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Urban Flood Risk Mapping with Coupling Storm and Sanitary Analysis Software (ASSA) and HEC-RAS Model, Case Study of Ladan Urban Watercourse, Mashhad, Iran

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Abstract

Flooding is among the most destructive natural hazards, causing significant human and economic losses. Urban flood risk zoning offers an effective approach to mitigating such damages by identifying vulnerable areas and assessing hazard intensity, thereby enabling proactive planning and management. This study aimed to perform flood risk mapping of the Ladan watercourse in 9rd District of Mashhad city, Iran, through hydraulic and hydrological modeling. The analysis employed Storm and Sanitary Analysis (ASSA) and HEC-RAS 6.2 software. Rainfall–runoff modeling was based on a uniform rainfall pattern, while hydraulic simulations were conducted for return periods of 25, 50, and 100 years. Flood hazard zoning for the 100-year flood was prepared in accordance with Iranian Guideline for flood hazard mapping (Code 821), in which the product of flow depth and velocity ($V \times D$) was considered as the flood hazard index. The findings revealed that the Ladan watercourse can convey floods with return periods of 25 and 50 years. However, during the 100-year flood, specifically, the initial 200 meters of the channel were identified as critical zones where overtopping and road inundation are likely to occur.

The outcomes of this research highlight the importance of flood risk zoning in supporting sustainable urban planning and flood management. The results provide a practical basis for prioritizing vulnerable zones and guide the development of preventive strategies and flood control structures.

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Introduction:

Flooding, as the most common natural disaster, causes numerous fatalities and economic damages every year (Zhi et al., 2020). With urbanization and climate change, an increasing number of cities are being affected by destructive floods (O'Donnell et al., 2020; Miller et al., 2017). An improved understanding of global Urban Exposure to Flooding (UEF) is essential for developing risk-reduction strategies for sustainable urban development. The global UEF increased more than four-fold from 16,443 km2 in 1985 to 92,233 km2 in 2018 with accelerated temporal trends. The most notable growth in UEF occurred in Asia (74.1%), followed by Europe (11.6%), Northern America (8.7%), Africa (2.9%), Southern America (2.2%), and Australia (0.5%), (Cao et al., 2022).The occurrence of heavy and unexpected rainfall leading to flooding is anticipated to be one of the major hazards for human societies in both the present and the future. Due to its specific climatic and geographical conditions, Iran faces a high level of risk in this regard and is considered one of the top ten disaster-prone countries in the world. In this ranking, Iran holds the fourth position in Asia, after India, Bangladesh, and China (Tajik et al., 2021).

Many researchers have employed GIS-based software by incorporating hydrological, hydraulic, and flood vulnerability parameters, together with multi-criteria decision-making methods such as AHP and fuzzy logic, to generate flood risk and building vulnerability maps for urban areas. These maps serve as effective tools for urban managers and land-use planners, as they enable the identification of high-risk zones and support preventive decision-making and effective flood management.

(Fotouhi et al., 2015) prepared a micro zonation of flood risk in Nahavand City, Iran by using the HEC-RAS code and adding the Analytical Hierarchy Process (AHP) for weighting criteria. The criteria considered for flood risk assessment included distance from the watercourse, slope, distance from fire stations, elevation, soil type, building age, building density, population density, distance from healthcare centers, distance from open spaces, distance from fueling stations, and distance from access roads. In this study, after preparing the layers of various criteria in GIS and normalizing each criterion, the final weight was determined using AHP, and flood risk map for Nahavand city was created. Also, (Yazdani et al., 2018) prepared a flood risk map for Tabriz City, Iran "using GIS-AHP. But, they considered more criteria such as Curve number (CN), a dimensionless index used to characterize the runoff potential of a specific land area due to a given rainfall event, runoff coefficient, open spaces, and building age. Furthermore, they assessed the extent of damage to residential buildings using the Simple Additive Weighting (SAW) method and prepared a risk map of residential units against the risk of urban flooding for the city of Tabriz.

Esmaeili (Alavijeh et al., 2020) assessed vulnerability to flooding in Tehran, Iran based on Fuzzy Analytic Hierarchy Process (FAHP), due to its higher probability degree for weighting the criteria. (Cikmaz et al., 2023) conducted a flood risk assessment by utilizing geophysical and socio-economic datasets for a case study in Cedar Rapids, Iowa, China. Flood risk outputs are generated based on three main risk groups: geophysical-based flood risk, socioeconomic risk, and combined flood risk.

For the city of Mashhad, which is the second largest and most populous city in Iran and is exposed to the risk of urban floods, urban flood risk assessment studies have been conducted by researchers such as (Vafaei rt al., 2023), (Hezareh and Qaz-Alhesar., 2018) and (Gheyami ., 2023). For instance, (Hezareh and Qaz-Alhesar., 2018) were considered six factors, such as distance from the flood plain, height, population density, slope, the direction of slope, and land use to extract risk map of Mashhad city, using GIS-AHP approach.

