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Application of Numerical Models for Flood Risk in Arid Regions

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ABSTRACT

In recent decades, arid and semi-arid regions have witnessed a marked increase in the intensity and frequency of extreme hydrological events due to climate change, leading to unpredictable floods and flash floods with catastrophic consequences. This paper aims to analyze flood risks in rivers within these environments, focusing on the Euphrates River in Anbar Governorate, Iraq, as a case study to determine the optimal numerical model for studying this river, which is characterized by limited data and a lack of sufficient gauging stations. The research included an analysis of discharge and water level data in the river, a review and evaluation of software and models used in flood risk analysis, with a particular focus on the HEC-RAS software through comparison with other numerical and physical models. A systematic review of fifty published scientific studies was also conducted, along with an analysis of trends in the use of numerical and physical models, and the integration of numerical models with geographic information systems (GIS) and remote sensing. The results showed that integrating numerical models such as HEC-RAS with GIS and remote sensing techniques is an effective tool to compensate for the lack of data in arid and semi-arid regions, particularly in the Euphrates Basin in Iraq, and provides a solid scientific basis to support decision-making in flood risk management.

1. INTRODUCTION

Floods are among the most dangerous natural disasters, threatening lives, infrastructure, and economic activities. Their severity is amplified in arid and semi-arid regions due to the irregular nature of rainfall, weak hydrological monitoring networks, and heavy reliance on dams and water infrastructure. Climate change has exacerbated this problem by increasing the extreme nature of hydrological events, such as short-term, intense rainfall that generates flash floods and unpredictable floods. Iraq is classified among arid and semi-arid regions, areas particularly vulnerable to climate change. United Nations reports indicate that Iraq is among the five countries most affected by these changes [1, 2]. Climate change has also caused extreme shifts in hydrological events, where drought periods can persist for three to four years, followed by a wet year that results in extremely high flash floods [3, 4]. An example of this occurred in season (2018-2019) when the Tigris and Euphrates River levels rose to unprecedented heights, which could have resulted in widespread flooding [5]. At least seven people were killed, and thousands were forced to flee their homes due to floods that hit areas surrounding the city of Sharqat, located north of the Iraqi capital, Baghdad (Figure 1).

In recent years, the world has witnessed catastrophic flood-related incidents, most notably the collapse of the Derna Dam in Libya, which resulted in significant human and material losses [6]. Due to heavy rainfall, two dams failed in the Libyan city of Derna on September 10, 2023. As a result, a substantial portion of the town was destroyed by floods and debris. Over six thousand people lost their lives, and thousands more were forced to leave the city [7]. Flooding can occur due to several factors, chief among them being heavy rainfall, often exceeding anticipated rates and the carrying capacity of the river channel [8]. These events highlight the importance of developing precise scientific tools for flood risk analysis, especially in environments characterized by data scarcity and hydrological uncertainty [9]. This provides the impetus for studying flood scenarios resulting from dam failures or unexpected events and their impact on downstream cities. It underscores the necessity of analyzing flood scenarios through flood maps to identify the most affected and inundation-prone areas. This allows for the development of essential plans to mitigate flood risks, protect lives and property, and raise public awareness to ensure safety. Climate change has altered rainfall patterns and increased the frequency and intensity of rainstorms in many arid and semi-arid regions. As a result, flooding has become more common, despite declining annual rainfall in some of these areas. Arid basins such as the Basin of the Euphrates River in Iraq are characterized by rapid hydrological response due to sparse vegetation cover and low soil absorption capacity, leading to high surface runoff over short periods. These characteristics make it difficult to rely on traditional flood forecasting methods and necessitate the use of advanced numerical models capable of representing these complex dynamics. In this context, numerical models emerge as a practical and effective solution for studying river behavior and assessing flood risks, particularly when integrated with geographic information systems (GIS) and remote sensing technologies.

