse duration per event	–
MHPD	✓		Mean high-flow pulse duration per event	–

¹ In the Marboreh watershed, the wettest and driest month flows are April and September, respectively

² Low-flow pulse defined as a period when flow drops below the 25th percentile, and high-flow pulse as a period when flow exceeds the 75th percentile, of daily flow in the entire period [57]

3 Results

3.1 Calibration and Validation of SWAT Model and Uncertainty

The results showed good agreement between discharge observations and the outcomes of SWAT modelling. According to SWAT model, the P-factor was 0.89, 0.92 and 0.85 for 1984–1989, 1994–1999 and 2004–2009, respectively (calibration periods) and 0.89, 0.97 and 0.82 for 1990–1992, 2000–2002 and 2010–2012, respectively (validation periods). The R-factor was, respectively, 0.25, 0.27 and 0.22 for the 1984–1989, 1994–1999 and 2004–2009 calibration periods and 0.13, 0.11 and 0.21 for the 1990–1992, 2000–2002 and 2010–2012 validation periods. The NS factor was, respectively, 0.90, 0.87 and 0.84 for the 1984–1989, 1994–1999 and 2004–2009 calibration periods and 0.88, 0.82 and 0.64 for the 1990–1992, 2000–2002 and 2010–2012 validation periods. Hence, based on Abbaspour et al. [1], the uncertainty in the calibration and validation periods of the SWAT model

was satisfactory (P-factor > 0.7, R-factor < 1.5) (Table 5 and Fig. 3). Simulated and measured discharge at the Doroud station showed a good match between time series of observed, calibration period and validation period values (Fig. 3).

Based on model sensitivity, the six top-ranked most sensitive parameters (Table 6) were optimised using the SUFI2 algorithm in SWAT-CUP. In SUFI2, uncertainties in model input, model conceptualisation, model parameters and observed data are considered in the parameter ranges as the procedure tries to capture most of the measured data within the 95% prediction uncertainty. In the present case, curve number condition II (CN2), base flow alpha factor (ALPHA_BF), base flow alpha factor for bank storage (ALPHA_BNK), saturated hydraulic conductivity (SOL_K), moist bulk density (SOL_BD) and available soil water capacity (SOL_AWC) were identified as the most sensitive parameters in the Marboreh watershed according to SUFI2. The initial and optimised values of the calibrated parameters are presented in Table 6.

Table 5 Level of agreement between the calibration and validation periods used for the SWAT model

	1983–1992		1993–2002		2003–2012	
	Calibration 1984–1989	Validation 1990–1992	Calibration 1994–1999	Validation 2000–2002	Calibration 2004–2009	Validation 2010–2012
Q observed	9.31	9.80	8.82	5.23	5.95	4.12
Q simulated	11.64	10.97	9.02	5.14	5.42	3.77
P-factor	0.89	0.89	0.92	0.97	0.85	0.92
R-factor	0.25	0.13	0.27	0.11	0.22	0.21
Nash-Sutcliffe efficiency	0.90	0.88	0.87	0.82	0.84	0.68

Fig. 3 Observed and simulated monthly discharge for (left) the calibration period and (right) the validation period used for the SWAT model

3.2 Statistical Trend Analysis

3.2.1 Observed Hydro-climatological Trends (1983–2012)

The seasonal Mann-Kendall test and Sen's slope indicator results showed that annual precipitation and discharge at the

Table 6 The six top-ranking sensitivity parameters and their initial and optimised (final) values (for parameter abbreviations, see text)

Parameters	<i>t</i> value	<i>p</i> value	Initial value	Optimised value
r_CN2	−6.93	0.00	−0.5, 0.5	0.18
v-ALPHA_BF	−2.41	0.01	0, 1	0.42
v-ALPHA_BNK	−2.33	0.02	0, 1	0.23
r-SOL_K	−2.30	0.02	−0.8, 0.8	0.1
r-SOL_BD	−2.21	0.03	−0.3, 0.3	0.09
r-SOL_AWC	−1.98	0.04	−0.3, 0.3	0.02

Aligudarz and Doroud stations decreased in significance in the Marboreh watershed during 1983–2012, while temperature at different time scales did not show a significant trend (Table 7 and Fig. 4). Seasonal Mann-Kendall test results for monthly scales revealed that January, February, March, April, May, June and December precipitation and January, February, March, April and December discharge decreased in significance during 1983–2012 (Table 7).

