Flood Hazard Detection in Data-Scarce Regions: A Case Study of a Semi-Arid River in Northeastern Morocco

Badr Layan[1*], *Lahcen* Benaabidate[2], *Mahmoud* Zemzami[3] *Mohamed* Hanchane[4] *Mohamed* Ben Abbou[5]

[1]Faculty of Sciences Dhar El Mahrez, Sidi Mohamed Ben Abdellah University, Fes, Morocco,
[2]Faculty of Sciences and Techniques, Sidi Mohamed Ben Abdellah University, Fes, Morocco,
[3]Higher School of Education and Training, Mohamed First University, Oujda, Morocco,
[4]Faculty of art and human sciences, Sidi Mohamed Ben Abdellah University, Fes, Morocco,
[5]Higher Institute of Nursing Professions and Health Techniques of Fez (Annex Taza), Taza, Morocco

Abstract. Forecasting flood hazard areas often presents substantial challenges in data-scarce regions. In our case study, we used HEC-RAS model to identify flood risk zones for various return periods along an ungauged river in a semi-arid region. Our focus was on the densely populated area surrounding the Larbaâ River in Taza City. The model inputs comprise peak flow estimates derived from the GRADEX method, physical parameters approximated using standardized tables (Manning coefficient), and other measurements taken directly in the field. During the calibration phase, critical adjustments were made to ensure the model's stability and its ability to generate results within an acceptable range. Our findings indicated that the numerical model successfully identified vulnerable areas. The floodplain closely aligns with the extent of the 100-year flood, highlighting all regions susceptible to flooding. The results were also consistent with flood events from the past two decades, underscoring the model's predictive accuracy regarding the river's behavior. These insights will inform future urban planning initiatives, enabling local authorities to implement effective mitigation strategies. This study demonstrates that the model is a valuable tool for comprehensive flood risk assessment, particularly in areas lacking monitoring.

1 Introduction

Around the world, flooding is one of the major natural hazards that regularly threaten human lives and properties [1]. Over the past decade alone, the flood risk has significantly risen by 23% [2,3]. Climate change and uncontrolled land use strongly correlate with this increase [4, 5, 6, 7, 8, 9]. In developing countries with limited protection measures, the impact of floods is particularly harmful. Morocco, like many nations, is still facing significant challenges in reducing the flood's effects [10]. To mitigate these harmful effects, a highly effective strategy involves using flood hazard maps as documentation to strengthen the enforcement of land use laws and regulations [6, 11, 12]. The common tendency to produce flood hazard maps is utilizing rainfall data and computer-based computations [6, 13]. These numeric tools have improved substantially with the development of computer capabilities, remote sensing, geographic information systems (GIS), and computational modeling [14, 15]. On the other hand, other studies use field surveys to delineate food-prone areas [16, 17]. These studies employ the hydrogeomorphological method, a technique with a long-standing history in France. This approach primarily relies on field evidence, including flood indicators observed on the ground, trees, and walls [12, 16]. It combines information about fluvial landscape history, morphogenetic processes, field observation, and laboratory experimentation [16, 17]. This integration positions the method as a comprehensive science for understanding and managing river systems [11, 18].

Currently, flood simulations employ various approaches, such as machine learning, artificial intelligence, and physics-based models [4, 6]. Over the past decade, researchers have used and investigated these methods worldwide. For instance, Ahmad et al. (2025) demonstrated the efficacy of machine learning for flood risk mapping in Indus Kohistan, Pakistan [19]. The authors leveraged historical flood data alongside meteorological variables, achieving high predictive accuracy compared to traditional methods. In a similar manner, Mishra and Prasad (2024) employed deep learning methodologies, particularly Long Short-Term Memory (LSTM) networks, to forecast river discharge and flooding occurrences in India [20]. Zeng et al. (2024) created a novel AI-based model for real-time flooding image recognition using a super-resolution generative adversarial network [21]. Furthermore, a search in the SCOPUS database showed that the number of publications with HEC-RAS in the title, abstract, or keywords has more than doubled in the past ten years. This notable growth can likely be attributed to the release of version 5.0 in 2016, which introduced several innovative tools, including a model for two-dimensional computations. A review of the relevant literature

* Corresponding author: layan.floods@gmail.com

indicates that the HR2D model has been widely utilized in flood mapping, specifically in urban areas [22]. In addition to these capabilities, the model is currently one of the most popular models worldwide [6] and is likely to become the standard for hydraulic modeling tools [23]. The model has also proved computationally efficient, especially for 1D modeling, which is highly suitable for specific analyses [4, 6]. In Morocco, the HEC-RAS model has been utilized since 2008 by academics, consulting firms, and hydraulic basin agencies to identify flood risks and develop protective measures.

In our study area, Taous et al. (2010) and Akdim et al. (2003) have already defined flood zones along the Larbaâ River in Taza City based on integrated geomorphology and hydrogeomorphology methods [24, 25]. These techniques have successfully identified areas that have historically experienced flooding and enabled detailed maps that categorize overflowing risks. However, the methods used appear to have limitations in highly urbanized areas, such as in the Al Malha neighborhood, where human occupation has significantly altered the natural topography. The present study emphasizes quantitative aspects by employing hydrological and hydraulic models, in contrast to the previous methods that focused on the qualitative zoning of flood risks. Such quantitative aspects provide concrete measurements to accurately identify flooding issues and develop solutions to assist decision-makers. Given that the study area falls in poor data regions, we were compelled to evaluate the flood peaks utilizing the GRADEX model, which was initially introduced by Guillot and Duband in 1967 [26]. Since then, local equations have refined the GRADEX method to better suit specific regions globally [27]. This method is highly suitable for return periods ranging from 2 to 1000 years in non-Karst basins with a surface area of 10 to 10,000 km² [28]. Several countries worldwide, such as the French metropolitan area, the United States, Australia, South Africa, Morocco, and Algeria, have verified the method and confirmed its effectiveness in designing the peak flows [11, 29].

Furthermore, we used the hydrodynamic approach to reproduce the rivers' behavior. This method is commonly considered an excellent tool to estimate flood amplitude. Given the HEC-RAS's significance in evaluating flood events, we were encouraged to utilize it to explore and assess its effectiveness. Thus, we used the HEC-RAS model to simulate floods in the Larbaâ River, which flows through a semi-arid region that lacks monitoring stations. This river was selected due to its considerable threat to the population and property along the floodplains. Over the past two decades alone, the local community has experienced numerous flooding events. Thunderstorm precipitation often leads to overflow incidents in the Larbaâ River and its tributaries [29]. In many instances, these intense and sudden rainfall events have resulted in violent torrential floods that have severely impacted the population.

In response to these serious threats, we aim to identify flood-prone areas along the river's sections, characterized by a complex and highly occupied alluvial plain. We seek to predict the flood extent in areas where human activities disrupt and modify the floodplain. Additionally, the study aims to replicate the river's behavior and simulate its responses to hydraulic structures during floods that exceed previously observed levels. We also intend to produce flood risk maps, which may serve as reference documents for urban planning and flood mitigation strategies. Finally, this study also assesses the effectiveness of such modeling tools in aligning with real-world flood scenarios.

