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Modeling Hydrologic Consequences of Land Use and Climate Changes: The Case of Zayanderud Basin

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ABSTRACT: The Zayanderud River basin supports vital economic and social functions in Iran, yet faces critical water security challenges. This study employs integrated modeling to investigate how climate and land use changes impact the hydrology of the Zayanderud basin. Using SWAT model, we successfully simulated streamflow, with Nash-Sutcliffe Efficiency values of 0.58-0.71 during calibration and validation periods. Downscaled CMIP5 projections indicate significant 21st-century warming, mainly in winter, and shifting precipitation patterns, influencing water availability. Predicted land use changes show a notable decrease in pasture area by 2060, accompanied by an increase in bare lands, as well as expansion of both rainfed and irrigated agriculture, leading to increased water demand. Through the incorporation of climate and land use projections, the SWAT model forecasts overall long-term increases in streamflow, though with expanding uncertainty reflecting heightened variability. Seasonally, there's an anticipated rise in winter flow and a decrease in summer flow. Detailed analysis of baseflow reveals similar trends, with winter peaks and summer reductions due to altered precipitation. Rising evapotranspiration due to warming and land use changes is also projected. These results underline the elevated risks of both severe low-flow periods and increased flooding. Urgent adaptive strategies are necessary to manage winter flows effectively while conserving water for drier periods to enhance resilience. This study's integration of robust hydrological modeling with climate and land use scenarios provides actionable insights for adapting the Zayanderud basin's water resources to intensifying hydroclimatic extremes under climate change. The methodologies provide transferable frameworks for sustainable water management globally.

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1- Introduction

The impacts of human-induced global warming are increasingly evident, as underscored in recent Intergovernmental Panel on Climate Change (IPCC) report, which implicates human enterprise as the dominant driver (Bernstein et al., 2008; Change, 2014; IPCC, 2007). Several reports indicate the Earth's temperature has already risen by 0.6 degrees Celsius, and projections estimate a further increase between 1 to 3.5°C by 2100, primarily due to greenhouse gas accumulation (Narsimlu et al., 2013; Stocker, 2014). These rising temperatures have far-reaching consequences, disrupting historical precipitation patterns, altering runoff dynamics, and affecting the recharge of aquifers. Consequently, the likelihood of extreme climatic events, such as floods and droughts, is expected to escalate under continued anthropogenic forcing.

Numerous studies have investigated the prospective impacts of climate change on river flows and water resources at global and regional scales (Amin et al., 2017; Arnell, 1999; Bohner et al., 2014; Lehner et al., 2006; Li et al., 2013; Nohara et al., 2006; Smiatek et al., 2014). These studies have utilized General Circulation Models (GCMs) to simulate and predict future climate conditions, considering different greenhouse gas emission scenarios across varying time horizons (Yates & Strzepek, 1998). Additionally, the accumulation of greenhouse gases, influenced by factors like population growth and industrial activities, disrupts the Earth's climate system through imbalances in heat dissipation. (Bernstein et al., 2008). To capture the spectrum of plausible emissions trajectories, the IPCC has delineated Representative Concentration Pathways (RCPs), including RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Van Vuuren et al., 2011).

Assessing the impact of climate change on water resources requires integrating statistical analysis and forecasting of climatic variables into hydrological models, while also considering factors such as topography, snowpack, and land use (Faramarzi et al., 2013; Yira et al., 2016). The joint impact of land use and climate change has been recognized as a crucial factor affecting watershed flow, highlighting the need for simultaneous consideration of these factors for more accurate modeling and analysis (de Hipt et

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al., 2018; Notter et al., 2013). However, changes in factors such as land use/land cover (LULC), modeling approaches, and meteorological conditions across different studies have yielded diverse results (Funk et al., 2008; Shongwe et al., 2011; Williams & Funk, 2011). This diversity in outcomes, sometimes contradictory, primarily arises from differences in regional focus, timescales, and climate modeling approaches (Näschen et al., 2019). Moreover, the sensitivities of streamflow to land use and climatic factors can differ based on the intrinsic characteristics of each watershed (Aghsaei et al., 2020). Seasonal temperature and precipitation also influence basin flow, with precipitation increases elevating flow while higher temperatures can diminish flow through increased evapotranspiration (Wang et al., 2008).

The Zayanderud River has long played a critical role in the social and economic progress of Isfahan, a key city in Iran. Its abundant waters have nourished the region, supporting agriculture, industry, and municipal supply for centuries. However, the once flourishing river now faces an uncertain future at a critical juncture. Unsustainable water uses and the inter-basin transfers have taken a toll, significantly, reducing its flow and leaving stretches of the riverbed dry. This growing water scarcity has led to far-reaching consequences, including conflicts among water users and severe challenges to regional sustainability and prosperity (Abou Zaki et al., 2020). Given these pressing challenges, gaining a comprehensive understanding of the dynamics of the Zayanderud River basin and predicting its future water availability is of paramount importance.

Multiple prior studies have assessed climate change impacts on Zayanderud basin discharge utilizing GCMs. Differing GCM projections have yielded variable forecasts of future temperature, precipitation, and associated streamflow alterations. Given inherent GCM uncertainty, approaches including multi-model ensembles and bias-correction of weighted scenarios have been employed (Zareian et al., 2015). Additionally, land use change has been investigated independently or concurrently to account for shifting future water demand in predicting available flows (Ahmadi et al., 2022). Moreover, crops demonstrate heterogeneous sensitivities to warming and precipitation changes. For example, water-intensive crops face greater risks to sustained production. Accurately forecasting climate changes enables consideration of alternative cultivation models per the economic and nutritional value of vulnerable crops in Iran (Gohari et al., 2013). Ultimately, such studies inform water allocation models like GAMS in leveraging scenarios for future water resource (Zareian, 2021).

In light of these complexities and knowledge gaps, this study aims to contribute to the understanding of climate change impacts on water resources in the Zayanderud River basin by integrating hydrological modeling, land use forecasting, and climate projections. Through an interdisciplinary approach integrating hydrological modeling, land use forecasting, and climate projections, this study aims to elucidate the impacts of climate change and land use dynamics on water availability and hydrologic processes in the Zayanderud River basin.

The specific objective of this study is twofold: first, to assess the impacts of climate change, including temperature and precipitation, on the discharge patterns and water availability of the Zayanderud River basin; and second, to analyze the influence of land use changes on the basin's hydrological processes. By examining changes in streamflow, baseflow, and evapotranspiration, we aim to understand how climate and LULC changes may influence the inflow rates to the Zayanderud Dam.

The significance of this study lies in its potential to inform sustainable water resource management practices in the region. The research findings may contribute to improving water allocation strategies, reservoir operation plans, and drought/flood management approaches. By understanding the future inflow patterns and water availability, policymakers and water managers will be better equipped to make informed decisions and develop effective measures to address water scarcity, ensure water sustainability, and reduce conflicts among water users. Furthermore, the study's findings can have broader societal and economic implications. Moreover, this research contributes to the understanding of climate change impacts on water resources in the region, providing valuable insights for similar river basins facing similar challenges globally. By undertaking this comprehensive analysis of the Zayanderud River basin, this study aims to advance knowledge in the field of water resources management and support sustainable development in the region.

