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Research Article

# Effective factors on flood occurrence using the system dynamics approach (Case study: Eskandari watershed-Isfahan, Iran)

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**ABSTRACT-** This study investigates the key factors influencing flood behavior through system dynamics modeling. Initially, the HEC-HMS model was employed to estimate flood levels across sub-basins due to its well-established capacity to simulate hydrological processes and quantify runoff within watershed areas. Its ability to integrate critical parameters, such as land cover and soil permeability, which influence the curve number (CN) and its relationship with runoff and slope, makes HEC-HMS particularly suitable for flood risk assessment. After identifying these relationships, system dynamics modeling was conducted using Vensim to simulate flood dynamics. Vensim's capability to model complex systems, especially feedback loops and nonlinear interactions among multiple variables, enabled a comprehensive representation of the interdependencies among flood-related factors. Sensitivity analysis highlighted land cover as the most significant variable affecting flood behavior. To evaluate its impact, two rainfall scenarios were analyzed: a 26.75 mm event on January 3, 2011, affecting 30% of the watershed, and an 18 mm event on February 20, 2011, covering 20% of the area. The analysis revealed that precipitation, land cover, watershed size, slope, and soil permeability were the primary drivers of flooding. This study demonstrates the value of combining HEC-HMS and system dynamics modeling to predict floods, particularly in data-scarce watersheds. The integration of these tools facilitates the formulation of mathematical relationships among key hydrological variables, thereby enhancing our understanding and management of flood risks.

## INTRODUCTION

The increasing frequency and severity of floods, along with the associated damages in many regions worldwide, underscore the urgent need for effective strategies to address this natural hazard (Karandish et al., 2014). Flooding, one of the most variable and complex hydrological processes on Earth, is influenced by a combination of geomorphological and climatic factors. Since the early 20th century, estimating runoff from precipitation has remained a foundational task in hydrology (Yamani et al., 2013), and understanding this process is central to the development of hydrological knowledge (Ebrahimzadeh and Bagheri Seyghalani, 2024). Quantitative and qualitative analysis of runoff plays a critical role in water resource management, and over the years, various models and techniques have been applied to simulate runoff dynamics. Among these, the system dynamics (SD) approach, rooted in systems thinking, has emerged as a powerful simulation method for modeling feedback relationships within complex systems (Dietz et al., 2003; Li et al., 2024). SD enables the integration of multiple interrelated factors that influence flooding and facilitates the simultaneous evaluation of their impacts. Its application in watershed management has proven effective, as dynamic simulation dissects system components, applies physical laws, and captures the interdependencies among various phenomena (Winz and Brierley, 2007). According to Bagheri (2006), SD treats systems as closed loops, where feedback mechanisms transmit outputs back as inputs. This framework is particularly useful for analyzing behavior patterns, modeling real-world systems, tracing information and process flows, and simulating the outcomes of different policy scenarios. Crucially, SD methods allow for the development of accurate behavioral models and realistic hypotheses even in data-scarce environments. System behavior is determined by the structural interactions among its components (Vlachos et al., 2007). By modeling these interactions, SD enables a deeper understanding of the dynamics that drive system behavior (Forrester, 1961; Sterman, 2000). For example, Khan et al. (2007) developed a system dynamics version of the Basin-wide Holistic Integrated Water Assessment (BHIWA) model using Vensim and provided a broad overview of systems-based approaches in water management. Similarly, Darbandi et al. (2014) simulated

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the rainfall–runoff process in the Lighvan Watershed using both genetic programming and Vensim, finding that the SD model achieved superior accuracy in replicating observed hydrological behavior. In another study, Feofilovs et al. (2020) proposed two SD models for urban flood response and resilience assessment. One model represented baseline system conditions at the onset of simulation, while the other evaluated the service supply-to-demand ratio over time. Although both were developed using the SD approach, they differed significantly in how they quantified resilience across time horizons. These studies collectively demonstrate that system dynamics can overcome the limitations posed by complexity, feedback, and interdependence in hydrological systems (Li et al., 2024).

In a separate study, Jiang et al. (2020) developed a generic System Dynamics Simulation Approach (SDSA) to investigate the interactions among multiple functions of the Three Gorges Reservoir in China. To explore how environmental and economic factors influence reservoir operations—particularly hydropower generation—they designed four scenarios: the reservoir power production sector (S_power), the fishery sector (S_fish), the sediment sector (S_sediment), and the landslide sector (S_landslide). Their findings demonstrated that the SDSA model effectively captured the interdependencies among reservoir functions and provided a useful tool for promoting environmentally sustainable reservoir management. In their systematic quantitative review, Phan et al. (2021) evaluated SD applications in water resource management by examining study objectives, scenario design, climate change considerations, validation and calibration methods, subsystem design, and spatial dimensions. They found that 82% of the reviewed studies employed scenario-based approaches to guide management decisions. Only 1.8% of the literature addressed optimization in water management, and 12% of the studies did not implement any form of model validation. Based on their analysis, the authors proposed a unified nine-stage SD modeling framework to manage complex and uncertain water resource systems. Wang et al. (2021) enhanced the qualitative assessment of water resource carrying capacity (WRCC) by integrating system dynamics modeling with fuzzy comprehensive evaluation. They developed a Vensim-based SD model to evaluate six scenarios between 2018 and 2025, each reflecting distinct development priorities: maintaining the status quo, strengthening the secondary industry, promoting primary industry development, enhancing the tertiary sector, adjusting the industrial structure, and improving water quality. Results indicated that the model helped reduce pressure on water resources, stabilizing WRCC at a “normal carrying” level (0.431 by 2025). To optimize irrigation water use in arid regions reliant on flood irrigation, Poulose et al. (2021) introduced a system dynamics model—SMITUV (System dynamics Modeling of Infiltration, solute Transport, and root water Uptake in the Vadose zone). This model was specifically developed to simulate infiltration processes, solute movement, and root uptake under varying irrigation scenarios. Jian et al. (2023) also employed the Vensim platform to develop a comprehensive method for assessing WRCC. Recognizing that water resources function within complex biological, environmental, social, and economic systems, their study incorporated these interconnections into the modeling framework. Their results underscored the urgent need to increase investments in environmental conservation and to initiate new freshwater storage projects to enhance regional WRCC. The findings also emphasized the importance of sustainable water ecology in addressing challenges linked to economic growth and population expansion. Using a system dynamics approach, Li et al. (2023) developed a model to assess urban rainstorm and flood resilience in Xi’an. The model elucidated behavioral mechanisms across various stakeholders and the internal dynamics of different dimensions of urban flood resilience. Their results showed that improvements in citizen engagement, government involvement, and information infrastructure led to reductions in damage loss rates by 44.44%, 10.8%, 9.48%, and 3.37%, respectively. Additionally, when projecting flood resilience across six development scenarios, the results revealed varying degrees of improvement in urban storm and flood resilience.

