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Application of Numerical Hydrodynamic Modeling for Flood Mapping and Simulation of the Euphrates River

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ABSTRACT

Flood risk along the Euphrates River downstream of Haditha Dam has become a critical concern due to increasing hydrological variability and the growing impact of climate change on extreme flow events. This study presents an integrated numerical modeling approach using Hydrologic Engineering Center- River Analysis System (HEC-RAS) and Hydrologic Engineering Center- Geographic River Analysis System (HEC-GeoRAS) for generating flood inundation maps along the river reach downstream of the dam. A calibrated and validated hydrodynamic model was developed to simulate river flow under different discharge scenarios corresponding to return periods of 50 and 100 years. The model outputs were coupled with Geographic Information Systems (GIS) to delineate flood extents and identify high-risk zones. The finding indicates that extensive regions along the river corridor are vulnerable to inundation under extreme discharge flow conditions. Flood maps revealed spatial variations in hazard levels, highlighting critical (highly susceptible areas) where inundation depth and extent pose significant risks to nearby communities and infrastructure. The simulations for 50- and 100-year return period discharges demons trate a substantial increase in floodplain coverage, emphasizing the potential for severe flood events. Furthermore, the study confirms that the integration of numerical hydrodynamic models with GIS tools provides a powerful framework for visualizing and assessing flood hazards. This approach enhances the ability of decision-makers to develop effective emergency response plans, optimize flood management strategies, and support sustainable river basin management. The results underscore the urgent need for proactive planning and risk mitigation measures in the Euphrates basin, particularly under evolving climate conditions that are likely to intensify extreme hydrological events. Unsteady flow modeling compare to steady flow modeling, offers more information on the dynamics of the flood waves, especially the propagation of the wave along the river. The result show the inundation damaged area can include 186124 Donum.

1. INTRODUCTION

Floods are ranked among the most destructive natural hazards globally, imposing severe threats to human lives and infrastructure [1]. In arid and semi-arid regions, such as the Euphrates River basin, one of the most important water resources in Iraq, these risks are exacerbated by hydrological instability and the scarcity of historical data for accurate forecasting [2]. Climate change has increased hydrological extremes, including droughts and floods, placing significant pressure on the operation of the main control structure of the Euphrates River, Haditha Dam [3–5]. Sometimes, droughts can last for up to three years, followed by a rainy year that may lead to floods, causing disasters, significant economic losses, and the displacement of residents from their homes [2, 6]. For example, the city of Al-Khalidiya in Anbar Province was flooded as a result of heavy rains on March 26, 2026, after seasons of drought (Figure 1).

Although dams such as Haditha Dam are vital for managing water resources, the possibility of dam failure or emergency releases presents an existential risk to downstream communities [7, 8]. Reservoir operations and changing climatic flow regimes play a significant role in the dynamics of the Euphrates River and need to be integrated into complex hydraulic models [9, 10].

The development of hydrodynamic numerical models has evolved significantly over the past decades. Early approaches relied on simplified analytical equations and field observations, which were limited in representing complex flood dynamics. With the advancement of computational techniques in the 1970s and 1980s, one-dimensional (1D) numerical models based on the Saint-Venant equations were introduced, enabling improved simulation of river flow. Subsequently, the 1990s and 2000s witnessed the emergence of two-dimensional (2D) models such as Hydrologic Engineering Center- River Analysis System (HEC-RAS) and

MIKE21, which allowed a more realistic representation of floodplain processes, including flow depth, velocity, and spatial inundation extent. The integration of these models with geographic information systems (GIS) further enhanced their capability to produce accurate flood hazard maps and assess risks to populated areas.

These models are among the most useful tools for simulating unsteady flow and studying dam-failure scenarios or unexpected discharges [11, 12]. Therefore, many researchers have used these models and techniques to analyze river floods and generate flood maps to support decision-making, emergency planning, and risk analysis.

In recent years, the field has rapidly progressed toward high-resolution modeling and the integration of artificial intelligence techniques. Modern approaches combine physics-based hydrodynamic models with data-driven methods, significantly improving computational efficiency and predictive accuracy. The growing importance of these models is driven by increasing climate variability, rapid urbanization in flood-prone areas, and the urgent need for effective flood risk management and early warning systems. Their ability to simulate multiple scenarios, integrate spatial data, and support decision-making has made them indispensable tools for researchers and practitioners worldwide.