3.2.2 Impacts of Land Use Change on Hydrological Indices

The SWAT simulation using observed climate data and different land uses in the period 1982–2012 showed significant changes in hydrological indices for the different land use scenarios. In the first scenario (SR1: 30 years of observed data 1982–2012), annual high-flow pulse duration and wettest duration coefficient showed decreasing trends ($p < 0.01$). April low-flow and mean high-flow pulse duration per event also

Table 7 Results of the Seasonal Mann-Kendall (SK) test and Sen's slope estimator (Sen) for monthly, seasonal and annual precipitation, temperature and discharge during 1983–2012

Time series	Precipitation			Temperature			Discharge		
	SK	<i>p</i> value	Sen	SK	<i>p</i> value	Sen	SK	<i>p</i> value	Sen
January	−1.909	0.026	−2.161	−0.161	0.872	−0.008	−3.515	0.000	−0.239
February	−2.232	0.037	−1.789	−0.410	0.682	−0.027	−3.015	0.003	−0.210
March	−1.846	0.041	2.024	0.607	0.544	0.017	−2.409	0.016	−0.421
April	−2.109	0.026	−1.908	−0.054	0.957	−0.003	−2.016	0.044	−0.371
May	−2.353	0.030	−1.838	1.445	0.148	0.032	−1.802	0.072	−0.239
June	−1.894	0.045	−1.798	1.017	0.309	0.036	−1.588	0.112	−0.072
July	−1.109	0.268	0.000	0.839	0.402	0.016	−1.695	0.090	−0.066
August	−2.245	0.025	0.000	−0.054	0.957	−0.002	−1.195	0.232	−0.027
September	0.495	0.620	0.000	1.302	0.193	0.029	−0.767	0.443	−0.019
October	−0.643	0.520	−0.041	0.660	0.509	0.022	−0.161	0.872	−0.003
November	−0.446	0.656	−0.283	1.499	0.134	0.029	−1.624	0.104	−0.088
December	1.053	0.293	1.067	0.018	0.986	0.000	−3.301	0.001	−0.210
Winter	−2.117	0.022	−2.931	−0.232	0.817	−0.009	−2.979	0.003	−0.301
Autumn	0.339	0.735	0.203	0.089	0.929	0.004	−2.016	0.044	−0.077
Spring	−2.013	0.037	−2.659	0.660	0.509	0.018	−2.194	0.028	−0.252
Summer	−1.118	0.263	−0.004	1.231	0.218	0.022	−1.017	0.309	−0.033
Yearly	−2.124	0.026	−2.942	0.696	0.487	0.007	−2.444	0.015	−0.178

showed a decreasing trend ($p < 0.05$). All HDI decreased, while all LDIs showed an increasing trend, but this was not statistically significant (Table 8 and Fig. 5). In the second scenario (SR2: which assumed that land use in the second [1993–2002] and third periods [2003–2012] was similar to

that in the first period [1983–1992]), low-flow pulse duration and driest duration coefficient (from LDI) showed increasing trends ($p < 0.01$ and $p < 0.05$, respectively). Among the HDI, there were decreases in annual high-flow pulse duration, wet-test duration coefficient ($p < 0.01$), minimum April-flow and

Fig. 4 Long-term trends in precipitation, temperature and discharge in the Marboreh watershed, 1983–2012

Table 8 Results of the Mann-Kendall (MK) test and Sen's slope estimator (Sen) for the historical (SR1) and land use (SR2) scenarios. *LDI* low dependency indices, *HDI* high dependency indices