In summary, this study employs an integrated modeling approach combining hydrological modeling, land use projections, and climate forecasts to comprehensively assess climate change impacts on water resources in the Zayanderud River basin. By quantifying the hydrologic effects of climate and land use change, this research aims to provide actionable insights to guide the adaptation of the Zayanderud basin's water resource system to intensifying hydroclimatic extremes under climate change. The findings will have significant implications for policymakers and water managers in the region seeking to ensure long-term water security. This work contributes to advancing knowledge on regional climate change impacts on water resources, offering transferable insights for similar basins confronting analogous challenges worldwide. Overall, this study strives to elucidate the complex connections between climate, land, and water resources to build resilience for local communities through sustainable water management strategies.

2- Materials and methods

2- 1- Study area description

The study focuses on the Zayanderud watershed, located in the central plateau of Iran, covering an area of approximately 41,254 square kilometers. The watershed is bounded by the Namak Lake watershed to the north, the Degh Sohrh watershed to the east, the Karun watershed to the west and southwest, and the Kavir Abragoo watershed to the south. The Zayanderud River, the primary water source in the region, receives contributions from important tributaries including the Dime Spring, Kohrang tunnel, Plasjan River,

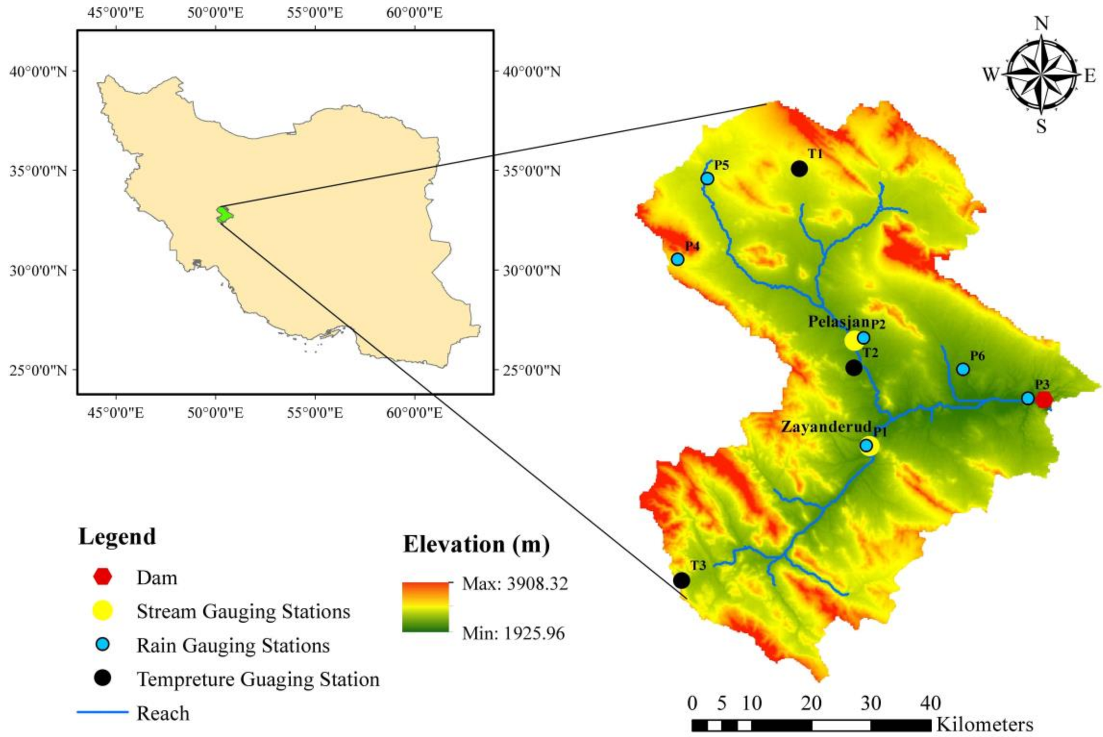

Fig. 1. Geographical and elevational map of the Zayanderud basin along with the location of meteorological and water measuring stations.

Langan Spring, and Marghab Spring. For this research, we specifically target the upstream area of the Zayanderud regulatory dam, encompassing about 4,200 square kilometers, as shown in Fig. 1 (Malmir et al., 2021).

The Zayanderud River's flow is strongly influenced by annual precipitation patterns, with the Kohrang section playing a significant role. Precipitation data from the Chalgerd (Kohrang) rain gauge station, located within the Zayanderud catchment area, indicate an average precipitation of 26.3 over a 50-year period. Additionally, temperature data collected from weather stations show a 2-degree Celsius increase in the region over the past 50 years, which is expected to impact evapotranspiration and snow-melting processes (Zareian et al., 2016).

During the month of April, the Zayanderud River experiences its peak flow, primarily driven by its main and larger tributaries. However, increased agricultural irrigation, evapotranspiration, and water usage for industrial and municipal purposes during the spring and summer months contribute to a decrease in flow. The agricultural sector, driven by population growth, represents the largest water user in the Zayanderud catchment area. Understanding the historical trends in land use ratios is crucial for flow forecasting, with a particular focus on water provision for irrigation and other uses through precipitation and surface runoff, excluding underground water extraction (Droogers et al., 2000; Mahe et al., 2005; Svendsen, 2005).

2- 2- Data Collection

In order to support the hydrological modeling process, a Digital Elevation Map (DEM) with a resolution of 90 meters was utilized (Fig. 1). The study area exhibits a diverse range of elevations, with the lowest point recorded at 1926 meters and the highest point reaching 3908 meters in certain elevated regions (Aster, 2020). Through processing the DEM data, a slope map was generated, categorizing slopes into three groups: 0-1%, 1-10%, and above 10%. These slope categories correspond to 1.85%, 51.86%, and 46.3% of the total basin area, respectively (Fig. 2-a).

Land use and land cover data were acquired from the Iran Natural Resources and Watershed Management Organization (NRWO), derived from Landsat satellite imagery captured in 2002 and 2020. The accuracy of the land use maps underwent validation through field visits and assessment using high-resolution imagery from Google Earth by the experts within the organization (NRWO, 2020). The land use categories were further grouped into six general classifications, with agriculture and pastures covering the largest area, while water surfaces occupied the smallest area (Fig. 2b). Also, due to the relatively small area of gardens, this land use is placed in a general group with agriculture in the rest of this study.