Flood hazard assessment has also evolved substantially through the integration of hydrodynamic numerical models and GIS. Recent studies, such as Mustafa et al. [13], demonstrated the effectiveness of coupling HEC-RAS 2D models with GIS datasets, including digital elevation models (DEMs), land-use data, and soil maps, to delineate flood-prone urban areas in Iraq. Similarly, hydrodynamic simulations conducted along the Euphrates River in Al-Anbar showed high predictive accuracy in estimating flow depth and velocity under various discharge scenarios [14]. Furthermore, dam-break simulations highlighted the severe flood risks associated with potential failure events, emphasizing the need for reliable flood inundation mapping [15]. Globally, the field has shifted toward integrating artificial intelligence with physics-based hydrodynamic models, as seen in recent frameworks such as FloodCast [16] and DL Hydro-FRAN [14], which significantly enhance prediction speed and accuracy.

Figure 1. Images showing the impact of floods of Al-Khalidiya city in Anbar Governorate 26/3/2026
Source: Water Resources Directorate

Based on the above review, despite these advancements, limited studies have focused on high-resolution flood mapping along the Euphrates River, particularly in populated areas, indicating a critical research gap that this study aims to address. There is a clear lack of recent studies after 2023 specifically on the Euphrates River in Anbar Governorate. In addition, few studies have linked flooding to urban exposure, and the application of high-resolution 2D models along the entire river remains limited.

2. STUDY AREA

The study area extends along the Euphrates River between Haditha Dam and the city of Hit in Al-Anbar Province, western Iraq (Figure 2). This river reach represents a hydrological and geomorphological significant segment characterized by diverse terrain, including low sedimentary plateaus and alluvial floodplains. The river exhibits noticeable meandering patterns that directly influence flow behavior and velocity distribution. The longitudinal slope of the river in this reach is relatively mild, resulting in reduced flow velocities in certain sections and enhanced sediment deposition, while relatively higher velocities occur in narrow or sharply curved segments.

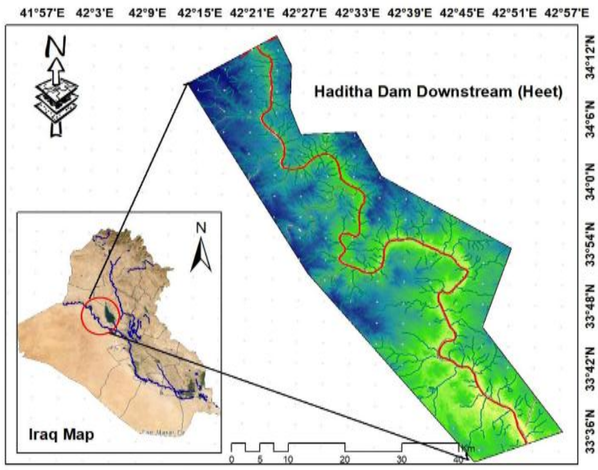

Figure 2. Location of study area

Haditha Dam is the largest hydraulic structure on the Euphrates River within Iraq and plays a critical role in regulating river discharge and controlling water levels. In addition, it serves as a major source of hydroelectric power generation [4]. The dam significantly contributes to sustaining life and economic activities in the region by ensuring water availability for domestic and agricultural uses, as well as mitigating flood risks within its operational limits.

Nevertheless, downstream areas, particularly between Haditha and Hit, remain vulnerable to flooding, especially during extreme hydrological events. These risks have intensified in recent years due to the impacts of climate change, which have increased the frequency and severity of extreme weather events. Floods in this region pose serious threats, potentially leading to substantial human losses, mass displacement, public health issues, and damage to critical infrastructure.

The Euphrates basin in Iraq is classified as an arid to semi-arid region and is highly sensitive to climate variability and change. According to available meteorological data, the average annual rainfall in the Upper Euphrates region ranges between 115 and 120 mm. The maximum recorded annual rainfall was 263 mm in 1988, which coincided with river discharges exceeding 3000 m^3/s in some sections. In contrast, the minimum annual rainfall recorded was 46.1 mm in 1962. Annual evaporation rates exceed 3000 mm, reflecting the region's arid climatic conditions.