Through active stakeholder engagement, Awah et al. (2024) explored and analyzed the complex interdependencies and feedback loops within the Limbe flood risk management system. Their findings emphasized the value of participatory modeling techniques in enabling diverse stakeholders to collaboratively identify and prioritize intervention options. This participatory approach fosters local ownership and active involvement in flood risk management—a critical step in addressing the escalating challenges posed by climate change and natural disasters. Similarly, Coletta et al. (2024) introduced a SD based participatory socio-hydrological modeling approach to quantitatively examine the interactions and feedbacks between urban system components and flood risk. Their results demonstrated how SD modeling provides a structured means of analyzing subsystem interactions and evaluating the effectiveness of various flood mitigation strategies. This approach offers valuable insights for decision-makers seeking to enhance urban flood resilience. Using the commercial software Vensim DSS, Goharshahi et al. (2024) conducted a dynamic analysis of sustainable water resource management in the cities of Madhim and Sarbisheh, South Khorasan province—an area where a carbon sequestration project is underway. Their 21-year simulation (covering the period 1390–1410 in the Iranian calendar) was based on the water–food–energy nexus and incorporated Monte Carlo sensitivity analysis across five scenarios. Among these, the fifth scenario—which included a 60% improvement in irrigation efficiency, a 30% increase in crop productivity, and a 50% adoption rate of new energy sources—was identified as the most favorable in terms of overall system sustainability. To promote social sustainability within human–water systems, Javanbakht Sheikhahmad et al. (2024) developed a hybrid policy framework using an SD-based approach. The model simulated long-term dynamics in the Gavshan Basin in western Iran from 2020 to 2050. Their findings revealed that the basin's water resources are insufficient to meet future population growth. Furthermore, inefficiencies in the irrigation system lead to wastewater losses, with 20% of water stored at the Gavshan Dam. Sensitivity analysis showed that in Scenarios 3 and 4, policies supporting wastewater reuse in agriculture significantly increased water availability and crop yield, highlighting their potential for sustainable water resource management. Li et al. (2024) focused on optimizing the socio-economic–flood–safety–ecological (SFE) system of the Landong floodplain in the Yellow River Basin. Their results indicated that system dynamics modeling can effectively simulate the coordination between SFE subsystems. The study concluded that the development of the Landong floodplain must not solely prioritize socio-economic growth, but must also incorporate flood safety and environmental protection. Comprehensive regulatory frameworks based on socio-economic indicators, flood safety metrics, and environmental quality are essential for achieving integrated, high-quality, and resilient development in the region.

The HEC-HMS model is widely used for runoff monitoring and hydrological simulations (Yener et al., 2023; Dastorani et al., 2011; Hojjati Marvast et al., 2024). Solyman et al. (2015) applied HEC-HMS to perform hydrological analysis and assess flood reduction in a valley in Yemen. Their hydrograph simulations showed that constructing flood-control structures in just two sub-basins would significantly reduce flood risks. Similarly, Dotson (2001) introduced a distributed hydrologic modeling system that integrated GIS with HEC-HMS to simulate rainfall-runoff processes and identify flood-prone areas. Due to Iran's distinct climatic conditions and the uneven temporal distribution of precipitation, understanding the mechanisms of flood generation and identifying contributing factors is essential. Peker et al. (2024) conducted flood modeling for the Goksu River Basin in Mersin, Turkey, using GIS, HEC-RAS, and HEC-HMS. Their analysis revealed that the region is highly susceptible to flood events with a 25-year return period (Q25). Sahu et al. (2023) reviewed various hydrological models with a focus on the HEC-HMS model and its associated loss methods, including SCS-CN, SMA, Green-Ampt (GA), and Deficit and Constant (DC). They found that SCS-CN and SMA are the most commonly used approaches in dendritic basin models. Although the D.C. method is less widely applied, it provides straightforward and accurate results. This study offers practical guidance for hydrological modelers and supports informed decision-making for water resource managers and policymakers pursuing sustainable development goals. Lin et al. (2022) investigated simulation performance of the HEC-HMS model in a web-based spatial flood forecasting environment (WSFF), using 12 historical flood events from the Chuanchang watershed in southeastern China. Nine events were used for calibration and three for validation. The model demonstrated strong performance, achieving an average Nash-Sutcliffe Efficiency (NSE) of 0.81 during validation, with peak flow prediction errors within 15% and timing errors under one hour. Hamdan et al. (2021) simulated runoff and flood potential in the Al-Adim River catchment and Earthen Dam region in Iraq using HEC-GeoHMS and GIS, based on daily rainfall data from 2015 to 2018. The model was calibrated over two years and validated for one year, showing a high degree of correlation between observed and simulated hydrographs. Mohammadi et al. (2013) found that flood contributions from sub-watersheds are not determined solely by their area or peak discharge. Instead, spatial factors such as distance to the watershed outlet, curve number (CN), and the routing effects along the main river significantly influence flood potential. Their study also showed that sub-watershed flood susceptibility rankings remained consistent across different return periods. In the Nahand watershed, Mikaeilzadeh (2014) evaluated the impact of watershed management measures on runoff using the HEC-HMS model. After calibrating and validating the model with nine observed flood events, flood hydrographs were simulated for return periods of 2 to 50 years. The results indicated that mechanical interventions had limited influence on increasing time of concentration, whereas biological measures led to an average CN reduction of 8.47% across the watershed. Abbasi and Talebi (2016) applied the HEC-HMS model to prioritize sub-watersheds within the Eskandari watershed based on flood susceptibility. Using design rainfall data for return periods of 2, 5, 10, 50, and 100 years, they found that sub-watershed I consistently ranked highest in terms of flood susceptibility, both independently and in combination with other sub-watersheds. Further analysis showed that sub-watershed A had the highest susceptibility for 5- and 10-year events, while sub-watershed G ranked highest for 50- and 100-year return periods.

Additionally, the integration of hydrological and hydraulic models employed in this study can be extended to various flood-prone areas for generalization and reliability assessment. These models also hold significant potential for flood control planning and real-time flood simulation, contributing to the reduction of material losses and the prevention of flood-induced damage. Overall, a review of the existing literature reveals that although numerous factors influence flood occurrence, most modeling approaches tend to assess these factors in isolation. In contrast, system dynamics (SD) allows for the simultaneous consideration of these interdependent factors and their feedback mechanisms within a unified framework. The Eskandari watershed, located in Isfahan Province, is a critical water source for domestic, industrial, and agricultural use. Its importance is further underscored by the fact that its outflow feeds into the Zayandeh roud Dam, a key reservoir supplying water to adjacent provinces and the broader zayandeh roud watershed. The primary aim of this study is to employ system dynamics modeling in the Eskandari watershed to examine the drivers of flood occurrence, with particular attention to the dynamic nature of runoff generation and flood processes, including their variability and interacting components. In other words, the study seeks to identify the key contributors to flooding by adopting a systems-based perspective. Despite limited availability of watershed data, the study establishes key relationships and linkages that enable the estimation of peak discharge in arid regions. The findings have important implications for flood behavior analysis, particularly in identifying the most flood-prone sub-areas. This information is essential for prioritizing watershed management and conservation interventions in critical zones. The present study addresses several research gaps through the application of a hybrid methodology. First, whereas most prior studies tend to focus exclusively on either hydrological models (e.g., HEC-HMS) or system dynamics models (e.g., Vensim), this research integrates both, thereby improving the accuracy of flood predictions, especially in data-scarce regions where empirical models alone may be insufficient. Second, while many previous studies rely on long-term statistical analyses of flood events, this study emphasizes the testing of specific flood scenarios. This approach allows for a more precise evaluation of how variations in rainfall intensity and spatial distribution affect flood behavior.

Third, while many hydrological models primarily rely on precipitation and slope as the main driving factors, this study incorporates additional variables such as land cover changes, soil permeability, and CN dynamics. This integrative approach enables a more accurate representation of runoff generation and flood risk. In this context, two hypotheses were proposed, with the first being the focus of the present study. The first hypothesis posits that the SD approach can identify the mathematical relationships among the components influencing flood occurrence with a reasonable degree of accuracy. The second hypothesis, which will be addressed in future work, suggests that flood events are more significantly influenced by the watershed's physiographic characteristics.

## MATERIALS AND METHODS

The Eskandari watershed, located west of Isfahan, serves as the study area. It covers approximately 1,649 km$^2$ and lies between longitudes 50°20´ to 50°30´ E and latitudes 32°42´ to 33°11´ N. The watershed has an average elevation ranging from 2,130 to 2,626 meters above sea level. The Pelasjan River, which originates in the Fereidon-Shahr highlands near Isfahan, flows through the Eskandari watershed and has an average annual discharge of approximately 131 million cubic meters. The region receives an average annual precipitation of 339 mm (Karimi and Talebi, 2023). The Pelasjan River is the second most important tributary of the Zayandeh roud watershed after the Zayandeh roud River itself. It joins the Zayandeh roud River near Ali-Abad Village, located upstream of the Zayandeh roud Dam. The geographic location of the Eskandari watershed within Iran and the Isfahan province are shown in Fig. 1.

