Article

Monitoring Flood Waves Due to Overtopping: Case Study of Mosul Dam from Iraq

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ABSTRACT

When highlighting water resource exploitation and environmental management, interest in dam break hydraulics is growing due to the possibility of hydrological events brought on by climate change and the catastrophic dam breaches that often result in severe loss of life. Several areas are exposed to flooding risk due to flood waves resulting from dam failure. The current study aims to apply a numerical model that predicts the flood wave's characteristics due to a hypothetical overtopping failure in two dimensions. A numerical model (hydrologic engineering centre river analysis system 2D HEC-RAS) is implemented in this study. Mosul Dam, located on the Tigris River in Iraq, is utilized as a case study in this work. The 2D flow area was delineated on the digital elevation model to determine the inundation region and extracted n manning from a land cover layer connected with RAS MAPPER. The results explained that the maximum values of the depth and velocity in km 5 are 60 m and 10.10 m/sec, respectively. At the same moment, it is shown that maximum flood discharge happened near the dam body and that there is a roughly linear relationship between the flood flow and water surface elevation. The study concluded that the models are successful in analyzing the dam breaches by representing the variation of flood wave depth and velocity in two dimensions. Moreover, the ability of the Model to produce maps monitors the spread of hydrodynamic waves that indicate risk areas that are threatened by inundation, which aids in controlling the risks resulting from them.

Keywords: Mosul Dam; Flood Wave; Overtopping Risk; Two-dimensional HEC-RAS

1. Introduction

The dam breach hydraulics is a topic of interest in water resources, environmental protection, and other areas. Numerous significant losses of life and possessions have been due to hydrological events brought on by climate change that have caused dam failures. Accurate routing of the propagation of flood waves associated with dam breaks plays an important role in planning and economic considerations [1]. Overtopping happens when a huge amount of water comes from an upstream area that exceeds the dam crest [2]. While, 38% of dam failures, according to reports [3], were the result of overtopping due to insufficient spillway capacity. For example, Al Taiee and Rasheed,2009 [4] studied the hypothetical Mosul dam break in the upper Tigris River basin by utilizing the geographic information system and the simplified dam break model (SMPDBK). The main conclusions of this study helped Utilizing this data, pertinent public sector groups create strategic plans aimed at mitigating the impact of fatalities on nearby communities in the dam's downstream sections. Joshi et al

2017 [5] Investigated the risk of flood inundation due to a potential dam break that occurs in the Ujjani dam by employing- an unsteady analysis within the HEC-RAS model. Dam failure factors were predicted, and then maps of flood waves were produced in two dimensions. Finally, the study indicated that evaluating maps is crucial in preparing emergency action plans and flood disaster management.ÜNAL,2019 [6] applied the two-dimensional HEC-RAS model and GIS technique to analyze the catastrophe that occurred in Berdan Dam. The maps were obtained by the model, which denoted the flood distribution due to probabilistic breaches in two significant scenarios (piping and overtopping). Considering the arrival time of the flood, the highest (depths and velocities) of the waves are taken into account to prepare emergency plans created by public safety officials in the event of a probable flood on this scale. Kumar et al.2020 [7] analyzed the impact of the possible collapse of the southern Crete Island Bramianos dam on an area that lies downstream of the existing. The hydraulic analysis program HEC-RAS was used to calculate the estimated propagation of flood waves resulting from the dam breach. This study compared