Regarding water levels, the highest recorded stage of the Euphrates River in Hit reached 59.86 m in December 1988, while the lowest recorded level was 43.14 m in October 2010 [17]. These significant variations in discharge and water levels highlight the sensitivity of the river system to climatic and hydrological fluctuations, emphasizing the need for advanced water resources management strategies and effective flood risk mitigation measures.

3. METHODOLOGY

In this research, the research methodology used is integrated research methodology which incorporates descriptive, analytical and quantitative research methodologies to evaluate and determine the risks of the flood along Euphrates River in the study area which is between Haditha Dam and Heet City. Such a process requires accurate data gathering, analysis, and interpretation of digital and descriptive data to manage flood risks. The Input data to the HEC-RAS model includes the longitudinal river section (geometric data), which is drawn with (Ras Mapper) option and based on DEM as a precise topographical foundation. Then the coordinates of the river cross sections projected on the longitudinal river section along the river. After completing the geometric data, the boundary conditions were entered, where the discharges were entered in U/S and the normal depth in D/S based on observed data. After that, the model calibration begins. The flood wave propagation will be analyzed with the help of HEC-RAS 2D (version 6.6 or higher), which will calculate inundation areas and create flood hydrographs to find out the water surface elevation, depth, and velocity of the flood-affected areas. The obtained results will be then combined with Geographic Information Systems (ArcGIS) (version 10.5 or more) with the help of such tools as Geo-RAS to create in-depth flood maps and identify and classify high-risk zones and create a spatial reference database to help manage flood risks and sustainable planning in the area. Figure 3 shows the approach of the current research.

The geometric input data were prepared using a DEM with a spatial resolution of 12.5 m within a GIS environment. Longitudinal and cross-sectional profiles were extracted using Hydrologic Engineering Center- Geographic River Analysis System (HEC-GeoRAS). Boundary conditions were obtained from the operational records of Haditha Dam and the gauging station in Hit. Manning's roughness coefficients were adopted from previous studies and further refined through calibration using observed data from the Water Resources Directorate in Al-Anbar. This approach ensures accurate flow representation and reliable flood mapping results and Table 1 shows input data for HEC-RAS 2D model for flood mapping.

