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Modeling of Flood Wave Propagation Due to Hemren Dam Failure

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ABSTRACT

The occurrence of dam failures and the consequent floods pose substantial risks to submerged regions, and their unpredictability increases the hazard of their impact. This research simulates the flood event scenario due to the dam failure of the Hemrem dam in Diyala Governorate, Iraq. HEC-RAC model jas been used to modeling the Hemren dam failure. The generated flood waves are routed downstream until the confluence of the Diyala and Tigris rivers, covering a large study area of 5,378.5 km². The configuration of the model's geometry is formulated using the Digital Elevation Model (DEM) that encompasses the geographical extent of the Diyala River study area, from Hemren Dam to the confluence with the Tigris River south of Baghdad. The length of this reach is approximately 210 km. Based on the inundation maps, the region's geography is classified as having catastrophic constraints due to the water depth and flow rate. The results demonstrate how to predict the magnitude of floods and highlight the severity if Hemren Dam were to fail. This underscores the need for effective risk management. Furthermore, the maps created by this study can be utilized to develop long-term flood control plans.

1. Introduction

A dam is a structure constructed across a river that stores and supplies water for various purposes improve the human life [1]. According to [2], there are more than 800,000 dams have been constructed around the world for controlling floods, irrigation purposes, water supply, hydropower, recreation benefits, navigation, and others. Dam failures are very rare [3], but they do occur where massive amount of water deposited beyond the dam's construction could endanger downstream residents' lives and property [4], where a dam failure could result in catastrophic flooding [5–8], it caused significant economic losses, loss of life, ecological disruptions, and severe consequences for vulnerable populations [9–12].

Earthen dams are highly regarded for their adaptability to different foundation conditions, ease of construction, and cost-effectiveness, making them one of the most commonly used dam types [13-14]. However, clay dams, with their reduced structural stiffness, are more prone to failure [15]. Even with the inclusion of adequate safety margins in dam engineering, failures can still occur due to various factors such as leakage, inadequate spillways, overtopping, seepage, seismic activity, and other natural disasters [16–19]. An extensive study of over 1,065 earthen dam failures has shown that overtopping and piping are major contributors to these failures. Overtopping can lead to weaknesses in spillways, downstream

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slopes, and foundations, while piping poses a risk throughout the entire dam structure [20–23].

Many dam failures start with an initial structural breach, causing the release of the stored water upstream, which then produces flood waves downstream of the dam [5]. Residents living downstream should be informed about the potential risks of dam breaches and any necessary expenditures for improving safety or addressing potential problems in the area [24].

The primary goals of dam break analysis involve predicting and accurately routing the outflow hydrograph that results from a breach [25–28]. Key aspects of dam break studies include assessing the extent of impact along the river and analyzing the characteristics of the resulting flood hydrograph. Consequently, dam break simulations typically consist of two stages: first, estimating the probable maximum flood (PMF) due to the dam break, which can be achieved using a one-dimensional model.The second stage is to route the flood wave of this PMF to the downstream area. Dam break studies could be achieved using physical models that simulate and different studies were presented around the world with acceptable results. However, using the physical models for dam break studies is restricted by different limitations such as difficulty in model building and it is considered costly. Therefore, most of the researchers tried to use the hydrodynamic model as a good alternative model for dam break simulation.

According to the International Commission on Large Dams, breaking or overtopping is responsible for around one-third of dam collapses. The second hazard, on the other hand, is created by pipelines, and the third case of failures is induced by external factors (liquefaction or settlements) [29]. Flood inundation maps and dam break research are required for emergency preparedness to determine the characteristics of a dam break flood and the size of the affected area. Flood inundation mapping has been used to analyze the flood wave extent downstream of the dam using a variety of models or software. The Hydrologic Engineering Centre's River Analysis System (HEC-RAS) model was established by the US Army Corps of Engineers' Hydrologic Engineering Centre in 1981. They are one of the most extensively used models. The HEC-RAS model has been enhanced with new modules in the most recent release (version 6.1). The shallow water equations are addressed through computational methods, employing a Finite Element mesh within the 2D HEC-RAS model. This mesh facilitates the visualization of the flood inundation map across a 2D flow area, encompassing both the river channel and floodplain in the model [30].

Many researchers have employed the 2D HEC-RAS model with various case studies because it can simulate complex flow conditions. Quirogaa, et al. [31] used the HEC-RAS V.5 to ascertain the depth of the floodwater, the velocity of the flow, and the temporal variations, a model was used to reproduce the Amazonian region of Bolivia which saw flooding. According to the study, the depth of flood can be used to identify places that are vulnerable to various levels of danger.

