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Flood Inundation Modelling and Reduction by Dike Construction in Urban Areas: A Case Study in Erbil, Iraqi Kurdistan

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Abstract

In recent years, Erbil has faced an elevated risk of floods due to climate change and incorrect land development design and management. To tackle this issue, this study uses Hydrologic Engineering Center River Analysis System (HEC-RAS) software to address flood inundation and reduction by constructing dikes. This involved using a digital elevation model (DEM) in the study area (Mass Village) east of Erbil. The study delineated the catchment area and employed watershed modelling system (WMS) software. Furthermore, Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software was used to create a flood hydrograph, which the HEC-RAS software used to estimate flood inundation areas, velocity, and water levels. The study identified water surface areas and velocities prone to flooding in the urbanised area, with water depths ranging from 0 to 5 m. The model was rerun after the construction of the dikes, resulting in water depths ranging from 0 to 7.2 m upstream of the dikes. The modelling results indicated a water depth of 0 m downstream of the dike (protected area), demonstrating that the dike's construction successfully reduced flooding in the urbanised area.

1. Introduction

Floods are among the most frequent, dangerous, and costly natural disasters, causing extensive damage to infrastructure and impacting the lives of humans each year. The ongoing trend of urbanisation will have significant implications for sustainability and human well-being. By 2030, nearly five billion people, or 60% of the global population, will reside in cities, substantially increasing from 2.9 billion people (47%). These urban areas' location and growth rate will play a critical role in determining the extent to which people and infrastructure are vulnerable to natural hazards [1]. Population growth and urbanisation have exacerbated the flooding problem, leading to more impermeable areas and runoff. In recent years, the frequency and intensity of flood events in Erbil have increased due to climate change, unsuccessful land development planning, and urbanisation, causing significant damage and losses to local communities [2].

The flooding that occurred in Erbil in 2021 has become an indicator of danger, as an unprecedented flood led to numerous fatalities, affected thousands of individuals, and resulted in significant economic losses [3, 4]. Flood modelling is an essential tool for predicting the behaviour of floods and the potential extent of inundation areas to develop flood risk management strategies. Dike construction is one strategy for reducing flood damages and losses. A dike is a hydraulic structure primarily designed to transport flood stormwater from catchments to an outfall location and protect urbanised areas. The HEC-RAS model provides an environment for experts to model floods and dike construction for flood reduction in urbanised areas. Numerous studies have investigated the effectiveness of dike construction in reducing flood propagation using HEC-RAS.

A study done in Jeddah, KSA, focused on modelling flood inundation in urban areas, where features like roads, buildings, and fences significantly influence flood inundation. The study employed hydraulic simulations using the WMS and HEC-RAS programs with 90 m and 10 m DEM resolutions. The findings indicate that using a higher resolution DEM in modelling will reduce the extent of the flooded area and increase flood depth [5]. Another study used HEC-RAS to simulate the effectiveness of dike construction in reducing flood propagation in the Karun River Basin in Iran. The flow model was simulated in the field, water levels were calculated, and flood propagation zones were determined. Then, the mathematical model was run based on the construction of a dike for flood control in the study area. The study found that dike construction effectively reduced flood propagation and the damage and losses caused by floods. Additionally, the study found that the effectiveness of dike construction depended on the design, height, and location of the dike [6].

Also, Cox completed a Master of Science thesis at the University of North Dakota, entitled "Determining Maximum Scour Depth for Spur Dikes Using a Validated Two-Dimensional HEC-RAS Model." Spur dikes are widely used globally as river training structures to improve navigation and enhance flood control. Determining the maximum scour depth is crucial for designing hydraulic structures, as inadequate scour design can lead to failure. Designing these structures without physical models can speed up the process, making it timelier and more cost-effective. This research demonstrates that modelling using HEC-RAS 2D can accurately determine the maximum scour depth and flow velocity. When used with HEC-RAS 2D outputs, it reduces the average error in determining maximum scour depth from 14% to 1%, enhancing design accuracy and efficiency [7].

Also, a study conducted in Saudi Arabia analysed dam breaks and simulated floods. The study focused on a case study of the Um Al-Khair dam in Jeddah. The analysis used data from a 2011 rainfall storm, corresponding to a 50-to-100-year return period. The study used the flood hydrograph to model flood inundation, employing HEC-RAS-2D software to draw flood inundation at different simulation times. The results show a reasonably good correlation between observed and modelled water depths [8]. A recent study evaluated the risks associated with dike breaks and their consequences. This study proposed a model for analysing and managing dike-break-induced floods in the Zhuhu detention basin in China's Poyang Lake district as a case study, using a MIKE21-based numerical model. The model estimates flood risks regarding area, human life, economic and environmental losses. The modelling results provide data on inundation areas, water depth, flow velocity distributions, and flood arrival times and peaks. They found that the dike protected most river areas, conforming to flood design standards. Based on these results, the basin is divided into varying severity flood disaster zones, optimising resource allocation and formulating customised evacuation and relocation plans [9].