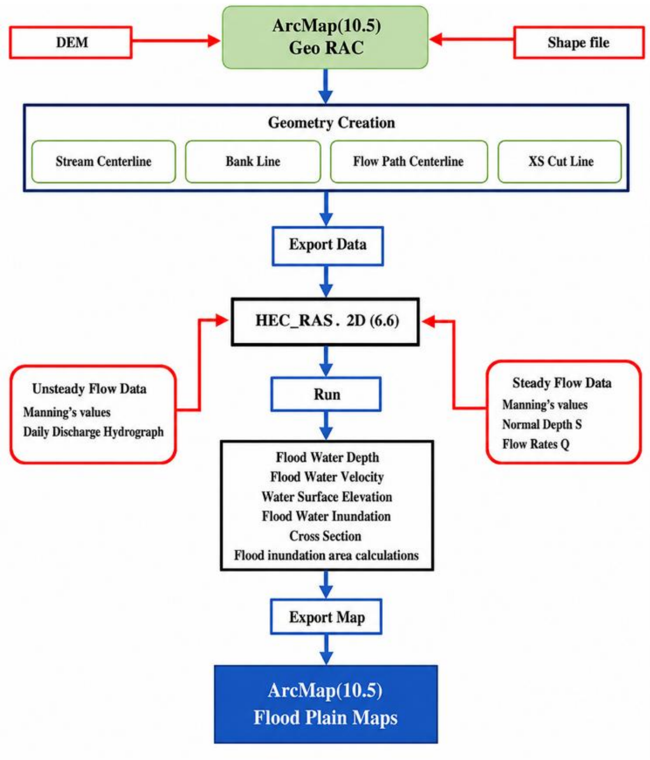

Figure 3. Methodology of the present study

Table 1. Input data for HEC-RAS 2D model for flood mapping

No.	Category	Input Type	Source	Extraction & Processing	Accuracy (Units)	Purpose
1	Geometry	DEM	USGS	GIS preprocessing & projection	12.5 m	Mesh generation
2	Geometry	Longitudinal Profile	DEM	Derived using HEC-GeoRAS	m	Hydraulic slope
3	Geometry	Cross Sections	DEM	Extracted via HEC-GeoRAS & GIS tools	m	Floodplain modeling
4	Boundary Conditions	Discharge hydrograph	Haditha Dam	HEC-RAS / Time series processing & formatting	m³/s	Upstream BC
5	Boundary Conditions	Stage hydrograph	Heet St.	Data filtering & temporal processing	m	Downstream BC
6	Model Parameters	Manning n	literatures	Literature-based + calibration	—	Flow resistance
7	Calibration	Observed Data	Water resource Agency	Model calibration & validation	m, m³/s	Model calibration

Note: Hydrologic Engineering Center- River Analysis System (HEC-RAS); Hydrologic Engineering Center- Geographic River Analysis System (HEC-GeoRAS); Geographic Information Systems (GIS); digital elevation model (DEM)

The course of the Wadi Hawran is narrowed by the river's longitudinal cross-section, while its discharges are considered as lateral flow in boundary conditions. Data provided by the Iraqi Ministry of Water Resources regarding the Wadi Hawran's discharges were used.

Calibration:

It is the process for adjusting input parameters to minimize the difference between model simulations and observed data, ensuring the model accurately represents a real-world system. It involves comparing numerical results against observed data, often focusing on parameter refinement to improve predictive accuracy, in present study the calibration is achieved for determination of Manning coefficient for the Euphrates River in studied area.

Several previous studies indicate that the Manning roughness index in rivers, such as the Euphrates, ranges between [values to be inserted here]. Based on available observational data obtained from the Anbar Governorate Water Resources Directorate, the official government body responsible for managing the Euphrates River, these values were tested for their consistency with the observed data in a section of the river downstream from the city of Hit. Table 2 shows the results of the calibration process, indicating that the roughness index value closest to the observed data is (0.032).

Validation:

It is the process of evaluation the model's predictive capabilities against independent data, proving the calibrated model holds true in a new scenario. In numerical modeling used in hydraulic and water resources engineering, validation is among the most important stages of model evaluation before using it for forecasting or decision support. In present study based on the available data, validation or verifying the accuracy of the numerical model (HEC-RAS) is achieved by comparing the model's results with actual or observed data. Statistical indicators are used to measure model accuracy using Nash-Sutcliffe Efficiency (NSE) formula or (Eq. (1)) and Table 3 represent the Nash-Sutcliffe Efficiency Rating.

$$NSE = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \ddot{Q}_{obs})^2} \quad (1)$$

where, Q_{obs} = observed value of (discharge or water level), Q_{sim} = simulated value of (discharge or water level), $\ddot{Q}_{obs}$ = average observed value of (discharge or water level).

The equation is applied to measure accuracy for determination both discharges (Q) and water level (H) (see Table 4). The accuracy or Efficiency for discharge is (0.99), and for water level (0.83). These results indicate a high degree of accuracy in representing the numerical model of both the discharge and the water level.

Table 2. Results of calibration

H (obs)	H (N = 0.28)	ER.	H (N = 0.03)	ER.	H (N = 0.032)	ER.
46.5	46.34	0.16	46.4	0.1	46.52	-0.02
46.68	46.39	0.29	46.5	0.18	46.68	0
46.72	46.42	0.3	46.59	0.13	46.72	0
46.78	46.48	0.3	46.61	0.17	46.77	0.01
46.85	46.57	0.28	46.7	0.15	46.85	0
46.9	46.6	0.3	46.72	0.18	46.89	0.01

Table 3. Nash-Sutcliffe efficiency

Value	Rank
0.75 – 1	Excellent
0.65-0.75	Good
0.5-0.65	Acceptable
< 0.5	Poor

Table 4. Observed and simulated values of Q and H

Q (obs.)	Q (Sim.)	H (obs.)	H (Sim.)
506	501	51.33	51.94
1366	1366	52.7	52.84
1555	1549	52.6	52.92
1755	1726	53.6	53.11
2015	2013	53.1	53.30
2565	2560	53.8	53.71
2691	2685	53.8	53.80