2 Materials and methods

2.1 Case study

The study area is in the northern section of Taza city, where the Larbaâ tributaries meet (Figure 1). The Larbaâ drainage basin, which spans 780 km², falls within Taza province's administrative boundaries. It includes various roads connecting neighboring cities and villages. Geomorphologically, we may divide the Larbaâ watershed into two separate sections. In the northern part, the pre-Rif Oriental Hills dominate the landscape, characterized by soft lithology consisting of marls and marly limestones dating back to the Cretaceous and the end of the Tertiary period (Figure 1a). The erosion of unprotected lands has created a hilly landscape [30]. On the other hand, the southern portion of the watershed extends over the northeastern Middle Atlas Mountains, composed of rigid and permeable limestone and dolomites from the Lias period (Figure 1a). These geological features limit water erosion, leading to steep landforms, with the highest point in the rural commune of Bab Bouidir reaching an altitude of 1400 meters [4, 31]. Except for the southern section, where perennial plants dominate in restricted regions, the land is largely bare in vegetation.

Additionally, the Taza region has a semi-arid climate with frequent, powerful, brief showers of precipitation. These rainstorms directly contribute to increased torrential flow and devastating floods [4, 30, 31]. Bouljraf, Laâzib, Jouana, Rhouireg, Dfali, and Taza are the essential tributaries flowing into the Larbaâ River (Figure 1a). They help move water downstream and cause terrible flooding in Taza City [13, 25, 31] (Figure 1, a and b). This city has witnessed a significant number of deaths in the past thirty years alone, highlighting the continuous threat to human life [32]. These floods have also caused important material damage. The flood on 9/27/2000 resulted in the collapse of 47 houses and damage to 126 others (Figure 2, a, b, and c) [32]. Moreover, this flood had a notable impact on cultivated areas, leading to the uprooting of fruit plants (Figure 2d) and a subsequent loss of productivity for 349 farmers in 2000 [33]. Similarly, the flood had significant effects on the railways, with estimated damages of 4 million dirhams for the floods of 9/27/2000 alone [34]. The flood displaced several sections of railway tracks by several meters, disrupting train traffic on the Rabat-Oujda line for two days [34] (Figure 2e). Moreover, the 2010 flood affected the roads, interrupting traffic in multiple sections and causing estimated losses of approximately 8 million dirhams [33] (Figure 2f).

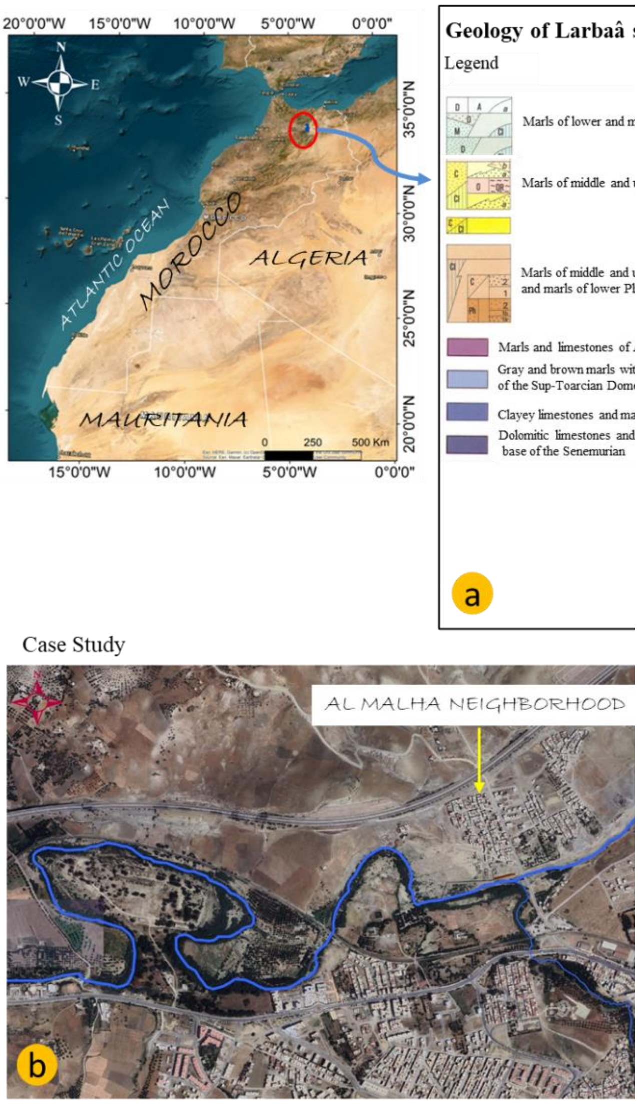

Fig. 1. Study area, (a), geology of Larbaâ basin, (b), section considered for flood simulations.

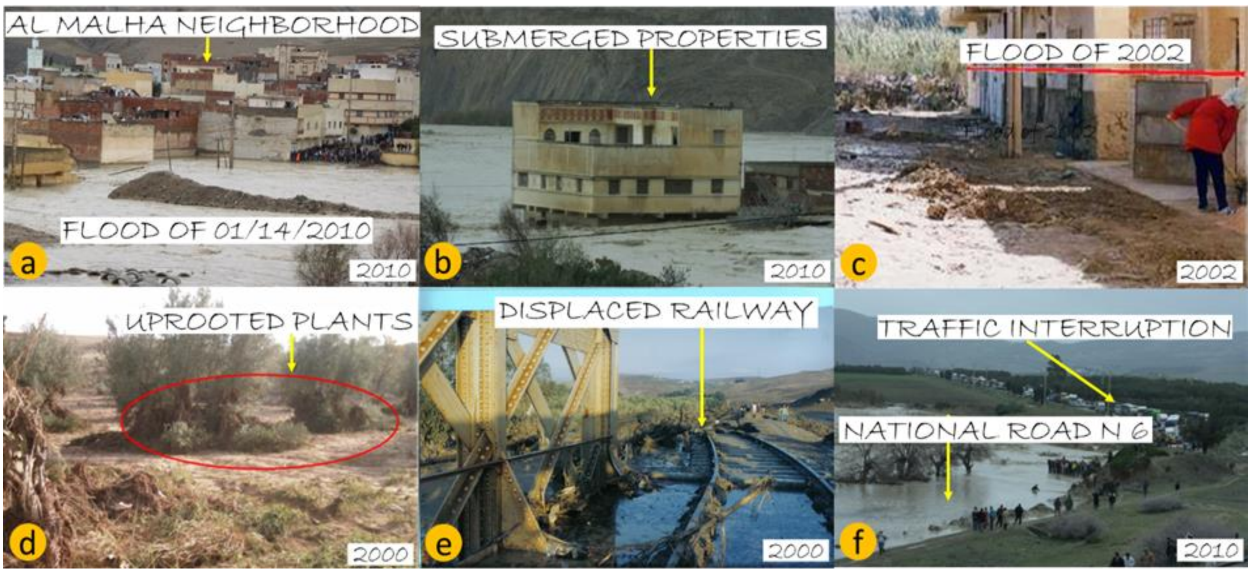

Fig. 2. Damages along the Larbaâ River, (a), flowing over the south part of Al Malha neighborhood, (b), submerged properties, (c), cleaning operations [29], (d), uprooted fruit plants, (e), railways displaced [34], (f), traffic interruption during floods incidents.

