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Article

Advancing urban flood mitigation and climate resilience: a GIS-based hydrodynamic modeling approach using HEC-RAS and remote sensing data

Navid Navidpour[1], Mohammad Reza Yari[2], Faraz Estelaji[3]*, Amir Maleki[4], Bita Rouhi Asl[5], Sahand Heidary[6]

[1]Department of Computer Engineering, faculty of software engineering, Amirkabir University of Technology, Tehran, Iran
[2]Department of Construction Engineering and Management, Faculty of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[3]Department of Construction Engineering and Management, Faculty of Civil Engineering, Khajeh Nasir Toosi University, Tehran, Iran
[4]Department of Civil, Water, and Environmental Engineering, Shahid Beheshti University, Tehran, Iran
[5]Department of Environmental Management, Faculty of Marine Science and Technology, Azad University-North Tehran Branch, Tehran, Iran
[6]Faculty of Computer Engineering, Khajeh Nasir University, Tehran, Iran

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*Corresponding author
Email address:
faraz.estelaji.1996@gmail.com

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ABSTRACT

Over the past decades, significant adverse effects, including the resiliency of critical centers, have emerged. The negative impact has manifested in the vulnerability of critical urban centers during natural disasters and emergencies, leading to their inefficiency, heightened public dissatisfaction, and a breakdown in service delivery during crises. In order to enhance the resilience of key centers, it is essential to first identify and assess the vulnerability of these crucial urban hubs to various risks and threats. In this research, the classification was graded and assessed following the formulation of a questionnaire and the collection of results. Utilizing the arithmetic mean of sample opinions, the Analytic Hierarchy Process (AHP) was applied through the Expert Choice software to assign weights to these criteria and sub-criteria. Subsequently, the key urban centers were identified. The hydrology within the city and its surroundings, along with the modeling of rivers during various return periods, were studied using the HEC_RAS. The results were then integrated into GIS to delineate flood risk zones in the city of Hamedan. Following the input of the arithmetic mean of sample opinions into the Expert Choice, the value of each indicator was meticulously determined. This delineation indicates that the quantitative level indicator benefits from the maximum weight, while the economics of assets hold the least weight in the assessment. Ultimately, by aligning key urban centers with flood-prone zones in the GIS framework, vulnerable centers were enumerated. The method used in this study can be extended to all cities based on their river flow modeling and urban zoning.

1. Introduction

Major cities, being the most densely populated nuclei, accommodate the highest levels of human resources, investments, economic projects, and infrastructure [1]. Due to reasons such as excessive concentration, non-principled land use, disregard for accessibility standards (building and road compatibility), the presence of multiple bridges, neglect of river buffer zones, limited attention to climatic elements like prevailing winds, precipitation in constructions, and even the lack of balanced and standard access distances in the distribution of emergency and rescue centers such as hospitals and fire stations, these cities are exposed to numerous threats and substantial damages [2]. These challenges, especially during crises, can significantly impact the lives of citizens. Therefore, taking appropriate measures within the framework of urban management plans and adhering to the principles is imperative [3]. Given recent climatic changes and the damages caused by floods and droughts, examining this issue holds great importance [4]. As floods typically affect, areas adjacent to rivers and economic activities, as well as human settlements, are often concentrated near rivers today, studying these regions in terms of flood-prone parameters and preparing flood zoning maps is essential for urban planning [5]. Floods are defined when water overflows its natural bed, inundating low-lying areas and riverbank territories, causing financial and human casualties [6]. Identifying and grading assets based on their importance for the continuity of urban life and the urban system's resilience in the face of natural and human-made crises facilitate crisis management processes. This resilience enables the urban system to meet city needs during crisis conditions, thereby easing the management of crises resulting from both natural and human-made disasters. The phase of recognizing and prioritizing assets in the case of the city is one of the fundamental steps in this research.

2. Literature review

Considering the principled and scientific design of the surface water collection network is very important as one of the most important components of the social welfare system of citizens, and for this system to function optimally to solve the problem of flooding in one of the rainiest cities in the country, different parts of Rasht can be collected and directed to the inlet channel by constructing a structure in appropriate locations that meet the required standard size. The runoff that flows from impervious surfaces can be properly collected and directed to the outlet, thereby solving the problem of localized flooding in most places. Of course, this requires the proper design of the urban drainage network along with an examination of the river flood level at the discharge site [7]. In a study aimed at evaluating the HEC-RAS model in flood prediction of the Qorveh watershed in Kurdistan province, various effective parameters in the hydrological modeling of this basin were studied. Then, using the HECRas sub-model and the US Soil Conservation Service (SCS) and Schneider methods, the basin flood hydrograph was simulated and then calibrated and verified. It was determined that the SCS method was more consistent with observational data in simulating the peak discharge of the hydrograph [8]. In this paper, flood zoning was studied using a hydraulic model of river analysis in the Manshad watershed of Yazd province. In this regard, with the aim of integrating the HEC-RAS hydraulic model with ArcGIS software through the HEC-RAS extension, the flood extent was calculated for return periods of 2 to 200 years in the riverside lands with the help of digitized topographic maps. Finally, the area of each of the land uses at risk of flooding with a return period of 200 years was determined, and the most at-risk land use was related to agricultural lands [9]. In the list of most natural hazards, floods are in the first place. Increased rainfall has made surface runoff disposal a critical problem in urban areas. Various hydraulic models have been developed to measure the amount of runoff in urban areas [10].