4. RESULT AND DISCUSSION

The research made use of the digital map as the main source of data. DEM is important in the derivation of stream network delineation, identification of sub basin and determination of the surface slope of watersheds. It is used as the basis to build the stream modeling. The Shuttle Radar Topography Mission (SRTM) (NASA Spatial Data) provided the DEMs of the watershed model. This Research was done with a spatial resolution of 1 arc-second, which equates to a 15m x 15m grid in the ESRI (.tif) format with a geographical projection of WGS84 datum.). Extracted and delineated DEM of watershed area in this study is presented in Figure 4.

The characteristics of Euphrates River basin Al-Anbar Province indicate too highly hydrologically complex. This intricacy is due to a combination of operational releases of Haditha Dam with lateral inflows of large downstream wadis (seasonal streams), such as Wadi Horan, Wadi Zaghdan and Wadi Hijlan. These are exacerbated by climate change effects that have raised the frequency and intensity of extreme hydrological events, especially the alternation of long droughts with brief, high intensity rainfall events.

Return period analysis (5, 50 and 100 years) shows that peak discharges can reach critical levels in case of simultaneous occurrence of various factors (Table 5).

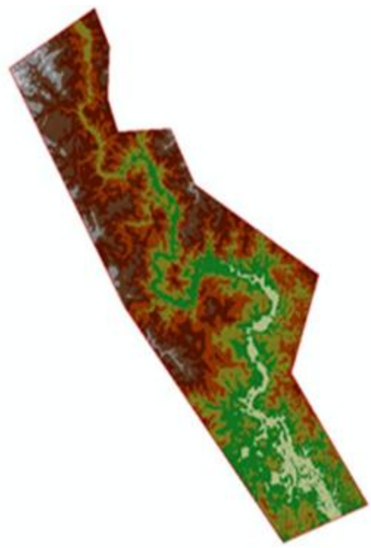

Figure 4. Digital elevation model (DEM) in a triangulated irregular network (TIN) format (Dem.tin) in (Geo-RAS)

Table 5. Discharge for return periods in study area

Return Periods (Year)	Discharge (m^3/s)
5	1055
50	2090
100	3048

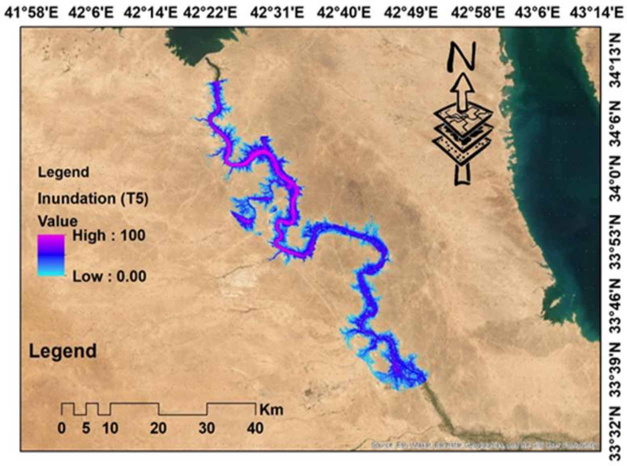

Figure 5. Flood inundation maps for steady flow (5-year return period)

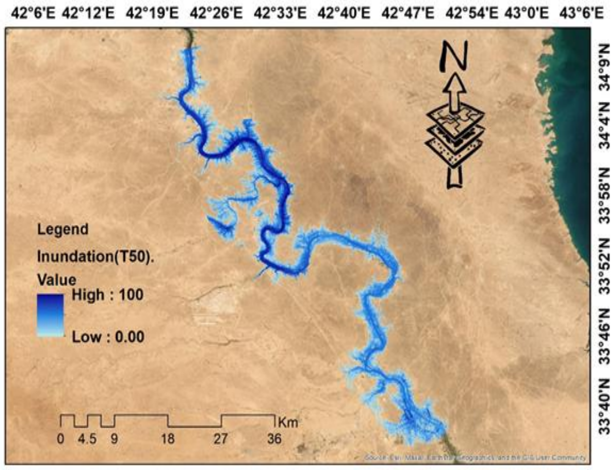

Figure 6. Flood inundation maps for steady flow (50-year return period)