*Physiographic parameters*

Digital maps were utilized to extract the physiographic parameters of each sub-basin within the Eskandari watershed, and the corresponding results are presented in Table 1. The average annual discharge recorded at the eskandari station is approximately 1.31 m$^3$/s. The watershed is divided into several sub-basins, namely A, D, E, F, and G, with sub-basin G covering the largest area and sub-basin E the smallest. The main river network and stream system of the Eskandari watershed are illustrated in Fig. 1.

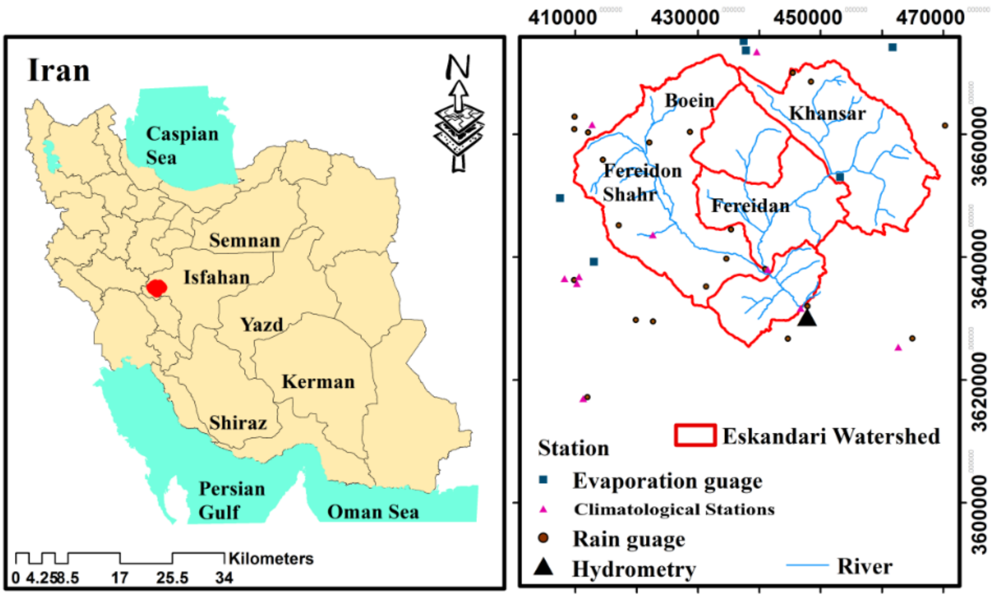


**Fig. 1.** Eskandari sub-watersheds, stations, and the main stream channel.

**Table 1.** Physiographic parameters of each sub-basin

| Physiographic parameter | A | D | E | F | G |
|---|---|---|---|---|---|
| Area (km$^2$) | 155.6 | 161.8 | 73.1 | 165.6 | 238.3 |
| Main stream length (km) | 17 | 12.6 | 14 | 15 | 16 |
| Perimeter (km) | 67.6 | 55.3 | 41.4 | 70.7 | 84.7 |
| Slope (%) | 8.3 | 12.1 | 12.6 | 24.6 | 19 |
| Concentration time (hr) | 6.1 | 3.1 | 3.3 | 1.8 | 2.5 |
| Impermeable areas (%) | 2 | 1 | 2 | 3 | 5 |

*Integration mechanism of the model*

This study employed the SD approach to analyze the key components contributing to flood occurrence within the Eskandari watershed. SD modeling was selected due to its capacity to represent and simulate complex, interrelated systems, making it well-suited for flood modeling in the study area. The watershed system was structured into five interacting subsystems (Karimi and Talebi, 2023). Initially, the HEC-HMS model was applied to estimate flood discharge across the sub-basins. Based on the identified influencing factors, the system was then modeled using the Vensim software through the SD approach. The research methodology is illustrated in the flowchart presented in Fig. 2.

*Simulation of hydrologic reaction of the basin using the HEC-HMS model*

The HEC-HMS hydrological model incorporates a variety of techniques, one of which is the precipitation method, used to estimate the maximum potential precipitation over a given area (Yu and Zhang, 2023). Through the simulation of precipitation and runoff in the watershed, the model can address multiple hydrological challenges, such as flood hydrology, precipitation distribution, and loss estimation. The model consists of three primary components: the basin model, the meteorological model, and the control specifications (USACE, 2000). It also includes parameter optimization capabilities. Among its core internal functions are estimating losses, transforming excess precipitation into runoff, simulating baseflow, and routing floodwaters through reservoirs (Scharffenberger, 2006). Input data for the model, including slope, land use and land cover, CN, and drainage network, were obtained using GIS and integrated into the HEC-HMS model. In this study, the SCS unit hydrograph method and lag time were used to simulate the conversion of excess precipitation into surface runoff and to model streamflow. After identifying the major flood-contributing factors, these parameters were imported into Vensim software, where their causal relationships were established. A model flow diagram was developed in Vensim to simulate the system's behavior. Key variables influencing flooding in the Eskandari watershed included soil permeability, vegetation cover, curve number, surface storage, precipitation, concentration time, and time to peak. The sub-basin configuration and their interrelations within the HEC-HMS model are illustrated in Fig. 3. Hydrological data from the Eskandari hydrometric station (located at the watershed outlet) and several rain gauge stations, including Fereidonshahr, Boein, and Savaran, were used in the modeling process. Five rainfall-runoff events, selected from the records of the Regional Water Company of Isfahan, were utilized for model calibration. These events and their key characteristics are summarized in Table 2. Model calibration was performed manually using four parameters: CN, lag time, impervious area percentage, and initial abstraction. The average of the calibrated parameters was then used for further simulations and model validation. The model was validated using five additional rainfall events recorded at the Boein rain gauge station.

*Hydrological model execution*

After entering the required data, the HEC-HMS hydrological model was configured according to the methods outlined in the preceding sections. The model was then executed for the selected rainfall-runoff events listed in Table 3. Following initial simulations, calibration was conducted to improve model performance. Parameters identified as most influential through sensitivity analysis were prioritized during the calibration process. A comparison between the observed and simulated hydrographs is illustrated in Fig. 4. Additionally, the mean values of model performance indicators for both the calibration and validation stages are summarized in Table 4. To assess model accuracy, four performance indicators were employed during both calibration and validation stages. Sensitivity analysis, based on the method described by Wen et al. (2022), was conducted for four key parameters: CN, lag time, percentage of impervious area, and initial abstraction. Variations of ± 10% and ± 15% were applied to the input values of the HEC-HMS model to evaluate how changes in these parameters influenced model outputs. The results of these sensitivity tests are presented as model response curves in Fig. 4. Among the parameters tested, the curve number and initial abstraction were found to be the most sensitive. The influence of modifying each input parameter on the model's output is further depicted in Fig. 5.