2.2 Data

In this research, we utilized the Advanced Spaceborne Thermal Emission and Reflection Radiometer model (ASTER_DEM), sourced from the USGS Earth Explorer. This model, featuring a resolution of 30 meters, served as the foundational dataset for constructing drainage networks and generating physical parameters of the basin. The high-resolution digital elevation model (DEM) effectively captured the complex topographical features vital for drainage system analysis. The analysis commenced with ArcGIS 10.8.2 software, which integrated Geographic Information System (GIS) capabilities with advanced remote sensing techniques. This combination enabled the manipulation and visualization of spatial data, facilitating a comprehensive morphometric analysis. To accurately delineate the boundaries of the sub-watersheds, we employed topographic maps at a scale of 1:50,000, provided by the poly-disciplinary Faculty of Taza. These maps supplied detailed spatial information necessary for defining sub-watershed extents and understanding the surrounding landscape features. Moreover, the software ArcGIS streamlined the processing of both the ASTER_DEM and the topographic maps, allowing for the extraction of key morphometric parameters, such as basin area, perimeter lengths, river lengths, and other critical metrics that define the characteristics of the sub-watersheds, as shown in Table 1.

Moreover, the hydrological analysis is predominantly based on annual maximum daily rainfall data and the Intensity-Duration-Frequency (IDF) curves obtained from the Taza rain gauge (Figure 3). The available rainfall dataset includes observations from 1962–2024, which is a long enough time for hydrological studies. The IDF curves make it easier to determine rain intensity for frequencies over a period of 10 to 100 years. Additionally, the Montana coefficients are essential for certain formulas associated with the GRADEX method. The parameters "a" and "b" are also derived from the IDF curves of Taza.

Table 1. Morphometric characteristics of the Larbaâ's sub-basins.

Sub-basins	C.A Km2	Thalweg L Km	Max H m	Min H m	*H* Δ	Basin's perimeter Km	Gravelius index Kg	Slope by %
Larbaâ	284	43	1361	439.5	921.5	90	1.51	2.14
Bouljraf	302	37	1182	439.5	742.5	96.5	1.57	2.01
Jaouna	48	22	1525	437	1088	47	1.91	4.95
Rhouireg	8	7.5	817	434.5	382.5	15	1.50	5.10
Dfali	22.5	13.5	1520	434	1086	28.5	1.69	8.04
Taza	43	15	1770	421	1349	33	1.42	8.99
Laâzib	7.5	5	642	437.5	204.5	13	1.34	4.09

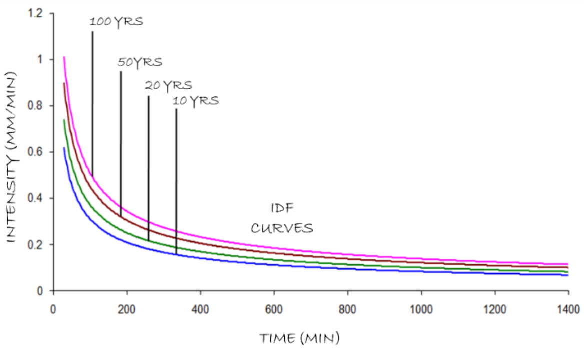

Fig. 3. Intensity-Duration-Frequency (IDF) curves of rain gauge station of Taza.

2.3 Methodology

To conduct numerical computations in HEC-RAS, the model requires several inputs, including observed or estimated flow rates, on-site measured cross-sections, and additional variables obtained from standard tables [11]. In the context of our case study, the process utilized a hydrological model to perform a hydraulic simulation. We calculated the highest peak flows for different time periods and then used those numbers to model how floods would behave. Overall, hydrological analyses and hydraulic simulations differ significantly, each possessing its own distinct methodology and necessitating specific datasets (Figure 4).

2.3.1 Maximum Peak flows for a given return period

To assess the maximum peak flow in ungauged basins, such as the one in question, specific treatment is necessary. This treatment involves determining maximum discharges using a hydrological model. In this context, we attempted to select the method that is workable with the available data. We ended up applying the GRADEX method to our case study, going through many interconnected stages as described in figure 4. The primary objective was to estimate two critical flood parameters: the peak flow (Qf) for return periods ranging from 10 to 100 years and the shape of the flood hydrograph. Such parameters are essential in conducting flood studies, thereby addressing data gaps related to ungauged basins. To guess the river's rare discharges, the GRADEX model used the drainage basin's geometric features and information about rainfall. The method was grounded based on the following hypotheses: (1) the catchment area uniformly experiences maximum rainfall, which is the sole factor triggering peak flow, suggesting that no other elements influence flood occurrences, and (2) both maximum rainfall and the corresponding rare flow exhibit the same statistical distribution. This congruence implies that the asymptotic laws governing rainfall distribution and flow are aligned.

The process commenced with an in-depth statistical analysis of maximum daily rainfall (MDR). In this analysis, we employed the Gumbel distribution, which serves as the most appropriate model for examining rare frequencies [4, 27, 28]. This distribution enabled the identification of the GRADEX and the maximum daily rainfall (MDR) over different return periods, ranging from 10 to 100 years (Table 3). We used a multiplication factor of 1.15 on the daily values to get a 24-hour rainfall estimate from the MDR. This considers how rainfall spread over time [29]. Thus, the rainfall data was first examined using a probabilistic analysis, then converted into flow through a combination of conceptual and empirical models [13, 28]; as explained below.

Additionally, the GRADEX method is fundamentally anchored in a specific frequency known as the reference (T), which typically ranges from 10 to 20 years, contingent upon soil permeability [29]. It is advisable to utilize a 10-year frequency for areas with impermeable lithologies and a 20-year frequency for those characterized by permeable soils [26]. According to HBAS (2011), a 10-year frequency is especially suitable for northeastern Morocco. Given that impermeable lithologies constitute over 80% of the basin's total area, they facilitate surface runoff rather than soil infiltration. Consequently, based on these physical parameters, we conclude that employing a decennial frequency is more appropriate for this analysis. To convert rainfall data into reference flow discharge, we utilized the Caquot model, which is recognized as the most suitable for application in Morocco [35]. This model allows for the assessment of the decennial peak flow, with these reference values being essential for the subsequent stages of the GRADEX method (Figure 4).

Furthermore, the flood hydrograph is crucial for estimating runoff and water volume associated with a specific reference frequency. Typically, these hydrographs are constructed by combining rainfall data with flood observations. However, due to limitations in data availability for this study, we opted for an alternative approach to generate unit flood hydrograph. This alternative method requires a base time that is twice the duration of the peak time (Figure 5). Following this, the reference volume for the 10-year return period was calculated by multiplying the concentration time by the corresponding flow rates. Additionally, we determined the runoff for the 10-year return period by dividing the 10-year volume by the area of the basin. Also, the GRADEX method is based on the premise that the assessment of a flood can be effectively determined by its peak flow, given that the watershed undergoes a rainfall event whose duration matches the concentration time of the catchment. Moreover, this approach asserts that a rainfall event with a defined return period (Tr) will generate a flood event that corresponds to that same return period.