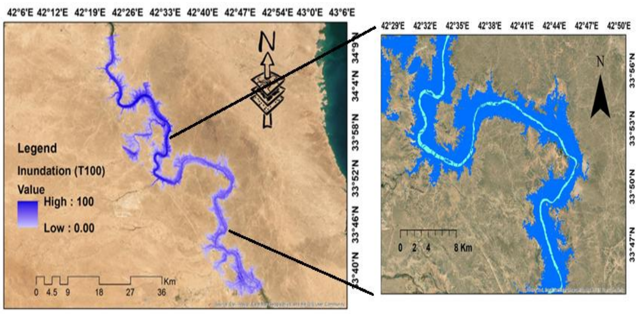

Figure 7. Flood inundation maps for steady flow (100-year return period)

The most notable of these are higher releases of dams to safely convey upstream floods, in conjunction with large flash floods of lateral wadis, which can add up to about 1500 m^3/s. This type of synchronization may cause abrupt rises in the river discharge, which may be greater than the hydraulic capacity of the river channel in particular reaches.

In addition, ephemeral wadis pose a significant source of uncertainty in hydrological measurements because of their extensive catchment areas and speedy reaction to rainfall occurrences. To give an example, Wadi Horan has a drainage area of over 13,000 km^2 which makes it extremely difficult to estimate discharge volumes and timing, particularly in the cases where there is inadequate monitoring data.

Flood inundation maps created by steady flow simulations in HEC-GeoRAS as indicated in Figures 5–7 indicate that large areas are susceptible to floods in conditions of increased return period (Table 2). These areas include critical infrastructure such as water supply systems, bridges, irrigation projects, as well as nearby settlements. This underscores the need to incorporate such modeling approaches in land-use planning and hydraulic infrastructure design.

The results show a significant increase in inundation extent area with increasing return periods (5, 50, and 100 years). The variation in flood discharges value with return periods can be caused by climate change impacts, which have led to:

- Increased frequency of extreme hydrological events
- Greater variability between wet and dry periods
- Higher probability of extreme discharges

This shift implies that extreme flood events (e.g., 100-year floods) may occur more frequently than historically estimated, leading to more inundation areas.

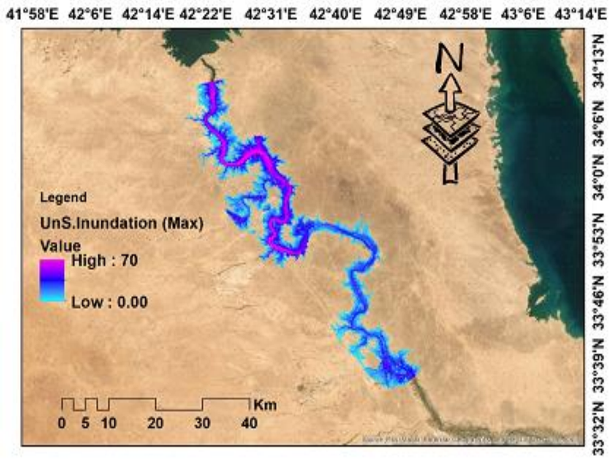

Figure 8. Unsteady flood maps (Max. daily discharge)

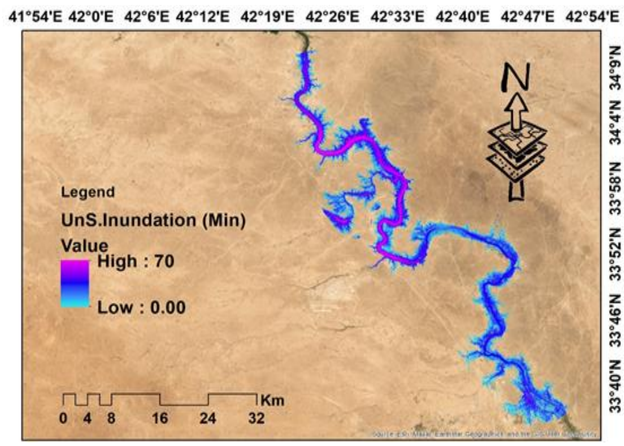

Figure 9. Unsteady flood maps (Min. daily discharge)