Indices	MK	<i>p</i> value	Sen	M-K	<i>p</i> value	Sen
SR1			SR2			
Maximum September flow	−0.232	0.817	0.000	−0.981	0.326	−0.001
Low-flow pulse count	1.752	0.080	0.107	1.814	0.070	0.125
Low-flow pulse duration	1.625	0.104	2.111	2.964	<i>0.003</i>	5.056**
Driest duration coefficient	0.857	0.392	0.009	2.571	<i>0.011</i>	0.029*
Mean low-flow pulse duration per event	0.393	0.694	0.148	1.500	0.134	0.455
Minimum April flow	−2.034	<i>0.042</i>	−0.008*	−2.177	<i>0.029</i>	−0.008*
High-flow pulse count	−1.266	0.206	−0.067	−0.745	0.456	0.000
Annual high-flow pulse duration	−3.123	<i>0.002</i>	−4.667**	−3.195	<i>0.001</i>	−4.957**
Wettest duration coefficient	−3.355	<i>0.001</i>	−0.032**	−3.069	<i>0.002</i>	−0.030**
Mean high-flow pulse duration per event	−2.267	<i>0.023</i>	−0.800*	−2.445	<i>0.014</i>	−0.856*
SR3			SR4			
Maximum September flow	−3.372	<i>0.001</i>	−0.004**	−1.731	0.084	−0.003
Low-flow pulse count	2.015	0.044	0.130	4.383	<i>0.000</i>	0.182**
Low-flow pulse duration	3.524	<i>0.000</i>	4.900**	4.333	<i>0.000</i>	4.500**
Driest duration coefficient	2.987	<i>0.003</i>	0.028**	4.333	<i>0.000</i>	0.023**
Mean low-flow pulse duration per event	2.362	<i>0.018</i>	0.942**	3.532	<i>0.000</i>	0.643**
Minimum April flow	−2.320	<i>0.020</i>	−0.008*	−2.248	<i>0.025</i>	−0.009*
High-flow pulse count	−1.593	0.111	−0.074	−3.213	<i>0.001</i>	−0.182**
Annual high-flow pulse duration	−3.444	<i>0.001</i>	−5.533**	−3.607	<i>0.000</i>	−6.130**
Wettest duration coefficient	−3.069	<i>0.002</i>	−0.025**	−3.497	<i>0.000</i>	−0.037**
Mean high-flow pulse duration per event	−2.606	<i>0.009</i>	−0.906**	−3.052	<i>0.002</i>	−1.406**

Italic value indicate the significant trend

*, ** indicate 5% and 1% significance level, respectively

mean high-flow pulse duration per event ($p < 0.05$) (Table 7 and Fig. 5). In scenarios SR3 and SR4, where land use in the second (1993–2002) and third (2003–2012) period was assumed as the land use of the whole 30-year study period, all LDI, except maximum September flow, showed increasing trends, while all HDI showed decreasing trends, at different levels of significance (Table 8, Fig. 5).

3.2.3 Impacts of Climate Change on Hydrological Indices

Scenario settings for different decadal climate periods showed that climate change influenced the hydrological index trends more than land use changes in the Marboreh watershed. Statistical test results for climate scenarios SR5, SR6 and SR7 were as follows: In SR5, all LDI (except maximum September flow) showed a decreasing trend ($p < 0.01$), while HDI showed non-significant increasing trends for minimum low flow during the wettest month (MLF), high-flow pulse duration (HPD) and mean high-flow pulse duration per event (MHPD) and non-significant decreasing trends for number of high-flow pulse counts per year (HPC) and wetness duration coefficient (WDC). In scenario SR6, all LDI increased (not

significantly) and all HDI (except HPC) decreased, although not significantly. In scenario R7, all LDI (except mean low-flow pulse duration per event (MLPD) increased (not significantly) and all HDI (except HPC) decreased non-significantly (Table 9 and Fig. 6).

3.3 Comparison Scenarios Based on Hydrological Indices

Based on the number of altered indices (with significance level, using t test), the scenarios were ranked in the order SR7 (with most variation in climate), SR5, SR4 (with most changes in land use) and SR6, with seven, six, three and one out of 10 altered indices, respectively (Table 10). For two other land use scenarios (SR2 and SR3), the results indicated no significance changes in hydrological indices. In land use scenario SR4, the number of low-flow pulse counts per year (LPC), annual low-flow pulse duration (LPD) and dryness duration coefficient (DDC) showed alterations ($p < 0.05$), but there was no significance alteration in other LDI or in all HDI (Table 10).