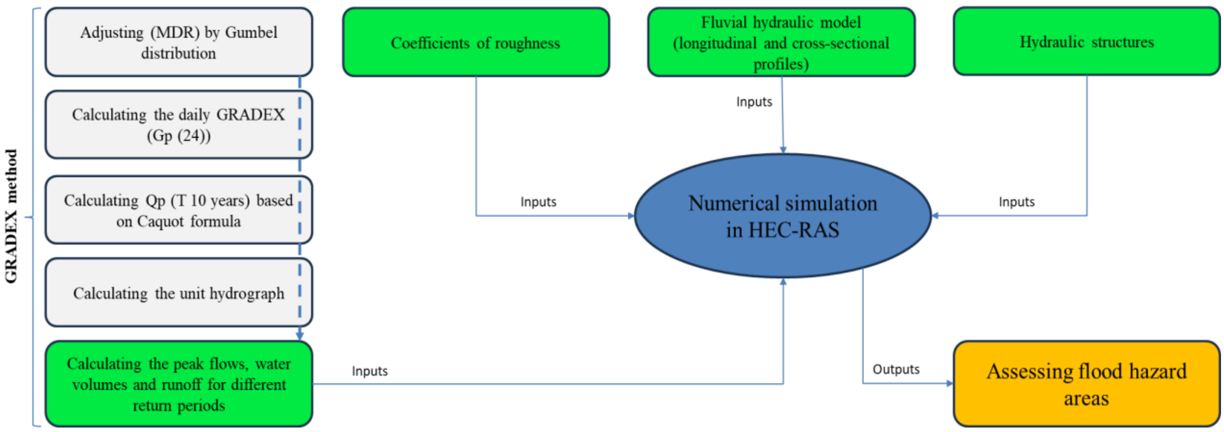

Fig. 4. Methodology flow chart of the hydrological-hydraulic models.

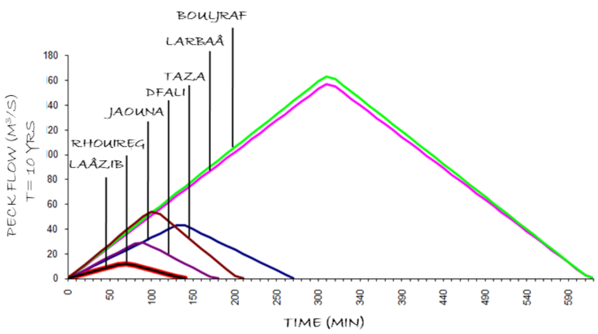

Fig. 5. Unit flood hydrograph.

2.3.2 Numerical model in HEC-RAS

Developing a numeric model in HEC-RAS relies fundamentally on the geometric representation of the Riverland, illustrated through cross-sectional profiles identified by their curvilinear abscissas along a longitudinal profile [36]. This profile is derived from a satellite image dated 2025 and is meticulously aligned with the channel's center. The HEC-RAS assumes that flow is channeled and organized consistently in a preferential direction over time [36]. Additionally, cross-sections are selected to provide precise information regarding morphological features. They were established in the field using measurements taken with a GPS, measuring wheel, and ruler. These profiles were drawn from left to right and placed close together to show the shape of the Larbaâ River accurately. Additionally, to address disturbances from human activities, we incorporated obstructions such as houses, bridges, and embankments within the floodplain during the model construction. The simulation utilized the 100-year peak flow as a representative flood event to create a detailed and reliable flood map of potential wet areas.

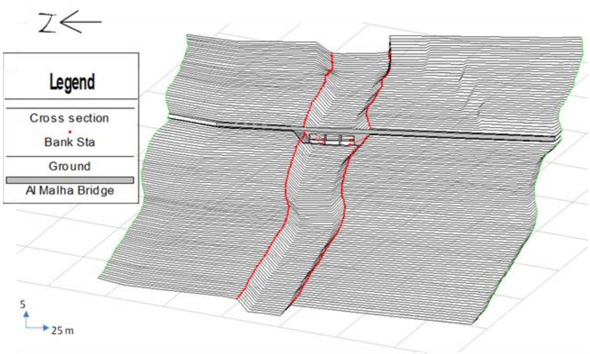

Fig. 6. Fluvial hydraulic model in HEC-RAS.

2.3.3 Coefficients of roughness

The roughness coefficient varies according to land characteristics. This concept is intricate and incorporates several elements that remain partially undefined. It considers factors such as vegetation density, riverbed irregularities, surface water width, and variations in soil composition. Each of these parameters affect flow resistance in different ways [37]. In determining the roughness coefficients, we utilized field observations alongside standard tables developed by Chow [38]. These coefficients were determined by the unique characteristics of the riverbeds and banks. The bottom of the Larbaâ River primarily consists of fine gravel, leading to roughness coefficients that range from 0.035 to 0.05. We propose that values between 0.03 and 0.05 effectively capture the potential range of coefficients relevant to the Taza region. According to hydraulic basin agencies, coefficients ranging from 0.04 to 0.05 may be more suitable for this context [35].

2.3.4 Model Calibration in Steady-State Conditions

To run the model under steady-flow conditions, HEC-RAS requires hydrological models that accurately evaluate peak discharges [36]. The GRADEX model is recognized as a pertinent method for precisely assessing discharge based on rainfall data, rendering it suitable for integration within a steady-flow hydraulic model [36]. Thus, in this study, we opted to calibrate the model under steady-state conditions, using the flood event that occurred on September 27, 2000, in the Larbaâ River as a reference point. We incorporated the discharges from this event into the upstream cross-section, considering them applicable to the entire simulated section. While flood discharges are treated as constant, the hydraulic model can adjust these values for specific sections where significant parameters impact flood dynamics. During our sensitivity analyses, we modified certain parameters and examined the resulting outputs. These adjustments enabled us to identify a configuration that ensures model stability and effectively replicates the observed flood dynamics.

3 Results

3.1 GRADEX method

The GRADEX method enabled the estimation of runoff, water volume, and peak flow for various return periods. We are specifically focusing on the 100-year return period due to its significance in assessing extreme flood events. The Bouljraf sub-basin displays the highest hydrological parameters within the Larbaâ watershed, characterized by maximum values for runoff, water volume, and peak discharge. The Larbaâ sub-basin has the second highest peak discharge, which is very close to the first (Table 2). These substantial values reflect a significant capacity for runoff generation and water accumulation, thereby emphasizing the acute flood risk associated with extreme precipitation events in this region. Additionally, the Jaouna and Taza sub-basins demonstrate moderate hydrological activity, suggesting a reduced flood risk compared to Bouljraf and Larbaâ. On the other hand, the Laâzib and Rhouireg sub-basins have the lowest peak discharges, which are 50 m^3/s and 52 m^3/s, respectively (Table 2). These figures indicate limited runoff generation and water storage capacity, implying a lower potential for flooding in these areas.

These results underline the diverse hydrological responses to rainfall incidences. The morphometric parameters of the sub-basins, such as surface area, concentration time, basin shape, and slope, closely link these responses. The surface area of a basin significantly influences its runoff potential and, consequently, its peak flow. For example, the Bouljraf (302 km^2) and Larbaâ (284 km^2) sub-basins, which have the largest surface areas, exhibit higher peak flows compared to smaller basins such as Laâzib (7.5 km^2) and Rhouireg (8 km^2). Furthermore, the Gravelius index, which measures basin shape, plays a crucial role in hydrological dynamics. A higher Gravelius index indicates a more elongated basin, which may result in longer travel times for runoff. For instance, Jaouna possesses the highest Gravelius index (1.91), which correlates with its lower peak flow values in relation to its surface area (Table 2).

3.2 Hydraulic simulation

Figure 7 illustrates the dynamics of flood risk frequencies derived from numerical simulations. Panel (b) depicts the extent of the 10-year flood, which primarily inundates the river channel and adjacent floodplain. This data suggests a relatively low flood risk, as water flows without affecting sections where the local population resides on the alluvial plains (Figure 7b). Panel (c) presents the dynamics of the 20-year flood, revealing a larger inundation area compared to the 10-year event, with water extending further into the floodplain. This expansion indicates an increased flood risk and possible impacts on nearby infrastructure (Figure 7c). Finally, panel (d) shows the extent of the 100-year flood, demonstrating water spread across the entire flood plain (Figures 7d and 8). The numeric visualization for the Malha neighborhood indicates that a significant portion is at risk of inundation, highlighting the possibility of severe impacts on residences during such extreme flood events. The centennial flood poses serious challenges along the Larbaâ River, underscoring the necessity for preparedness and proactive measures to mitigate potential impacts on vulnerable areas (Figure 8).