Soil data, crucial for understanding the hydrological processes within the basin, were extracted from the global soil map by (FAO, 2021). The moderate permeability of the soils, indicated by their hydrological group D and the

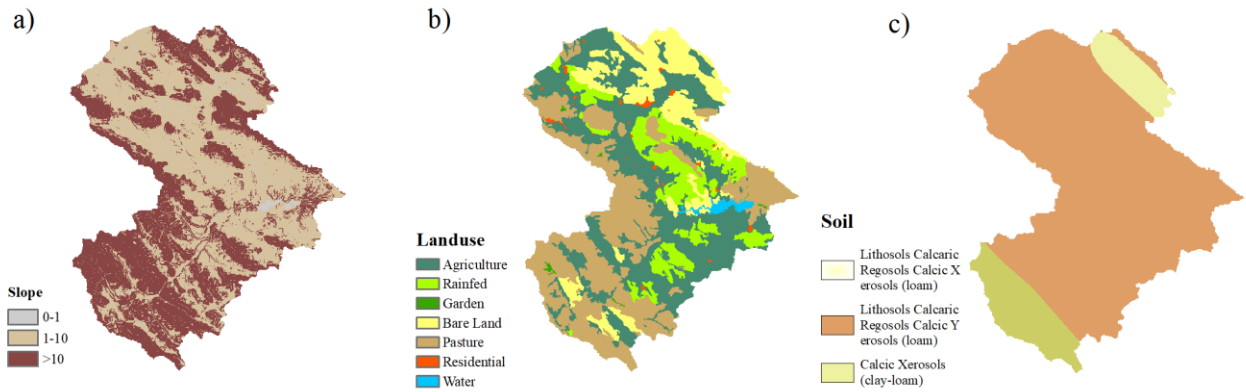

Fig. 2. slope map (a), land use (b), and soil type (c) in the study area

presence of loam and clay loam textures, suggests balanced water movement and adequate water retention. These soil properties significantly influence water flow dynamics, and infiltration rates, and contribute to maintaining water balance and base flow in the Zayanderud River.

To complete the dataset, temperature and rain gauge station information, as well as hydrometer station information, were obtained from the Isfahan Regional Water Company for use in basin modeling (ESRW, 2020). The locations of these stations can be seen in Fig. 1.

2- 3- Hydrologic modeling

The SWAT (Soil and Water Assessment Tool) model was chosen as the hydrological modeling framework for this study due to its conceptual nature and semi-distributed approach, which enables the representation of physical relationships at the basin scale with high computational efficiency (Neitsch et al., 2011). The SWAT model divides the study area into multiple sub-basins, which are further subdivided into hydrological response units (HRUs) that exhibit homogeneity in terms of land use and soil characteristics. This hierarchical division allows for the consideration of variations in evaporation and transpiration rates specific to different soils and vegetation types within each HRU. Additionally, runoff calculations are performed separately for each HRU, and the cumulative runoff for the entire catchment area is determined.

The Digital Elevation Map (DEM) serves as a fundamental component of the SWAT model. It is used to delineate the watershed boundary, compute cumulative flow, and determine the slope and slope direction within the basin. In this study, a one-year warm-up period was assigned to stabilize the model, followed by a calibration period spanning nine years (2004-2012) and a validation period covering seven years (2013-2019).

The calibration process begins with a sensitivity analysis using the SUFI2 algorithm (Abbaspour, Yang, et al., 2007) to identify the most sensitive parameters influencing model outputs. The t-stat and p-stat indicators produced by SUFI2 are used to quantify parameter sensitivity, with higher absolute t-stat and lower p-stat values indicating more sensitive parameters. Based on the sensitivity analysis results, the most sensitive parameters related to surface runoff, evapotranspiration, and groundwater are selected for calibration.

The calibration process then utilizes the Sequential Uncertainty Fitting 2 (SUFI2) algorithm, which aims to identify optimal values for these sensitive model parameters through iterative recalibrations. The SUFI2 algorithm searches for parameter combinations that yield acceptable optimization results and improves the model's ability to reproduce observed data. The calibrated parameter values are subsequently used for model validation. If the validation results are deemed unsatisfactory, the optimization process is repeated to further refine the parameter values. In this study, the SUFI2 algorithm was executed over 2,000 iterations to calibrate the model. The SWAT-CUP ,SWAT Calibration and Uncertainty Programs, software (Abbaspour, Vejdani, et al., 2007) provides a range of parameter changes after each iteration aiding in the enhancement of accuracy evaluation criteria such as Nash-Sutcliffe Efficiency (NSE) and percent bias (Pbias):

$$\mathrm{Pbias} = 100\,\frac{\sum_{i=1}^{n}(\mathrm{O_i} - \mathrm{S_i})}{\sum_{i=1}^{n}\mathrm{O_i}} \tag{1}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{O_i} - \mathrm{S_i})^2}{\sum_{i=1}^{n}(\mathrm{O_i} - \bar{\mathrm{O}}_i)^2} \tag{2}$$

where, S_i is the simulated flow value for the *i*-th time step and Oi is the observed flow value for it. Also, $\bar{O}$ is respectively the average values of simulated and observed for the duration of the period (Nash & Sutcliffe, 1970). SWAT model is calibrated and validated at two main hydrometry stations of Zayanderud and Plasjan, as shown in Fig. 1.

The separation of baseflow, which represents the portion of streamflow derived from groundwater sources, is a critical step in hydrological modeling. In this study, the digital filter method was employed for baseflow separation (Kang et al., 2022). The filtered direct runoff is calculated using equation (3):

$$q_t = \alpha \times q_{t-1} + \frac{1+\alpha}{2} \times (Q_t - Q_{t-1}) \quad (3)$$

where q_{t-1} represents the direct runoff in the t-1 time step, q_t represents the direct runoff in t time step, and Q_{t-1} and Q_t represent the total flow in t-1 and t time steps. The filter parameter α determines the output of the digital filter, influencing the separation of baseflow from total flow.

Previous studies utilizing the digital filter method for baseflow separation have considered a range of filter parameter values between 0.9 and 0.99. In this study, the default value of the Lyne-Hollick (LH) method, which is equal to 0.95, was adopted (Kang et al., 2022). The difference between the calculated direct runoff and the total flow represents the estimated base flow.

By employing the SWAT model for hydrological modeling and utilizing the digital filter method for baseflow separation, this study aims to accurately simulate natural streamflow patterns, excluding water transferred in through external projects, and understand the contribution of baseflow to the overall flow dynamics within the Zayanderud River basin. These modeling approaches provide valuable insights into water availability, runoff generation, and groundwater interactions, supporting effective water resource management and informed decision-making processes.

2- 4- Climate projections

The study uses CMIP5, models that simulate the general circulation of the planetary atmosphere or oceans, and data from all different institutions worldwide, covering all available models (Gupta et al., 2013). These models simulate the general circulation of the planetary atmosphere or oceans and are sourced from different institutions worldwide. To account for the uncertainty in the effects of human activities and greenhouse gas emissions on climate parameters, multiple climate scenarios (RCP26, RCP45, and RCP85) are employed for each model. Therefore, 44 different states of these models and scenarios are used in this study, which are: ACCESS 1-3, BCC-CSM1-1, CanESM2, CMCC-CM, BCC-CSM1-1, CMCC-CM, CNRM-CM5, CSIRO-MK36; EC-EARTH, GFDL-CM3, GISS-E2-R-CC, HadGEM2-ES; NCAR-CCSM4, NCAR-CESM1-CAM5, NorESM1-M, MPI-ESM-MR, MIROC-ESM, INMCM4, IPSL-CM5A-MR.

To obtain microscale climate data based on the global climate model outputs, this study uses the LARS-WG model. The LARS-WG model is a semi-empirical weather generator that simulates weather variables such as precipitation, minimum and maximum temperature, and solar radiation for both current and future climate conditions. The model utilizes parameters calculated from observed daily weather data to generate climate time series by approximating the probability distributions of dry and wet series of daily precipitation, as well as maximum temperature and minimum temperature, using semi-empirical distributions (Semenov et al., 2002).