It should be noted, using HEC-RAS and its extensions instead of solely relying on GIS offers significant advantages for urban flood risk assessment, particularly when detailed hydraulic simulation is required. HEC-RAS allows dynamic modeling of river and channel flows, providing precise calculations of depth, velocity, and energy along the watercourse, which GIS alone cannot achieve. It enables simulation of floods with various return periods and the computation of hazard indices such as the product of velocity and depth ($V \times D$), facilitating accurate identification of high-risk areas. Moreover, HEC-RAS outputs can support the design of flood control structures, including bridges, channels, and levees, which are not directly possible using GIS. In practice, combining HEC-RAS with GIS allows integration of precise hydraulic results into spatial maps, enhancing the overall accuracy of urban flood risk evaluations and providing practical tools for planners and engineers. Nowadays, an increasing number of researchers such as (Azvag et al., 2018; Iroumi et al., 2020; Emadeddin et al., 2023; Vafaei et al., 2023) are inclined to use hydraulic models such as HEC-RAS in combination with GIS-based models to achieve more accurate assessments of urban flood risk. This integrated approach allows the incorporation of measurable variables, including flow depth and velocity, providing a detailed understanding of flood hazards and enhancing the precision of risk evaluations.

Flood modeling in urban watercourses using HEC-RAS requires access to accurate topographic data and detailed information on existing urban features. The lack of accurate up-to-date urban topographic maps and the frequent changes in urban features over short time intervals pose a major challenge for using precise software models. In this study, to address this challenge, software models have been selected that, in addition to providing acceptable accuracy, are less sensitive to the need for highly detailed topographic data. In the current study, the peak discharge was estimated using ASSA software for return periods of 25, 50, and 100 years. Due to the complexities present in urban runoff drainage systems, this study utilizes the Autodesk Storm and Sanitary Analysis (ASSA) model, with the SWMM module, along with GIS and HEC-RAS software, to perform rainfall-runoff calculations and assess the hydraulic performance of flow in the studied stream.

The novelty of this research lies in its methodological integration and spatial focus, which distinguish it from previous flood hazard studies in Mashhad. While (Vafaei et al., 2023) limited their analysis to the Ferdowsi University campus, and (Gheyami., 2023) provided a city-wide overview without emphasizing a specific district, the present study concentrates on 9rd District, identified as the most flood-prone area of Mashhad. This focused approach allows for a more detailed and operationally relevant understanding of local flood dynamics in a high-risk urban setting.

The integration of the ASSA model with HEC-RAS constitutes a methodological innovation. Previous studies relied solely on hydrodynamic or hydrological models, whereas the combined use of these two complementary tools enhances both the precision of flood simulations and the flexibility for testing management scenarios. This dual-model approach ensures that both rainfall–runoff processes and channel hydraulics are represented more realistically.

Furthermore, the use of updated topographic maps incorporating recent urban construction and land-use changes provides a higher level of accuracy compared to earlier studies. Since urban development is a key driver of flood risk in semi-arid cities, accounting for these changes strengthens the reliability of the results and ensures their applicability in real-world planning and design.

Materials and Methods

Study Area

The study area is the watershed of the Ladan watercourse, located in Ladan Boulevard in 9rd District of Mashhad city, Iran. According to recent studies, District 9 is among the most flood-prone areas of Mashhad (Gheyami, 2023). The Ladan neighborhood covers 190 hectares, accommodating approximately 27,000 residents, with a population density of 141 people per hectare. The dominant land use is residential (51%), followed by administrative and military (13%), sports (2.5%), and commercial (2%). The Ladan stream originates near Bagheh Pachenar (23rd Ladan) and drains northeastward, crossing several neighborhoods in 9rd District (Figure 1).

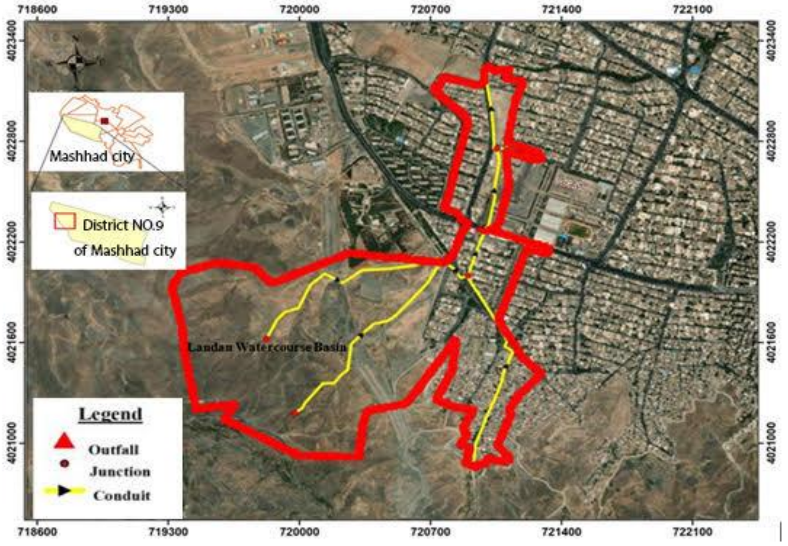


Fig 1: Study Area (Ladan Stream Watershed, Mashhad, Iran)