Another study on the Bengawan Solo River on Java Island, Indonesia, investigated reducing flood risk using HEC-RAS software. According to the study, a 10-year return period flood with a discharge of 3,784.7 m^3/s in the existing conditions caused flooding in 42 villages. The classification of risk levels was low flood risk, medium flood risk, and high flood risk. The hazard index from the discharge of the Bengawan Solo River mainly influences the flood risk in Sragen Regency. To mitigate this, a flood risk reduction analysis used a structural approach by simulating the construction of dikes around the Bengawan Solo River. Dike heights of 2, 4, and 6 m were tested for their effectiveness in preventing flood inundation [10].

Also, a study conducted on river flood risk in Europe assessed the effectiveness of four primary adaptation strategies in reducing flood risk across the continent, relying on flood risk modelling and cost-benefit analysis. The study revealed that the most economically attractive option is reducing flood peaks using detention areas. The risk reduction potential of strengthening dikes is somewhat lower, while implementing building-based floodproofing and relocation measures, although less cost-effective, can effectively minimise impacts in localised areas [11]. A study conducted in Brandenburg, Germany on flood-mitigation dike construction modelling using the HEC-RAS model examined various parameters in flood modelling simulations.

1. Grid size and cross-sectional distance: The interpolated distances between cross-sections did not significantly affect flood patterns.
2. Roughness coefficient: Higher coefficients increased flooding, emphasising the role of vegetation in flood prevention.
3. Renaturation project in Brandenburg: Comprehensive measures like vegetation changes, dredging, and dikes greatly reduced flooding. The study emphasised the importance of striking a balance between flood prevention and preserving the natural conditions of the river. Consequently, implementing measures such as vegetation changes (Manning's n), dredging, and dikes effectively reduced flood inundation [12].

Also, a study conducted on the flood in Erbil, Iraq, investigated the catchment area of floods in the city. The study found that the reasons for flooding are climate change, the filling of natural water streams, the removal of existing protective earthen dikes, and the refilling of artificial drainage channels initially built to control the flow of rainwater toward Erbil. Therefore, the city requires flood-mitigation measures like dikes and open channels [13].

The gap in the literature is that most residential areas in Erbil are designed without a hydrological study, resulting in exposure to floods and subsequently experiencing human and material losses. This study aims to enhance the effectiveness of modelling flood-mitigation infrastructure by improving analysis methodologies. Five hydrological studies will achieve this: meteorological, morphological, flood hydrograph extraction, hydraulic modelling, and flood-mitigation analysis. The study will also integrate cutting-edge tools and technologies, such as the HEC-RAS software for dike construction. The case study for this research is Mass Village, where modelling by HEC-RAS will be used to design effective dikes that meet engineering standards.

The objective is to evaluate the effectiveness of dike construction modelling as a hydraulic structure in reducing flood inundation and its associated impacts on Mass Village.

2. Materials and Methods

The proposed method consists of the following steps:

1. Data collection for the study area and digital elevation model (DEM).
2. Data collection for rainfall, intensity-duration-frequency curve.
3. Morphological and soil analysis using WMS software for constructing geometric data including the streamline, catchment boundary and area, and classification of soil groups using Harmonized World Soil Database (HWSD) viewer, land use, and land cover for finding the curve number (CN).
4. The application of hydrological modelling by HEC-HMS includes hydrograph and peak discharge information.
5. Hydraulic modelling is used to conduct floodplain delineation to obtain the flood inundation area, involving flood depth and extent.

2.1. Description of the Study Area

Erbil governorate is located in northern Iraq, in a flat plain area, with hilly terrain in the north and east of Erbil and elevations ranging from 400 to 1000 m above sea level [13]. Its population is estimated at more than 1.75 million [14]. Urban expansion has caused an increase in Erbil's ratio of land covered with concrete and asphalt. Erbil is frequently exposed to flash floods. Figure 1 shows the catchment area, with the urbanised area situated at its outlet. As shown in Figure 1, the catchment area that feeds the main streamline and causes flooding is about 6.83 km^2, and the slope of the main streamline is about 3%. The elevation range is from 500 to 680 m above sea level. The total length is about 5.5 km.