The critical crisis areas in the urban structure against floods and inundation were identified, and the damages caused by floods were presented in the form of a damage assessment map [11]. In another investigation, flood zoning was carried out using hydraulic modeling in the province of Yazd, specifically in the Manshad plain. HEC-RAS was employed in this study, revealing that the integration of geographic information systems with the HEC-RAS model facilitates calculations, reduces field operations, and is highly recommended for application in watersheds [12]. Ouma et al. [13] utilized building characteristics and their surrounding environment as fundamental information for assessing vulnerability to floods. They establish a direct relationship between the type of construction and building vulnerability. Bloemen et al. [14] emphasized the crucial role of planning, decision-making processes, and appropriate technical execution in flood risk management. However, the often-overlooked technological aspects of building resilience to floods can significantly contribute to vulnerability reduction and flood risk management.

Bennett and Blamey [15] introduced a novel method that not only studies vulnerability but also incorporates economic assessment and valuation for historical buildings. Their approach assesses vulnerability by examining the exposure of historical buildings to floods, considering factors such as architectural form, preservation, and archaeology. Albano et al. [16] highlighted the importance of vulnerability analysis for elements exposed to flood risks and the subsequent implementation of hydrological risk reduction strategies. Their study focuses on assessing economic and social damages through modeling, examining the intensity trend, the impact on exposed elements, and the physical response of buildings.

Qiu et al. [17] employed a cellular-based metric system to evaluate urban resilience in Dalian City, China, against floods. They simulate floods using the CADDIES model and identify vulnerable areas within the city's 31 sub-watersheds. Their study emphasizes the effectiveness of the new metric in reflecting the system's performance changes, aiding the selection of tailored strategies for enhancing resilience. Karber [18] delved into urban design principles for flood resilience in the Mekong Delta, Vietnam. Instead of focusing on post-flood damage, they propose alternatives for proactive adaptation to flooding, drawing insights from local ecological knowledge in rural areas and emphasizing the use of local capacities for urban areas.

Eakin et al. [19] explored the resilience of urban structures in Mexico City against climatic hazards, particularly floods. They underline the complexity and sequenced nature of building resilience, influenced by social, economic, and institutional conditions. Harirchian et al. [20] suggested the use of an intelligent system for assessing and retrofitting buildings prone to flood damage. This system, comprising vulnerability assessment, retrofitting options, and fundamental damage assessment subsystems, aids in calculating the vulnerability of structures and recommending appropriate retrofitting strategies based on the degree of vulnerability.

3. Methodology

Hamedan Province spans approximately 19,546 square kilometers, situated in the western mountainous region of Iran [21]. Its geographical coordinates range from 2 degrees 33 minutes to 2 degrees 38 minutes north latitude and 2 degrees 45 minutes to 2 degrees east longitude. The most populous city within the province is Hamedan city, positioned at an elevation of 1,870 meters [22]. The precise geographical location of Hamedan city is illustrated in Figure 1.