Methodological Framework

The methodology integrates hydrological and hydraulic modeling using ASSA (Autodesk Storm and Sanitary Analysis), HEC-RAS, and HEC-GeoRAS within a GIS environment. The framework follows four major stages: data preparation, hydrological simulation, hydraulic modeling, and flood hazard mapping. Figure 2 illustrates the methodological flowchart for the current research. The working method in this research is that first the hydrological units are identified using AutoCAD software, the produced map is then called into ArcGIS with three layers: Sub-basin, Junction, and Link, and these three layers are converted to the Shape file format. In the GIS environment, by adding fields to the three Shape files, it is possible to input information such as land use, slope of the basin, initial depth, bed elevation, node numbers, basin numbers, percentage of impermeable area, Manning's coefficient, etc. Another capability of GIS is the ability to quickly and accurately calculate the required information, such as slope, area, length, and width of the basin, and attach it to each hydrological unit. Subsequently, the study area consists of sub-basins and a drainage network including nodes and channels transferring the information to the ASSA model and preparing the rainfall pattern and also, deign discharges. After that, HEC-RAS compute water surface profiles under steady/unsteady flow conditions, based on input data included cross-sectional geometry, Manning's roughness, slope, boundary conditions and design discharges from ASSA outputs. After modeling and extracting flow parameters (Velocity and Depth), flood risk zoning was performed based on the Guideline for flood hazard mapping, Code 821, which uses the product of two parameters (D*V) flood hazard map constructed in ArcGIS 9.3.

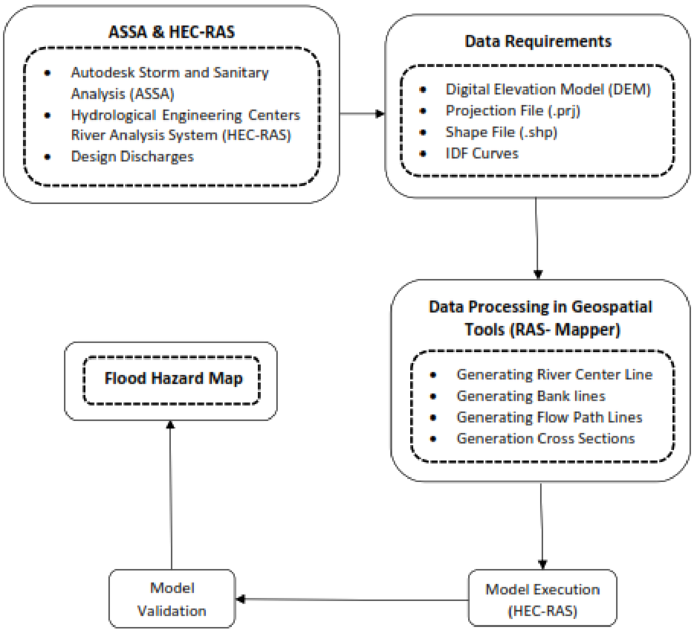


Fig 2. Methodological Framework for Flood Hazard Assessment of the study

Hydrological Modeling (ASSA)

The structure of the Autodesk Storm and Sanitary Analysis (ASSA) model, joint with SWMM module, which is advanced while maintaining simplicity. In this model, each watershed is divided into smaller sub-basins, and the physical and drainage characteristics of each sub-basin and the precipitation data are constitute the input data. Each sub-basin is simulated as a nonlinear reservoir, and a unit hydrograph is then calculated for it based on the given specifications. This hydrograph is routed in the form of a kinematic wave to the outlet point of the watershed, and finally, the output flow from the sub-basin is determined. A linear reservoir is defined as a source where the volume and water storage have a linear relationship with the output flow. If the ratio of the stored water volume over a specific time period to the output flow is not constant, it is considered a nonlinear reservoir.

Watershed boundaries were first delineated in AutoCAD and then imported into ArcGIS. Three layers—sub-basin, junction, and link—were converted to shapefiles (Figure 3). Attributes such as land use, slope, elevation, Manning's coefficients, and impermeable percentages were added in GIS. Sub-basins were then categorized into five groups based on their concentration times. Rainfall input was defined using uniform temporal distribution for the 25-year return period.

The Horton infiltration model (Eq.1) was employed to calculate infiltration losses in pervious areas, where the infiltration capacity rate is an exponential function of time, which decays to a constant rate. It is written as follows:

$$f = f_c + (f_0 - f_c).e^{-kt} \qquad (1)$$

Where:

f = the infiltration capacity rate (mm/hr.) at time t;

f_o = the initial infiltration capacity rate (mm/hr);

f_c = the final infiltration capacity rate (mm/hr);

k = the decay rate, depending on the soil type (1/hr.).

The selected parameters inserted in Table 1 and were adopted from local guidelines (Iran National Planning and Budget Organization, Code 118-3, 2016), which is one of the official regulations of Iran regarding wastewater and surface water and is in accordance with international standards. The slope of the stream was also obtained based on the insitu measurement and was included in the software. In order to integrating the studies on surface water collection in Mashhad city, the

Mashhad Municipality has notified these parameter to all consultants to use in their simulations.