The catchment area, depicted in Figure 3, exhibits a mix of hilly and flat topography. The main valley has a predominantly east-west orientation. Various small valleys dispersed throughout the study area converge towards the central main valley.

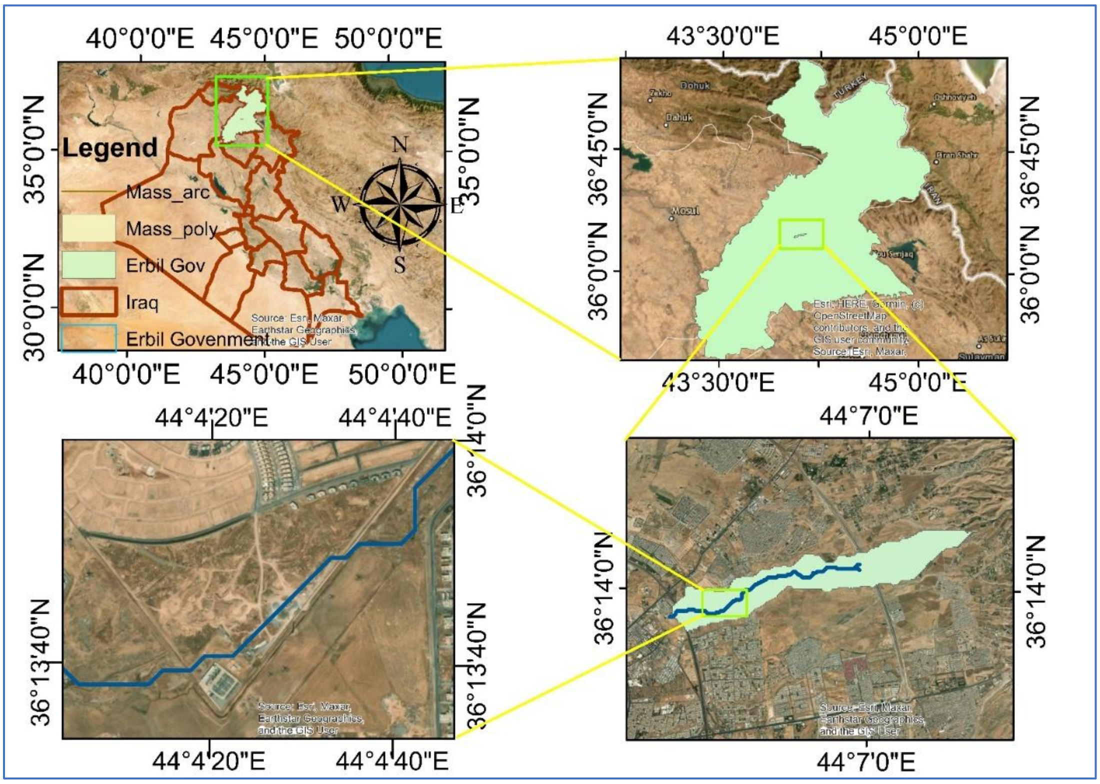

Figure 1. Location of the study area (Mass City)

2.2. Rainfall Data Collection

The maximum daily rainfall depth at the Erbil station, as indicated in Table 1, came from the Ministry of Transport and Communications [15].

Table 1. Data representing the maximum daily rainfall recorded at the Erbil station

Ear	Max Daily Rainfall mm	Year	Max Daily Rainfall mm	Year	Max Daily Rainfall mm	Year	Max Daily Rainfall mm
1980	57.6	1991	62.4	2002	32.3	2013	71.8
1981	40.9	1992	15.7	2003	59.2	2014	51
1982	38.1	1993	79	2004	41.4	2015	37.6
1983	32.9	1994	41.7	2005	34	2016	55.8
1984	42.7	1995	75.7	2006	103.9	2017	36.4
1985	72.7	1996	22.3	2007	38	2018	51.1
1986	73.6	1997	35.8	2008	37.8	2019	59.5
1987	31.8	1998	36.8	2009	41	2020	36.8
1988	37.2	1999	25.8	2010	33.8	2021	16
1989	48.4	2000	46.4	2011	67		
1990	35.8	2001	48.3	2012	21		

Table 1 contains the maximum daily rainfall for each year through 41 years of historical data for the study area. Figure 2 shows the intensity-duration-frequency (IDF) curve of the Erbil station by A. H. Dawood and D. K. Mawlood [16].