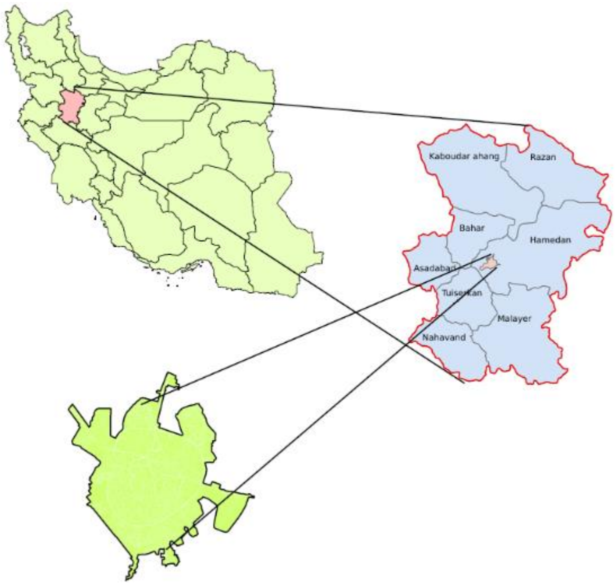

Figure 1. Geographical location for Hamedan city

The current investigation falls within the realm of applied research, aiming to enhance the state of a phenomenon in Hamadan city. The research methodology is rooted in theoretical objectives, adopting a descriptive-analytical approach. In the descriptive phase, library and documentary studies were employed to compile the necessary information and data [23]. The statistical population encompasses experts, activists, and professionals specializing in the city's natural risks. These individuals were selectively sampled using a purposive sampling method, chosen for their suitability in gathering specialized and precise data on the research subject. A questionnaire was employed with the goal of identifying specific criteria and sub-criteria directly influencing the assessment of endangered assets. Expert Choice software facilitated the prioritization of these criteria, sub-criteria, and strategies. The integration of these procedures, along with the simultaneous execution of quantitative and qualitative analyses, positions the current study within the realm of mixed research [24].

The assessment of the weight of influential resilience indicators is conducted through a comprehensive five-stage process focusing on flood-vulnerable key centers.

3.1 Determination and identification of assets

Prioritization of key centers in the face of impending threats is accomplished based on criteria and indicators categorized into three levels: life, sensitivity, or importance [25]. Quantification of qualitative criteria and indicators for key centers is achieved. Table 1 shows criteria, sub-criteria, and indicators.

Table 1. Scores of the main criteria of the grading matrix [26]

No	The main criteria	grade	Considerations
1	Fundamental importance	10	1 sub-criterion and 5 quantitative indicators
2	Scope of influence	20	3 sub-criteria and 10 quantitative indicators
3	Possibility of replacement	20	1 sub-criteria and 7 quantitative indicators
4	to be unique	6	5 quantitative indicators
5	Role-Playing	14	3 quantitative indicators
6	Capital value	5	2 sub-criteria and 7 quantitative indicators
7	Consequences of injury	10	3 quantitative indicators
Total	-	100	-

3.2 Weighting of the main criteria of the Ministry for Asset Leveling and Evaluation

After selecting the effective criteria in zoning in order to combine them together as information layers, the weight of each criterion must be determined in proportion to their importance according to one of the weighting methods. Given that among the selected criteria, some are quantitative, and some are qualitative, we must use a method that allows us to compare and weigh quantitative criteria with qualitative ones, which is one of the problems of weighting in multi-criteria decision-making problems. The weight given is given as a number in the evaluation, which indicates the relative importance of that criterion compared to other criteria. This method has found many applications in social and economic issues and has also been used in urban management in recent years. In this research, the Analytic Hierarchy Process (AHP) method was used to weight the criteria. The Analytic Hierarchy Process (AHP) method was founded by Saati in 1977. The method is based on performing pairwise comparisons and determining the degree of preference of elements over each other with respect to the desired criteria and is used to solve multi-criteria evaluation problems and determine the priority of multiple options with respect to the desired criteria [27]. Utilizing the indicators outlined in Table 2.

The results are classified into one of three categories: critical, sensitive, or important. This classification scheme, proposed by Troy et al. [28], provides a comprehensive overview of the criteria used to determine the critical, sensitive, and important classifications for the assessed assets.

Table 2. Classify different levels based on the final score

level	Rating	Range of grade
1	Special	93-100
2	Vital	83-92
3	Sensitive	71-82
4	Important	56-70
5	Protective	36-55

3.3 Using the HEC_RAS model

This model is widely used to model urban drainage channels [29]. GIS and HEC-RAS software have recently been used to display flooded areas [30]. HEC-RAS software with the HEC-GEORAS tool can model and display flooded areas with different return periods [31].

4. Results and discussion

The selected assets were those whose removal would impact the provision of services, disrupting the primary functions of the city. To validate the results obtained from the evaluation of key assets in Hamadan city, the weighting of asset evaluation indicators becomes crucial. This is because the influence of each index is determined by its weight in defining the significance of an asset. Since the indicators listed in Table 3 do not carry equal weight, a questionnaire was designed and distributed, and its results were collected. The AHP technique in the Expert Choice software was then employed to calculate the weights of these indicators. Subsequently, the software determined the weight of each index separately based on the arithmetic average of the sample comments. The resulting weights are presented in Table 3, providing a comprehensive understanding of the relative importance of each indicator in the asset evaluation process.

Table 3. Weight of asset valuation indicators

Priority	Asset valuation indicators	Weight
1	Functional value	0.117
2	Quality level of operation	0.133
3	Quantitative level of operation	0.416
4	Environmental value	0.188
5	Possibility of replacement and repair	0.073
6	Dependence on the outside	0.045
7	Economic value	0.022

4.1 Prioritizing important assets

Adhering to the priority law (80/20), which posits that prioritizing activities based on their importance leads to 80% success with 20% effort, time, and resources, it is crucial to underscore the significance of proper prioritization. Neglecting key priorities can result in 80% effort, time, and resources yielding only 20% success in achieving goals.