instances from the DSM and DEM. It demonstrated how DSM details might more precisely depict surface relief and naturally occurring barriers like flora, structures, and greenhouses, allowing for more accurate hydraulic simulation results. Shahrim et al. 2020[8]compared one and two-dimensional models for the flood wave parameters due to the failures that occur in the Temenggor dam using HEC-RAS software. According to 1-D analysis, breach flow can reach 281588 m^3/s for pipe failure and 331030 m^3/s for overtopping failure. While, in the 2-D analyses, the flood discharge is 268,341 m^3/s in the pipe model and 328869 m^3/s in overtopping failure. The study deduced that the improvement of the inundation maps obtained from the 2-D model over a large area aids in preparing emergency action plans by illuminating the amount of flood hazard risk. Namara et al.,2021 [9] applied both HEC-RAS and HEC-GeoRAS models to produce maps that illustrated floods in the case of Awash Bello, upper Awash River basin, Ethiopia. The study concluded that the ability of the model to simulate the flood flow. Ge et al., 2021[10] examined the significant factors that impact life loss due to dam breaks. Based on interval analysis, it showed that social factors and hydrodynamic factors had a significant effect on live loss. Mhmood et al.2022[11] stimulated the flood parameters due to the virtual Haditha dam overtopping failure and the effect of these waves downstream the dam on the Euphrates River, Iraq, a long 124 km to Heet City. 1D HEC-RAS version 5.07 and ARC GIS were employed in this work. It concludes that the inundation maps obtained from numerical models contribute to preparing an emergency plan. Mohamed et al,2023 [12] highlighted the sensitivity analysis of soil properties and the size of the reservoirs on the dimension of the breach that potentially occurs in Mosul dam by using 2DHEC-RAS software.

The study concluded that soil properties and reservoir capacity had a greater effect on breach dimensions. Mohamed et al,2023[13] simulated the break in Mosul dam due to piping failure by the 2D HEC-RAS model. The study concluded that the two dimensions gave a good indication of the risk of the flood by producing a map that illustrated the distribution of the wave in two dimensions. Darji, K. et al,2024[14] Hydrodynamic modelling of dam breach floods for predicting downstream inundation scenarios using an integrated approach of satellite data, unmanned aerial vehicles (UAVs), and Google Earth Engine (GEE). This comprehensive research of hydrodynamic modelling in data-poor locations highlights the potential of sophisticated surveying and modelling approaches in flood assessment and management by assisting in the precise calculation of future likely flooding in downstream areas in the case of a dam breach. Regardless of the type of dam and how the breach forms within the dam body, a catastrophic dam failure causes uncontrollable and immense flooding downstream. The Hydrologic Engineering Center-River Analysis System HEC-RAS is a common method for simulating dam breaches. The chief aims of this research include the following: 1- An examination of the influence of a hypothetical overtopping case in Mosul dam using 2D HEC RAS version 6.2 and directing the flood wave's propagation within the Tigris River at a distance of about 225 km downstream the dam body .2- Producing maps of specific flood zones to assess the risk in the overall area in two dimensions.

2. Materials and methods

2.1. Description of study area

Mosul dam is deemed one of the largest earth dams constructed in 1985. It is 113 meters high and 3600 meters wide and is situated in the North of Iraq. It is constructed from zoned earth, filled with a mud core in the centre. The project serves multiple objectives, including flood control and water storage with a volume of 11.11 billion cubic meters at the highest operational level to generate electricity and utilize the reservoir for irrigation and tourism. The flood wave routing due to the hypothetical failure in Mosul dam is confined between the section of river that begins at Mosul dam and the downstream meeting point of the Tigris with the Great Zab River approximately 225km, in length, as illustrated in Figure 1 [15, 16]. Additionally, the hydraulic design specifications such as the maximum, normal and minimum water level and dimensions of the dam, etc. have been demonstrated in Figure 2 [17].
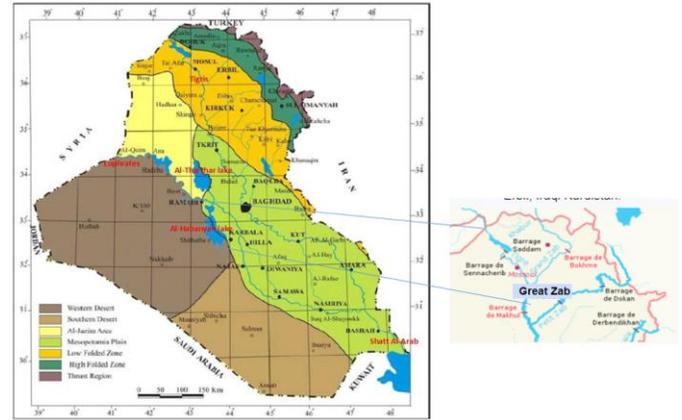