Fig. 5 Long-term trends in different hydrological indices under different land use and historical scenarios (SR1–4). P.C. pulse count, P.D. pulse duration, L(H).F.D./N.D) low (high)-flow duration/normal day (low (left panel) high (right panel)

Of all the hydrological indices tested, DDC showed the highest sensitivity to both climate change and LULCC, while MHPD showed the lowest sensitivity. In the land use and climate scenarios, LDI showed more changes than HDI. With increasing change in land use (from SR2 to SR4), LDI values decreased (except MLF), while HDI values increased (except WDC) (Fig. 7). With climate shifts (from SR5 to SR7), LDI values increased (except MLF), while HDI values decreased (Fig. 7 and Table 8).

4 Discussion

In recent decades, land use changes have been rapid in many developing semi-arid regions such as Iran, which has affected water flow regimes significantly [22]. In the area examined in the present study, the main land use changes were an increase in rainfed agricultural area in the catchment (+ 14.66%) and a decrease in rangeland area (− 18.4%). These changes did not

seem to have affected the hydrological indicators studied, however. This is important, as a reduction in flow would be problematic because the Marboreh watershed is an important source of hydropower energy in Iran [52]. Land use mapping, which influenced the results, depends on many factors, such as research target, landscape complexity and scale, which are usually pre-determined by the user's requirements. This study focused on analysis of some of the factors that can be controlled, to improve classification accuracy and prepare for land use mapping based on the ground trust. The results obtained for the Marboreh watershed show that the land use changes from 1988 to 2008 have been associated with degradation of natural resources.

Two driving forces, LULCC and climate change, affect hydrological conditions. Distinguishing the long-term changes in hydrological conditions caused by the separate and combined impacts of LULCC and climate change is crucial for sustainable water resource planning. Some previous studies have assessed the relative impacts of LULCC and climate change on stream flow in watersheds (e.g. [18,

Table 9 Results of the Mann-Kendall (MK) test and Sen's slope estimator (Sen) for hydrological indicators used in (upper section) the historical scenario (SR1) and climate scenario SR5; and (lower section) climate scenarios SR6 and SR7. *LDI* low dependency indices, *HDI* high dependency indices

Indices	MK	<i>p</i> value	Sen	MK	<i>p</i> value	Sen
	SR1			SR5		
Maximum September flow	−0.232	0.817	0.000	−0.375	0.708	−0.001
Low-flow pulse count	1.752	0.080	0.107	−2.658	0.008	−0.071**
Low-flow pulse duration	1.625	0.104	2.111	−2.841	0.004	−0.923**
Driest duration coefficient	0.857	0.392	0.009	−3.043	0.002	−0.007**
Mean low-flow pulse duration per event	0.393	0.694	0.148	−2.750	0.006	−0.462**
Maximum September flow	−2.034	0.042	−0.008*	0.339	0.735	0.001
Low-flow pulse count	−1.266	0.206	−0.067	−1.608	0.108	−0.091
Low-flow pulse duration	−3.123	0.002	−4.667**	0.393	0.695	0.526
Driest duration coefficient	−3.355	0.001	−0.032**	−0.553	0.580	−0.006
Mean low-flow pulse duration per event	−2.267	0.023	−0.800*	1.463	0.143	0.795
	SR6			SR7		
Maximum September flow	1.195	0.232	0.002	0.785	0.432	0.001
Low-flow pulse count	−0.722	0.470	0.000	1.078	0.281	0.067
Low-flow pulse duration	0.162	0.872	0.000	1.499	0.134	1.235
Driest duration coefficient	0.072	0.943	0.000	1.017	0.309	0.009
Mean low-flow pulse duration per event	0.539	0.590	0.056	−0.143	0.886	−0.043
Minimum April flow	−0.731	0.464	−0.002	−1.320	0.187	−0.003
High-flow pulse count	−0.018	0.985	0.000	−0.507	0.612	0.000
Annual high-flow pulse duration	−1.698	0.090	−0.889	−0.915	0.360	−0.400
Wettest duration coefficient	−1.803	0.071	−0.006	−0.789	0.430	−0.003
Mean high-flow pulse duration per event	−1.519	0.129	−0.375	−1.295	0.195	−0.294