Figure 1. Flood in the city of Sharqat, Iraq (2018-2019)

2. DESCRIPTION OF THE EUPHRATES RIVER BASIN IN IRAQ

The Euphrates River enters Iraq at the city of Al-Qaim, near the Syrian border, and flows through Anbar Governorate, passing through all its cities except Rutba. The area extending from the Haditha Dam to the administrative borders of Heet is of great historical and economic importance in the Iraqi Anbar Governorate (Figure 2). Historically, it has been a vital part of Mesopotamia, hosting ancient civilizations and serving as an ancient trade route. The Haditha Dam is a modern engineering landmark. The area is also characterized by its diverse topography, where the river's gradient is relatively high, and its flow velocity is higher until it reaches the city of Ramadi, where the gradient and water velocity are much lower. Economically, the area thrives on its fertile, river-fed lands, supporting extensive agriculture, fishing, and livestock. Haditha Dam is critical for hydropower and water management, sustaining regional life and economy. However, this valuable region is highly susceptible to Euphrates floods, intensified by climate change. Flood events risk severe human casualties, mass displacement, and widespread health issues. Material losses would be catastrophic, impacting infrastructure, property, agriculture, and livestock, while disrupting essential services and economic activities. Environmental degradation and damage to irreplaceable cultural heritage are also major concerns. Therefore, flood risk modeling is essential for developing protective strategies and ensuring regional resilience.

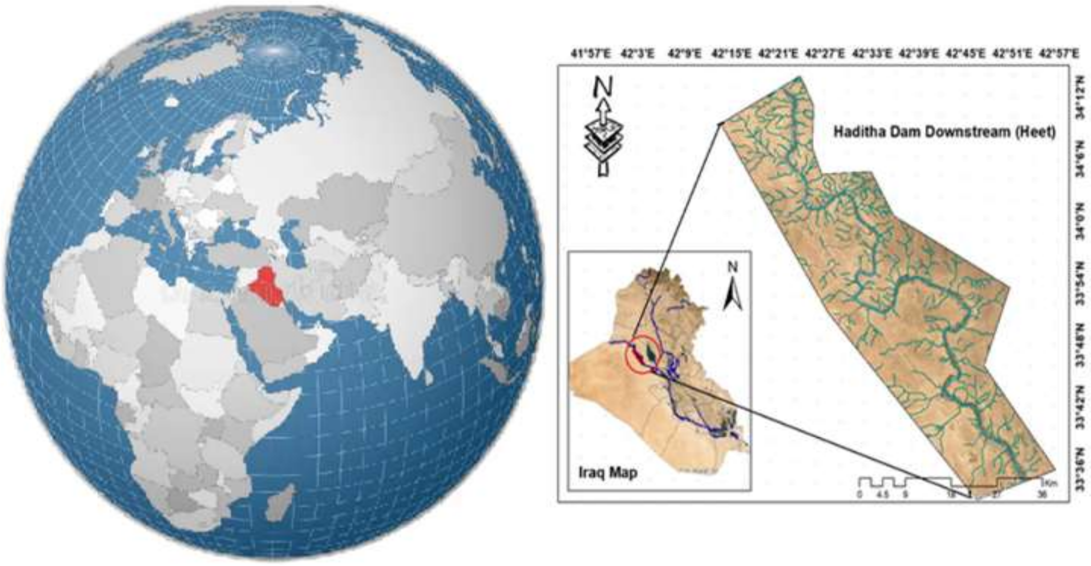

Figure 2. Location of study area

2.1 The Euphrates River in Iraq

There are no tributaries of the Euphrates River inside Iraq, but there are several valleys that flow into the river, supplying it with large quantities of water from its torrents during the rainy season. The river's flow depends on the water inflows from the river's headwaters in Turkey and its tributaries in Syria, which have been affected by climate change and the construction of dams in both countries. After the construction of the Haditha Dam in 1985, the river's flow became completely controlled by this dam. During some rainy seasons, large quantities of water are released, which may coincide with heavy floods from the Horan, Zaghdan, and Al-Mohammadi valleys into the river after Haditha Dam. This causes river levels to rise and poses a threat of flooding, especially in areas near the river. Figure 3 shows the maximum and minimum water elevation of the Euphrates River in Ramadi (capital of Anbar province) for the period (2018-2025). For the city of Ramadi, the difference between the lowest and highest water levels was recorded in 2019, reaching 3.67 m. The highest water level was recorded on October 10, 2019, and the lowest water level was recorded on May 25, 2019.