Joshi and Shahapure [32] used for a study on dam breach flood routing simulation for Ujjain Dam under overtopping failure, incorporating Pandharpur City as a study region, a 2D HEC-RAS modeling approach was used to estimate flood-prone sites on the downstream side of the dam. According to the authors, overtopping is to blame for the majority of earth-fill dam failures.

There are several dam break studies have been conducted around the world in generally and in Iraq specifically. Kumar et al. [33] employed the 2D HEC-RAS v.5.0.7 simulation software and utilized resources from the Global Flood Monitoring Method (GFMS) to develop a framework for assessing flood magnitudes and delineating distinct flood risk zones in Prayagraj, India, nearby nearby nearb near the confluence of the Ganga and Yamuna Rivers. Sattar et al. [34] used hydrodynamic modeling tools to analyze the potential of South Lhonak Lake as a hazard in the Indian state of Sikkim. According to the findings, the worst-case scenario for a glacial lake outburst flood GLOF occurs when the dam overtops. The South Lhonak GLOF's effects were significantly reduced by a strong topographic obstacle that was placed 15.6 kilometers downstream from the lake, which caused the flood wave to contact with it. Albu et al. [35] employed the 2D HEC-RAS simulation model to figure out the hydro-morphometric parameters (flow rates, flood periods, depths, and velocities), as well as the affected structures and land use categories that have undergone damage, to figure out the spatial risk of backwater flooding. Based on this theory, the Sulita Dam on Romania's Sitna River has been broken. Pilotti et al. [36] studied to see if the 2D HEC-RAS model could be used to predict floods in steep alpine valleys when dams break. To find out what would happen if the Cancano Dam broke, the research involved a comparison between the discharge hydrographs generated by the 2D HEC-RAS model and those observed in a historical physical model constructed based on Froude's similarities in northern Italy. The investigation focused on the propagation of the resulting flood wave along a stretch 15 km downstream of the Alpine region. The study successfully aligned the experimental hydrographs and the measured extent of flooded areas with the computer models employed. Ríha et al. [37] examined the breaching of a series of three very modest embankment dams in the Moravian-Silesian Region of the Czech Republic's iina River watershed. Several techniques, including empirical equations, analogies, and hydraulic models, were used to conduct the analysis. The results indicate that the diminishment of small reservoirs' volume is insignificant when compared to the overall flood volume. Consequently, the reduction in peak discharge typically ranges from 5 to 10%. The study's objective was to illustrate the relationship between the spacing of dams and the mitigation of dam-break floods.

Nazif [38] integrated the hydrological model with gene expression techniques to study the analysis of Mosul dam failure. She used the simplified Dam Bream Model (SAMDBK) to doing the dam break analysis. She obtained the flood characterstics such as the maximum discharge, time to maximum discharge and the flood wave along the revier from the SAMDBK model. After that, the gene expression techniques has been used to build a model for prediction of the flood charaterstics. Additionaaly, the ststistical index (R2) has been adopted to evaluate the performance of the gene expression model. Where the value of the (R2) has been found to 0.9. Abdulrazzaq et al. [39] study estimate the different breach parameters include breah width, breach side slope and breach using different existing approches. They adopted different equation for estimate the dam breact parameters (Froehlich, Macdonald and Langridge-Monopolis, Von thun & Gillete, USBR and Singh. They take Hemren dam as case study to apply their study. The results revelaed that the breach width are slight seneitive to the value of the maximum discharge. Al-Badowi et al. [40] study the behavior of Badush dam due to the complete dam failure of Mosul dams. They estimate the level that the water will balance in the tewo dams afther Mosul dam failure. Two mathematical models have been buile in this study. The first one for prediction the water level of Mosul reservoir according to the storage volume. While the second model was used to estimate the water level at Badush dam due to Mosul dam failure. The results indicate that the Badush dam can accomadte the maximum discharge at level 330 m.s.a due to Mosul dam failure at level 333 m.s.a. Abdulrahman et al. [41] study the simulation of dam failure of Khassa Chai dam in Kirkuk. They used a two dimentional HEC-RAS model in their study. The results indicate that when the Khassa Chai dam is failure, the flood wave will effect almost of the infrastructures in Kirkuk cite. Addidtionally, they concluded that the flood wave will arrive to the city center within onr hour.