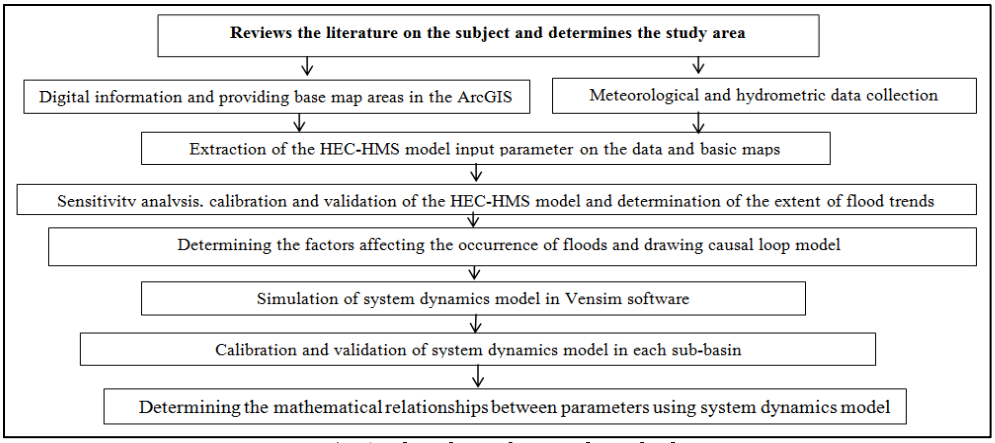

**Fig. 2.** Flowchart of research methods.

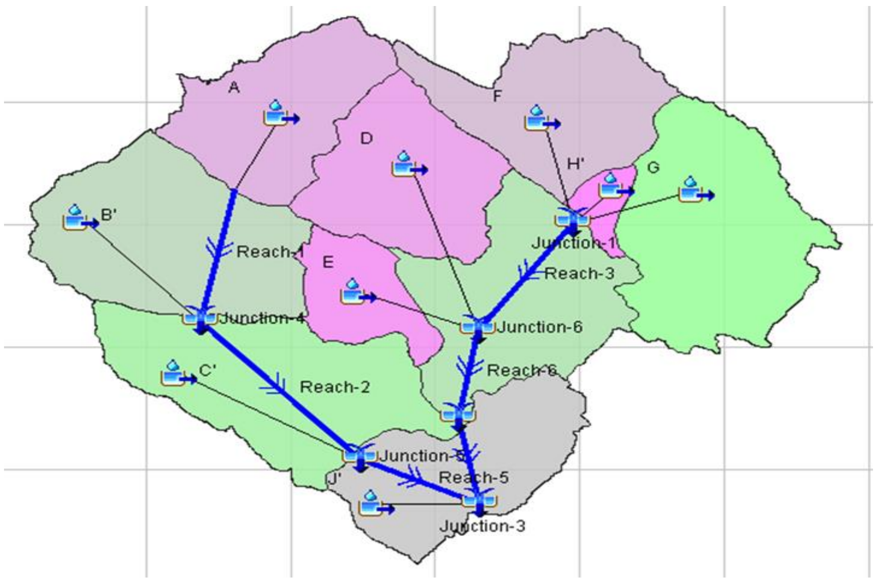


**Fig. 3.** Schematic design of sub-basins and how they are related in HEC-HMS model.

**Table 2.** Selected rainfall events and their continuity

| Event | Rainfall amount (mm) | Rainfall duration (h) |
|---|---|---|
| 2008/07/04 | 28.5 | 10 |
| 2009/02/20 | 18 | 13 |
| 2009/10/26 | 14.25 | 6 |
| 2010/11/04 | 26.75 | 7 |
| 2012/02/14 | 21.5 | 11 |

**Table 3.** Selected rainfall events and their duration

| Event | Rainfall duration (h) | Height (mm) |
|---|---|---|
| 2007/04/11 | 9 | 24.2 |
| 2009/05/09 | 23 | 17.4 |
| 2010/04/09 | 6 | 19.8 |
| 2010/05/04 | 12 | 27.9 |
| 2011/03/14 | 8 | 16.6 |

**Table 4.** Mean values of model performance indicators during the stages of validation and calibration

| Assessment index | Calibration | Validation |
|---|---|---|
| Nash-Sutcliffe | 0.84 | 0.19 |
| Bias in estimating flow volume | 0.95 | 1.84 |
| Error percentage in peak discharge | 4.91 | 35.47 |
| Minimum mean square error | 2.11 | 10.22 |

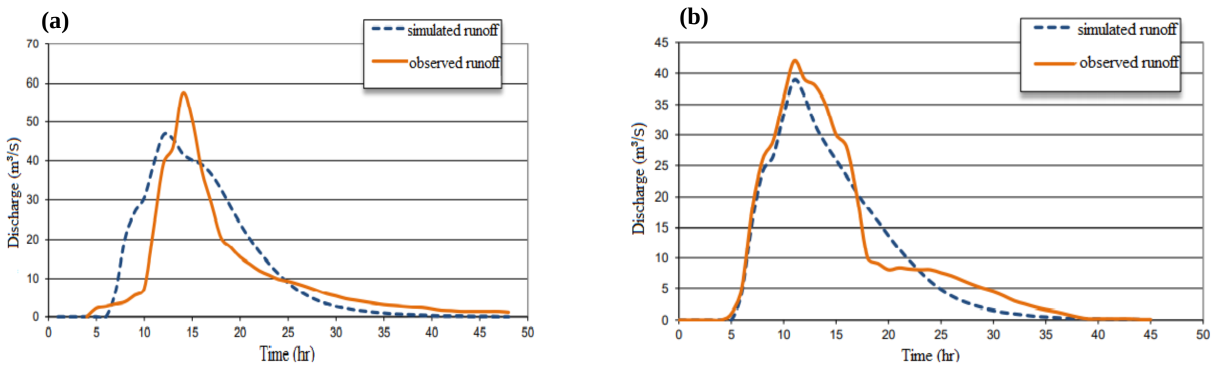


**Fig. 4.** (a) Simulated and observed hydrographs of the rainfall event of March 14, 2011 after calibration. (b) Validation diagram of simulated and observed hydrographs of the rainfall event of January 3, 2011 at eskandari hydrometric station.

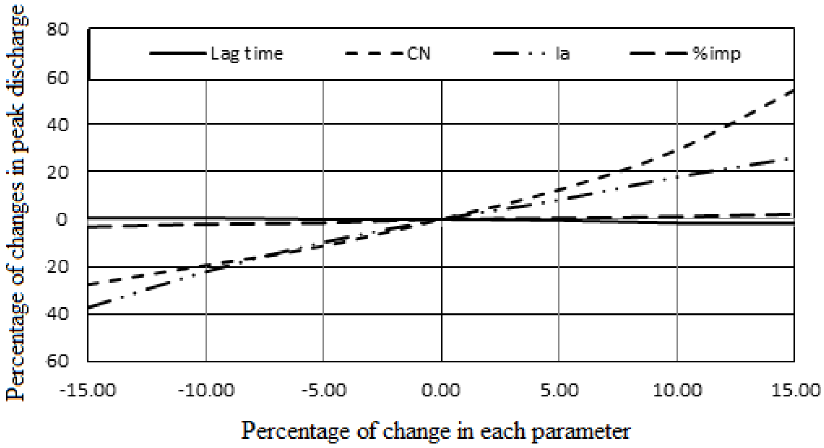


**Fig. 5.** Relation between the changes in the input parameters and the changes in the output.

*System dynamics approach*

A system can be understood as a network of interconnected pathways that influence fixed quantities over time, a concept fundamental to SD (Deaton, 2000). The feedback principle inherent in system dynamics requires information to flow between the various components of the system. SD models can be conceptualized, documented, simulated, analyzed, and optimized using tools like Vensim (Ventana Systems, 2004). Vensim provides a straightforward and flexible set of tools for simulating models through causal loop or stock-and-flow diagrams. It supports a range of functions for sensitivity testing, policy optimization, and model calibration (Pruyt, 2013). Van den Belt (2004) emphasized that in watershed management, much of the focus when applying system dynamics is on population growth and its relationship to water resources. This study specifically investigates the effects of five key parameters: soil permeability, basin slope, area, precipitation, and vegetation. The stock-and-flow diagram for these parameters is presented in Fig. 6.