In this study, the LARS-WG model is utilized for downscaling and prediction of minimum temperature, maximum temperature, and precipitation based on the outputs of the global climate models for all emission scenarios. These downscaled climate data serve as inputs for the hydrological model, enabling the assessment of their potential impacts on the water resources system. The model is calibrated using observed data from temperature and rain gauge stations and statistical measures of R^2 and NSE to ensure accuracy.

The downscaled climate data obtained from the LARS-WG model serve as inputs for the hydrological model, enabling the assessment of their potential impacts on the water resources system. By combining the global climate model outputs with the downscaled data from the LARS-WG model, this study aims to improve our understanding of potential future climate conditions in the Zayanderud River basin.

By combining the global climate model outputs with the downscaled data from the LARS-WG model, this study aims to enhance the understanding of potential future climate conditions in the Zayanderud River basin. These climate projections are crucial for assessing the potential impacts of climate change on water availability, streamflow patterns, and overall basin hydrology. The integration of climate projections into the hydrological model allows for improved water resource management strategies and adaptation measures to address the challenges posed by a changing climate.

2- 5- Land use change

Forecasting future water availability requires an assessment of water consumption across various sectors, including agriculture, industry, and domestic use, especially in the context of land use change. In this study, land use percentages within the basin are analyzed for the period between 2002 and 2020. By examining the linear changes in land use percentages during this time frame, predictions can be made regarding future water consumption patterns for different time periods: Early-century, Mid-century, and Late-century. These predictions are based on the projected land use percentages for the years 2030, 2060, and 2090.

The forecasted land use percentages for these future periods are then incorporated into the SWAT model for all sub-basins within the study area. This modification enables the calculation of the anticipated future flow within the basin. By considering the potential changes in land use and its associated water demands, the study aims to improve understanding of the long-term implications of land use

Table 1. Calibration and validation results for monthly Stream flow

	Calibration period		Validation period	
	Zayanderud	Pelasjan	Zayanderud	Pelasjan
Pbias	9.6	12.8	4.6	7.8
NSE	0.66	0.58	0.71	0.66

change on water availability and flow dynamics.

3- Results and discussion

The results and discussion section presents a comprehensive assessment of the individual impacts of land use changes and climate variability on the hydroclimatology of the Zayanderud basin in Iran. The section begins by discussing the calibration and validation results of the hydrological model, providing an evaluation of its performance in simulating streamflow patterns. Subsequently, the focus shifts to the forecast of climatic variables using downscaled CMIP5 projections and the LARS-WG model. The impacts of land use changes on hydroclimatology are then explored, followed by an analysis of flow forecasting results considering the predicted climatic variables. The section further discusses the baseflow separation results and concludes with an analysis of precipitation and surface runoff patterns in the future.

3- 1- Model calibration and validation

The sensitivity analysis of 24 SWAT model parameters revealed that some parameters have a significant impact on the streamflow outputs. Specifically, the baseflow alpha factor (ALPHA_BF) and SCS runoff curve number (CN2) were identified as the two most influential parameters affecting model predictions of streamflow. Other notable sensitive parameters included OV_N for manning's roughness for overland flow, SURLAG, which lags a portion of the surface runoff release, GWQMN for shallow aquifer storage, and CH_K2 for channel hydraulic conductivity.

After calibration and validation, the SWAT model demonstrated good performance in simulating monthly streamflow at the Zayanderud and Pelasjan stations. The Nash-Sutcliffe efficiency (NSE) values for the calibration period were 0.66 and 0.58 for the Zayanderud and Pelasjan stream gauge stations, respectively (Table 1). For the validation period, NSE values were 0.71 and 0.67 for the two stations. These results exceed the threshold of 0.5 for satisfactory model performance (Moriasi et al., 2007), indicating that SWAT was able to sufficiently capture the monthly dynamics of streamflow over both the calibration and validation periods.

In addition to NSE, other statistical measures further validated the model's capabilities. The Pbias values were reasonably low for both stations and periods, signifying limited systematic over- or under-prediction in the simulated flows. The close match between observed and SWAT-simulated hydrographs, as evident in Fig. 3, provides further visual confirmation of the model's robust performance. For most months, the simulated streamflow closely tracked the observations, with only occasional peak flow events exhibiting noticeable deviations.

Overall, the SWAT model provided reliable simulations of monthly streamflow regimes for the two major tributaries in the Zayanderud basin. With satisfactory calibration and validation results, this model demonstrates potential utility as a predictive tool and presents a good foundation for long-term hydrological assessment and forecasting in the basin.

3- 2- Climatic variables forecast

Table 2 and Table 3 present the statistical properties of monthly precipitation and temperature for various meteorological stations in the basin, comprising both observed and simulated data, along with the validation outcomes of the LARS-WG model simulation in the base-period (2010-2019). Table 2 summarizes the statistical characteristics of the total observed and simulated precipitation for all rain gauging stations in the Zayanderud River basin, along with their related statistical tests. The results show that the mean values of observed and simulated monthly precipitation vary across the stations, ranging from 23.1 mm to 110.7 mm and from 25.4 mm to 110.3 mm, respectively. The standard deviation values for observed and simulated monthly precipitation also vary across the stations, ranging from 18.3 mm to 75.3 mm and from 20.6 mm to 74.2 mm, respectively. These results suggest that the simulated data is able to capture the variability of the observed data reasonably well.

The statistical measures estimated on the simulated data for the observation stations, variable values of Pbias and NSE, show satisfactory results. Specifically, Pbias values range from 1 to 1.5, and the NSE values range from 0.93 to 0.99,