Table 2. Runoff, water volume, and peak flow for different return periods (ranging from 10-year to 100-year).

Sub-basins of Larbaâ watershed	Runoff in mm				Water Volume in Mm^3				Q p in m^3/s			
	10 yrs	20 yrs	50 yrs	100 yrs	10 yrs	20 yrs	50 yrs	100 yrs	10 yrs	20 yrs	50 yrs	100 yrs
Larbaâ	10.19	13.56	31.12	44.28	2.9	3.85	8.84	12.57	157	209	480	682
Bouljraf	9.94	14.13	32.43	46.14	3	4.27	9.79	13.93	163	232	531	756
Jaouna	7.02	9.87	22.64	32.21	0.34	0.47	1.09	1.55	43	61	139	198
Rhouireg	5.69	7.65	17.55	24.97	0.05	0.06	0.14	0.2	12	16	36	52
Dfali	6.27	8.46	19.41	27.62	0.14	0.19	0.44	0.62	29	39	89	126
Taza	7.33	9.51	21.81	31.04	0.32	0.41	0.94	1.33	54	71	162	231
Laâzib	5.88	7.75	17.79	25.31	0.04	0.06	0.13	0.19	12	15	35	50

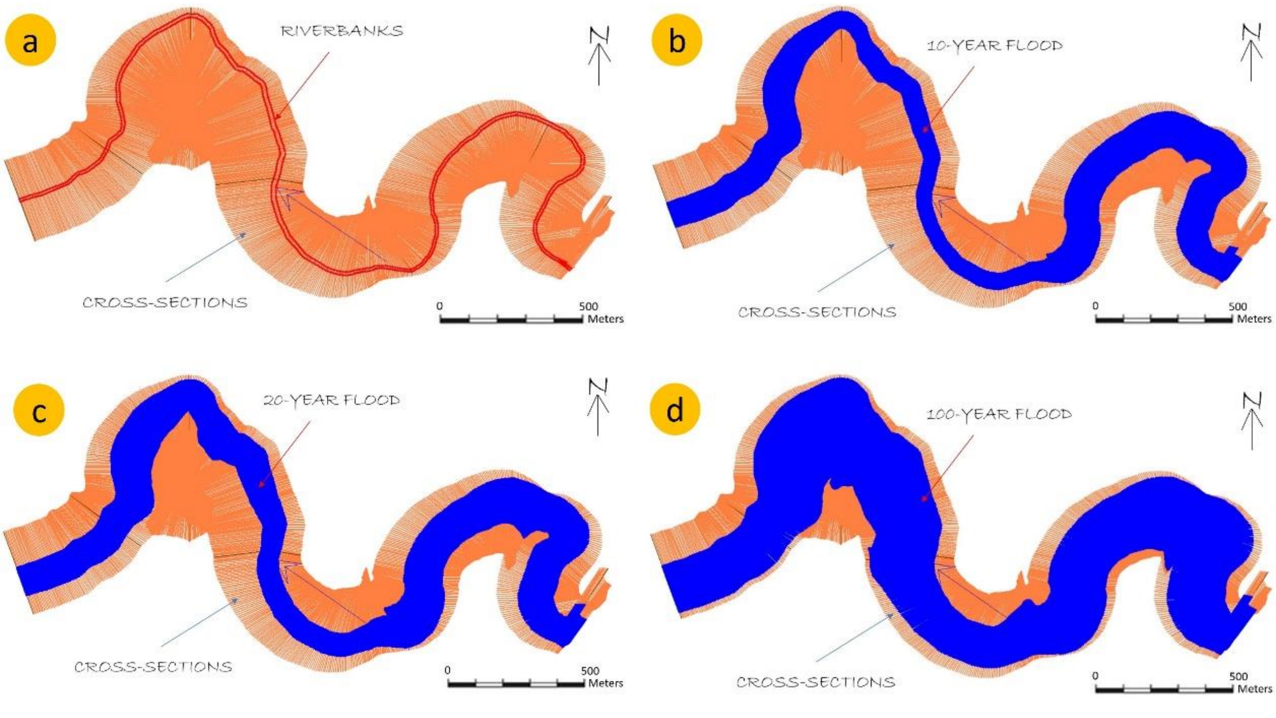

Fig. 7. Flood Dynamics under different frequencies, (a), hydraulic model before the inputs data, (b), extent of 10-year flood, (c), extend of 20-year flood, (d) extent of 100-year flood.

Concerning the hydraulic responses to various flood events, we noted that the existing bridges along the urban section of the Larbaâ River are inadequate for managing floods with return periods of 50 and 100 years. The Al Malha Bridge, the largest cross-structure in Taza City, remains undersized and unable to effectively handle flow during floods exceeding 20 years (Figures 9 and 10). During such flood events, the water significantly surpasses the bridge's height. Here, the hydraulic structure functions as a barrier, obstructing flowing water rather than facilitating it (Figures 8, 9, and 10). This blockage contributes to waterlogging and retains water in the upstream section of the bridge. Consequently, the flood impacts intensify both upstream and downstream, restricting water evacuation and leading to extensive overflows exceeding 300 meters in width (Figures 8, 9, and 10). Along the Al Malha neighborhood, centennial flooding completely covers the floodplain, dispersing significant volumes of water into residential areas and agricultural fields (Figures 8 and 10). The 100-year flow rate elevates water levels to 426.45 AMSL, resulting in an overflow of 2.61 meters over houses nearing the Al Malha bridge (Figures 9 and 10).

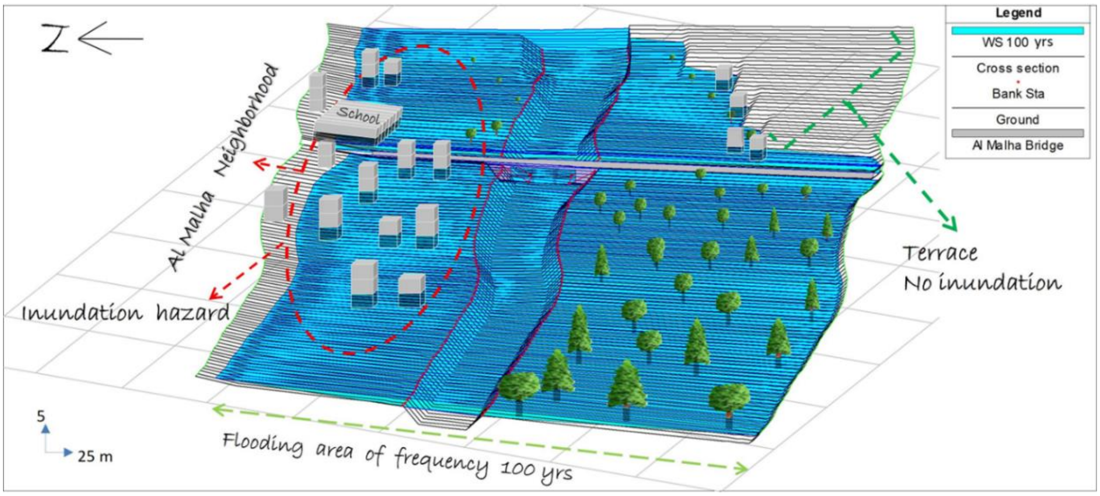

Fig. 8. 100-year flood scenario in the Al Malha neighborhood.