Table1. Data and parameters used in ASSA model

(mm/hr) f_c	f_0 (mm/hr)	(1/hr) k	Impervious Area Depression Depth (mm)	Manning Value	Loss Coefficient
150	40	0.0025	2	0.015	0.5

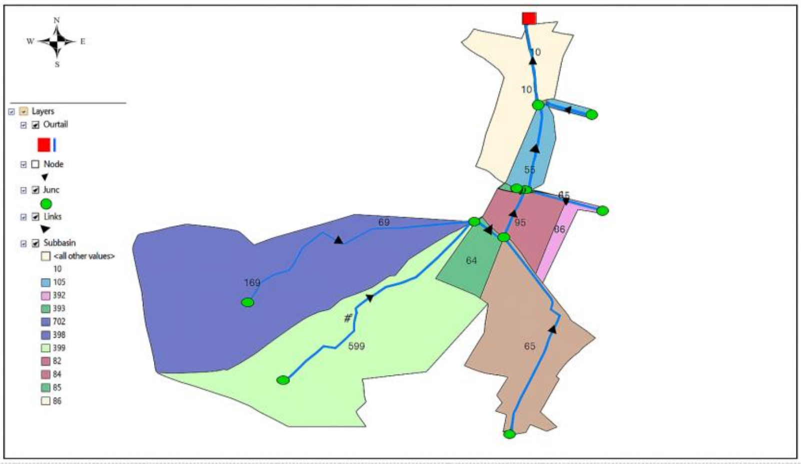


Fig 3. Importing watershed data from AutoCAD to ASSA and Preparing Shapefile (Shp)

2-4- Rainfall Data and IDF Curves

The first step in flood design estimation is the selection of the design precipitation. The design rainfall does not have a constant or uniform intensity; in practice, its intensity varies over the duration of the rainfall event. The Intensity–Duration–Frequency (IDF) curves for Mashhad city have been systematically developed by Ghahreman (1998), utilizing long-term hydro-meteorological records of maximum rainfall intensities corresponding to storm durations ranging from 10 to 540 minutes, based on the historical dataset spanning the period 1969–2021 from the Mashhad Airport synoptic station (Figure 4). These curves were constructed for return periods varying from 2 to 100 years, thereby providing a comprehensive framework for the probabilistic characterization of extreme rainfall events in the region. Considering the semi-arid climatic conditions of Mashhad City, where precipitation events are typically short-lived, sporadic in nature, and exhibit relatively uniform intensities compared to humid regions, the assumption of a uniform rainfall pattern is deemed more representative of the actual hydrological behavior of the area. From an engineering perspective, the design of urban stormwater collection and conveyance systems primarily requires the estimation of peak discharge, for which the uniform rainfall distribution provides a sufficient and practical approximation. Importantly, this methodological approach has been formally endorsed by the Municipality of Mashhad and promulgated as an official directive, thereby serving as a standardized guideline for both design practices and academic research.

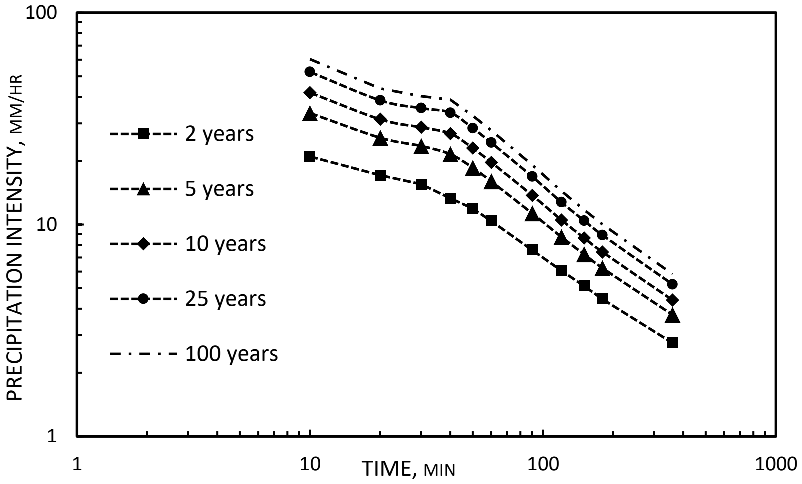
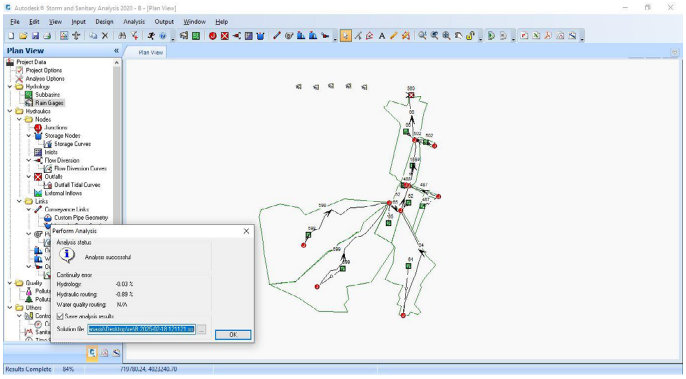


Fig 4. Intensity-Duration-Frequency Diagram for Mashhad City (Ghahreman, 1998)

After importing the Shapefiles into the ASSA software and entering the precipitation data, the simulation was conducted, and the input flow to the Ladan watercourse with different return periods were estimated (Table 2 and Figure 5). To estimate the peak discharge, the uniform flow method was used.