Hydraulically, this reflects the nonlinear relationship between discharge and water surface elevation, particularly in low-gradient systems like Euphrates River basin. In these systems any increases in discharge can result in substantial rises in water levels. The geomorphological characteristics of the Euphrates—low longitudinal slope and relatively wide cross-sections—enhance the likelihood of overbank flow once the channel capacity is exceeded. The case of steady flow conditions assumes constant discharge over time and provides simplified hydraulic conditions. But, produces less dynamic flood maps and may underestimate peak flood extent. Conversely, unsteady flow modeling (Figures 8 and 9), offers more information on the dynamics of the flood waves, especially the propagation of the wave along the river. Such outputs are fundamental to the creation of effective early warning systems and emergency evacuation plans, which will allow them to be better prepared and reduce risks. In the unstable flow conditions, flow was simulated and flood mapped using the maximum and minimum daily flow of the Euphrates River flood in 1988, which represents a 100-year return period. Table 6 shows the inundation area for two cases (steady and unsteady) with different return periods that explain the above discussion.

Table 6. Inundation area (donum) for study area

Flow Conditions	Return Periods (Year)	Inundation Area (Donum)
Steady	5	150823
Steady	50	156782
Steady	100	161290
Unsteady	100 (Max. Daily flow)	186124
Unsteady	100 (Min. Daily flow)	131400

From a hydraulic point of view, unsteady flow simulation is more reliable for floodplain analysis, especially in rivers with significant temporal variability such as the Euphrates. Flood maps for the studied area reveal that urban areas located within or near the floodplain are highly vulnerable. This is mainly due to:

- Low ground elevations
- Proximity to the main channel
- Insufficient flood protection infrastructure

As return periods increase, flooding extends beyond the main channel of the Euphrates River into developed areas, indicating river capacity exceedance.

The integration of HEC-RAS with alongside utilizing a DEM as an accurate topographic base. This kind of data is essential in achieving credible analytical results consistent with the research focus on arid regions with Geographic Information Systems (ArcGIS) with tools such as Geo-RAS to produce detailed flood maps that can be used to identify and categorize high-risk areas and create a spatial reference database to support flood risk management and sustainable planning in the region imagery proved to be a strong framework of flood mapping in the Euphrates River.t. Flood hazard maps have demarcated areas and agricultural lands in the region between Haditha and Hit as High-Risk areas. These areas might not have the current river capacity to accommodate extreme floods (100-year return period) as a result of sedimentation and riparian encroachment.

5. CONCLUSIONS

The results demonstrate a nonlinear increase in inundation extent with return period. Specifically, inundated areas expand as the return periods increase from 5 to 50 and 100 years, indicating the high sensitivity of the Euphrates floodplain to extreme discharge events. The limited channel conveyance capacity of the Euphrates River further contributes to this pattern, as the main channel is insufficient to convey high-return-period discharges, resulting in overbank flooding and expansion into adjacent urban areas.

The study also confirms the superiority of unsteady flow modeling, which provides a more realistic representation of flood dynamics, including water depth, velocity, and peak arrival time, compared with the steady flow model. In addition, the findings highlight the significant impact of climate change, suggesting that intensified hydrological extremes have increased the likelihood and severity of flood events.

Urban areas show high vulnerability, as a considerable portion of the urban land located within the floodplain is highly susceptible to inundation, particularly under high-return-period scenarios. The influence of topography and river morphology is also evident, with the low longitudinal slope and wide cross-sections contributing significantly to lateral flood expansion and larger inundation areas.

Furthermore, the discharge–inundation relationship is strongly nonlinear, meaning that higher discharges cause disproportionately larger flooded areas. The integrated hydraulic–GIS approach proved effective in generating accurate flood hazard maps and identifying high-risk zones. Finally, the study emphasizes the need for periodic flood hazard updates to ensure that flood maps reflect changing climatic conditions and land-use dynamics.

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