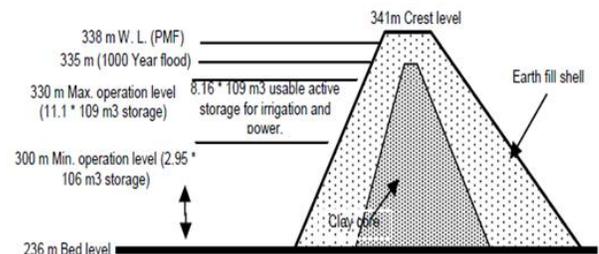**Figure 1**: The position of the study area

Figure 2: Layout of the Mosul dam: a). Image - satellite of Mosul dam and b). Typical profile

2.2. Digital Elevation Model

A wide range of fields and communities, including geomorphometry, hydrology, remote sensing, agriculture, cryosphere, defence, sport, land planning, natural hazards, and soil sciences, have adopted digital topography expressed as a Digital Elevation Model (DEM) [18]. The raster format that was allocated for the DEM, which potentially used with a GIS system[19]. Also, provides a basic representation of the 3D geometry of the Earth's surface. Which The Shuttle Radar Topography mission provided the Digital Elevation Model for the research region. Using a grid cell size of 14 m x 14 m that represented the topography level as shown in Figure 3 [20].
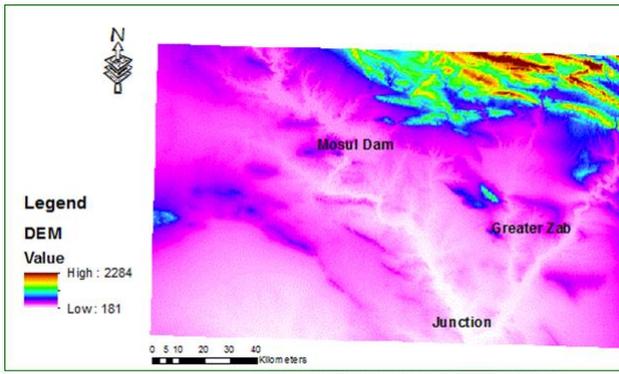
Figure 3: Digital Elevation Model of the study area

2.3. Land cover

The Landsat 8 satellite imagery, which has 3 bands with a spatial resolution of 30 m is used to represent the land cover map and is available on the website at [21]. The land cover map in Figure 4 has been treated in a GIS environment into supervised categories and then exported into HEC-RAS to determine the appropriate Manning's roughness coefficient values for each sort classified in the map, as indicated in Table 1. The roughness coefficient, is related to the entire land cover. Classes based on the HEC-RAS Hydraulic Reference Manual [22].
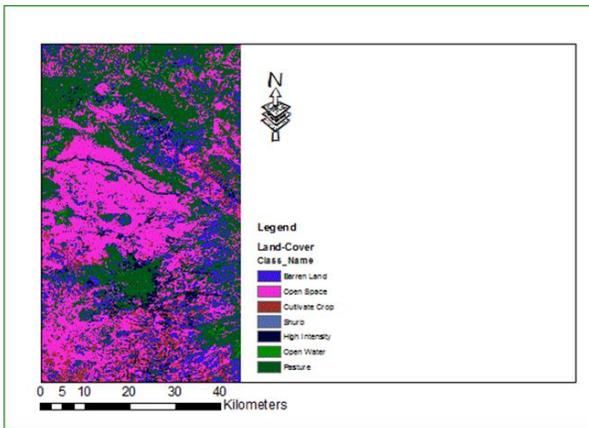

Figure 4: Land cover classification map.

Table 1:
The land covers types and parameter ranges.