In a petite, unmeasured watershed located in northwest Crete, Sarchani et al. [42] Utilized the flow hydrograph alongside two high-detail digital elevation models (DEMs) within the 1D/2D HEC-RAS model to determine the extent of inundated areas. They found that the highest flood depths, wave velocities, and the area of the floodplain at peak discharge were all better predicted by the combined 1D/2D HEC-RAS model. In another investigation conducted by Shahrim and Ros [43], a breach hydrograph and a map illustrating inundation were generated employing the HEC-RAS model to simulate the effects of a dam break caused by pipe failure and overtopping. A 2-D HEC-RAS model, in accordance with the researchers, can offer an inundation map of a dam failure across a greater area, enabling the calculation of flood hazard risk and the creation of an emergency action plan.

The employment of the 2D HEC-RAS model offers a suitable investigation into dam failure and the downstream flow of flood waves, as evidenced by the aforementioned study. In this study, the model was utilized to forecast and illustrate the devastating outcomes of a theoretical dam collapse. This involved computing key flood attributes, including penetration metrics, surface water levels, flood depth, flow velocity, and the timing of flood wave arrival in the vulnerable area.

The main objectives of this study is intended to answer the following practical problem, " What is the behavior of the possible flood waves expected from dam break events in Hemren Dam?". This aim is achieved by conducting a HEC-RAS model in order to estimate the probable maximum discharge (dam break outflow hydrograph) that expected to results deo to dam failure. After that, the hydraulic model has beed built in order to rought the flood wave of dam break outflow hydrograph at the downstream region.

The purpose of this paper outlined above is divided into a set of objectives such as Providing a sufficient description of the dam and downstream area in terms of geometric and hydrologic conditions and computing the predicted arrival time and the maximum water level covered by the main cities along the reach of Diyala River and Estimate the flood hazardous zones within the study area.

2. Materials and methods

2.1. Description of the study area

Hemrem Dam is an earthen dam that was constructed on the Diyala River in Diyala governorate, Iraq. Hamrin Dam, a significant and strategically vital project constructed on the Diyala River in Iraq (as shown in Figure 1), stands approximately 10 km upstream from the Diyala Dam and approximately 120 km northeast of Baghdad, Iraq. The length of the dam body of the aggregate dam is (3500) meters and its maximum height is (53) meters in the old Diyala River section. The height of the crest level of the dam is (109.50) meters above sea level. The hydrological records indicate that the annual precipitation ranged between 171 mm and 413 mm.The main goal of the dam is flood management, irrigation and hydroelectric generation. The dam and the attached power house were built in years 1976-1981. The reservoir of Hermren dam has a full–pool operating altitude of 92 m above mean sea level and its boundaries extend between a latitude of 25º61' 34º14' N and a longitude of 30º12'- 44º09'E. The volume of water that stored by Hemren dam is 2.06 billion cubic meters with a surface area of about 327 km^2 at high level period. Figure 1 shows the cross section of Hemren dam [43, 44].