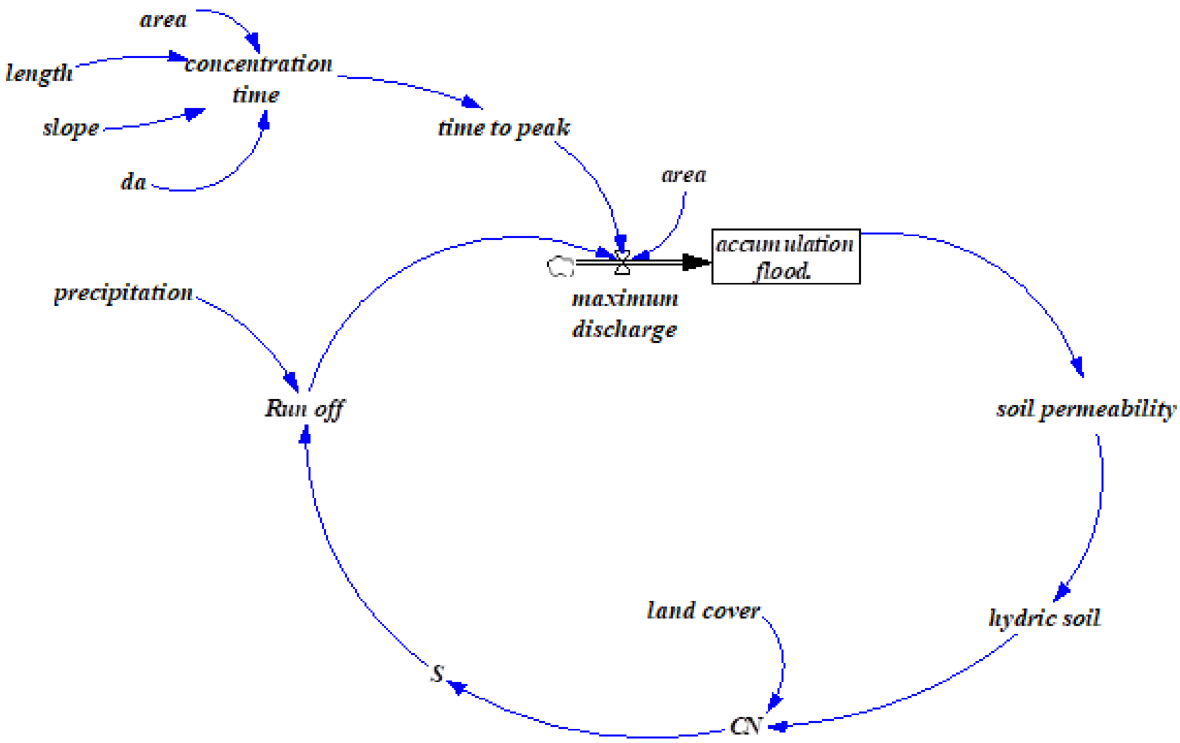


**Fig. 6.** Stock and flow diagram of system dynamics model in Vensim software.

## RESULTS

### *HEC-HMS model*

The HEC-HMS model was executed after completing data entry and defining the relationships among sub-basins, the meteorological model, and control parameters. The output was a simulated hydrograph representing the rainfall-runoff response. Overall, the model accurately simulates the flow of the Pelasjan River, demonstrating good agreement with observed data.

### *System dynamics model*

*Sensitivity analysis of system dynamics model*

Five key characteristics were analyzed: watershed area, precipitation, land cover, basin slope, and soil permeability. The impact of a 20% increase in each parameter on flood magnitude is illustrated in Fig. 7. The results indicate that land cover and precipitation exert the most significant influence on flooding, respectively.

*Calibration and validation of system dynamics model*

After identifying the primary factors influencing the flood event using Vensim software, simulations were conducted for each sub-watershed. A histogram of the calibrated model results for the sub-basins is presented in Fig. 8a. The model was then validated using five separate events, with the validation histogram shown in Fig. 8b. Sub-watersheds F and G exhibited the highest peak discharges, likely due to the rocky outcrops, steeper slopes, and limited vegetative cover. In contrast, Sub-watershed E recorded the lowest peak discharge, possibly attributable to the reduced vegetation. Precipitation emerged as a critical driver of sub-watershed output across all events: higher precipitation levels produced greater runoff, while lower precipitation resulted in reduced flooding.

### *Scenarios in the SD model*

The vegetation parameter that significantly affects the watershed's flood was altered for the purpose of scenario planning and evaluation in the event that floods change as a result of parameter modifications. It was stated how changes in the CN, runoff, surface storage, and flood relate to the changes in the vegetation.

*Checking vegetation variations trend and its impact on the maximum flow rate*

A land use map of the Eskandari watershed was first developed using Landsat satellite imagery. False color composites were generated through the band correlation method, followed by the application of various image processing techniques. Supervised classification was then employed in successive stages to distinguish between land use classes. The classification results demonstrated high reliability, with an overall accuracy of 89.3% and a Kappa coefficient of 0.85 (Karimi and Talebi, 2023). According to the findings, garden areas represent the smallest proportion of land use, while a combination of irrigated and rain-fed agriculture constitutes the largest share of the watershed's surface area. The study also investigated vegetation change patterns and their impact on peak discharge rates under two different precipitation scenarios. The vegetation map of the Eskandari watershed is presented in Fig. 9.

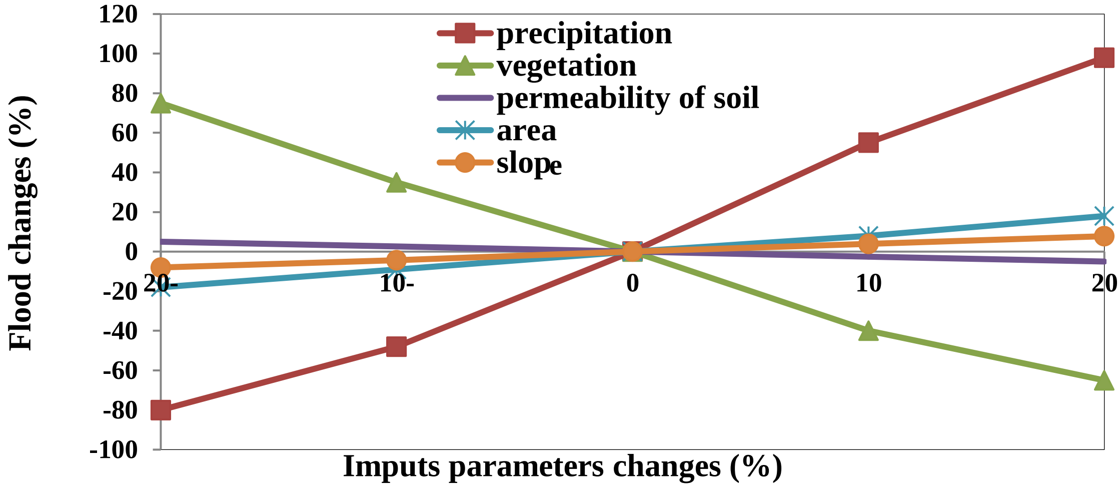


**Fig. 7.** Flood discharge due to a 20% increase in each parameter.

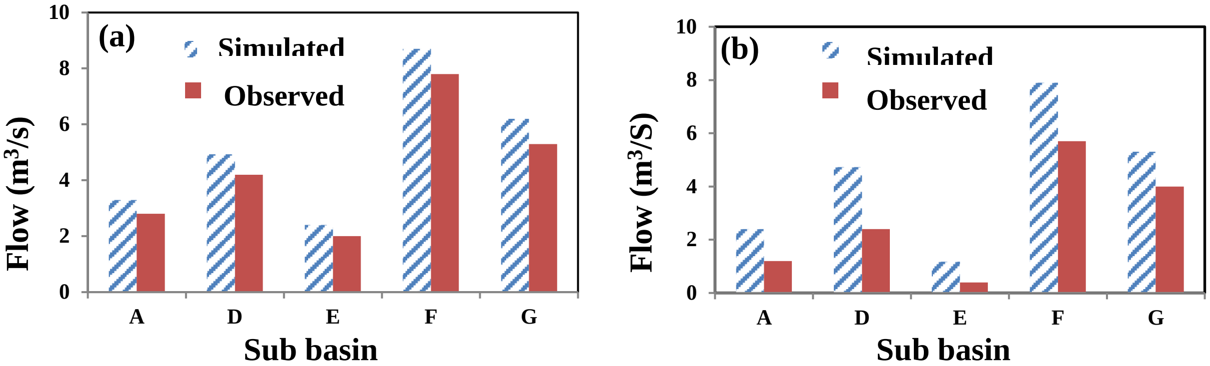


**Fig. 8.** Simulated and observed calibration histogram of flow event dated (a) January 3, 2011 and (b) February 21, 2010 at Eskandari watershed sub-basins.