Land Use Type	Pasture	Arable land	Vegetated river	Bushy grasslands	Urban area	Lakes	Clean river
Area (ha)	300	750	360	102	400.42	100.8	209
n Manning's	0.023-0.03	0.025-0.05	0.07-0.16	0.03-0.05	0.12-0.2	0.02-0.05	0.025-0.05

3. 2D HEC-RAS model

Version 6.2 of the Hydrologic Engineering Center United States' River Analysis System 2DHEC-RAS Army Engineers Corps has been extensively used to model and examine steady and erratic flow in natural and artificial open channels and sediment transport[23]. It comprises a user interface HEC-RAS MAPPER, discrete hydraulic analysis components, data storage, management capabilities, and graphics. The interaction of the data with the GIS software enhanced the ease of use of HEC-RAS in the dam failure simulation. In the 2D HEC-RAS software, the dynamic Shallow Water formula (SWEs) was applied. To route the flood propagation model that compounds Equations 2 and 3 as follows.

Equation (1), or the 2D diffusion wave equations (2) and (3) [24].

$$\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} + q = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + \frac{u \, \partial u}{\partial x} + \frac{v \, \partial u}{\partial y} = -g \, \frac{\partial H}{\partial x} + vt \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - C_f \, u + fv \qquad (2)$$

$$\frac{\partial v}{\partial t} + \frac{u \, \partial v}{\partial x} + \frac{v \, \partial v}{\partial y} = -g \, \frac{\partial H}{\partial x} + vt \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - C_f v + fu \qquad (3)$$

Where: H: total height L, h: wave depth L, $u \, and \, v$: velocity components LT^{-1}, q: sink/ source flux L^2T^{-1}, g: acceleration,9.8 LT^{-2}, vt: (Eddy viscosity) $ML^{-1}T^{-1}$, Cf: Friction coefficient, and f: The parameter of Coriolis. The formation takes a trapezoidal shape to evaluate the breach parameters of fill dams. The width from the top, the width from the bottom, the gap, the depth, and the lateral slope are all geometric factors. Numerous empirical equations are developed for guessing the dam failure's breach factor and creation time [25]:

$$B_{avg} = 0.27 \, K_o \, V_w^{0.32} \, H_b^{0.04} \qquad (4)$$

$$t_f = 0.0176 \left(\frac{V_w}{g*H_b^2} \right)^{0.5} \qquad (5)$$

In which B_{avg}: breach width L, K_O: factor 1.3, V_w: the volume of reservoir over the bottom of the breach L^3, H_b: perpendicular distance from the peak dam to the breach reversal L, t_f: time T, g: gravity L/T^2.

4. 2D Simulation Model

The gathered data is deemed the main part of the methodology to simulate the dam failure using the 2D HEC-RAS model. It is divided into two categories: geography data, which gives a physical description of the case study (Digital Elevation Model (DEM) and Land Cover (LC) maps), and flow data, which provides information on the flow through dam characteristics like reservoir volume, dimensions, and probable maximum flood (PMF). Based on the irregular triangular network TIN obtained from a digital elevation model (DEM) with a 14m resolution after processing in RAS MAPPER, a hypothetical Mosul dam break is simulated and analyzed using the 2D HEC-RAS model. TIN is considered the main part of the 2D Model utilized for determining the 2D area flow downstream of the dam and Mosul Lake. Figure 5 shows the selection of the dimension of the cell applied to the 2D area of flow. The initial condition in the case of simulation is the flood risk or dam failures, which represent the distribution of water in the whole area before starting the simulation steps. The area elevation curve, the reservoirs of both dams and the depth of water in the Tigris River are considered the initial boundaries. Whereas, the reservoir outflow hydrograph and probable maximum flood (PMF) of the dam are deemed boundary conditions.
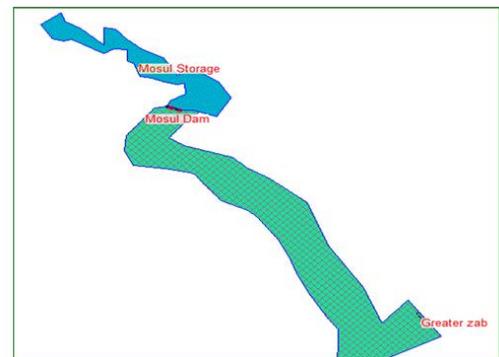

Figure 5: 2D Area flow connection.