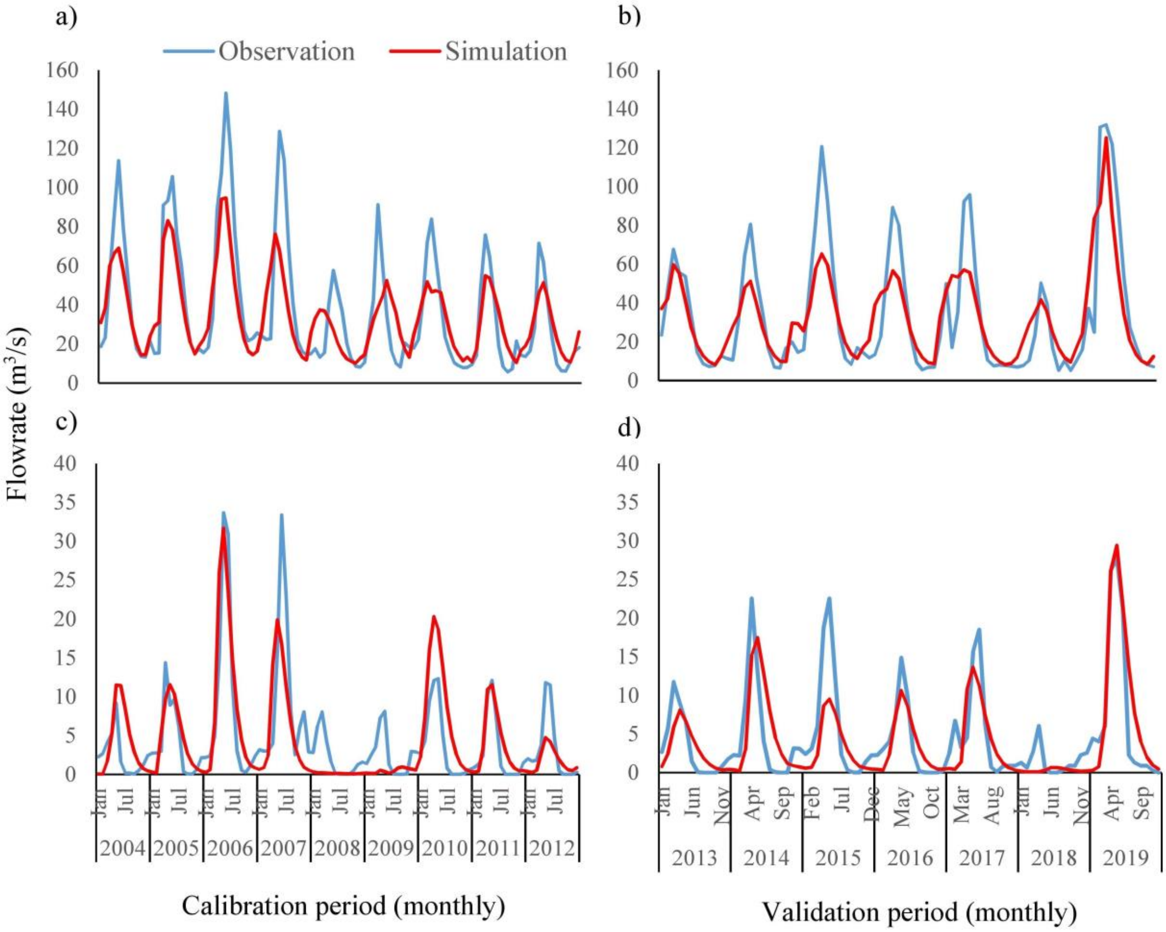

Fig. 3. Monthly observed and simulated flow in the Zayanderud sub-basin (calibration period (a) and validation period (b)) and Plasjan sub-basin (calibration period (c) and mn (d))

Table 2. Summary of statistical characteristics of monthly observed and simulated precipitation and their related statistical measures

Station	Mean (mm)		Standard deviation		Pbias	NSE
	Observed	Model	Observed	Model		
Badijan	27.6	27.5	22.6	21.9	1.4	0.95
Singerd	29.4	31.4	25.5	27.1	1.4	0.96
Kuhrang	110.7	110.3	75.3	74.2	1	0.99
Fereidoonshahr	23.1	25.4	18.3	20.6	1.3	0.93
Ghaleshahrokh	30.5	31.4	25.9	25.2	1.5	0.97
Organ	33.6	37	28.7	29.9	1.5	0.94

Table 3. Summary of the statistical characteristics of monthly observed and simulated temperature and their related statistical measures

Station	Min/Max	Mean(mm)		Standard deviation		Pbias	NSE
		Observed	Model	Observed	Model		
Badijan	Min Temp	2.8	2.7	11.6	11.7	1.6	0.98
	Max Temp	16.7	16.9	9.9	9.9	1.7	0.97
Singerd	Min Temp	2.8	2.7	11.6	11.7	1.3	0.94
	Max Temp	16.7	16.9	9.9	9.9	1.5	0.93
Kuhrang	Min Temp	2.6	2.6	6.8	6.8	1.5	0.95
	Max Temp	16.6	16.8	8.4	8.3	3.2	0.86

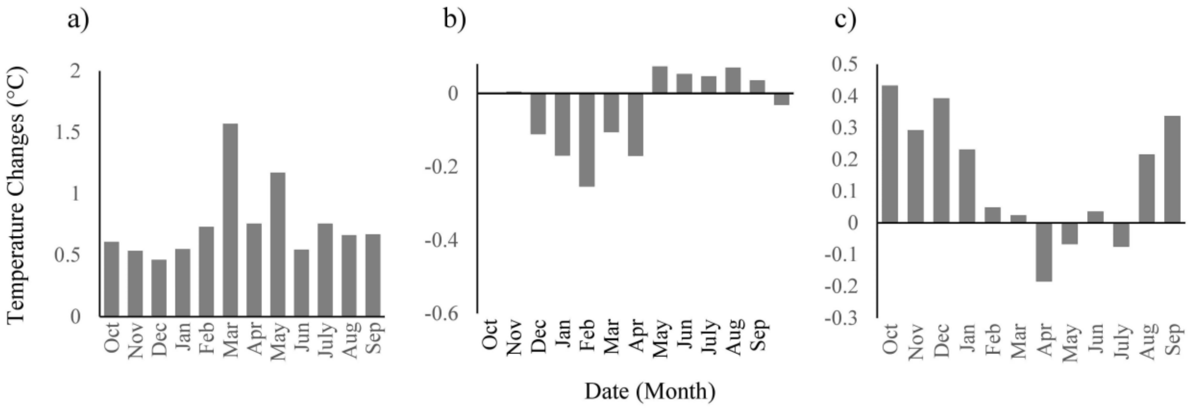

Fig. 4. Average monthly temperature changes between the periods of (a) Early-Century, (b) Mid-Century, and (c) Late-Century compared to the Base-period

indicating that the LARS-WG model was able to accurately simulate the precipitation patterns in the studied watershed. Overall, the results from Table 2 suggest that the simulated monthly precipitation data is a reliable source of information for predicting future precipitation patterns in the Zayanderud River basin.

Table 3 summarizes the statistical properties of the total observed and simulated temperature for all temperature gauging stations in the basin. The findings reveal that the model accurately captured the observed monthly temperature patterns in the watershed, as indicated by the high R^2 and NSE values. For instance, the Pbias values range from 1.3 to 3.2, and the NSE values range from 0.93 to 0.98.

The simulated data, along with the statistical distribution derived based on the base-period data, were utilized to predict the temperature and precipitation parameters for the future period, 2021-2100, to investigate temperature changes for different months of the year during different periods of the 21st century, the average values predicted by GCM models for each period, Early-century (2030-2039), Mid-century (2060-2069), and Late-century (2090-2099), were compared with the base-period.

The results indicate that the temperature in the Zayanderud River basin is anticipated to rise during the 21st century. The Early-century is projected to experience temperature increases in all months of the year. March is expected to exhibit the largest temperature change (1.6°C), while December is anticipated to show the smallest temperature increase (0.5°C) (Fig. 4-a). The cold and warm periods of the year are expected to experience temperature increases of 0.7°C and 0.8°C, respectively, with no significant difference between them.

Table 4. percentage of land uses predicted for the years of 2060, 2030 and 2090

Period	Year	Agriculture& Gardens	Pasture	Bare Land	Rainfed	Residential	Water
Base	2002s	17.6	73.1	4.6	3.1	0.9	0.8
	2020s	34.3	35.2	14.5	12.5	1.9	0.9
Early	2030s	42.1	17.9	15.2	21.5	2.4	0.8
Mid	2060s	48.4	0	20.5	27.5	2.9	0.6
Late	2090s	47.3	0	21.4	27.9	2.9	0.5

In the Mid-century, the temperature changes in the cold period of the year are anticipated to decrease as the middle of the century progresses (Fig. 4-b). The temperature is projected to decrease from December to April, with the maximum temperature decrease of 0.25°C occurring in February. Conversely, the warm period of the year is expected to experience an increase in temperature, with May exhibiting the highest increase of 0.07°C. The average temperature changes for the cold and warm periods during this period are -0.13°C and 0.04°C, respectively, which are lower than the previous period. This suggests that there will not be a significant temperature difference in the middle of the century.