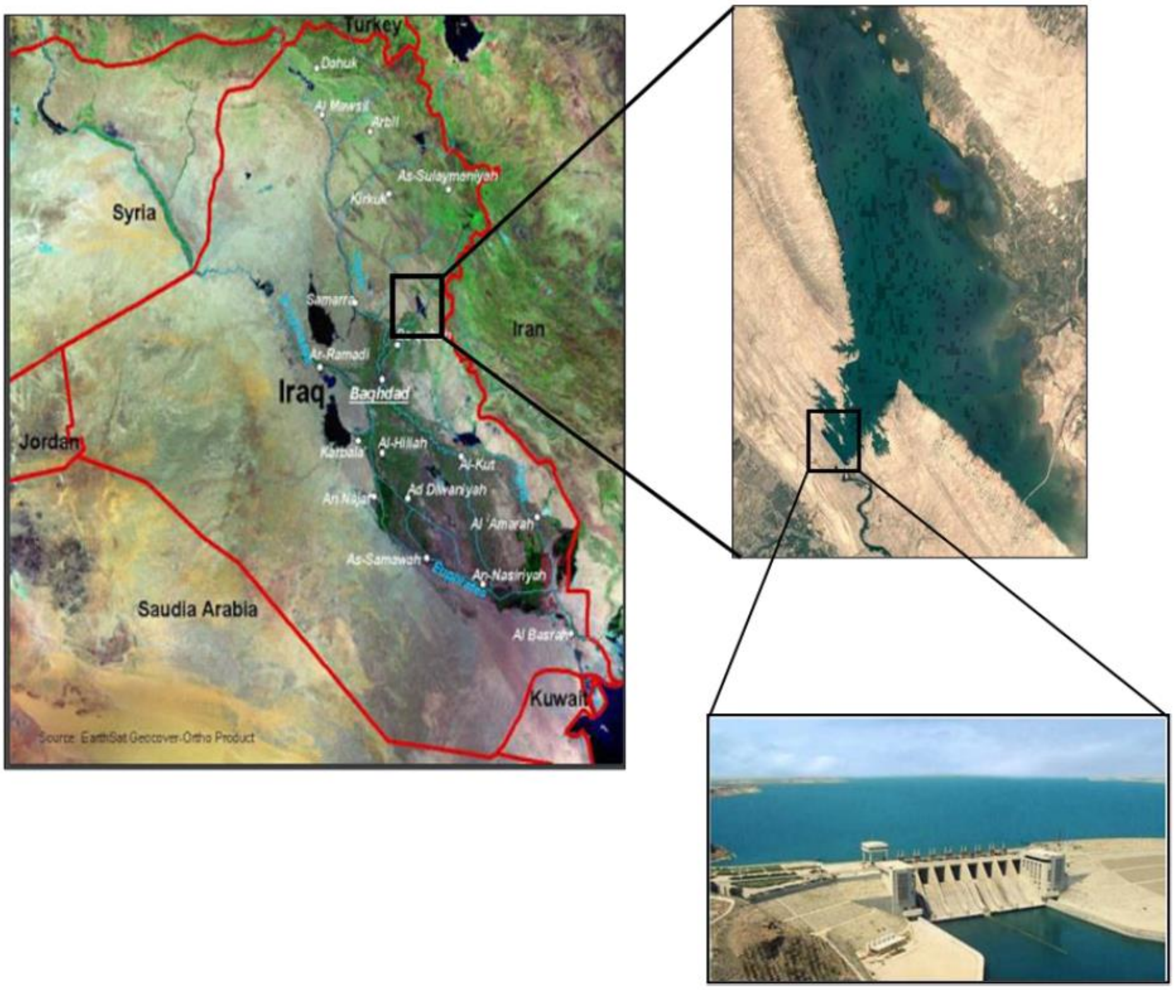

Figure 1. Location and a general view of Hemren Dam

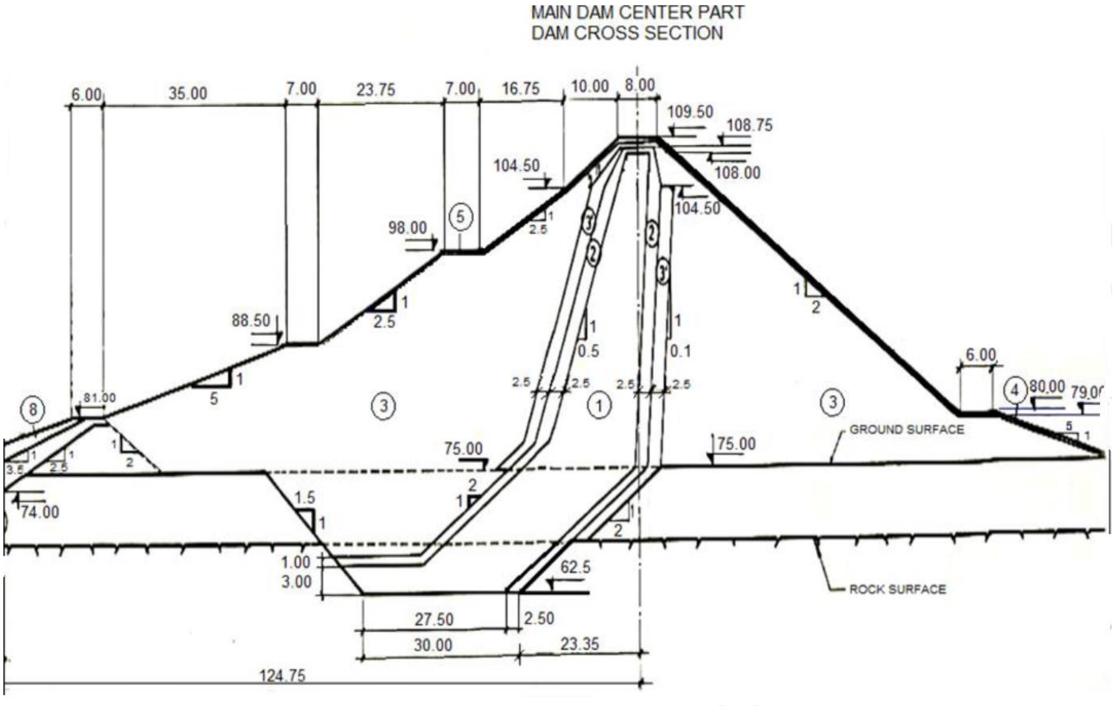

Figure 2. Hemren Cross Section [44]