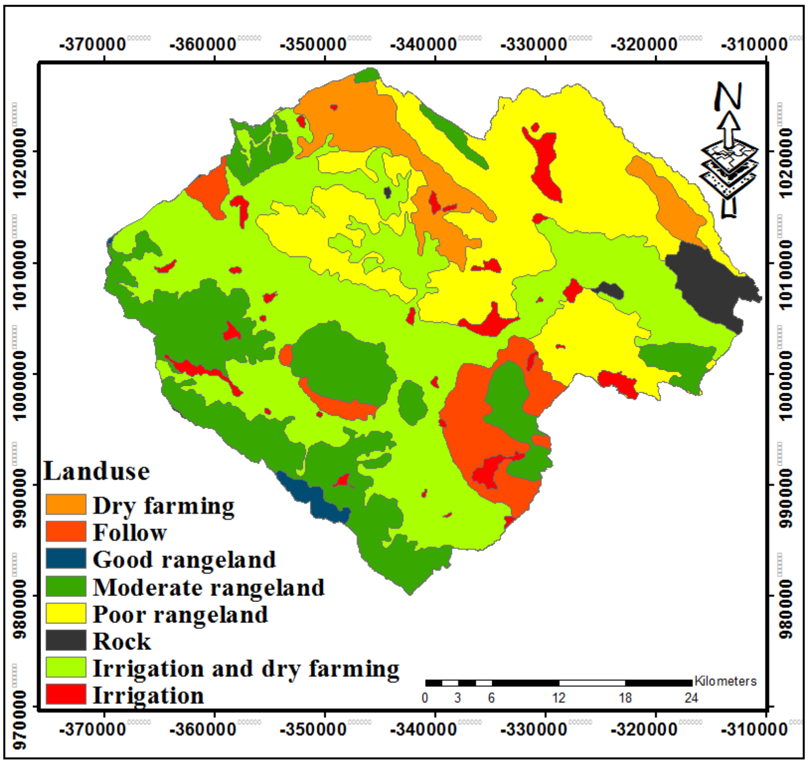


**Fig. 9.** Eskandari watershed land cover map.

As expected, the data indicate that increased vegetation coverage contributed to a reduction in flood magnitude. Sub-basins D and E exhibited the highest peak discharges, likely due to their steeper slopes, extensive rock outcrops, and limited land cover. In contrast, sub-basin C recorded the lowest flood rate and peak discharge, which may be attributed to its relatively higher land cover proportion compared to its total area. As shown in Fig. 10a and Fig. 10b, optimal vegetation cover accounted for approximately 30% of the watershed's surface on January 3, 2011, when 26.75 mm of precipitation was recorded, and about 20% on February 20, 2009, with 18 mm of rainfall. Subsequently, a soil hydrological group map was generated based on soil properties such as texture, infiltration capacity, and infiltration rate (Fig. 11). Notably, hydrological group A—characterized by high infiltration and low runoff—was absent from the basin. The remaining groups, B, C, and D, which produce medium, relatively high, and very high runoff respectively, were distributed across the watershed at proportions of 57.2%, 25.0%, and 17.8%. Since groups C and D together comprise 47.8% of the basin, the overall runoff production capacity is classified as medium to high. This significantly contributes to the intensification of flooding in the region.

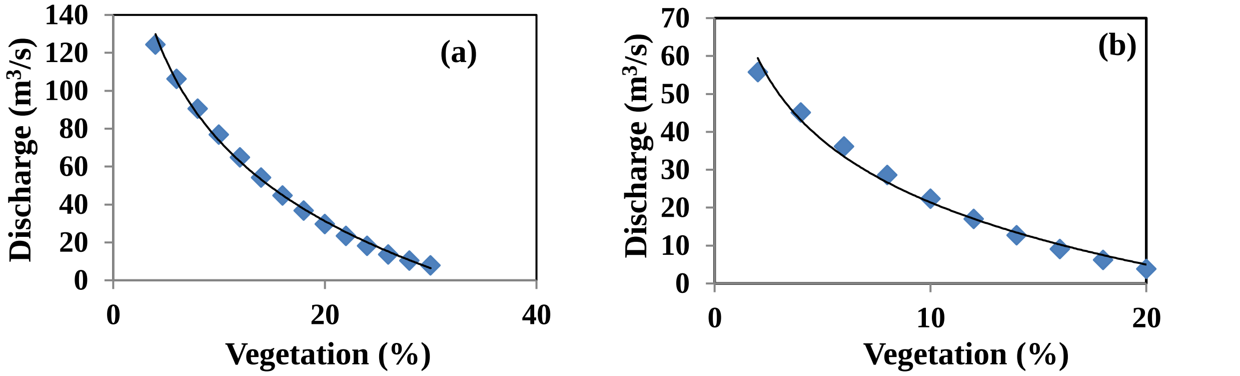


**Fig. 10.** Vegetation variations trend and its impact on the peak discharge in (a) January 3, 2011 event and (b) February 2, 2009 event.

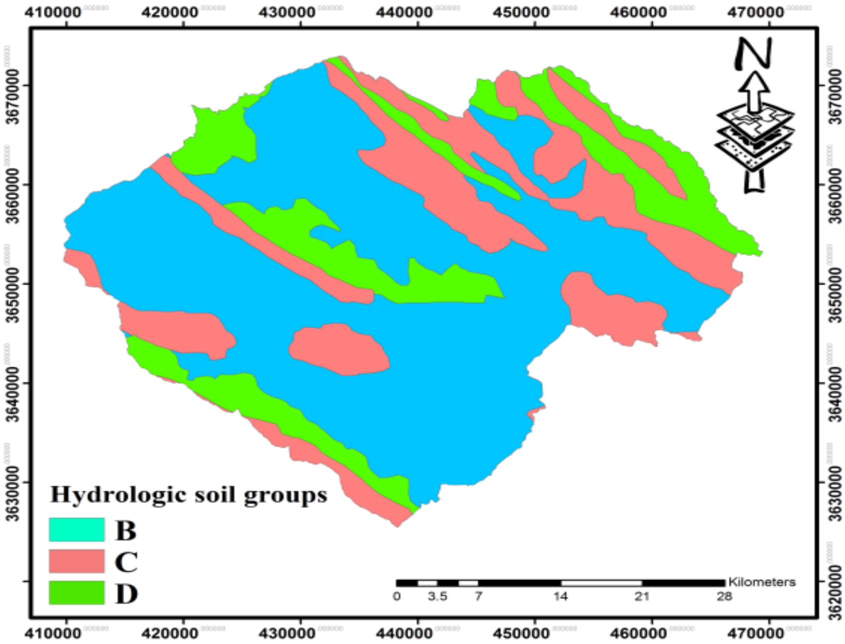


**Fig. 11.** Map of hydrologic soil groups.

*Evaluation of vegetation variations trend and change rate of the CN, runoff, and total losses*

For the rainfall event in sub-basin G on January 3, 2011, precipitation was measured alongside concurrent evaluations of the CN, total losses (S), runoff and vegetation cover percentage. As shown in Fig. 12, an increase in surface vegetation led to a corresponding decrease in the CN, with values ranging from 90 to 70. This indicates that land cover is the most influential factor affecting the CN in this watershed. Fig. 13a illustrates the relationship between land cover change and S. As vegetation cover increases, the CN decreases, resulting in greater total losses due to the enhanced infiltration and reduced surface runoff potential. Fig. 13b shows that as surface vegetation and total losses increase, runoff decreases, up to a threshold, beyond which further increases in vegetation yield minimal additional reduction in runoff. This suggests a saturation point in the vegetation-runoff relationship, where further vegetation growth has diminishing effects on runoff reduction.

*Relationship between the CN changes and slope, with peak discharge rate*

Following the system dynamics simulation, the key components contributing to flood generation were identified. Using Excel and SPSS software, graphs were generated and statistical correlations between these components were established. One focus of the analysis was how the CN responds to changes in peak discharge rate. Regression analyses were performed to examine the relationships between CN, slope, and peak discharge during the November 5, 2009, rainfall event across all sub-basins. These relationships are illustrated in Fig. 13a and Fig. 13b. As expected, an increase in CN corresponds with increased runoff, which in turn leads to higher peak discharge rates. Fig. 14 illustrates the relationship between slope percentage and peak discharge, showing that peak discharge increases with steeper slopes. However, the influence of slope on CN in the Eskandari watershed is less significant compared to the impact of vegetation cover.