Finally, the Late-century is anticipated to experience incremental temperature increases in most months of the year, particularly in the cold period. October and December are expected to exhibit the highest temperature increases of 0.43°C and 0.39°C, respectively (Fig. 4-c). The average temperature changes for the cold and warm periods during this period are 0.23°C and 0.04°C, respectively. Thus, the hot months of the year are not expected to experience significant temperature changes.

3- 3- Land use change forecast

The percentage of land use in the basin in 2002 and 2020, as depicted in Table 4, was utilized to determine linear changes and forecast future land use for 2030, 2060, and 2090. The findings suggest that agriculture and residential land use are projected to increase, while pasture, water, and rainfed areas are expected to decrease. The desert area is predicted to experience a moderate increase.

In 2002, agriculture occupied 17.6% of the land, with pasture dominating at 73.1%, and the desert accounting for only 4.6%. However, by 2020, agriculture more than doubled to 34.3%, while pasture declined by over half to 35.2%. Based on these trends, agriculture is projected to reach 42.1% by 2030, 48.4% by 2060, and plateau around 47-48% after 2060 as available pastureland is largely converted.

The area of pasture is forecasted to continuously decrease from 73.1% in 2002 to nearly zero by 2060, driven by the conversion of grasslands to various land uses, including irrigated and rainfed agriculture and residential areas. As pasture area diminishes, the proportion of bare land is projected to rise from 4.6% in 2002 to more than 21% by 2090. While water body areas are expected to experience declines over time, these changes are anticipated to be modest. This suggests that their conversion will be limited. Finally, a significant increase in residential areas is anticipated. Although, currently comprising only less than 1% of the land, residential areas are projected to more than triple between 2002 and 2090.

In summary, the primary land use changes between 2002 and 2090 indicate a substantial shift from pasture to agricultural land, accompanied by a moderate increase in bare land and residential area. However, after the depletion of most pasture by 2060, the conversion of remaining land uses is expected to slow down considerably.

3- 4- Flow and baseflow forecasting results

In this section, we explore the complex interaction of climate dynamics and hydrological response, unraveling the consequential implications of changing climate patterns on the flow regime of the Zayanderud basin. By carefully combining temperature and precipitation data, synthesized by the LARS-WG models, into the SWAT model, future input rates for the Zayanderud Dam was predicted. This helps us better understand how changing climate dynamics could affect the water flow in the basin.

Fig. 5 emerges as a detailed visual representation, portraying the predicted inflow to the dam across diverse GCM models and scenarios. Across pivotal timeframes- Early-century (2010-2039), Mid-century (2040-2079), and Late-century (2080-2099) along with the reference base-period (1971-2009), it reveals the changing hydrological annual patterns. The temporal profile of inflow, inscribed by the trendline, unveils a gradual increase in the Early-century,

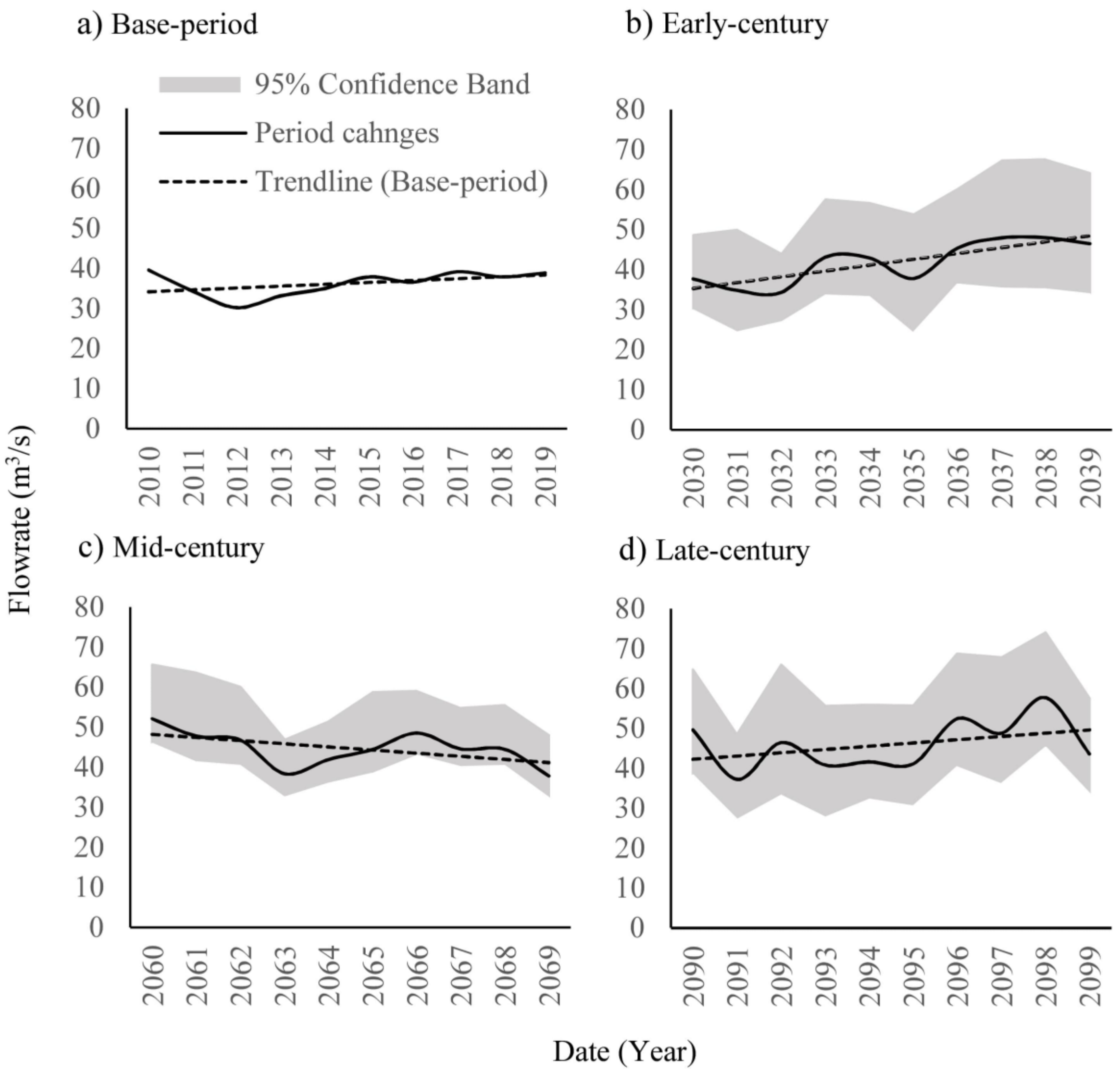

Fig. 5. Graphs of annual inflow to the dam in the base-period (a), as well as predicted values for Early-century (b), Mid-century (c), and Late-century (d), along with their resulting 95% confidence band

suggestive of an incremental intensification. However, a fascinating inflection emerges in the Mid-century, wherein a broadening confidence band, indicating greater variability, is accompanied by a reduction in the average inflow. This pattern shifts again in the Late-century, where the confidence range narrows, and the average inflow rises once more.