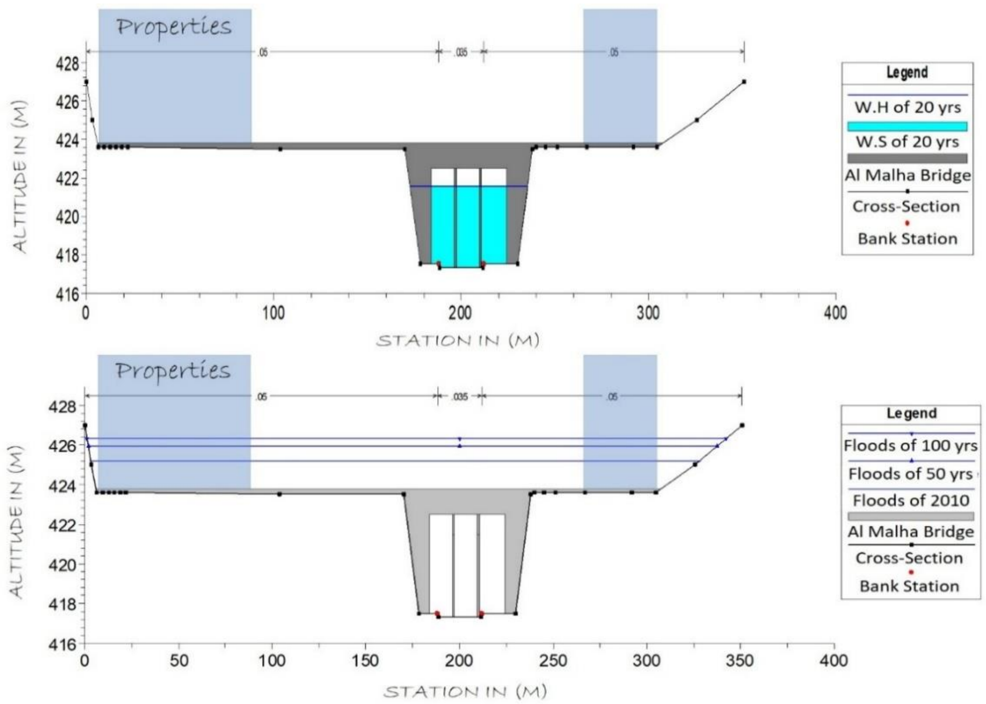

Fig. 9. Al Malha Bridge under observed and estimated floods (W.H, water heights; W.S, water sections).

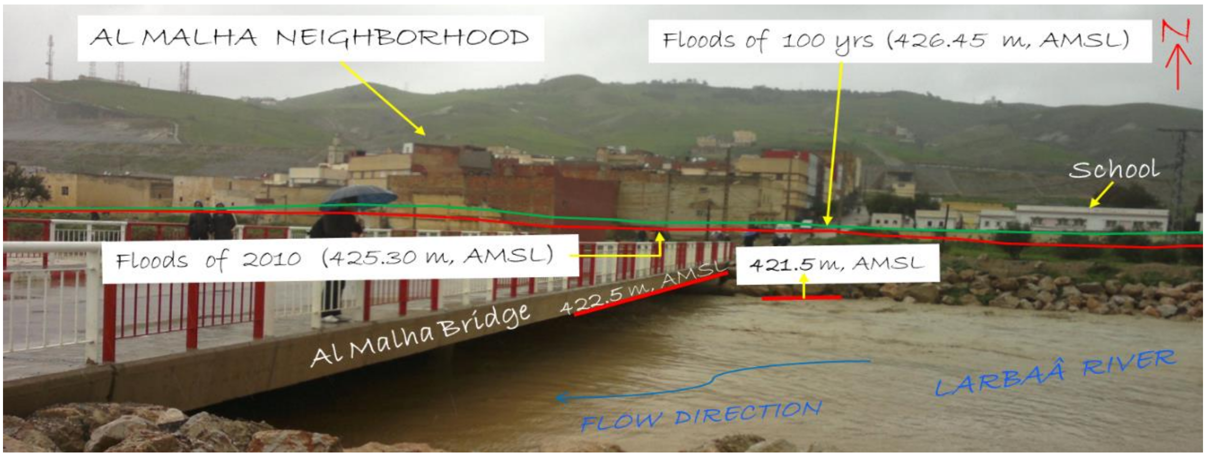

Fig. 10. Graphical illustration of the 2010 and 100-year floods (AMSL, Above Mean Sea Level).

4 Discussion

Our model has effectively identified flood dynamics and evaluated the performance of hydraulic structures. The results indicate that the integration of hydrologic and hydraulic modeling serves as a valuable approach for estimating flood amplitudes. The GRADEX method proved to be an effective tool for estimating rare frequency flows in data-scarce regions. Also, the HEC-RAS model accurately simulated the river's behavior and determined flood zones (Figures 7 and 8). Moreover, the modeling tools facilitated an understanding of the river's response to cross-structures and properties (Figures 8, 9, and 10). The wet areas associated with centennial floods were considered as potential boundaries for floodable regions (Figures 7, 8, and 11). The process enabled the mapping of flood-prone areas where human factors have altered natural configurations. This indicates that the model can estimate flooding over highly urbanized areas. Additionally, eyewitness accounts validated our flood hazard maps, corroborated by earlier field flood observations (Figure 11). Our findings support a 2001 study by HBAS, which classified the 2000 flood as a centennial event affecting the entire alluvial plain of the Larbaâ River [29].

Furthermore, the model may serve as a foundation for further research into mitigation strategies and the implementation of effective measures to reduce or prevent flooding impacts. The model's capacity to integrate reinforcement parameters within its interface facilitates simulating the effects of protective measures. Several simulation tests indicated an increase in water levels with the installation of preventive structures, demonstrating the model's appropriate response and its efficiency in flood mitigation. While awaiting more precise methodologies and advanced versions of HEC-RAS, the GRADEX method and current software version have enabled the evaluation of probable flood dynamics.