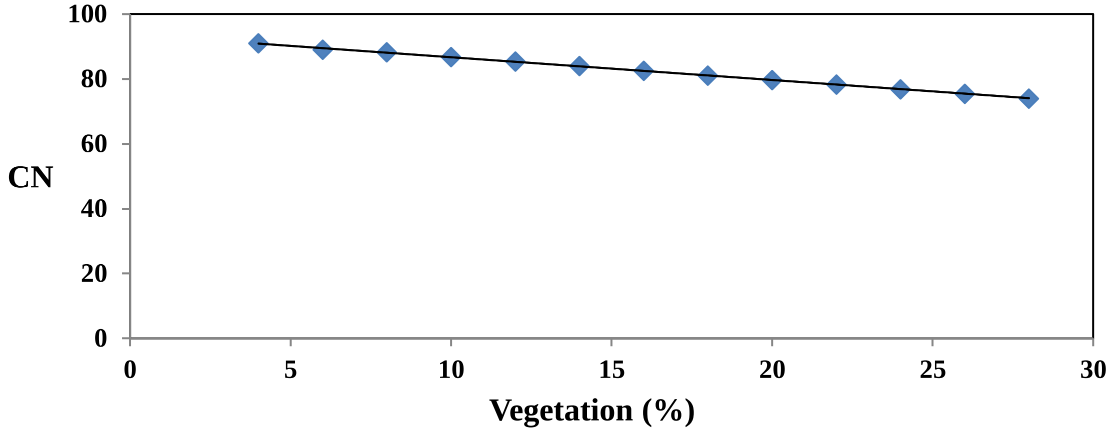


**Fig. 12.** The relationship between changes vegetation and the curve number (CN).

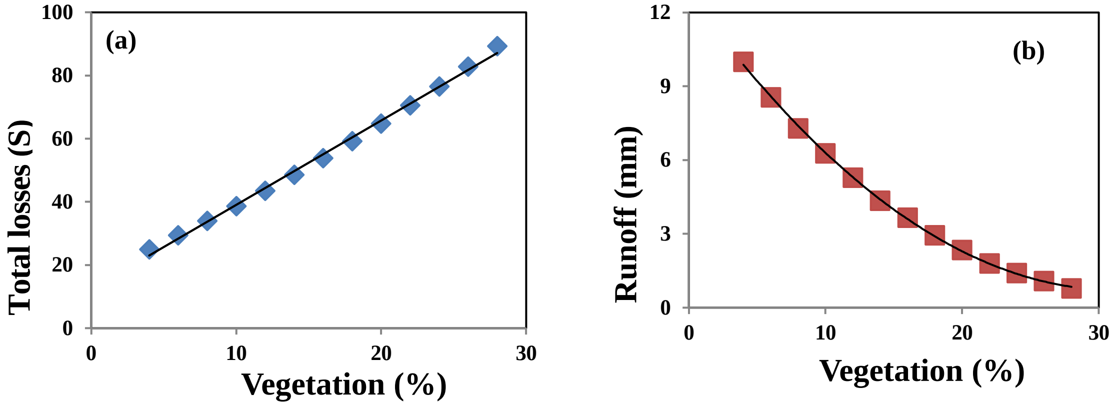


**Fig. 13.** (b) The relationship between changes in area surface vegetation and the soil storage. (b) The relationship between changes in area surface vegetation and runoff.

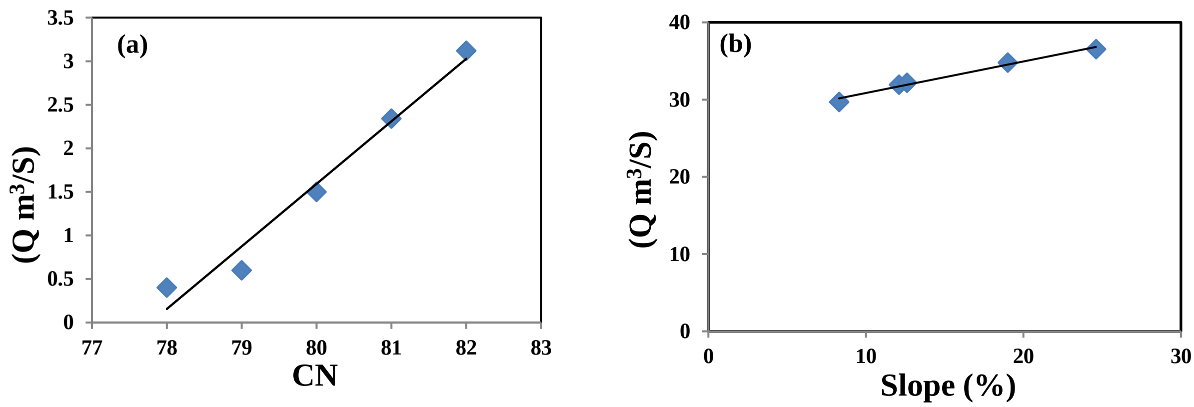


**Fig. 14.** (a) The relationship between the curve number changes and peak discharge. (b) The relationship between the slope changes and peak discharge.

*Determination of mathematical relationships between parameters using system dynamics*

If we know the amount of surface vegetation and precipitation and we only use one rainfall event, we can estimate peak discharge using the following equations. This may be helpful for watersheds where there is a lack of data. A correlation between (a) peak discharge and (b) the concentration of CN can be deduced (Eq. (1)):

$a = 0.812b - 63.49$ Eq. (1)

In addition, the relationship between (c) percentage of vegetation cover and (a) peak discharge was extracted (Eq. (2)).

$a = 0.2c2 - 9.37c + 107.48$ Eq. (2)

The relation between (d) slop and (a) peak discharge is presented (Eq. (3)):

$a = 0.4d + 26.77$ Eq. (3)

Subsequently, a relationship for CN was proposed based on soil permeability (a1) and percentage of vegetation cover (c) (Eq. (4)):

$CN = -1.55a1 - 0.28\ c + 88.192$ Eq. (4)

## DISCUSSION

The objectives of this study were to (1) identifying the most effective sub-basin for flood mitigation in the

Eskandari watershed, (2) analyzing the factors influencing flooding using a SD approach, and (3) exploring the applicability of this approach to understanding flood behavior. By employing the SD method, which captures the dynamic and interrelated processes of runoff generation and flood response, the study evaluates the watershed system as an interconnected whole to determine which sub-basin contributes most effectively to flood prevention. Given the Eskandari watershed's role as one of the primary contributors to the Zayandeh roud Dam, understanding its flood behavior is crucial. System dynamics modeling was selected due to its capacity to simulate complex hydrological systems. The watershed system was conceptualized as comprising five subsystems. Initially, the HEC-HMS model was used to estimate flood characteristics at the sub-basin level. This study distinguishes itself from previous works, such as those by Solyman et al. (2015) and Datson (2001), by integrating HEC-HMS outputs into a dynamic modeling framework using Vensim, thereby enabling a more comprehensive analysis of interactions among flood-related variables. After identifying the flood-prone sub-basins and key influencing factors, the SD model was executed using Vensim. Model parameters were calibrated, and mathematical relationships between variables, such as changes in CN, vegetation cover, runoff, slope, and soil permeability, were established through system dynamics-based evaluation. Sensitivity analysis revealed that vegetation had the greatest impact on flooding, prompting a closer examination of its role under two different land cover scenarios. The results are consistent with findings by Mohammadi et al. (2013), who emphasized that sub-basin characteristics, including spatial location, CN, and routing effects, play a more significant role in flood potential than peak discharge alone. Similarly, studies by Peker et al. (2024) and Sahu et al. (2023) affirmed the utility of HEC-HMS, particularly when using CN-based loss methods, and underscored the impact of land cover and CN changes on runoff generation. These findings support this study's conclusion that vegetation dynamics and urbanization are critical determinants of hydrological response. Moreover, the observations align with Mikaeilzadeh (2014), who reported that while watershed management measures may not significantly alter the time of concentration, they do contribute to reductions in CN values. This suggests that structural interventions alone are insufficient for flood control. In line with these insights, the current study demonstrates that land cover modification, particularly through biological interventions, offers a more effective strategy for flood mitigation compared to purely mechanical approaches.