Moreover, Fig. 5 sheds light on the range of uncertainty encapsulating the predictions. Notably, the confidence bands expand for the Early-century and Late-century, attesting to an elevated uncertainty in the estimation of inflow during these periods. This increased uncertainty is primarily due to the expected heightened impact of climate change on the hydrological dynamics of the region in the coming decades.

Collectively, Fig. 5 confirms a noticeable trend of increased inflow to the dam over the long term, likely driven by factors including changes in precipitation patterns due to climate change. However, the exact extent of this increase remains uncertain, especially in the time periods of the Early-century and Late-century.

To explore the complex realm of hydrological dynamics, a thorough analysis of seasonal variations by examining the patterns of monthly average flows across different timeframes were conducted. The results are shown in Fig. 6, a graphical representation characterized by a 95% confidence interval, offering insights across three distinct time periods.

Fig. 6 presents a notable discovery, revealing the orchestrated rhythm of inflow fluctuations. The seasons of spring and summer, with their decreased precipitation, result

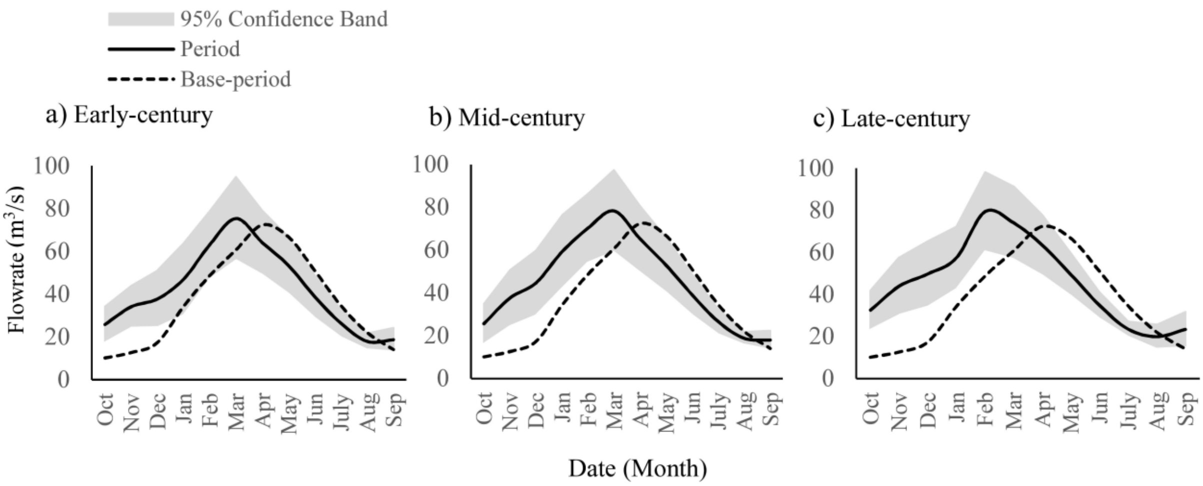

Fig. 6. Monthly inflow to the dam in Early-century (a), Mid-century (b), and Late-century (c), along with the base-period values and their resulting 95% confidence bands

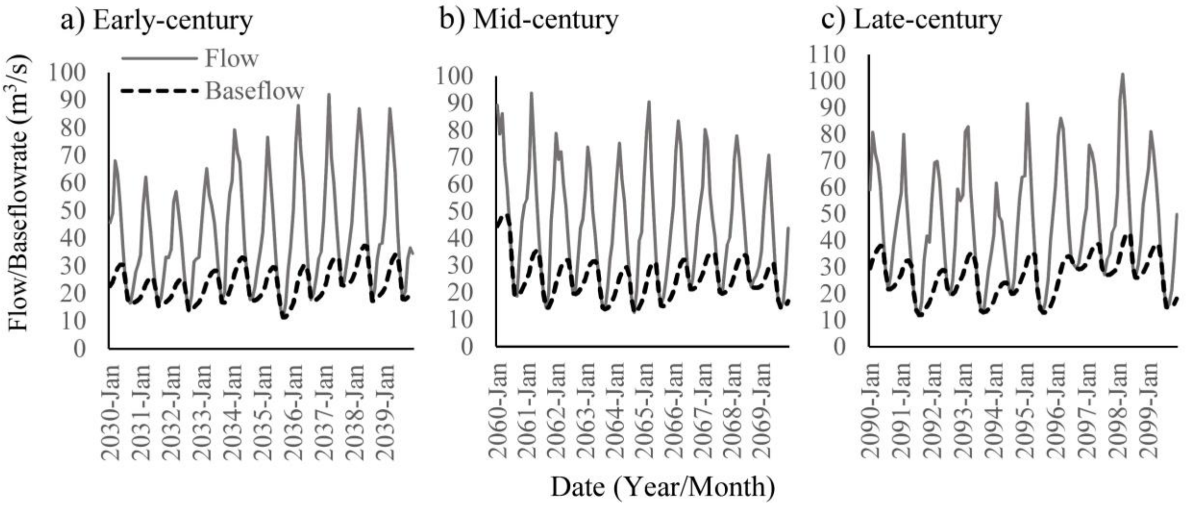

Fig. 7. Total flow and baseflow for the Early-century (a), Mid-century (b), and Late-century (c) time period with the monthly time step

in reduced flow, while the transition to autumn and winter brings heightened water flow, closely tied to increased precipitation. This highlights the importance of considering seasonal variations when analyzing streamflow changes. A significant observation that emerges from this analysis is the sharp increase in the rising limb of the hydrograph and earlier peak flow. These findings hold significance as they project an amplification throughout the current century, providing insight into an impending intensification of the hydroclimatic pattern. However, it's crucial to acknowledge that these projections are subject to uncertainties, as highlighted by the confidence intervals depicted in the figure.

Exploring the complex hydrological processes further, this study examines the interaction between water inflow patterns, climate changes, and the foundational concept of baseflow. This essential element, closely tied to surface water dynamics, serves as a reliable marker of climate change and variations. As the seasons transition, the consistent patterns of baseflow align with the changing climate. The increasing trends in baseflow, particularly during the cold and early warm periods, further strengthen the link between the projected increase in streamflow and the influence of climate change on the basin's hydrology. These hydrological complexities unfold in coordination with the evolving climatic shifts, projected to amplify over the course of the present century.