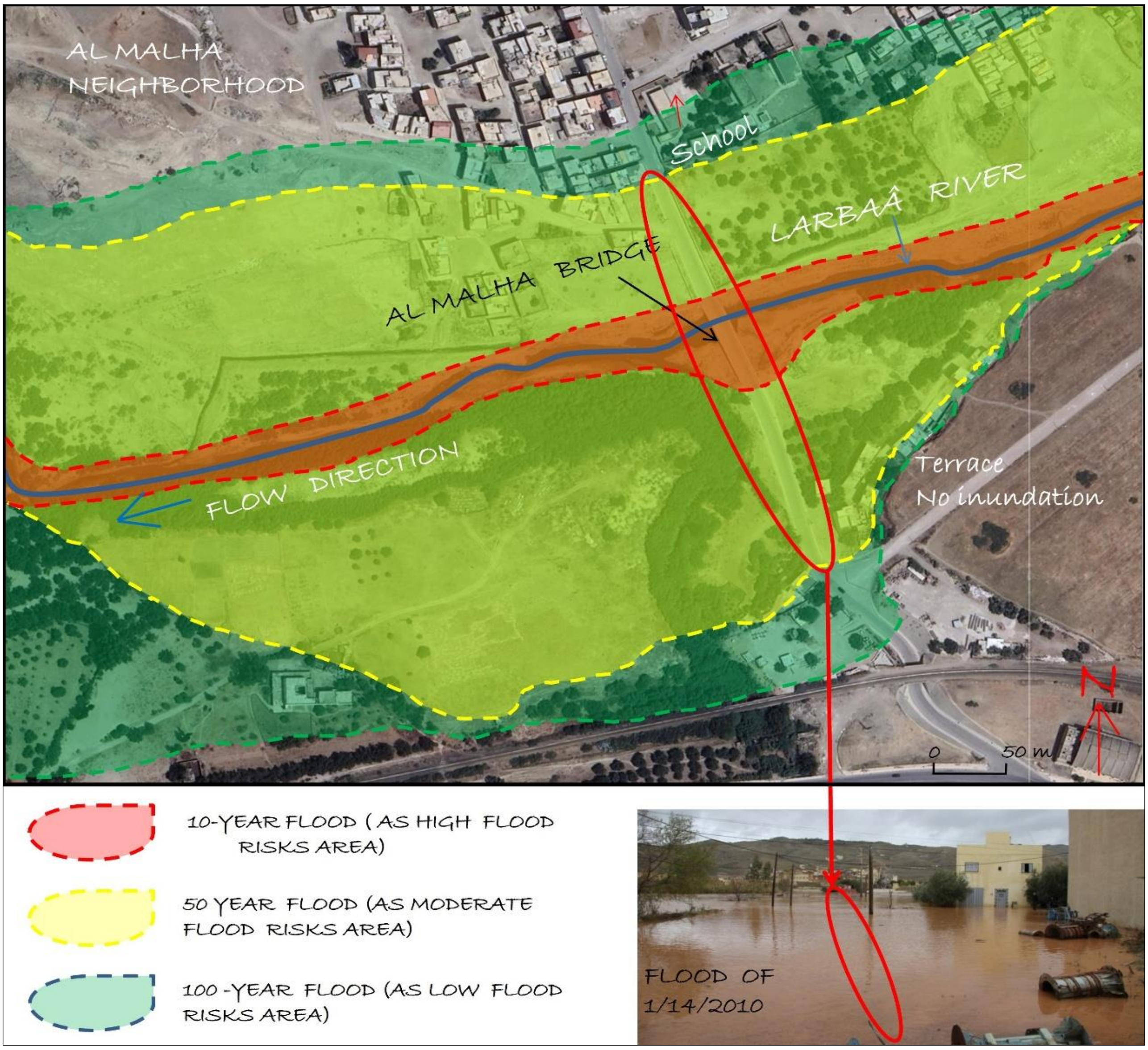

Fig. 11. Spatial representation of different flood frequencies on a satellite image of 2024.

5 Method limits

Although the computational approach has valuable capabilities, it still suffers from many challenges. These challenges include insufficient hydrometeorological data, the need for highly detailed digital terrain models, the absence of real-time satellite flood observations, difficulties in calibrating models, and the complexity in determining precise roughness coefficients [11, 36, 37]. The complex nature of flooding events often makes the process of developing hydrologic-hydraulic models more challenging [13]. There is a lack of in-depth examinations of current issues and their solutions in the literature [11, 39]. Consequently, we assert that specific gaps exist in modeling tools due to inadequate attention to input elements. Before discussing model limitations, it's crucial to note that output quality directly depends on input accuracy. In our case study, the scarcity of observations compelled us to use the GRADEX model to estimate flow rates. This model is like other hydrological models that exhibit a discrepancy between reality and numerical representation. As we mentioned previously in the methodology section, the GRADEX method is based on key assumptions, including the statistical reliability of historical data, the stationarity of hydrologic and climatic conditions, and watershed homogeneity. The method also assumes data accuracy and comprehensiveness. These assumptions have been widely debated within the hydrological community, with none being regarded as absolute scientific truths. Significant limitations exist regarding uncertainty in peak flow estimation. Dependence on rainfall data alone can result in over- or underestimations, and the results may also be highly sensitive to the choice of runoff coefficient values. Therefore, understanding these assumptions and limitations is essential for improving the accuracy of peak flow assessment.

The HEC-RAS model is based on empirical principles that synthesize the interactions of physical variables to demonstrate the processes of river hydraulics. We acknowledge the challenges associated with estimating these variables in the field, as even those identified can vary over time and space. Besides these challenges, we also encountered problems with model calibration. To calibrate the model, we numerically recreated the observed flood scenarios. Adjustments were made to variables such as Manning's coefficients to achieve the observed water levels. Although this calibration technique appears logical, it has certain limitations. One of the main drawbacks is that the specific physical factors that caused the recorded flood are often unknown. As a result, there is a risk of overestimating or underestimating the variables, which can affect the accuracy of the results. Furthermore, model calibration in steady-state conditions relies on constant fluvial hydraulic parameters. In nature, these scenarios cannot exist, as peak flows are highly sensitive to changes. Selecting roughness coefficients based on local conditions and the modeler's judgment further affects model outputs. Additionally, temporal changes in land use or vegetation cover may render initial roughness estimates outdated, introducing additional uncertainty.

6 Conclusion

The Modeling tools greatly enhance flood management and urban planning by enabling the development of advanced inundation risk maps. They prove particularly powerful in regions characterized by limited data availability and altered floodplain morphology. The integration of hydrological and hydraulic models facilitates the accurate identification of flood-prone areas and the evaluation of their associated impacts. The numeric simulations adeptly pinpoint sensitive zones that require protective measures. Such precise information equips stakeholders with the necessary insights to formulate effective flood mitigation strategies. Additionally, feeding the models with real-time precipitation data could improve predictions for impending floods. This analysis would enable authorities to anticipate scenarios and coordinate intervention plans. Prior flood prediction practically guides emergency response and determines relief operations.

References

1. Federal Emergency Management Agency, FEMA, National Threat and Hazard Identification and Risk Assessment (THIRA) Overview and Methodology. Website visited on 10/05/2025. (2019).https://www.fema.gov/sites/default/files/
2. Center for Research on the Epidemiology of Disaster, CRED, Website visited 09/10/2025. (2021).https://www.preventionweb.net/organizatio
3. UN Office for Disaster Risk Reduction, UNDRR, The non-COVID year in disasters. Website visited, 09/15/2025. (2020).https://www.undrr.org/publication/2020-non-covid-year-disasters
4. B. Layan, M. Zemzami, M. Ben Abbou, L. Benaabidate, M. Hanchane, Identification of morphometric parameters that determine rare flood occurrences in data-poor regions: case study of a semi-arid catchment area, Northeastern Morocco. Euro-Mediterranean Journal for Environmental Integration.(2025a).https://doi.org/10.1007/s41207-025-00912-0.
5. World Bank, From disasters to opportunities: building a resilient future in Morocco, Results sheets. (2024). https://www.banquemondiale.org/fr/results/2024/04/18/
6. L. Pavesi, C. Angelo, E. Volpi, A. Fiori, RESCUE: A geomorphology-based, hydrologic-hydraulic model for large-scale inundation mapping. J Flood Risk Manag, e12841. (2022). https://doi.org/10.1111/jfr3.12841.
7. H. Winsemius, J. Aerts, VL. Beek, FP. Bierkens, A. Bouwman, et al. Global drivers of future River risk. Nature Clim Change 6: 381-385. (2016).