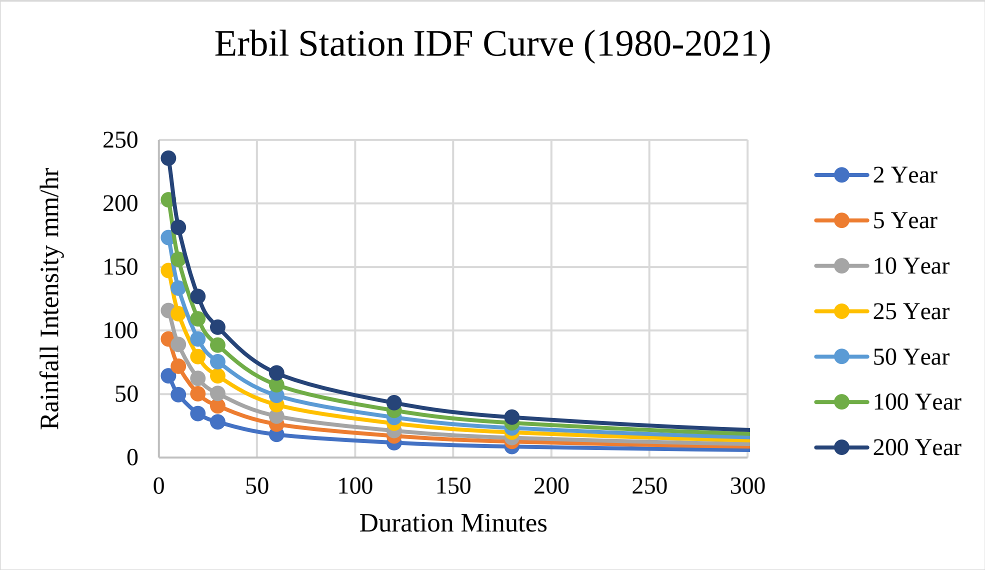

Figure 2. IDF curves for Erbil station [16]

2.3. Morphological and Soil Analysis

The HWSD was used for the required soil properties data in the study area to carry out the current study, as shown in Table 2 [17].

Table 2. Study area soil class properties from the HWSD [17]

Properties	Dominant	Associate
Percentage of sand fraction in the topsoil.	40	16
Percentage of silt fraction in the topsoil.	37	29
Percentage of clay fraction in the topsoil.	23	55
Classification of topsoil texture according to the USDA system	loam	clay (light)
Reference bulk density of topsoil (kg/dm^3)	1.39	1.21
bulk density of topsoil (kg/dm^3)	1.31	1.65
organic carbon content in topsoil (% weight)	0.56	0.75
Percentage of silt fraction in the subsoil	36	28
Percentage of clay fraction in the subsoil	27	57
Classification of subsoil texture according to the USDA system	clay loam	clay (light)

Table 2 includes various soil properties relevant to flood inundation modelling and dike construction in the study area. These properties play a crucial role in determining how water interacts with the soil, its ability to infiltrate or run off, and the potential for soil erosion or saturation during heavy rainfall events.

The IDF curve in Figure 2 is a fundamental tool used in hydrology and water resources engineering to understand the relationships among rainfall intensity, duration, and frequency of rainfall storms. The results of the IDF curve provide valuable insights into the rainfall characteristics of the study area. The IDF curve typically presents rainfall intensity (I) as a function of rainfall duration (D) for different return periods or frequencies (F). Each curve on the IDF plot represents a specific return period, such as two-year, five-year, ten-year, 25-year, 100-year, and 200-year storms. Then, the topographic survey for the study area used a DEM with a resolution of 30×30 m, which is free and suitable for flood modelling. Most flood modelling research uses this resolution [5], [18] and watershed modelling system (WMS) software to draw the boundaries of catchment areas and natural streamlines. To determine lag time based on the physical characteristics of a specific watershed, the equation from the National Resources Conservation Service, presented in Equation 1, is commonly employed [19].

$$Lag\ Time = \left(\frac{L^{0.8} (\frac{1000}{CN-9})^{0.7}}{1900 * Y^{0.5}} \right) \dots \dots \qquad \dots \dots \dots (1)$$

where: L represents the hydraulic length measured in metres, Y represents the average slope of the catchment in percentage, and CN represents the curve number.

The runoff calculations used the CN-SCS model HEC-HMS to draw the flood hydrograph, and those for flood modelling used the HEC-RAS model to simulate the flood propagation area, velocity, and depth. The calculations for flood modelling with dike construction used the HEC-RAS model.

2.4. Hydrological Modelling

Hydrologic modelling using HEC-HMS involves the following steps and processes to simulate the hydrologic response of a watershed to precipitation.