Generally, in the Ramadi region, the land is flat and the river slopes gently, resulting in a lower river speed. The highest recorded discharge in Ramadi is 2050 m^3 per second. However, the situation is different in the city of Hit (approximately 200 km downstream of the Haditha Dam), where a discharge of 5000 m^3 per second was recorded in 1989, after the Haditha Dam became operational. Following the construction and operation of the Haditha Dam in Anbar Governorate, river discharges are now largely controlled through this dam. However, in many cases, especially during rainy seasons when rainfall exceeds normal levels, river levels can rise significantly, increasing the risk of flooding. Due to climate change in the region, river levels fluctuate significantly, and the difference between the highest river levels during dry seasons can reach more than 15 m. Figure 4 shows the Euphrates River levels in the city of Heet for the period from 2007 to 2008. The highest Euphrates River level in Heet was recorded on December 8, 1988, at 59.86 m, while the lowest river level in Heet was recorded on October 17, 2010, at 43.14 m. Based on the above data, which illustrates the hydrological condition and hydraulic behavior of the Euphrates River, as well as the problem of the lack of continuous data and sufficient measuring stations to monitor the river's behavior, with the increasing extremism in hydrological incidents as a result of climate change, the probability of danger to cities located within the river basin has increased significantly. Therefore, it is very important to use numerical models and modern technologies such as GIS and remote sensing to overcome the problem of scarcity of data and measurements for the purpose of studying flood risks and developing the necessary emergency plans, especially in densely populated areas on the banks of the Euphrates River, such as the cities of Hit and Ramadi.