8. P. Zope, T. Eldho, V. Jothiprakash, Impacts of land useland cover change and urbanization on flooding: A case study of Oshiwara River Basin in Mumbai, India. Catena 145: 142-154. (2016).
9. K. Schilling, P. Gassman, C. Kling, T. Campbell, M. Jha, et al., The potential for agricultural land use changes to reduce flood risk in a large watershed. Hydrol Process 20(8): 3314-3325. (2014).
10. Ministry of Equipment, Transport, Logistics and Water, METLW, Rôle de la direction de la recherche et de la planification de l'eau dans la gestion des risques d'inondation. Département de l'eau, Royaume du Maroc, (2019), 26p.
11. B. Layan, M. Zemzami, B. Bougdira, L. Benaabidate, Assessment of the potential flood hazard of the Larbaâ Wadi, rural center of Sebt Boukellal,Taza, Morocco. BIO Web Confer 109:01026. (2024a). https:// doi. org/ 10. 1051/ bioco nf/ 20241 09010 26.
12. JL. Ballais, S. Chave, N. Dupont, E. Masson, MJ. Penven, La méthode hydrogéomorphologique, détermination des zones inondables. Géographie Physique et Environnement. Collection Ouvrages (ISSN 1958-573X). 172p. (2011).
13. B. Layan, M. Zemzami, B. Bougdira, Numerical Model for Flood Hazard Forecasting in an Urban River of Taza City, Morocco. J Hydrogeol Hydrol Eng 13:2. (2024b). DOI: 10.4172/2325-9647.1000301
14. B. Layan, M. Zemzami, L. Benaabidate, M. Ben Abbou, Gis tools and numeric model to forecast the floods extend along the Rhouireg river, city of Taza, Morocco. (2025b). https://doi.org/10.1051/e3sconf/202560704018
15. TV. Bijeesh and K. Narasimhamurthy, Surface water detection and delineation using remote sensing images: a review of methods and algorithms, Sustainable Water Resources Management. VL - **6** (2020). DO - 10.1007/s40899-020-00425-4JO -
16. JL. Ballais, G. Garry, M. Masson, Contribution de l'Hydrogéomorphologie a l'´évaluation du risque d'inondation : le cas du Midi méditerranéen français, Comptes Rendus Géoscience, 337, 1120–1130. (2005).
17. G. Arnaud-Fassetta, E. Cossart, M. Fort, Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, Southern French Alps), Geomorphology, **66**, 41–67. (2004).
18. E. Gautier, J. Corbonnois, F. Petit, G. Arnaud-Fassetta, D. Brunstein et al., Multi-disciplinary approach for sediment dynamics study of active floodplains Approche multidisciplinaire de la dynamique sédimentaire des plaines d'inondation actives. Géomorphologie : relief, processus, environnement, n° **1**. (2009), p. 65-78.
19. A. Ahmad, J. Chen, X. Chen, N. Khadka, MU. Khan, C. Wang, M. Tayyab, Flood risk modelling by the synergistic approach of machine learning and best-worst method in Indus Kohistan, Western Himalaya. Geomatics, Natural Hazards and Risk, 16(1). (2025). https://doi.org/10.1080/19475705.2025.2469766.
20. P. Mishra, SK. Prasad, Reviewing Flood Susceptibility Mapping Utilizing Machine Learning: Insights and Prospects for Future Research, 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC), Salem, India, pp. 649-655, (2024). doi: 10.1109/ICAAIC60222.2024.10575530.
21. Y. Zeng, M. Chang, G. Lin,. A novel AI-based model for real-time flooding image recognition using super-resolution generative adversarial network, Journal of Hydrology,Volume 638, 131475, ISSN 0022-1694, (2024). https://doi.org/10.1016/j.jhydrol.2024.131475.
22. A. Mulie, A. Tade Mule, C. Walelgn Dilnesa, Application of the HEC-RAS and HEC-HMS Models for Flood Risk Analysis in the Gumara River, Upper Blue Nile Basin, Ethiopia. Advances in Meteorology. First published: 05 August (2025). https://doi.org/10.1155/adme/5092932
23. E. Trevor, HEC-RAS: Its history, benefits, drawbacks, and alternatives. Autho desk. (2024). https://www.autodesk.com/blogs/water/2023/10/2
24. A Taous, Kh. Obda, M. Amyay, M. Laaouane, et al., Cartographie et zonage de l'aléa d'inondation à Taza, Maroc. Application de la méthode géomorphologique intégrée. Géomaghreb. (2010) n 6, pp. 1-19.
25. B. Akdim, M. Laaouane, A. Taous, Risques hydrologiques dans la région de Taza (Maroc) genèse, conséquences, et problèmes d'aménagement. Géomagreb, n° **1**, PP 47-60. (2003).
26. P. Guillot and D. Duband, La méthode du GRADEX pour le calcul de la probabilité des crues à partir des pluies, in Floods and Their Computation. Proceedings of the Leningrad Symposium, IASH Publ 84: 560–569. (1967).
27. MR. Khaleghi, J. Varvani, Simulation of relationship between river discharge and sediment yield in the semi-arid river watersheds. Acta Geophysica. SN - 1895-7455. (2018). https://doi.org/10.1007/s11600-018-0110-9.
28. M. Zemzami, L. Benaabidate, B. Layan, A. Dridri, Design flood estimation in ungauged catchments and statistical characterization using principal components analysis: Application of GRADEX method in Upper Moulouya. Hydrol. Process 27(2): 186-195. (2012).
29. Hydraulic Basin Agency of Sebou, HBAS, Etude de délimitation du niveau des plus hautes eaux de l'Oued Larbaa, ville de Taza. 4P+annexes. (2001).
30. A. Sadiki, H. Mesrar, A. Faleh, J. Chaaouan, Modélisation et cartographie des risques de

l'érosion hydrique : cas du bassin-versant de l'oued Larbaâ, Maroc. Papeles de Geografía N° 55-56. (2012), pp. 179-188.

31. A. Tribak, Erosion and Flooding Risks in the Marly Basins of the Eastern Prerif Mountains (Morocco): A Response to Exceptional Climate Events or to…. Revista de Estudios Andaluces, 40, 159-182. (2020). https://dx.doi.org/10.12795/rea.2020.i40.09.
32. Taza Urban Agency, TUA, Rapport portant sur les inondations survenues à Taza, le 27 septembre (2000).6P.
33. Taza province, Rapports détaillés sur l'inondation du 27 Septembre (2000). 15 P.
34. National office of RailWays, NORW, Rapport complémentaire de la crue de 27 septembre 2000. 9 P. (2000).
35. Hydraulic Basin Agency of Sebou, HBAS, Étude d'actualisation du plan directeur d'aménagement intégré des ressources en eau du bassin hydraulique de sebou, Secrétariat d'Etat chargé de l'Eau et de l'Environnement Rapport du PDAIRE. p 108. (2011).
36. HEC-RAS, HEC-RAS User's Manual, hydrologic Engineering Center, United States Army corps of Engineers,USACE. (2023).
37. Y. Aizhong, Z. Zheng, Y. Jinjun, M. Feng, D. Qingyun, Dynamic Manning's roughness coefficients for hydrological modeling in basins. Hydrol Res 49 (5): 1379-1395. (2018).
38. VT. Chow, Open Channel Hydraulics, McGraw-Hill Book Company, Inc. New York. (1959).
39. P. Costabile, C. Costanzo, D. Ferraro, P. Barca, Is HEC-RAS 2D accurate enough for storm-event hazard assessment? Lessons learnt from a benchmarking study based on rain-on-grid modelling. Journal of Hydrology. Volume 603, Part B, (2021). https://doi.org/10.1016/j.jhydrol.2021.126962