1. Create a schematic project using DEMs, land use, soil type data, and meteorological data.
2. Assign parameters to each element. This involves defining the area, slope, and hydrologic properties (e.g., CN, initial loss, infiltration rate).
3. Input precipitation data. This includes historical rainfall data and design storms.
4. Run the simulation to generate outputs such as hydrographs and flow data.
5. Flow Analysis: Evaluate flow volumes, peak flow rates, and timing of flows.

This is essential for calibrating flood inundation models and assessing the effectiveness of dike construction in reducing flood risk under different rainfall scenarios.

2.5. Hydraulic Modelling

The HEC-RAS model is a widely used tool for flood propagation modelling and is employed in this case study to investigate the effectiveness of dike construction in reducing flood propagation.

The steps in hydraulic modelling with HEC-RAS are:

1. Input the schematic of the stream system.
2. Input the hydrograph.
3. Set the boundary conditions for the upstream and downstream ends of the river reach.
4. Run the hydraulic simulation and carefully check for any errors or warnings.
5. View the computed water surface profiles and flow characteristics.
6. Use the RAS Mapper tool to create floodplain maps and other visualisations.
7. Repeat these steps, incorporating hydraulic structures like dikes into the model.

3. Results and Discussion

3.1. Rainfall Analysis

Two alternatives were used to select the maximum rainfall design depth for the design depth and the return period of a rainfall storm. The first one is demonstrated in Table 1, with a maximum rainfall depth of 103.9 mm for a 41-year return period (length of time record data). The second alternative uses a design return period of 50 years for dike design, according to Boota et al. [20]. Figure 2 shows the IDF curve for Erbil [16]. For dike design, a 50-year return period and a duration of 20 minutes correspond to a design depth of 11 m. To simulate the design depth of the rainfall storm for modelling between these two alternatives, the maximum depth of 110 mm was used. The Synthetic Storm Hyetograph, developed by the United States Department of Agriculture (USDA) and SCS, was formulated by analysing the temporal precipitation sequence corresponding to the highest daily rainfall. This approach delineates storm patterns by examining sub-daily intervals, starting from zero, gradually intensifying, reaching a peak at the midpoint of the duration, and subsequently diminishing from the peak to zero [21].

3.2. Watershed Delineation

The attributes of the catchment area in the Mass Village were assessed using a 30×30 m DEM, with the assistance of WMS software for delineating the watershed boundary. The United States Geological Survey (USGS) DEM was employed to identify topographic features, as described by [22]. Figure 3 depicts the boundary and drainage lines; Table 3 provides the details.

Table 3. Primary parameters concerning the catchment

Basin name	Area (km^2)	Basin length (m)	Basin slope (m/m)	Mean basin elevation (m)
Mass	7.55	8000	0.03	570

3.3. Land cover and land use data

The streams within the mass catchment area lack gauging, meaning no recorded runoff data is available. The Soil Conservation Services Curve Number (SCS-CN) is commonly employed to estimate runoff.

Table 2 uses the maximum daily rainfall. The soil in the catchment area was classified as soil group D using the HWSD viewer [17], as shown in Table 2.

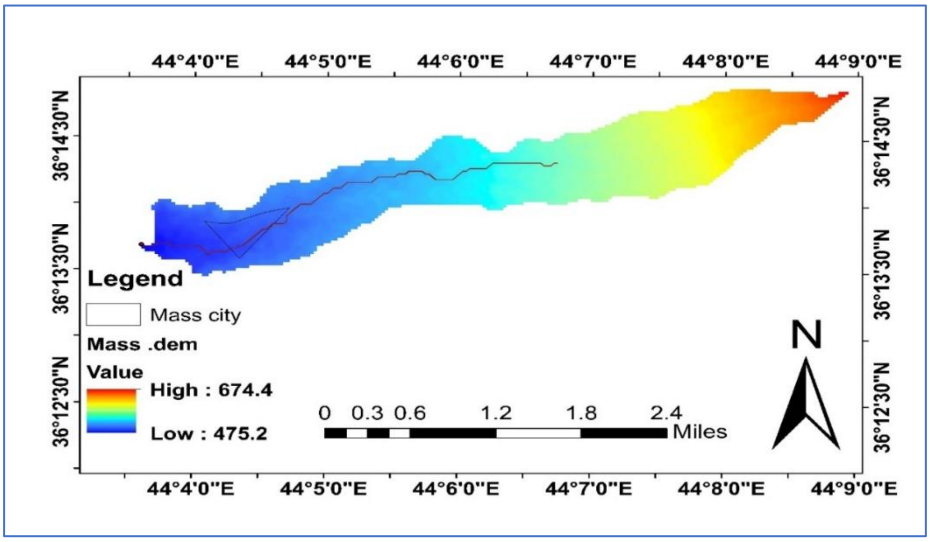

Figure 3. DEM depicting the mass catchment area

Approximately 25% of the catchment area is allocated for wheat and barley cultivation. However, during the last rainy season (2021-2022), farmers refrained from ploughing due to delayed rainfall, resulting in decreased infiltration, increased CNs, and a transformation of the area to sagebrush with a grass under-story weed-grass mixture and brushland covering 60% of the catchment area. Urban areas account for 15% of the catchment area. According to Table 4, the most suitable CN for estimating runoff in developed urban areas (including paved parking lots, roofs, and driveways) is 78, as per the guidelines of the CN for land use and land cover type for each soil group [23].