Table 2. Flood Flow Values (ASSA Software Output Results)

Discharge (m^3/s)	Return Period (*years*)
4	25
4.60	50
5.20	100



Perform Analysis

Analysis status

Analysis successful

Continuity error

Hydrology: -0.03 %

Hydraulic routing: -0.89 %

Water quality routing: N/A

☑ Save analysis results

Solution file: \Desktop\ue\B 2025-02-18 121121

Fig 5. Simulation of the Ladan watercourse in ASSA Software Environment

Hydraulic Modeling (HEC-RAS / HEC-GeoRAS)

The Hydrological Engineering Centers River Analysis System (HEC-RAS) is a comprehensive software performing one-dimensional flow hydraulic simulations, with geometric data prepared using HEC-GeoRAS in ArcGIS. The HEC-RAS can compute water surface profiles under steady/ unsteady flow conditions, based on input data included cross-sectional geometry, Manning's roughness, slope, boundary conditions and design discharges from ASSA outputs (Table 2). In the current model, the upstream and downstream boundary conditions are considered as critical and normal, respectively, and the flow is modeled as steady one-dimensional flow (see Table 3).

HEC-GeoRAS extension (Hydrologic Engineering Center-Geospatial River Analysis System) is an essential tool for preparing and extracting various river Feature Classes in a Geo Database format within the ArcGIS environment for this study. After extracting the required layers and performing the necessary processing, the results are transferred to the HEC-RAS model. Following analysis and modeling, the results are eventually transferred from HEC-RAS to ArcGIS to generate floodplain maps.

The Ladan channel is a concrete-lined drainage channel with a rectangular cross-section, which is covered in some sections of its path. It conveys surface runoff to the water and electricity drainage channel. The width of the channel varies from 1.4 meters to 5 meters, and its depth ranges from 1.4 meters to 2 meters.

Figure 6 illustrate plan of Ladan watercourse and position of cross-sections in HEC-RAS model and figure 7, 8 shows a Ladan watercourse geometry of cross section and longitudinal profile.

Table 3. Data and parameters used in HEC-RAS model

Stream Slope	Channel Section	Manning Value		Boundary Condition		Design Discharge (m^3/s)		
		Main Channel	Asphalt Road	Upstream	Downstream	25y	50y	100y
0.02	Rectangular	0.015	0.016	Critical	Critical	4.00	4.60	5.20