The study focuses on a selected study area and the hydrological characteristics of the Diyala River, a major tributary of the Tigris River, the catchment area of Diyala River is divided between Iraq and Iran. It's an important resource for two Iraqi governorates (Diyala and Sulaymaniyah). Table 1 lists several lists of Diyala Gathering Real Estate. Variation in altitudes between the start and the mouth of the river is clear. This drop translates to the rise of the river and the energy of the flow, which gave the river an unpredictable and demanding control structure to provide safety and take advantage of this power potential [45 – 46].

Table 1: Characteristics of the Diyala River catchment area [46 – 47]

Criteria	Unit	Value	Notes
Catchment Area	km^2	33010	42.8 % in Iraq
Max. Elev.	m.a.s.l	3322	Sanandaj
Min. Elev.	m.a.s.l	29	Tigris Confuence
Basin Slope	%	0.7	
Main River Length	km	387	With Iraq and Iran
Flow paths Length	km	687	390 km in Iraq
Aver. Annual Volume	BCM	4.6	
Contribution to Tigris	%	11	Annual Income

The estimated life expectancy of the Hemren Dam is between 100 and 150 years. Hydrologically, the Hamrin Dam was designed at (70%) of the potential maximum flood. The reservoir capacity is 3.95 billion cubic meters, and the reservoir area is 445 km^2 at the flood level (107.5) meters above sea level. The area of the feeding basin (Catchment area) is about (72000) square kilometers. The main sources of water feeding for the reservoir are the Diyala River (launched from the rear of the Derbandikhan Dam), the Wand River, and the seasonal natural valleys. The operational level is (104.50) meters above sea level. The minimum level is (92) meters above sea level. The normal level of storage in the summer (104.50) is meters above sea level. The maximum level of storage in the event of a flood (107.50) meters above sea level [48].

2.2. Survey data and the geometry of the model

The geometry of the model is prepared depending on field survey data for the Dayala River and the Digital Elevation Model (DEM) covered the study area of the surrounding Diyala River from Hemreen Dam to the south of the confluence with the Tigris River. The length of this reach is about 210 km. The study area was divided into about 369809 elements for use in the model of HEC-RAS. Figure 3 shows the geometry of the model. The Survey data was conducted along the Dayala River reach that was extend from Hemren Dam to the confluence with Tigris River, this cross section was gotten from the Iraqi Ministry of Water Resources, Center of Studies and Engineering Design., where the area out of the river was covered by the DEM. The DEM was downloaded from the website of USGS earth explorer. The maximum elevation of the study area was about 3322 m.s.a while the minimum elevation was about 29 m.s.a.