Key urban centers should be leveled based on their importance. The implementation of crisis management measures should be prioritized across three grades: 1st grade, 2nd grade, and 3rd grade centers. The quantification of qualitative criteria and indicators is essential for this leveling process. A table designed by the crisis management organization serves as the basis for prioritizing urban infrastructure centers in different areas, categorizing them into three levels: "grade 1, grade 2, and grade 3" (Table 3).

In this research, after evaluating and assigning scores to each indicator, the total score is recorded in the "Score Total" column. Based on these scores, the level of the relevant key center is determined, categorizing it into one of the three levels: grade 1, grade 2, or grade 3. Indicators of effectiveness and performance level, recovery ability (reversibility time - recovery level), and 12 consequential effects (losses [human], damages [physical-real], injuries [psychological]. The simulation of river flow and city zoning against floods using the HEC_RAS model is a critical step in enhancing resilience. Identifying threats in a timely manner is essential for implementing intelligent countermeasures, thereby mitigating weaknesses and reducing vulnerability. By developing a rainfall-runoff model, design flood values are determined for different return periods, as shown in Figure 2. This comprehensive approach provides a thorough understanding of possible flood scenarios and helps to develop effective preventive measures and urban zoning strategies.

Leveraging road surface numbers, a digital elevation map of Hamedan city was created, integrating it with the elevation digital map of suburban lands to obtain a comprehensive digital elevation map of Hamedan city and its surrounding suburban basins. Two key considerations are taken into account when determining the watershed boundaries: the first pertains to the area, and the second is related to land use within each sub-basin. Design precipitation, a crucial parameter in rainfall-runoff modeling, is tailored to the needs of the selected precipitation-runoff model. Four characteristics are established for design precipitation, including the continuity of total rainfall, depth of total rainfall, temporal distribution, spatial distribution of rainfall, and the structure of the rainfall-runoff model. This meticulous approach ensures the accuracy and relevance of the hydraulic modeling process, contributing to a comprehensive understanding of the hydraulic adequacy of the network.

To model the basin for calculating design floods at the project site, a rainfall-runoff model was constructed using the HEC_RAS software. The model incorporates the extra-urban basins of Hamedan city with six sources, 24 sub-basins for Hamedan city, and 23 waterways representing the city's rivers. The flooding of suburban waterways in the model is considered based on the outcomes of hydrological studies. Precipitation loss determination and the conversion of precipitation to runoff are carried out using methods provided by the SCS soil protection organization, and river flood routing is conducted using the Muskingum Cunge method.