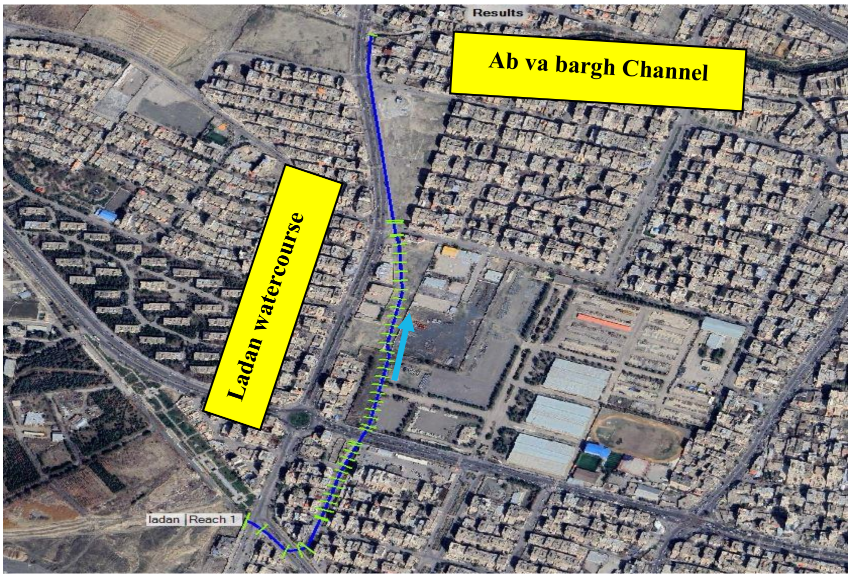


Fig 6. Plan of Ladan watercourse, geometry modeling and cross-sections

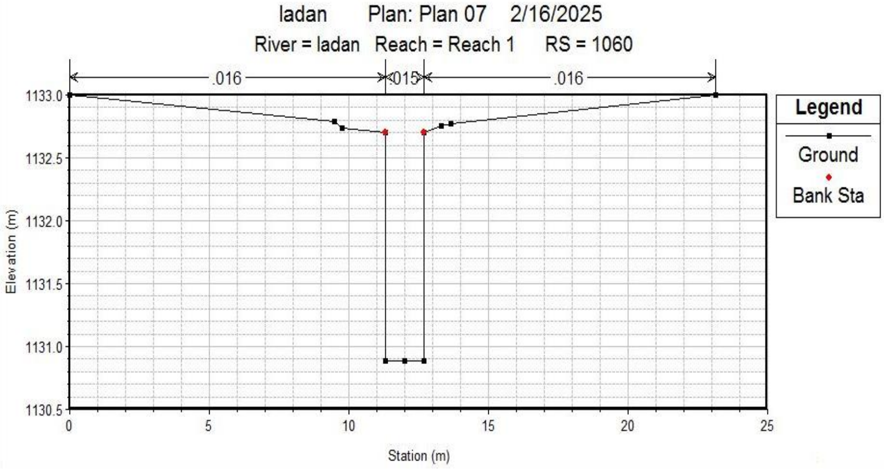


Fig 7. Inputting geometric data – Cross-section#1060

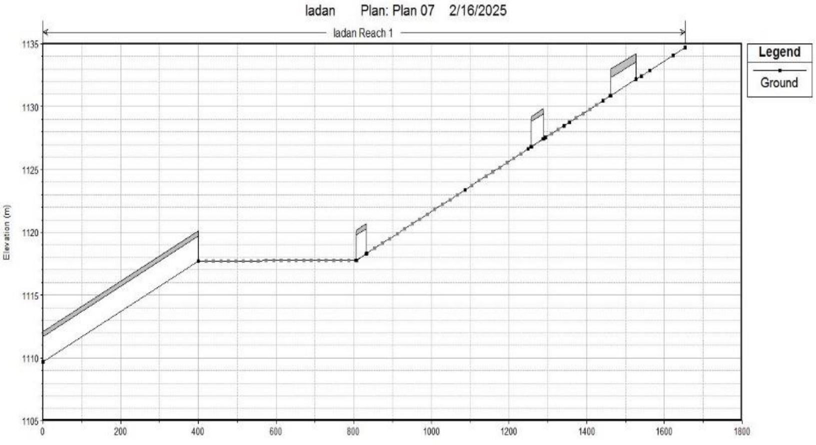


Fig 8. Longitudinal profile of the Ladan watercourse

After importing GIS processed data into HEC-RAS, steady flow state simulations were performed entering the discharge flow data at the upstream cross section of each reach, and the water profiles in the cross sections were calculated by the Standard Step Method. The unknown water surface at a cross section is determined section by section throw the iterative solution of Equations 2 and 3, energy equation and energy head loss equation, respectively (USACE, 2010):

$$Z_1+Y_1+a_1V_1^2/2g = Z_2+Y_2+a_2V_2^2/2g + H_e \tag{2}$$

he where Z_1 and Z_2 are the elevation of the main channel inverts [m]; Y_1 and Y_2 are the depth of water at cross sections [m]; V_1 and V_2 are the average velocities [m.s^{-1}] (total discharge/ total flow area); the a_1 and a_2 are the velocity weighting coefficients; g is gravitational acceleration [m.s^{-2}]; and H_e is the energy head loss [m].

$$H_e=L*S_f+C\ (a_2V_2^2/2g- a_1V_1^2/2g) \tag{3}$$

Where, H_e is the energy head loss between two cross sections [m]; L is the discharge reach length [m]; S_f is the representative friction slope between two sections [m.m^{-1}]; and C is the expansion and contraction loss coefficient. The computational procedure is as follows:

1. Assume a water surface (WS) elevation at the upstream cross section (or downstream cross section if a supercritical profile is being calculated).
2. Based on the assumed water surface elevation, determine the corresponding total conveyance and velocity head.
3. With values from step 2, compute S_f and solve Equation 3 for H_e.
4. With values from steps 2 and 3, solve Equation 2 for WS_2.
5. Compare the computed value of WS_2 with the value assumed in step 1; repeat steps 1 through 5 until the values agree to within 0.01 feet (0.003 m), or the user-defined tolerance.

Simulation outputs included water surface profiles, velocities, flow depths, and hazard levels. Floodplain maps were then generated by exporting results back into ArcGIS 9.3.

Validation

Model validation was carried out to assess the reliability of the hydrological and hydraulic simulations and the resulting flood hazard maps. The validation process involved comparing the model outputs with both observed hydrological records and documented flood events in 9rd District of Mashhad. First, the hydrological component (ASSA) was validated by ensuring that the estimated peak discharges for different return periods were consistent with values derived from regional IDF relationships and national design codes (Iran National Planning and Budget Organization, Code 118-3, 2016). The modeled runoff volumes and concentration times for the Ladan watershed fell within the expected ranges reported in previous hydrological studies of Mashhad (Ghahreman, 1998; Gheyami, 2023). Second, the hydraulic component (HEC-RAS/HEC-GeoRAS) was validated through a comparison with historical flood records. In particular, the simulated flood extents for the 0.4 m^3/s closely matched reported inundation areas during past severe events, as documented by (Gheyami ., 2023). The overlay of simulated floodplain boundaries and observed flood-prone zones in ArcGIS revealed a high degree of spatial agreement, particularly in the upstream 200 meters of the Ladan channel, where overtopping and road flooding have been historically observed.

Finally, the flood hazard zoning maps based on Code 821 criteria (depth × velocity) were cross-checked against municipal reports of vulnerable areas. Zones classified as H4 and H5 by the model corresponded to neighborhoods and road sections previously identified by Mashhad Municipality as flood hotspots.

Overall, the validation results highlight the competent accuracy of the integrated modeling framework and its capability to replicate real-world flood dynamics.

Flood Hazard Assessment

Flood hazard is quantified by considering the flood depth and velocity in combination ($D \times V$ product). When quantifying and classifying flood hazard, it is important to understand the relative degree of hazard and the underlying flood behavior causing the hazard (e.g. high depth, high velocity, depth and velocity combined), as these may require different management. Where the site under consideration is small and flood behavior is relatively uniform, and a simplified method has been used to quantify the flood behavior on the floodplain, it may be that a single point value of $D \times V$ is appropriate. However, in cases where there is significant variability in the flood behavior across the floodplain, a map of flood hazard assessing the spatial variability of flood hazard is more appropriate.

In preliminary assessment of risks or as part of a constraints analysis for strategic land-use planning, a combined set of hazard vulnerability curves such as those presented in Figure 9 can be used as a general classification of flood hazard on a floodplain. (Guideline for flood hazard mapping, Code 821, 2015). The combined flood hazard curves presented in Figure 9 set hazard thresholds that relate to the vulnerability of the community when interacting with floodwaters. The combined curves are divided into hazard classifications that relate to specific vulnerability thresholds as described in Table 4. Table 5 provides the limits for the classifications provided in Table 4. A flood hazard map classified against these general vulnerability thresholds based on the flood behavior derived using flow modelling.