Table 4. Estimated SCS-CN for case study catchment area

No.	Matrix calculating CN	CN	Area (km^2)	Area %	Weighted CN
1	Barley cultivation	68	1.71	25	17
2	Brush weed-grass	77	4.09	60	46
3	Urbanised area	98	1.02	15	14.7
	Total		6.83	100	78

3.4. Hydrologic Modelling by HEC-HMS

The modelling of the drainage network was based on the DEM with a resolution of 30 m, and Figure 1 shows the stream network. The National Resources Conservation Service's equation is typically used to compute lag time based on the physical characteristics of a specific watershed.

The Hydrologic Engineering Center of the United States Army Corps of Engineers developed the HEC-HMS model beginning in 1992, designed to simulate the hydrological processes associated with rain and runoff in drainage basins. Particularly applicable to arid and semi-arid regions, this model can compute various hydrological parameters at user-defined reference intervals, relying on historical rainfall data. Key parameters include the computation of flood hydrographs, estimation of losses, quantification of soil infiltration, determination of surface runoff volume, and identification of peak flow timing.

The precision of the model's outcomes represents the accuracy and quality of the data used, the design depth of rainfall, a morphological analysis of the drainage network, land cover, CN, soil group, and the Manning coefficient [24]. Figures 4 and 5 show the hydrograph results.

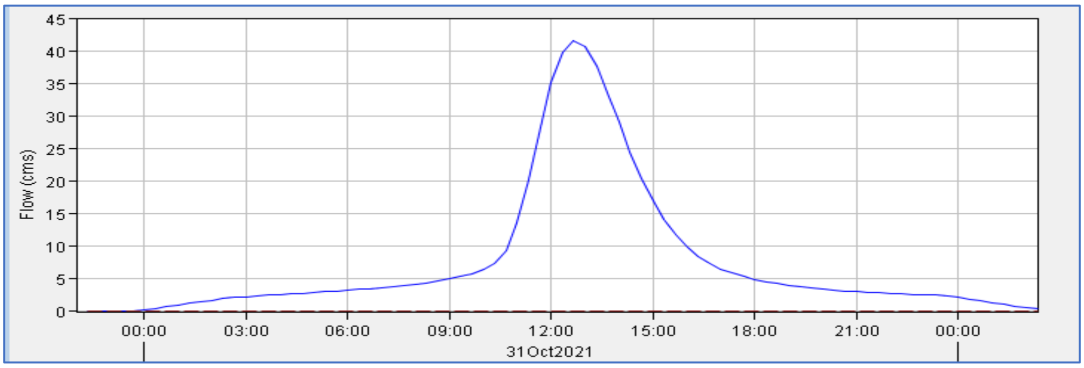

Figure 4. Hydrograph results for a 50-year return period using HEC-HMS

Through flood hydrograph, the peak discharge is 43.6 m3 per second. The volume calculated by HEC-HMS is 419,200 m^3.

3.5. Hydraulic Modelling by HEC-RAS

3.5.1. Flood Inundation

The HEC-RAS model was used for flood inundation of flood hydrograph generated by the HEC-HMS model. The model's foundation rests on the Saint-Venant equations of water flow, as outlined by Yazdan et al. [12]. The flood area was subdivided into a network of smaller meshes with dimensions of 10×10 m to enhance modelling capabilities. This subdivision aimed to facilitate creating an inundation map and depth and velocity analysis, as depicted in Figures 5 and 6.