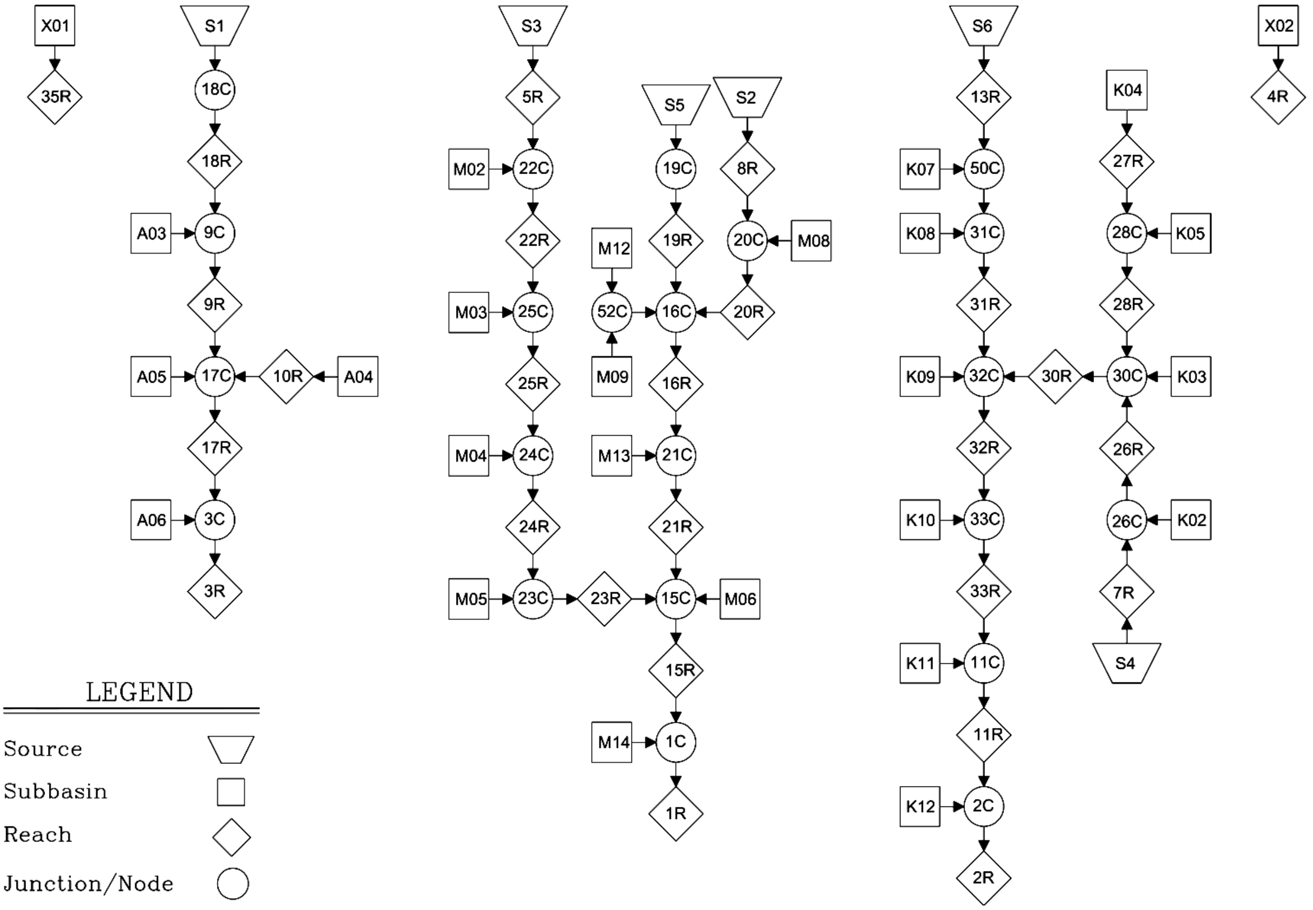

Figure 2. Structure of rainfall-stream

Given that water infiltration in the soil depends on factors such as soil type and texture, land use, and vegetation type and density, the amount of rainfall losses can be determined using these data and common methods. For the calculation of design floods, the 6-hour rainfall from Hamedan airport station was considered as the representative rainfall. This rainfall was adjusted according to the level of each sub-basin using point rainfall reduction coefficients, aligning with the time distribution pattern of 6-hour rainfall. In this modeling approach, out-of-town areas are treated as a source, and the design rainfall is applied to the urban lands. Table 4 provides an overview of the design floods entering the rivers of Hamedan City, reflecting the outcomes of this comprehensive rainfall-runoff modeling effort.

4.2 Analysis for river modeling

Some specifications of the river modeling are as follows:

A) Determination of transverse sections and specifications of existing bridges and culverts along the flow path.

B) Manning coefficients.

C) Drop coefficients resulting from the expansion and contraction of the flow.

D) Flow rate.

E) Boundary conditions.

The analysis of river flow at various times was conducted using HEC_RAS software. Figure 3 illustrates an example of the flow in Morad Beig and Divin River as an outcome of this modeling effort.

Analysis of the water carrying capacity in different segments of Hamedan City Rivers was conducted based on the current conditions. The methodology involved considering the downstream section of each river as the zero-kilometer reference point, and distances to other sections were measured accordingly. Additionally, the general slope of the ground at each section location was determined using the city's topographical map. The capacity of each section was then calculated using Manning's formula.

Figure 3 illustrates the kilometer plan of the Divin River. The horizontal axis represents the distance from the zero section (chainage), while the vertical axis depicts the water-passing capacity of the sections (bankful discharge). Notably, the graph reveals that the capacity of river sections does not consistently increase downstream, highlighting the suboptimal water-passing capacity of these channels. It's essential to note that design floods, including a 50-year flood, have also been incorporated into the figure, providing a comprehensive overview of the water-carrying capacity and potential flood scenarios in Divin River (Figure 4).