Table 4. Definition of Flood Hazard Levels (Guideline for flood hazard mapping, Code 821, 2015)

Description	Flood Hazard Levels
Generally safe for vehicles, people, and buildings.	H1
Unsafe for small vehicles.	H2
Unsafe for vehicles, children, and the elderly.	H3
Unsafe for vehicles and all people.	H4
Unsafe for vehicles and all people, with the potential for structural damage to all types of buildings.	H5
Unsafe for vehicles and people. Dangerous for all types of buildings.	H6

Table 5. Combined hazard curves – vulnerability thresholds classification limits (Guideline for flood hazard mapping, Code 821, 2015)

Hazard Vulnerability Classification	Classification limit ($V*D$) m^2/s	Limiting still water depth (D) m	Limiting velocity (V) m/s
H1	$V*D \leq 0.3$	0.3	2.0
H2	$V*D \leq 0.6$	0.5	2.0
H3	$V*D \leq 0.6$	1.2	2.0
H4	$V*D \leq 1.0$	2.0	2.0
H5	$V*D \leq 4.0$	4.0	4.0
H6	$V*D > 4.0$	-	-

Results and Discussion

After extract flood discharges with return period of 25, 50, and 100 years using ASSA model, flood simulations of the Ladan watercourse were carried out for return periods HEC-RAS and flow velocity, depth and water surface elevation calculated in each cross-sections. After modeling and extracting flow parameters (velocity and depth), flood risk zoning was performed based on the Guideline for flood hazard mapping, Code 821, which uses the product of two parameters ($D*V$) flood hazard map constructed in ArcGIS 9.3. The analysis of the slope and dimensions of the canal in first 200 m shows that, given the dimensions of the canal (height: 1.4 meters and width: 1.4 meters) and the volume of the 100-year return period runoff, the issue arises from the small cross-sectional

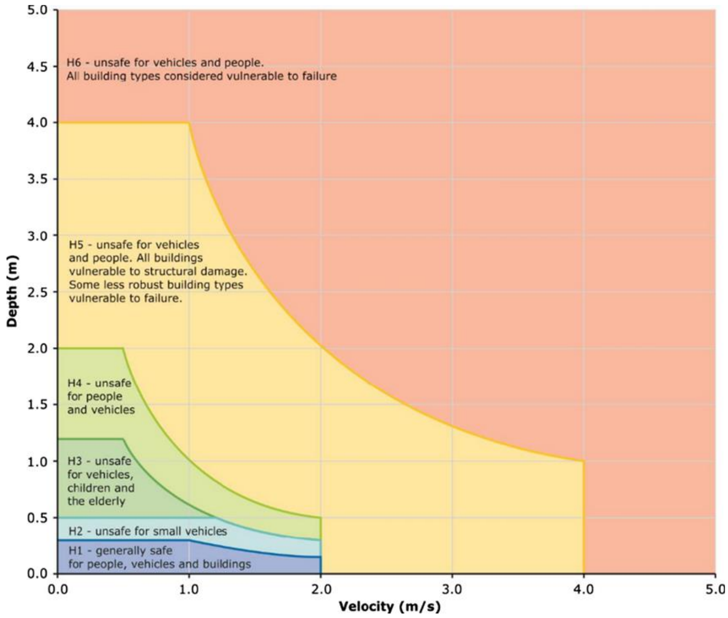


Fig 9. General flood hazard vulnerability curves (Guideline for flood hazard mapping, Code 821, 2015)

area for flow conveyance. Therefore, it is recommended to modify the cross-sectional dimensions and increase the hydraulic capacity to ensure that the flood can safely pass through the studied canal.

Flood hazard index calculated using $V \times D$ and results for different channel section put in Table 6 and also, illustrated in Figure 10 using ArcGIS 9.3. Based on the hydraulic simulation results for a 100-year return period flood (which is the most critical flood period for this study), the hazard level along the Ladan channel was evaluated according to the criteria defined in Code 821. The flood hazard index was mapped to the six hazard categories (H1–H6).

Table 6 shows that the flood risk is not uniform across the channel. For example, it shows that in the first 200 meters the hazard is at the level of H4–H5, in the middle of the channel H2, and at the end H1.

Table 6: Comparing the severity of flood risk for Ladan watercourse in different sections of the canal based on $V \times D$

According to the obtained results, the Ladan Channel has the hydraulic capacity to handle the 25-year and 50-year flood events. However, during the occurrence of a 100-year flood event, certain sections of the channel do not have the required capacity to carry the runoff, and in the first 200 meters of the channel, the runoff enters the roadway, which will lead to probable impacts.

Fig 10. Flood hazard zoning map of Ladan watercourse based on Code 821 for a 100-year return period flood.

Figure 11 illustrates the spatial distribution of the flood hazard index along the channel. It shows that the first 200 meters of the channel are categorized as H4 (unsafe for vehicles and people), the following 400 meters are mostly H2 (unsafe for small vehicles), and the remaining downstream section falls under H1 (generally safe).