5. Results

5.1. Result of breach failure

The Froehlich equation predicts that the overtopping failure occurs. (1:1) (H: V) is the side slope of the breach. At the same time, the top width of the break is 620 meters, and Figure 6 shows additional specific information about the dam breach
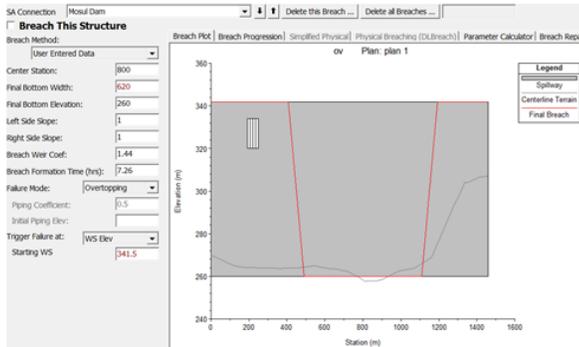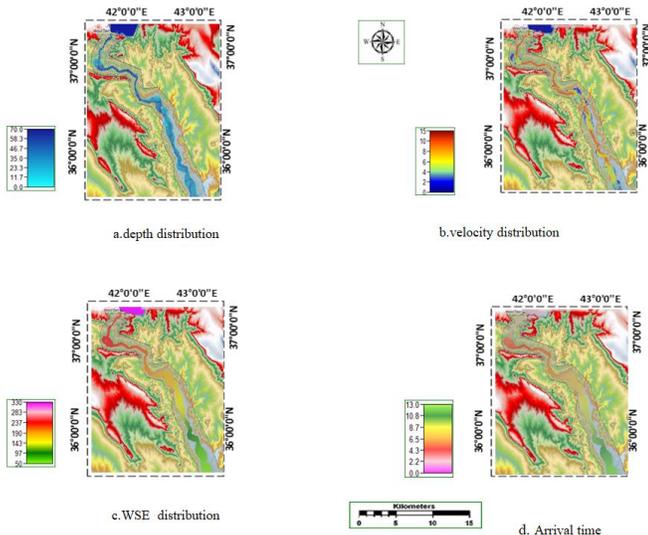

Figure 6: Section of breach parameter.

Figure 7: Dam break parameters distribution due to overtopping model.

5.2. Result of the Model of Hydrodynamics

Generally, the model conducts the dam break evaluations and monitors the flood routing at km 225 downstream of the Mosul dam. The initial level of the reservoir, which is 341.5 m, and the PMF for six hours at these moments are deemed initial and boundary conditions. Figures 7 (a-d) show the maximum water flow and water surface elevation within arrival time due to overtopping failure along the distance between Mosul dam and the point that meets between the Tigris River with Great Zab. The output maps that have been displayed on the digital elevation model with RAS-Mapper assistance can be utilized to model the flood wave that results from the overtopping breach. The depth varied from 20 m to 64 m at kilometer 5 from the dam body. While the velocity reaches 9.1m/sec near the dam body. It noted a high value of the flood discharge at km 17 approximately 300000m^3/s 5hr due to meandering. The values of WSE vary between 320 m neighbouring the body of the dam and then decrease with the flow direction due to energy losses to reach 200 m at km 225. The results of the studies are represented regarding the level of the water's surface, its depth, its velocity, and the time it takes for flooding to occur. The produced maps that illustrated the distribution of dam break parameters are illustrated in Figures 8 (a–d).