Table 4. The modeled floods going to Hamedan's Rivers

⁄Node Sub basin		Place of entering modelled flood	Modelled flood (m^3/sec)					
	Node	**Range**	**100-yr**	**50-yr**	**20-yr**	**10-yr**	**5-yr**	2-yr
A04	0.0	Heidare	34.20	28.20	20.30	14.60	8.90	2.20
S1	11240.0	Abbasabad-01	24.50	21.90	18.50	16.00	13.20	9.10
9C	2126.7	Abbasabad-01	32.80	28.60	23.20	19.20	15.10	9.50
17C	2447.0	Abbasabad-02	68.00	57.70	44.20	34.30	24.30	11.80
3C	1210.0	Abbasabad-02	69.00	58.60	44.80	34.70	24.60	11.80
S5	1760.9	Park mardom	19.90	6.70	5.60	4.90	4.00	2.80
S2	6032.6	Divin-01	10.20	9.10	7.70	6.60	5.50	3.80
20C	3424.1	Divin-01	14.40	12.30	9.90	8.10	6.40	3.90
52C	868.8	Park mardom	4.20	3.50	2.60	1.90	1.20	0.30
16C	3650.7	Divin-02	38.20	32.50	25.20	19.70	14.20	7.70
21C	2280.0	Divin-02	43.40	36.50	27.70	21.10	15.30	7.80
S3	10937.9	Moradbeig-01	22.30	20.00	16.90	14.60	12.00	8.20
22C	6100.0	Moradbeig-01	30.10	26.20	21.10	17.50	13.70	8.50
25C	4386.2	Moradbeig-01	37.30	32.10	25.30	20.30	15.50	8.90
24C	3286.0	Moradbeig-01	44.50	37.90	29.50	23.10	17.20	9.30
23C	1106.0	Moradbeig-01	45.90	39.00	30.10	23.80	17.60	9.40
15C	700.1	Moradbeig-01	91.00	76.70	58.60	45.50	33.20	17.30
S6	3664.1	Faqire-01	5.60	5.10	4.30	3.70	3.00	2.10
50C	2039.3	Faqire-01	11.10	9.40	7.20	5.70	4.20	2.30
K08	1799.7	Etehad	15.10	12.30	8.80	6.10	3.50	0.90
31C	2834.4	Faqire-01	26.10	21.60	15.90	11.50	7.70	3.10
S4	6848.0	Khezr-01	19.90	17.80	15.00	13.00	10.70	7.30
26C	3058.7	Khezr-01	26.10	22.70	18.30	15.30	12.00	7.50
30C	1843.3	Khezr-01	62.00	52.90	40.70	31.90	22.80	10.70
32C	2234.3	Khezr-02	89.80	76.30	58.00	45.20	31.70	14.20
33C	1532.8	Khezr-02	106.90	90.40	68.10	52.40	36.10	15.30
11C	0.0	Khezr-02	113.10	95.50	71.90	55.20	37.80	15.80

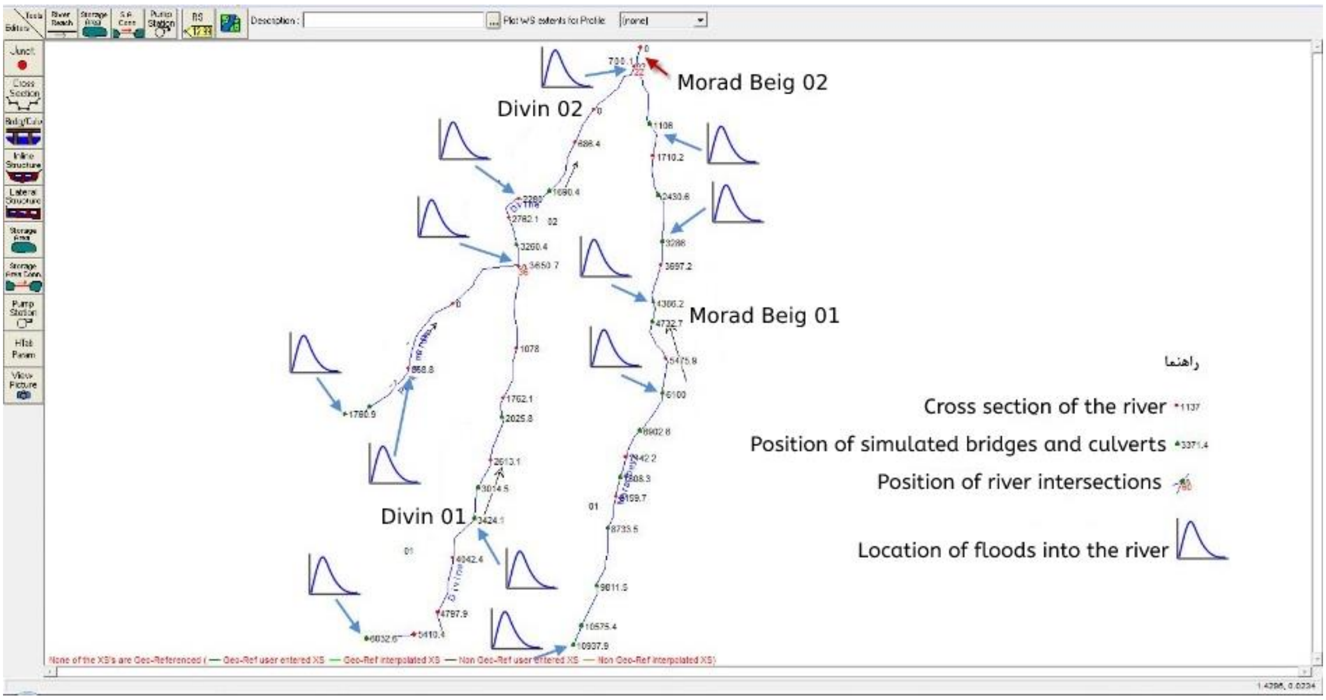

Figure 3. Analysis of River Crossings at Morad Beig and Divin Using HEC-RAS Software