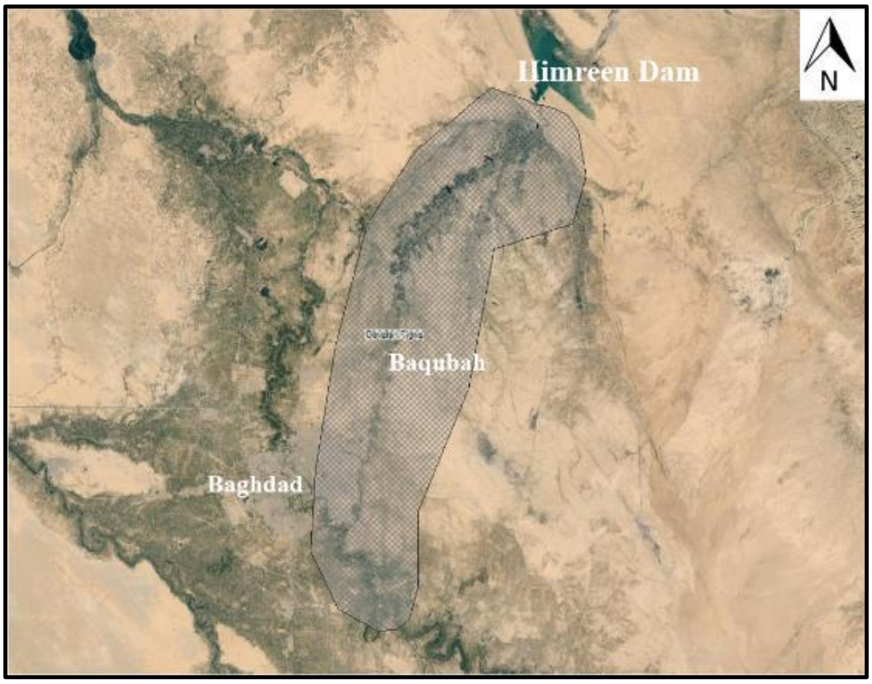

Figure 3. The geometry of the model along the Dayala River in HEC RAS

3. The Hydraulic model

The numerical model for the flood wave is carried out by the software, Hydraulic Engineering Center-River Analysis System (HEC-RAS 6.1), which is the most updated of HEC RAS versions. The software was prepared by The United States Army Corps of Engineers. The software has been extensively used in hydraulic modeling of flow in rivers and channels, sediment transport, water quality analysis, floodplain determination, and scouring around bridge piers. The software is capable of obtaining the water surface profile for steady and unsteady flow. The computation process of water surface profile for one dimensional, steady, gradually varied is based on solving the energy equation in an iterative procedure, which is the standard step method. For the one-dimensional, unsteady flow simulation, the computations are based on solving the continuity and momentum equations by the implicit finite difference’s method. The model is available for 1D and 2D modeling. In this study, a 2D HEC-RAS model was utilized in this research.

3.1. Boundary conditions

For unsteady-state flow in the models, the condition of the upstream boundary is simulated as a flow hydrograph that results from the overtopping dambreak of Himreen Dam as Shown in Figure 4 [49]. The criteria of this flow Hydrograph are that the water level in the dam lake reach to 110m which leads water to be overtopping the dam crest.

Where the condition of the downstream boundary is set to be normal depth depending on the slope of the reach. This case of dam failure suggested that the Himreen lake level is at 109.5 m.a.s.l, and the maximum discharge of Tigris River at the confluence is 2500 m^3/s which represented the worst case of Tigris River in Baghdad.

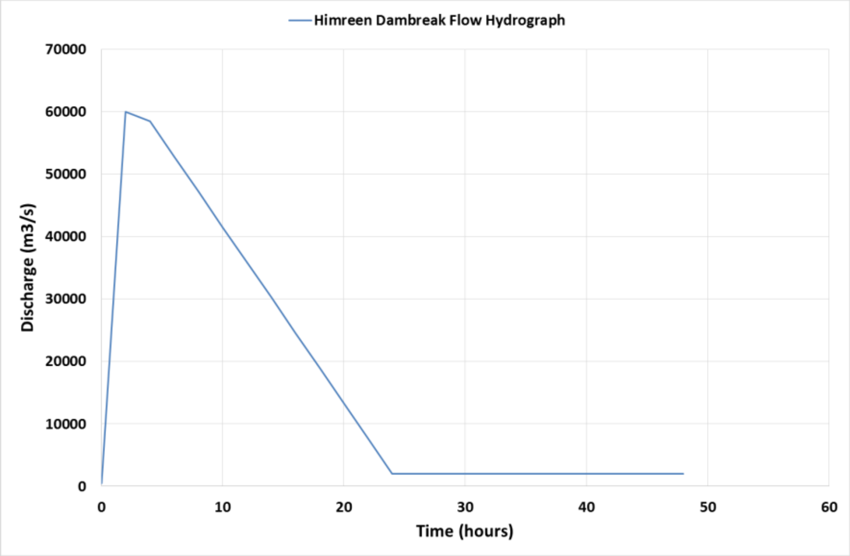

Figure 4. Hemreen dam break flow hydrograph [48]

4. Results and discussion

The HEC-RAS model was used to simulate the dam failure. Therefore, several parameters should be specified to run the HEC-RAS model. These parameters include breach width, breach height, time failure, and breach side slope. Additionally, the hydrological information related to the dam and reservoir should be specified before the model runs.

After all the required parameters were selected, the HEC-RAS 1-D model was run to estimate the maximum probable flood hydrograph from the dam breach that was formulated due to the overtopping flood scenario was estimated as shown in Figure 5 and Table 2. As shown in Figure 5, the maximum value of the estimated flood value has been found to be equal to about 60000m^3/sec.