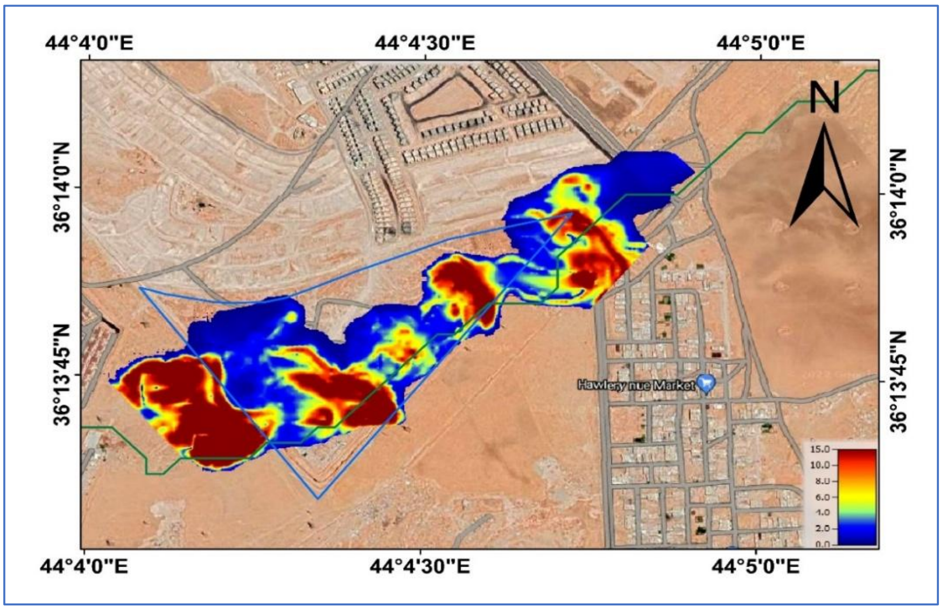

Figure 5. Mapping the extent of flooding and illustrating the depth of inundation during the peak discharge

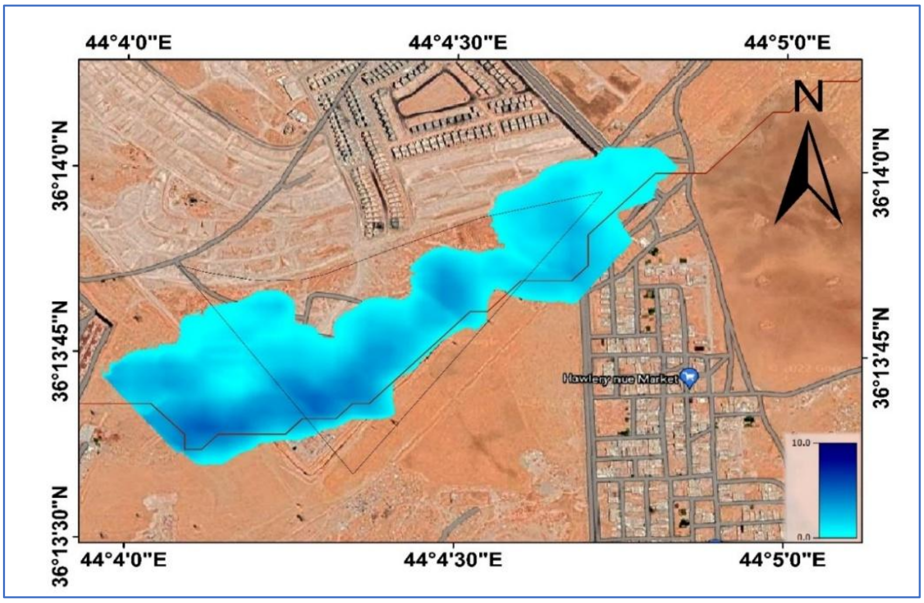

Figure 6. Mapping the velocity of flooding during the peak discharge

Table 5. Results related to flood depth and the extent of flooding based on Q = 43.6 m^3/s

Flood depth m			Flood perimeter km	Flood extent km^2	Maximum velocity m/s
Min.	Max.	Avg.			
0.01	5.02	2.51	3.480	0.316156	12

The results in Table 5 show that the mean depth is 2.51 m, the inundation area is 0.316156 km^2, the flood perimeter is 3.48 km, and the maximum velocity is 12 m/s.

3.5.2. Flood Reduction by Dike Construction

The maximum flood flow will extend over the study area. For the hydraulic design, the dike height is 10 m in the HEC-RAS model. Figures 7 and 8 show flood modelling that uses a dike to protect the study area.