Italic value indicate the significant trend

*, ** indicate 5% and 1% significance level, respectively

26, 36, 46, 76, 77]). Ward et al. [67] concluded that, by the end of the twentieth century, LULCC had had more serious effects than climate change on hydrological conditions, while over the early decades of the twenty-first century climate change became more important. In the present study, catchment sensitivity to LULCC and climate change was assessed in a scenario-based approach by comparing responses in 10 hydrological indices in the Marboreh watershed, Iran. It should be noted that identifying the combined impacts of land use and climate changes on hydrological conditions is complex. Some studies have examined the interactions between land use and climate change on hydrological conditions [16, 57, 77], but there is a large amount of uncertainty in the results and more scientific investigation is needed. In this study, we attempted to quantify the hydrological impacts of land use change and climate change using the *t* test method. The results revealed that climate change affected the hydrological indices studied more significantly than land use change, particularly in the case of low dependency indices (there were more significant changes in 10 hydrological indices under the climate scenarios than under the land use change scenarios). Overall, our analysis revealed that climate change

over a period of 30 years (through natural climate variation and/or human-induced global) can have a stronger effect than LULCC on hydrological indices in semi-arid headwater regions such as the study area. However, this finding can partly depend on the limited length of the study period and the occurrence of wet conditions in the early part of the period and dry conditions in recent years. Further observations and studies are need to confirm long-term hydrological trends in the region.

Future analysis could also consider future land use changes (by applying a LULCC model, e.g. Land Change Modeller (LCM), or climate change scenarios when predicting hydrological changes in this basin). Although our framework contains several uncertainties, e.g. using SWAT as a hydrological model, the uncertainty lies mainly in the daily climatological data and the use of one LULC map for each decade [28, 57]. However, due to the use of current data and the fact that climate models, downscaling, emission scenarios and hydrological modelling for future periods are not needed, a large number of uncertainty sources are eliminated from the impact analysis. Moreover, other hydrological indices could be used (e.g. an indicator of hydrological alteration) to obtain better resolution in identifying the sensitivity to LULCC and climate change.

Fig. 6 Long-term trends in different hydrological indices under different land use and historical scenarios (SR1 and SR5–7). P.C. pulse count, P.D. pulse duration, L(H).F.D./N.D) low (high)-flow duration/normal day (low (left panel) high (right panel)

5 Conclusions

Watershed hydrological responses to the impact of land use/land cover change (LULCC) and climate change were assessed with SWAT modelling based on the three different

types of scenario (historical, land use, climate). The results showed minor changes in hydrology due to land use change from rangeland to rainfed agriculture. These were accompanied by smaller changes in irrigated area in the Marboreh watershed compared with other regions in Iran in the period,

Table 10 Comparison of mean hydrological index results obtained using *t* test for scenarios SR1–SR7 (for index abbreviations, see Table 4)

	Low dependency indices (LDI)					High dependency indices (HDI)				
	MLF	LPC	LPD	DDC	MLPD	MHF	HPC	HPD	WDC	MHPD
SR1–SR2	0.186	0.491	0.061	0.065	0.445	0.052	0.164	0.064	0.704	0.351
SR1–SR3	0.214	0.947	0.758	0.983	0.481	0.981	0.277	0.292	0.155	0.444
SR1–SR4	0.062	0.002**	0.002**	0.005**	0.115	0.122	0.12	0.053	0.063	0.056
SR1–SR5	0.557	0.003**	0.003**	0.023*	0.037*	0.122	0.057	0.002**	0.029*	0.087
SR1–SR6	0.896	0.623	0.107	0.021*	0.277	0.643	0.769	0.963	0.527	0.92
SR1–SR7	0.032*	0.103	0.000**	0.001**	0.274	0.036*	0.029*	0.003**	0.003**	0.094

* $p < 0.05$, ** $p < 0.01$

Fig. 7 Changes in different hydrological indices in scenarios SR1–SR7 during the 30-year study period. * $p < 0.05$, ** $p < 0.01$

owing to the headwater and mountainous characteristics of the watershed.

The main driver of hydrological changes in the Marboreh watershed was thus climate change, caused by natural variability and/or anthropogenic changes. In the period 1983–2012, the basin became drier due to less annual precipitation and runoff and this drying effect influenced the trend slopes of hydrological indices more significantly than LULCC in the watershed in the same period.

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