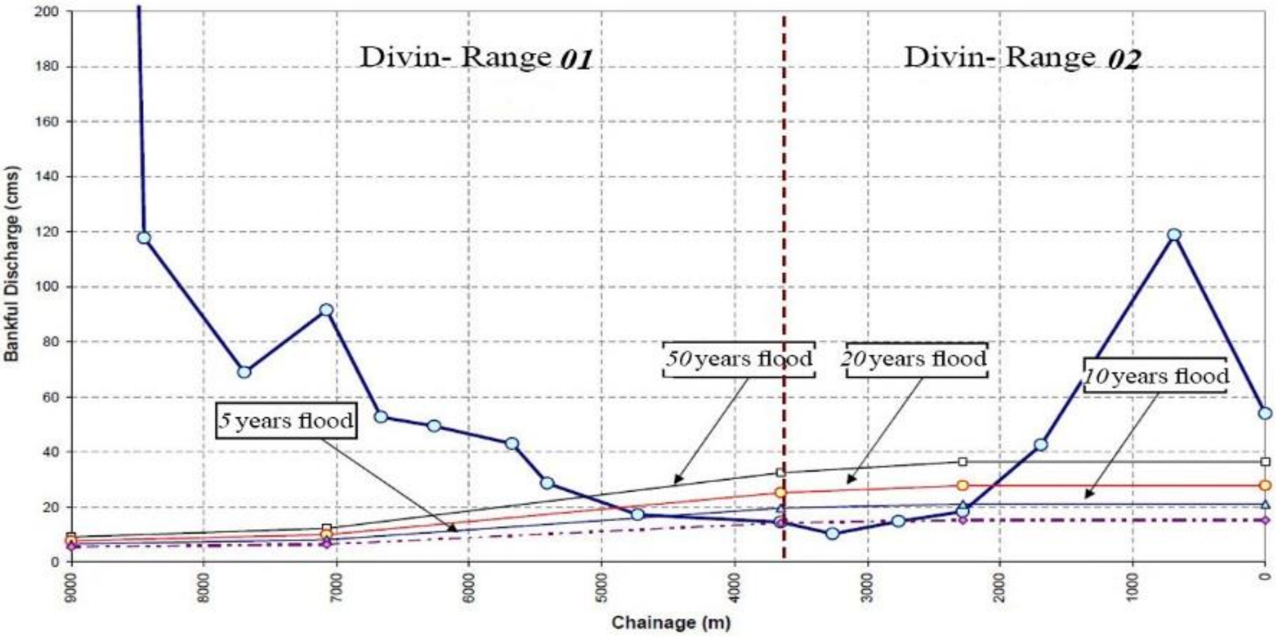

Figure 4. Divin River water intake capacity

4.3 Results of river hydraulic calculations

Examination of the longitudinal profiles reveals that in certain segments of Hamedan City Rivers, the current conditions are inadequate. During designed flood events, water exceeds the channel capacity, leading to road flooding. The insufficient capacity of sections and the inappropriate dimensions of bridges and culverts contribute to the inability of Hamedan City Rivers to safely convey floodwaters out of the city.

Figure 5 depicts areas with flood potential based on the conducted modeling. Specific sections along each river exhibit inadequate cross-section capacity to accommodate the design flood. Notably, significant portions of the Divin and Khizr rivers are incapable of handling a 50-year flood. However, some segments within these rivers pose even more critical conditions than others. Addressing these challenges is crucial to enhancing the overall flood resilience of Hamedan city.

4.4 Integration of assets layer and river modeling output in GIS platform

The layers containing key assets of Hamedan City and the river conditions have been harmonized within the GIS platform, and a comprehensive output map has been generated, as illustrated in Figure 6. This map encapsulates the calculated results of the adaptation process, offering a visual representation of the interplay between critical city assets and the state of its rivers.

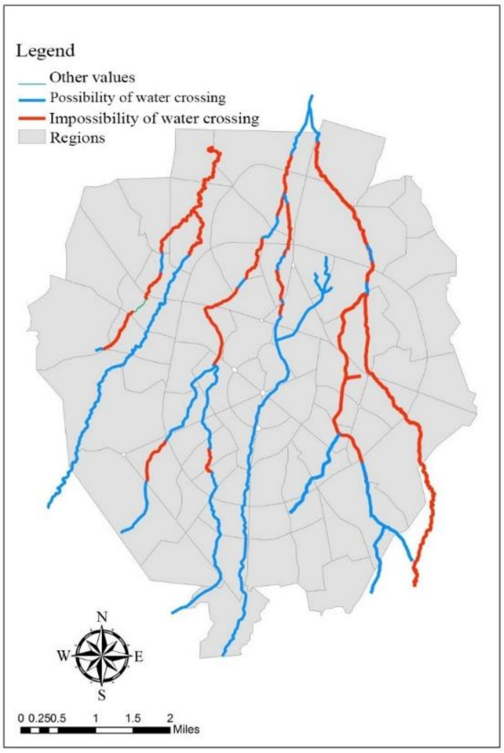

Figure 5. Flood-prone areas with no capacity for water infiltration were identified through hydraulic modelling