Fig. 7 unfolds an intricate tableau, showcasing the predicted streamflow values synchronized with delineated baseflow across pivotal timeframes: Early-century, Mid-

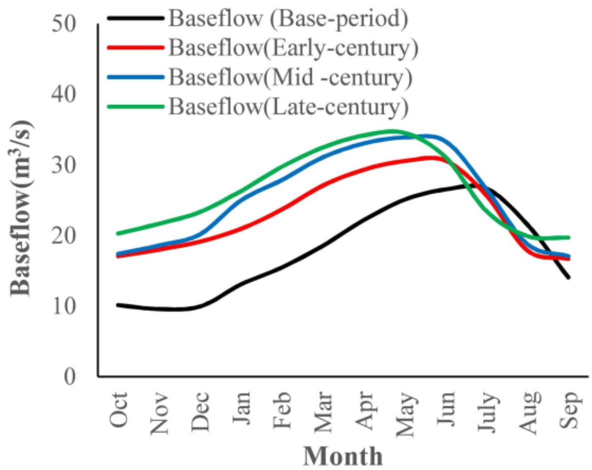

Fig. 8. Comparison of the base flow as a monthly average throughout the year for the Base-period, Early-century, Mid-century, and Late-century

century, and Late-century. Our analysis further extends to Fig. 8, where the baseflow's temporal transformations across various months and periods are examined.

The evaluation of the projected changes in the base flow between the base-period and the Early-century reveals an increasing trend across all months, while a decreasing trend commences from the middle of the warm period (June and July) and persists until the end of the year. Notably, December exhibits the most pronounced surge with a 92% increase, whereas, August demonstrates the most substantial reduction at 17%.

Transitioning to the Mid-century, a distinct increase spanning from the onset of the cold season to the mid-warm period becomes evident in comparison to the base-period. Again, December stands out, revealing a pronounced elevation in baseflow by 103%, while the lowest increase materializes in September at 21.5%. Similar patterns characterize the changes in Late-century baseflow compared to the base period. As the century advances, higher baseflow values manifest earlier in time. December witnesses a notable increase in baseflow by 135%, whereas June indicates a more moderate rise of 17%.

In summation, the overarching observation indicates a tendency for increased baseflow during the cold and early warm periods, counterbalanced by a decline during the remaining months. Notably, this trend is projected to intensify as the century progresses.

3- 5- Evapotranspiration forecasting results

Transitioning our focus, we delve into the intricate realm of evapotranspiration dynamics as simulated by the SWAT model over specific time periods. These insightful simulations reveal a clear pattern: a gradual growth in evapotranspiration as we move through the present century. This significant increase is influenced by various factors, with a primary focus on the changing land uses, particularly the transformation of pastures into agricultural areas. Additionally, the heightened requirement for water resources in agriculture also plays a role in shaping this unfolding scenario.

Fig. 9 depicts the mean monthly evapotranspiration across the four closely examined time periods within the present century. Noteworthy is the peak values, occurring during the months of June and July. As the century progresses, the intricate interactions that shape the evolving evapotranspiration patterns come into play, influenced by various factors that work together to create a complex shift in the catchment area. This provides an opportunity for a more profound comprehension of these hydrological intricacies, offering insights for well-informed strategies in managing water resources amid changing environmental conditions.

4- Summary and conclusions

This comprehensive study delves into the intricate interplay between shifting climatic conditions and evolving land use patterns. It examines how these factors jointly influence the water inflow to the essential Zayanderud Dam through a comprehensive integrated modeling approach. The research incorporates various climate predictions derived from Global Climate Models (GCMs), employing the LARS-WG downscaling model. This is combined with projected land use changes, all integrated into a meticulously calibrated SWAT model.

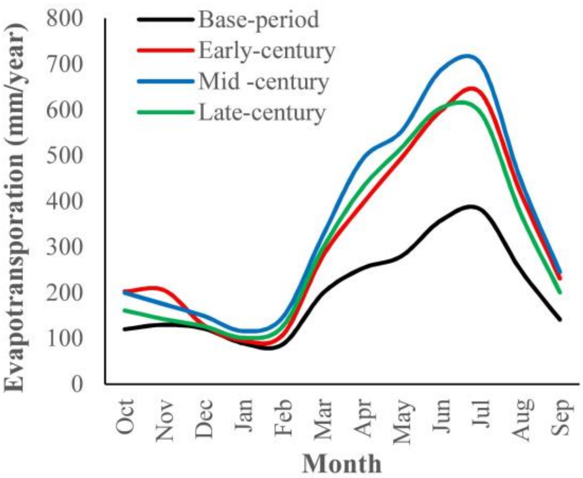

Fig. 9. Average rate of evapotranspiration for different periods during different months of the year.

Synthesizing the intricate interactions, the SWAT model projects sizeable overall increases in mean dam inflow of 13%, 21%, and 24% for the Early-, Mid-, and Late-21st century respectively, relative to the reference period of 1971-2010. This emphasizes the prominent influence of climate-related factors in driving an upward trend in inflow. Conversely, alterations in land use contribute to higher water consumption, partially offsetting the increase. As we extend into the future, uncertainties expand, underscoring the intricate interplay of intensified human-induced changes.

Counterbalancing climatic effects, evolving land use exerts opposing influences rainfed croplands increase was projected to substantially boost hot season evapotranspiration losses, thereby diminishing inflow. Agricultural expansion through the 21st century is expected to drive heightened irrigation requirements, further stressing summer water availability.

Summing up the intricate interplay, the SWAT model forecasts significant increases in average dam inflow of 13%, 21%, and 24% for the Early-, Mid-, and Late-21st century respectively, compared to the reference period of 1971-2010. This underscores the prevailing influence of climate change, potentially through increased precipitation, while land use shifts contribute to higher water consumption. As we look ahead, uncertainty widens as we project into the future, highlighting the intricate dynamics resulting from intensifying human-driven changes in the environment.

Critically, the results underscore the urgency for taking proactive measures in water management, guided by solid evidence and considering the influences of both climate dynamics and changes in land use. It becomes crucial to implement adaptable strategies for reservoir operations and conservation efforts, with the aim of maximizing the benefits of increased winter water availability while ensuring sufficient supply during the drier summer months, especially in the face of heightened seasonal hydrological variations. This necessitates the incorporation of climate resilience principles throughout various aspects, including governance, infrastructure, and efficient utilization of resources, to achieve sustainable outcomes. Additionally, recognizing the projected increase in inflow during the colder seasons due to climate change, despite potential decreases in summer flow, further emphasizes the need for adaptive management strategies to address the evolving hydrological dynamics.

The land use change model employed in this study utilized a linear trend analysis based on historical data (2002-2020). The linear trend method provided a useful starting point for our analysis, especially considering the limitations of available historical data. While it does not capture the full complexity of land use change drivers, it allowed us to establish a baseline for future land use projections. We recognize the need for more sophisticated models that can incorporate additional variables, such as socioeconomic conditions, government policies, and water availability. These future refinements will enable us to achieve a more nuanced understanding of land use dynamics in the Zayandehrud basin.

As the Zayanderud Basin represents a microcosm of water challenges, this integrated modeling approach offers a prototype for adaptable resource stewardship globally among anthropogenic changes. The methodologies provide transferable frameworks applicable across climate-vulnerable basins worldwide. While uncertainty remains, this analysis delivers sufficiently sharp insights to inform time-critical adaptation planning.

In conclusion, this study emphasizes the vital importance of responding to intricate connections between shifting environmental elements and policy choices that impact interlinked resources. The outcomes underline the essential relationship between the environment and decision-making, steering judicious management of resources even amid instability. Through proactive approaches built upon modeling techniques, water security can be improved despite escalating pressures at the climate-land-water nexus. While facing uncertainties, it is crucial to engage in scientifically informed planning now for the sake of sustainable water management in the future.

Data availability statement

Data will be made available upon a reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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