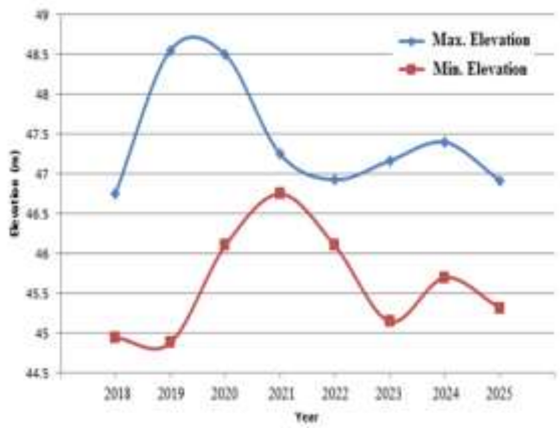

Figure 3. Maximum and minimum water elevation of the Euphrates River in Ramadi

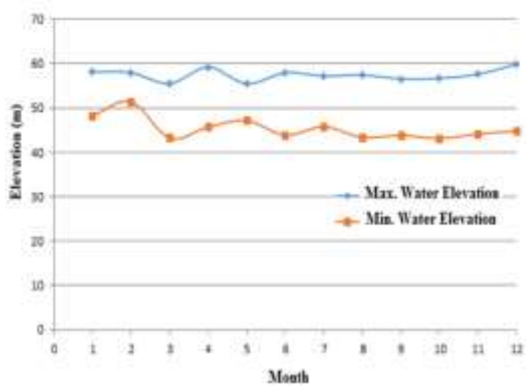

Figure 4. Maximum and minimum water elevation of the Euphrates River in Heet

3. METHODOLOGY

The present study aims to identify and select a numerical model for flood risk assessment in the Euphrates River basin in Anbar Governorate, Iraq. This region is classified as arid and clearly shows the effects of climate change. Furthermore, the area suffers from a lack of available data on its hydrology, a limited number of monitoring stations, and significant fluctuations in the Euphrates River's flow from season to season and year to year, fluctuations exacerbated by climate change. The selection and determination of the optimal numerical model in this study depend on the orientations of researchers around the world and their experience in using and applying these models in environments and regions with hydrological and geographical characteristics similar to the Euphrates River basin region in Iraq. This approach and methodology can compensate for the lack of experience in the possibility of using any of the numerical models and their applicability in arid regions, and the possibility of supporting them with modern technologies provided by GIS and remote sensing to compensate for the lack of data and reduce application costs. A survey was conducted of the most important studies and research that dealt with the subject of flood risk analysis in rivers in arid and semi-arid regions around the world to find out what the modern trends of researchers are and what is the optimal model that suits these regions, which are characterized by a lack of available data and measurement stations [10-28]. Four numerical models were identified as potentially suitable for flood risk analysis in arid regions, with a case study of the Euphrates River. These models are HEC-RAS, MIKE Flood, Flood Modeler, and Kalypso. Specific criteria were adopted to determine the optimal model, such as the cost of licensing the model, the need for data and its details, the model's application to rivers within the Euphrates River basin (Middle East), the technical and software skills required to run the model, and its compatibility with GIS and remote sensing technologies to compensate for data gaps and reduce costs [29]. The literature search encompassed prominent databases, focusing on studies that employed diverse techniques, including hydrological modeling, remote sensing, and GIS-based flood mapping, to assess the impacts of floods on cities and inform the development of robust emergency strategies [30]. A review was conducted of studies and research addressing the topic of flood risk analysis in rivers using various numerical models, models based on field measurements, and models employing Artificial Intelligence (AI). The temporal scope of the reviewed studies ranged from 2010 to 2025. This specific timeframe was chosen based on expert consensus in Iraq that the noticeable effects of climate change, particularly concerning flood or dryness events in vulnerable regions such as Iraq, began to manifest significantly from 2010 onwards. Data extraction focused on the innovative methodologies employed, key findings regarding flood risk estimation, and recommendations for improving emergency preparedness. This approach allowed for a robust synthesis of the state-of-the-art, highlighting best practices and emerging research directions in enhancing urban resilience against flooding. In addition, the current study aims to provide insight into the most effective numerical models and modern software for analyzing flood risks with the highest possible accuracy. Table 1 provides a simple comparison between the four numerical models mentioned. From this table, it can be concluded that the HEC-RAS program can be adopted for studying flood risks in the Euphrates River, as it is well-suited to the river's conditions in terms of available data, and is applicable in most countries worldwide, including arid regions. Furthermore, it is easy to use and cost-effective compared to the other models.

Table 1. Comparison among numerical models

HEC-RAS	MIKE Flood	Flood Modeler	Kalypso
Most widely used in river flood analysis worldwide, free and supported by water resources engineers.	It is very advanced, but it often requires an expensive license.	Excellent, but it requires very detailed data and models.	It can be used, but it requires more programming knowledge.
It is frequently used with GIS for mapping flood hazards.	It becomes more complicated if the main objective is to study river floods.	The level of support and integration with GIS is lower compared to HEC-RAS.	It is not very popular in studies of major rivers in the Middle East.

To determine and evaluate the applicability of the HEC-RAS numerical model, which we indicated in Table 1 as a suitable model for studying flood risk in the Euphrates River, a statistical analysis was performed on fifty studies analyzing river flood risk. By comparing the percentages of studies that rely on numerical models (such as the HEC-RAS model or other methods), it can be determined that an optimal model for studying flood risks aligns with the trends of researchers and their expertise in this field.

4. RESULTS AND DISCUSSION

A survey was conducted across major websites and platforms on the internet, as well as various scientific journals and publishing houses, for research and studies addressing the topic of flood risk analysis. A sample of 50 scientific papers covering the topic of flood risk analysis was selected. Through a review of these papers, it was found that the HEC-RAS software attracted the most attention from researchers (Table 1). Therefore, the analysis and review of these research papers, to identify and determine the most important global trends in the study of flood risk analysis, relied on the following criteria or categories:

A. Research on employing HEC-RAS in conjunction with other software.
B. Research exclusively utilizing HEC-RAS.
C. Research incorporating AI.
D. Research based on information surveying.
E. Research utilizing flood maps.
F. Research employing other software programs.

The period from 2010 to 2025 was adopted because reports from experts in Iraq indicated that the impact of climate change became clear starting from 2010. Figure 5(a) shows that during this period, most studies and research papers relied on the HEC-RAS program along with other programs such as GIS and Remote Sensing, which amounted to (26%), while studies based on field surveys amounted to (22%). The use of modern technology, represented by GIS and Remote Sensing, has increased significantly because it can reduce costs and save time significantly. For the same period above, it has been observed that the adoption of AI programs to study and analyze flood risks has increased significantly over the past five years, as shown in Figure 5(b). The use of these technologies provides engineers and researchers with a flexible means to overcome many accuracy-related issues, such as interruptions in the sequence of recorded data, especially in areas that have witnessed events that cause security instability, such as Iraq. These interruptions in recorded data can significantly impact the accuracy of the models and programs used.