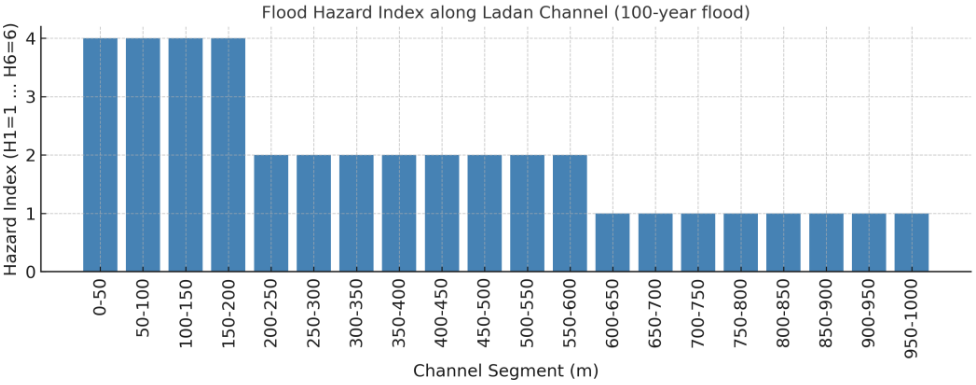


Fig 11. Flood hazard index along Ladan Channel for a 100-year flood event.

Also, Figure 12 summarizes the percentage of the total channel length falling into each hazard class. Approximately 20% of the channel is classified as H4, 40% as H2, and the remaining 40% as H1. This analysis highlights the most vulnerable upstream segments requiring structural modifications.

A comparison with similar studies in semi-arid and urbanized environments highlights the consistency of these findings. For instance, (Azouagh et al., 2018), who investigated flood risk in northern Morocco using an integrated HEC-RAS and GIS framework, reported that under-designed urban channels often fail to convey flows

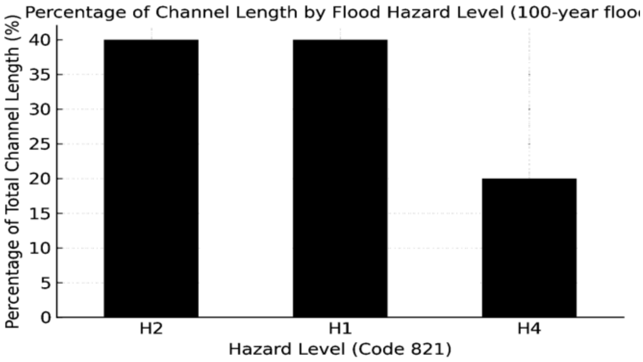


Fig 12. Percentage of channel length in each flood hazard class (100-year event)

associated with high return periods, leading to recurrent flooding and infrastructure damage. Similarly, (Gheyami., 2023) emphasized the district 9rd of Mashhad city (including Ladan Watershed) is among the most risk-prone areas due to urban flood where short-duration, high-intensity rainfall events dominate.

To mitigate these risks, structural modifications to the channel are recommended, including enlargement of its cross-section, reinforcement of sidewalls, and periodic dredging to prevent sediment accumulation. Complementary non-structural measures, such as the construction of detention basins, diversion channels, and temporary storage reservoirs, would further reduce runoff volumes entering the channel and enhance system resilience. These parallels reinforce results that both structural reinforcement and integrated stormwater management approaches are essential for achieving long-term flood resilience in Mashhad city.

Conclusion

Analyzing the flood extent for different return periods is possible to understand overflow water dynamics on the contiguous areas. Current study demonstrated a comprehensive flood hazard assessment for the Ladan watercourse in 9rd District of Mashhad City, Iran, by integrating hydrological (ASSA) and hydraulic (HEC-RAS/HEC-GeoRAS) modeling with GIS-based spatial analysis. The results highlighted that, although the existing channel geometry is sufficient to convey flood discharges associated with 25- and 50-year return periods, it fails to accommodate runoff generated during a 100-year flood event. Specifically, the initial 200 meters of the channel were identified as critical zones where overtopping and road inundation are likely to occur.

By applying the national guideline for flood hazard mapping (Code 821), hazard levels were quantified based on depth–velocity criteria, leading to the development of flood hazard zoning maps that clearly illustrate unsafe conditions for vehicles, pedestrians, and surrounding infrastructure. The findings further underscore that the limited cross-sectional capacity of the channel, compounded by urban land-use pressures and high population density, significantly increases flood risk in the area. To mitigate these risks, structural measures such as modifying channel dimensions, reinforcing sidewalls, and periodic dredging were recommended, alongside non-structural strategies including detention basins, diversion channels, and temporary storage reservoirs. These measures, when combined, can enhance the resilience of the Ladan watershed to extreme rainfall events.

Overall, this research provides a reproducible methodological framework for urban flood hazard assessment in semi-arid environments. The integration of ASSA and HEC-RAS modeling, validated against national codes and municipal directives, offers a robust decision-support tool for urban planners and flood risk managers. Importantly, the results align with previous studies in Mashhad and other semi-arid cities, reinforcing the urgency of adopting both structural and non-structural adaptation strategies to reduce future flood risk under increasing urbanization and climate variability.

Future research should consider coupling 1D/2D hydraulic models, testing climate change and land-use scenarios, and integrating green stormwater infrastructure (e.g., permeable pavements) to design sustainable long-term flood risk management strategies.

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