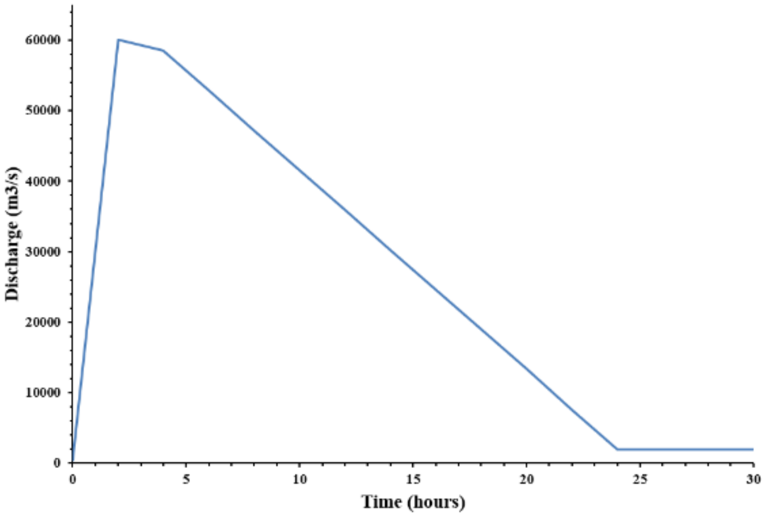

Figure 5. Hydrograph of maximum flood due to Hemren dam failure

When the maximum flood hydrograph has been estimated, the HEC-RAS 2-D model is used to route the flood wave at the downstream region. The obtained results were exported to the Ras mapper. Ras mapper in HEC RAS is a very important tool in graphical output such as inundation maps.

The routing of the flood wave was estimated at seven locations along the studied reach including (Diyala weir, Al-Muqdadia, Abu Sayda, khrnabat, Baqubah, Khan Bani Saad, and the region of the confluence of Tigris and Diyala River. To generate inundation maps, it is very important to simulate the results of water depth and velocity profiles along the study reach as shown in the following section.

4.1. Velocity distribution

The velocity distribution of flood waves along different selected locations downstream of Hemren dam are presented in the Figures (6-12). As we can see from the figures, the max velocity value was found about 5m/s which was obtained at the location of Diyala weir 7km downstream of Hemren dam as shown in the figure in Figure 6. while the minimum value of velocity was found equal to about 0.8 m/s at location of confluence of Tigris and Diyala River. The variation in the value of the flood wave velocity could attributed to the geometry of the study area.

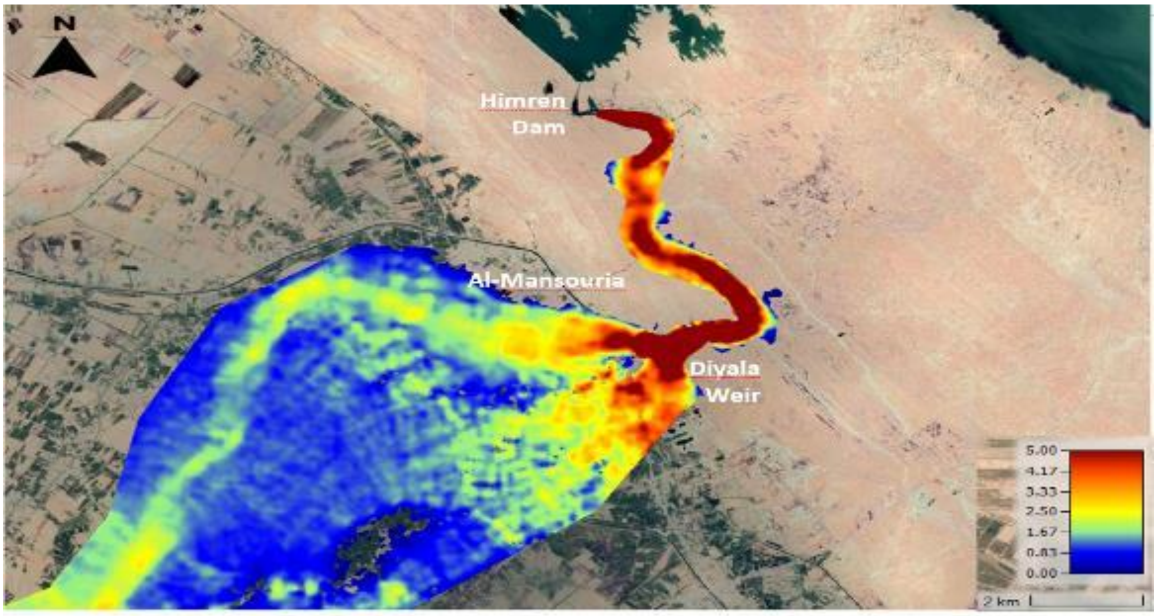

Figure 6. Velocity distribution (Himren dam, Diyala Weir, Al-Mansouria)