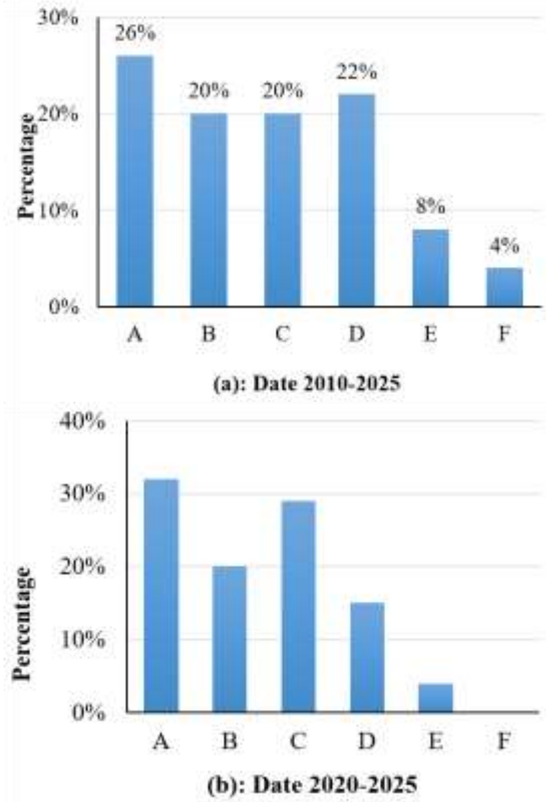

Figure 5. Categorization of reviewed studies by their publication timeframe: (a) 2010 to 2025, (b) 2020 to 2025

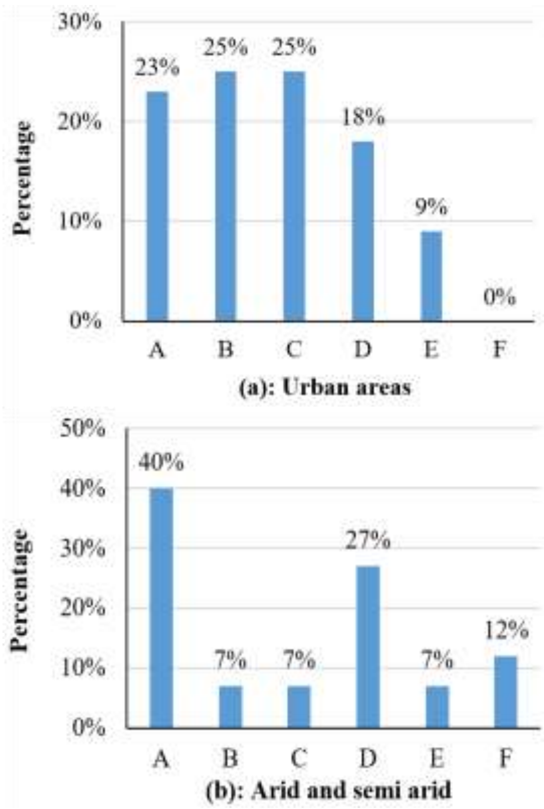

Figure 6. Research was classified by urban areas and arid regions

Figure 6 shows the percentages and research that addressed flood risk analysis in urban (humid) and arid regions, including the Euphrates Basin in Anbar Governorate, Iraq. As shown in Figure 6(a), for urban areas that utilize numerical models using AI or exclusively utilizing HEC-RAS software constitute the largest percentage (25%), while in arid regions, numerical models using HEC-RAS are the most prevalent (40%), see Figure 6(b).

5. CONCLUSIONS

A systematic survey was conducted of fifty published scientific studies that addressed flood risk analysis in rivers, focusing on arid and semi-arid environments. The review revealed that:

- A significant proportion of studies relied on numerical models.
- A smaller number used only physical models.
- An increasing proportion of studies integrated numerical models with GIS and remote sensing techniques.
- These findings indicate a clear shift in research direction towards the use of integrated numerical models as a primary tool in flood risk analysis.

Furthermore, HEC-RAS is one of the most widely used numerical models for river flood analysis globally. It offers both one-dimensional and two-dimensional modeling capabilities, supports unsteady flow analysis, and represents the impact of dams and hydraulic structures. Compared to other programs such as MIKE Flood and Flood Modeler, HEC-RAS stands out for its ease of use, widespread availability, free access, and ease of integration with GIS. These characteristics make it an ideal choice for applied studies in developing countries and data-limited regions.

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