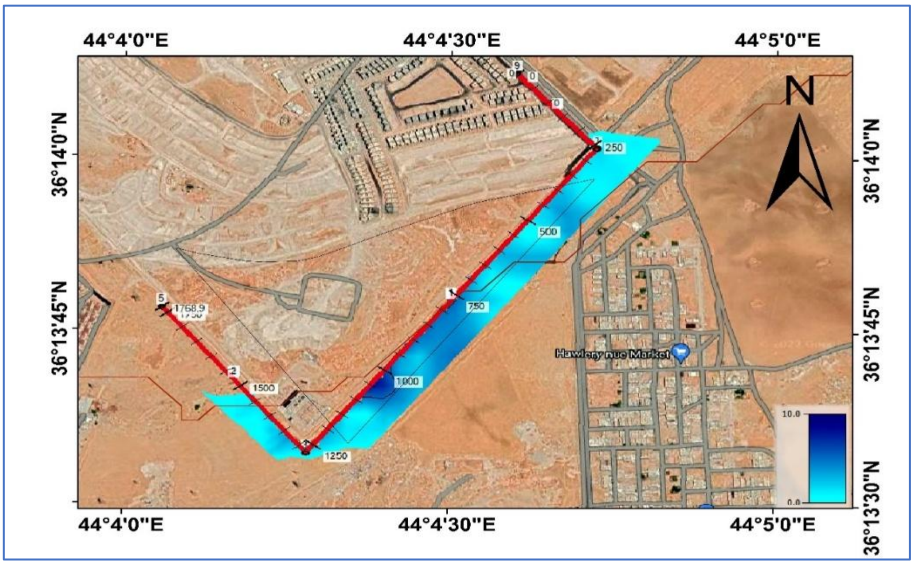

Figure 7. Flood-mitigation modelling by HEC-RAS for protection of an urbanised area Mass Village

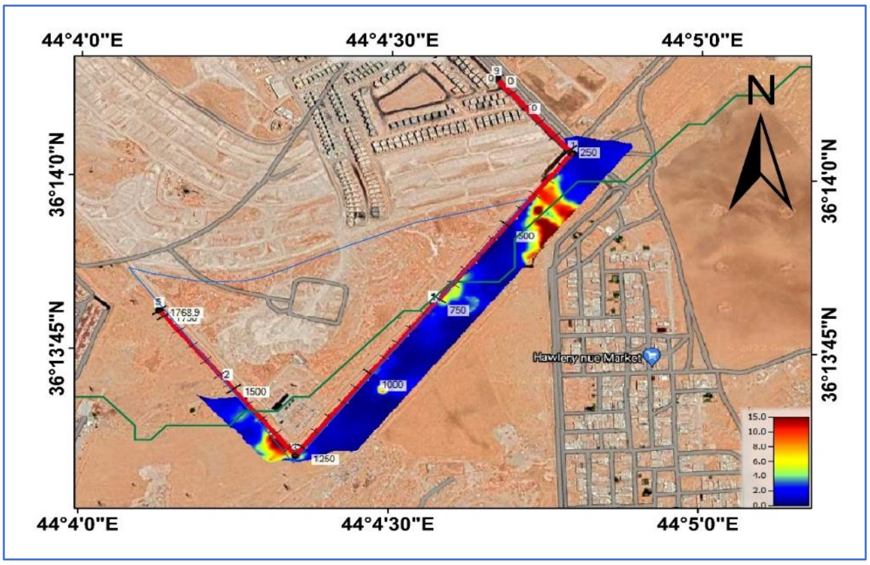

Figure 8. Flood-mitigation velocity modelling by HEC-RAS for protection of an urbanised area Mass Village

Table 6. Results related to flood depth and the reduction of flooding based on Q = 43.6 m^3/s with dike construction

Flood depth m			Flood perimeter km	Flood extent km^2	Maximum velocity m/s
Min.	**Max.**	**Avg.**			
0.01	**7.21**	**3.61**	**2.835**	**0.076991**	**13**

The results of flood depth and extension with dike construction show that the mean depth is 3.61 m, the inundation area is 0.076991 km^2, the flood perimeter is 2.835 km, and the velocity is 13 m/s as shown in Table 6. The simulated flood inundation map presented in Figures 6 and 7 displays the effects of dike construction in protecting residential areas from flood disasters.

4. Conclusion

This study used the HEC-RAS model to help the authorities protect urban areas from flood disasters. The findings show that HEC-RAS models are important for flood inundation modelling and reducing floods with dike construction. Flood velocities and depths range from 2 to 12 m/s and 0.01 to 5 m, respectively, without a dike.

The model simulation for constructing the dike with a hydraulic height of 10 m indicates that water depths upstream range from 0.01 to 7.2 m. The water depth in the protected area downstream is reduced to 0 m, demonstrating flood-mitigation effectiveness in the urbanised region by constructing the dike. This design significantly reduces flood damage and inundated areas.

This information is vital for the structural design and foundational considerations of the dike's placement. The results highlight the importance of flood risk management strategies and emphasise the need for regular inspections and maintenance of flood-mitigation measures to ensure their resilience and effectiveness.

Declaration of Competing Interest The authors declare that they have no known competing of interest.

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