6. Discussions

A 2D HEC-RAS program was used in the current study to simulate the Mosul dam breaking, including mathematical relationships (Froehlich 2008), for the available dam break methods, the size of the breach, and the maximum dam break parameters. Then, it was noted that a breach occurred within 7.27 hours with a 1:1 side slope maximum width of 620 meters, as shown in Figure 6. While, the maximum depth is 60 m at km 5 downstream, south of the Mosul dam, and decreases slightly to the junction point between the Tigris River and the Great Zab to reach about 20m. Simultaneously, the outcomes illustrated that the maximum velocity value is 10.10 m/s at 5 km, decreasing slightly to reach 2.7m/s at km 225. Figure 7 illustrates the extent of the flood wave's dispersion along the river's two dimensions for arrival timings (5.1, 5.8, 6.8, 8.1, 11.8, 12.1) hr.
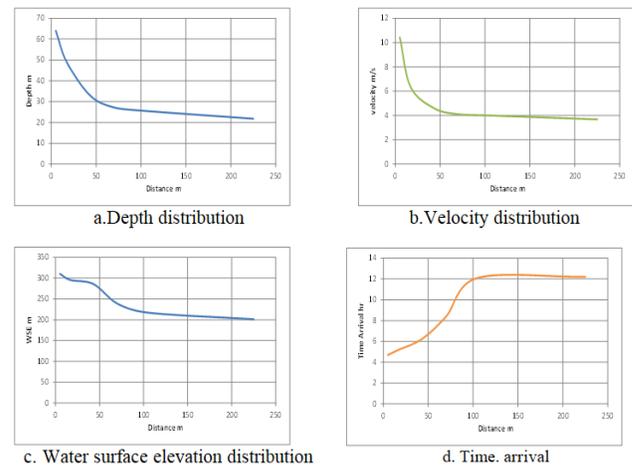

Figure 8: Relationship between the parameters of flood waves with distance.

The variations of depth, velocity, and water surface elevation are represented along the length of the Tigris River in Figure 8. Moreover, the maximum flow is 342939.2 m^3/s, and the corresponding WSE is 310.7 m. At the initial breach time, a reservoir's capacity is higher due to the overtopping failure due to meandering. While the slope of the WSE fluctuation due to enlargement or narrowing in the cross-section of the river. Figure 9 illustrates the relationship between water surface elevation and maximum flow. The highest value of the wave height results in the primary stages of the break.
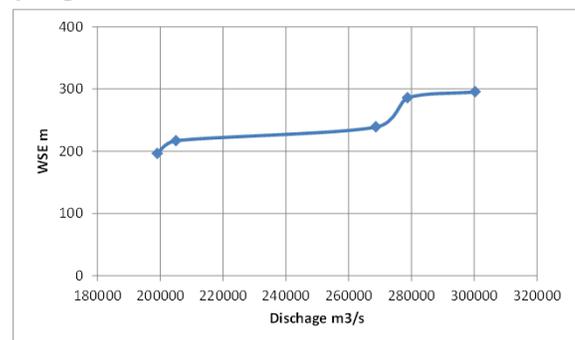

Figure 9: Relationship between stage and discharge due to overtopping failure.

7. Conclusion

The HEC-RAS model has successfully produced maps in two dimensions along the study area. The maps that were incorporated with the digital Terrine model represented the distribution of depths, velocities, and other parameters with the arrival time resulting from the phenomenon of overtopping failure. This analysis was able to estimate the period of creation of the Mosul dam breach, the direction of the flood wave propagation downstream, and provide a summary of the sequential events. The results have shown that maximum flood discharge happened near the dam body; moreover, high variations in depth, velocity, and flow values are due to overtopping failure. It noted a linear relationship approximately between the Water Surface Elevation and flood flow from upstream to downstream for the study area. The results explained that the maximum values of the depth and velocity in km 5 are 60 m and 10.10 m/sec, respectively. At the same moment, it is shown that maximum flood discharge happened near the dam body and that there is a roughly linear relationship between the flood flow and water surface elevation. Moreover, the maximum flow is 342939.2 m^3/s, and the corresponding WSE is 310.7 m. While the slope of the WSE fluctuation due to enlargement or narrowing in the cross-section of the river. Ultimately, this is one of the appropriate approaches to prepare for and avoid the risk due to flooded waves. Further studies should focus on methods for flood control to reduce catastrophic risk. By viewing the satellite images in the 2DHEC-RAS mapper, it is observed that there are median islands and bars along the Tigris River within the study area. Therefore, we recommend removing them and training the cross sections to pass the largest possible amount of flood flow.

Declaration

Reference

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