Additionally, scenario analysis was conducted in this study using historical rainfall events to assess flood response under varying land cover and precipitation conditions. Notably, the two most significant rainfall events occurred on January 3, 2011, with 26.75 mm of precipitation and approximately 30% land cover, and on February 20, 2009, with 18 mm of precipitation and about 20% land cover. The system dynamics modeling revealed that the following parameters, in order of significance, influenced flooding in the Eskandari watershed: precipitation, vegetation, area, slope, and soil permeability. These findings support the effectiveness of the modeling approach in accurately simulating watershed hydrology, particularly in the Pelasjan River sub-system. This is consistent with the work of Bazrkar et al. (2013), who also demonstrated the robustness of system dynamics models in simulating flow hydrographs. Moreover, the performance of the HEC-HMS model in this study aligns with results obtained by Anderson et al. (2002) and Ali et al. (2011), who confirmed the model's effectiveness in flow simulation and hydrograph generation. The results of this study validate the first research hypothesis, that the system dynamics approach can accurately identify mathematical relationships among flood-related variables, especially when the model is carefully calibrated and validated using empirical data. Furthermore, sensitivity analysis confirmed that precipitation and vegetation cover are the most influential factors affecting flood output. The analysis also indicated that increases in vegetation cover lead to reduced flooding up to a threshold, beyond which flood levels remain relatively stable. The findings also emphasize a strong correlation between precipitation volume and peak discharge, reinforcing the importance of rainfall intensity in flood behavior. The second hypothesis, that flooding is strongly influenced by the watershed's physiographic characteristics, is likewise supported. These characteristics, including topography, slope, soil type, vegetation cover, and drainage structure, collectively govern the manner in which water flows, accumulates, and transforms into flood events within the watershed. In the case of the Eskandari watershed, steep mountainous topography results in rapid runoff generation during intense rainfall, with water quickly funneled to lower elevations. Furthermore, urbanization in downstream regions such as Isfahan has led to the development of impervious surfaces that inhibit infiltration, exacerbating flood risks. These findings highlight the critical role of both natural physiographic features and anthropogenic alterations in shaping hydrological responses. The comparative insight from Goharshahi et al. (2024), who utilized Monte Carlo sensitivity analysis to assess water resource sustainability across five management scenarios, provides a useful contrast. While their study emphasized irrigation efficiency and renewable energy in improving water resource management, the present study focused specifically on flood mitigation. Nonetheless, both underscore the utility of modeling tools in informing water-related decision-making. Additionally, integrating system dynamics with other methods, such as hydrological models like HEC-HMS or emerging machine learning techniques, can enhance model precision and improve predictive reliability in future research.

The significance of this study's findings lies in their ability to forecast flood behavior in watersheds where data is scarce by employing a SD technique to uncover mathematical correlations. Planning for the management of this watershed can also be aided by a deeper comprehension of the traits and actions of the watershed that will contribute to floods in the upcoming decades.

1. It is suggested to prioritize the factors affecting flooding using system dynamics methods. Stakeholders can develop a SD model to simulate the interactions between key factors influencing flooding, including rainfall, land cover, soil permeability, and human interventions (e.g., dam operations and road construction). Through simulations, they can identify the most influential variables, such as soil saturation or deforestation, in flood generation. This analysis enables the prioritization of mitigation strategies, such as enhancing soil management practices or optimizing infrastructure design, to address the most significant contributing factors effectively.
2. Given that vegetation cover has a significant impact on the amount of flooding in the area, it is recommended to implement corrective actions to preserve vegetation cover and adjust crop patterns in the region. Since vegetation cover enhances infiltration and reduces runoff, stakeholders can implement reforestation initiatives or promote agroforestry systems. Additionally, experts may encourage farmers to adopt drought-resistant or low-water-demand crops, which help stabilize soil, minimize erosion, and improve natural water retention. To facilitate adoption, workshops and incentive-based programs could be organized to introduce these sustainable practices.
3. Considering that two tunnels have been added to the area in recent years, the role of these tunnels in increasing flooding potential should be examined using system dynamics methods. The construction of tunnels may modify the hydrological dynamics of the region, potentially disrupting the natural drainage system. By modeling both pre- and post-tunnel conditions within a SD framework, stakeholders can quantify the tunnels' impact on flood risks, such as increased water velocity or flow constrictions. The results can inform mitigation strategies, including tunnel design modifications or the implementation of buffer zones to regulate water flow.
4. It is recommended that the impact of the various land-use changes in the region on increasing the flooding potential of sub-basins be studied. As urbanization and agricultural expansion modify the landscape, it is essential to evaluate how these land-use changes influence flood risks across different sub-basins. Stakeholders can create land-use maps and overlay them with flood-risk zones to identify areas with high flood potential. A SD model can simulate the effects of land-use changes, such as urban sprawl or deforestation, on runoff. Based on these simulations, the model can recommend strategies like controlled urban development, improved land zoning, or increasing green spaces in high-risk areas to mitigate flood risks.

*Research limitations and uncertainty levels*

1. The accuracy of the results is dependent on the quality and resolution of input data, including precipitation, land cover, soil properties, and topographic characteristics. The scarcity of high-resolution spatial and temporal data may introduce uncertainty in model outputs.
2. SD modeling requires certain assumptions regarding relationships between variables, such as land cover changes and runoff generation. These assumptions, while based on empirical data and mathematical formulations, may not fully capture the complex, nonlinear interactions governing flood behavior.
3. The calibration of HEC-HMS and SD models was performed using available historical rainfall-runoff events. However, the limited number of observed flood events and the potential errors in historical records may impact the reliability of the model's predictive capabilities.
4. Sensitivity analysis highlighted land cover as the most influential factor in flood response. However, uncertainties in defining land cover classes and their hydrological impacts could influence the estimated CN and runoff values. Further refinement of parameterization is necessary to improve model robustness.
5. The study considered two rainfall scenarios to evaluate flood response. While these scenarios are based on historical events, future climatic variations and anthropogenic land cover changes could alter the flood dynamics, limiting the long-term applicability of the results.
6. The study focused on a specific watershed and time frame, meaning the findings may not be directly generalizable to other regions with different hydrological and climatic conditions. Additionally, the temporal resolution of the model may not fully capture rapid hydrological responses during extreme rainfall events.

*Future research directions*

- Integrating more variables such as climate change impacts, groundwater interactions, and human interventions.
- Developing a coupled HEC-HMS and SD framework to improve flood forecasting under different land-use change scenarios.
- Examining how land-use policies, urbanization, and agricultural practices influence flooding.
- Assessing community resilience and response strategies to floods using participatory modeling approaches.
- Investigating the effectiveness of nature-based solutions in flood reduction.
- Simulating the impact of structural and non-structural flood control measures using SD.
- Using high-resolution remote sensing data to refine land cover and soil moisture inputs.
- Applying machine learning techniques to optimize parameter estimation in system dynamics modeling.
- Extending the methodology to other watersheds with different climatic and hydrological conditions.
- Comparing system dynamics-based flood modeling with traditional hydrological models to assess accuracy and adaptability.

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Software: Zeinab Karimi and Zahra Eslami; Validation: Zeinab Karimi, Yahya Zare Mehrjardi, and Zahra Eslami; Formal analysis: Zeinab Karimi, Ali Talebi, Yahya Zare Mehrjardi, and Zahra Eslami; Investigation: Zeinab Karimi, Yahya Zare Mehrjardi, and Zahra Eslami; Data curation: Zeinab Karimi, Yahya Zare Mehrjardi, and Zahra Eslami; Writing—original draft preparation: Zahra Eslami; Writing—review and editing: Zeinab Karimi; Visualization: Zeinab Karimi and Zahra Eslami; Supervision: Ali Talebi; Project administration: Ali Talebi; Funding acquisition: Ali Talebi.

## DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

## ETHICAL STATEMENT

Our research was conducted in accordance with ethical standards, ensuring the integrity and confidentiality of all participants.

## DATA AVAILABILITY

The authors declare that the datasets are available from the corresponding author on request.

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