5. Conclusions

The evaluation and mitigation of urban flood vulnerability stand as imperative prerequisites in urban flood management. The vulnerability of key structures during natural disasters can lead to their inefficiency, exacerbating public dissatisfaction and hindering emergency response services. Floods, alongside earthquakes and droughts, hold the highest ranks concerning both human and financial losses among recognized natural disasters. Urban floods have intensified due to climate change, urbanization growth, and constraints in urban drainage infrastructure. Over the past decade, these floods have left significant adverse effects. Hence, this study focuses on urban and suburban hydrology, hydraulic network analysis, and modeling of the rivers in Hamedan city across various return periods. Utilizing the HEC-RAS software and integrating the results into GIS, the flood hazard zone of Hamedan city was delineated. Key vulnerable centers to floods were identified, emphasizing the necessity for officials to adopt and implement strategies and resilience models to mitigate the cascading impacts of these vulnerabilities. Essentially, this research serves as an introduction to proposing resilient solutions for urban structures. In the contemporary era, the convergence of urban life complexities on different fronts, ranging from natural hazards and technological crises to social and security crises, has diminished urban resilience. The primary focus of this research is to elucidate and propose resilient strategies for vital and sensitive urban structures, particularly during natural threats, especially floods. To achieve this, high-sensitivity key centers were first identified, and their vulnerability to flood-related risks and threats was examined. Criteria and sub-criteria for asset grading and evaluation were established, and, after questionnaire adjustment, results were collected, weighted using the Analytic Hierarchy Process (AHP) technique in the Expert Choice software. Subsequently, key urban centers were determined. The hydrology of both urban and suburban areas, hydraulic network analysis, and river modeling in Hamedan City across various return periods were studied using the HEC-RAS software.

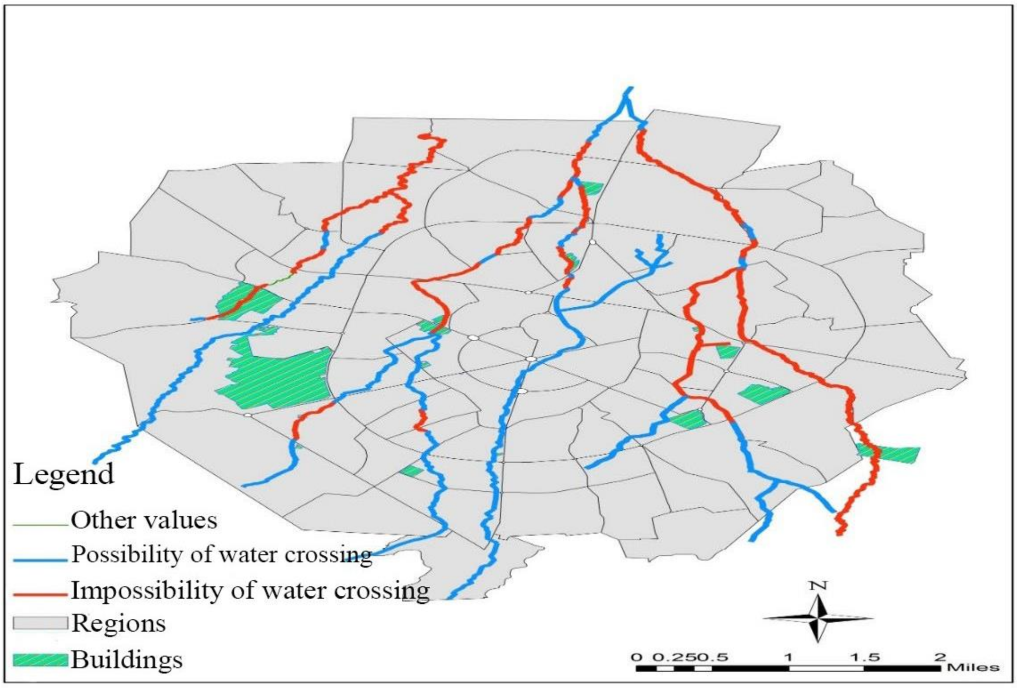

Figure 6. Modification of the asset layer in Hamedan city and the flood permeability of various sections of its rivers

The results were then transferred to GIS for flood hazard zoning in Hamedan city. Finally, by aligning key centers and flood-prone zones within GIS, vulnerable centers were identified, and the results were presented. The results indicate that the green-colored zones, representing key centers and assets, intersect with the red lines, indicating inadequate river passage, signifying a critical issue. In this region, key structures and essential infrastructure are not safeguarded against potential future flood hazards.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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