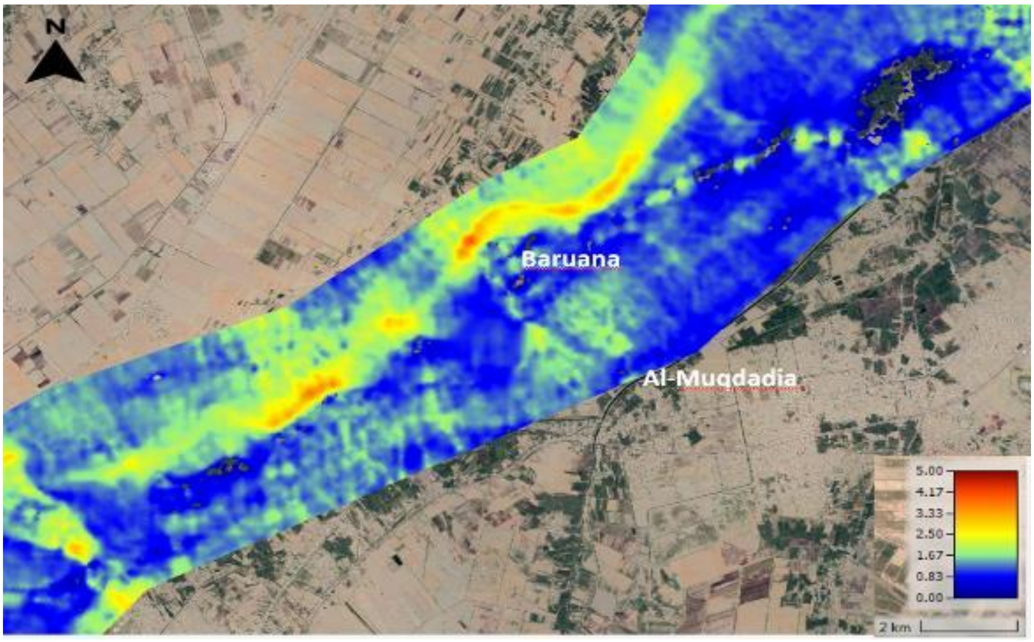

Figure 7. Velocity distribution (Baruana, Al-Muqdadia)

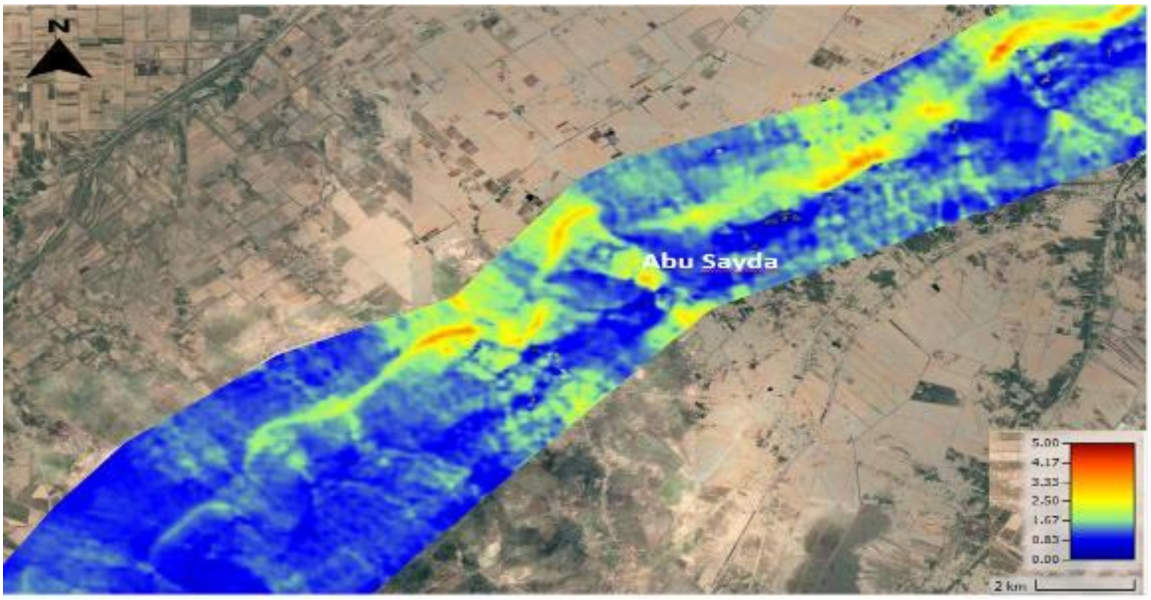

Figure 8. Velocity distribution (Abu Sayda)

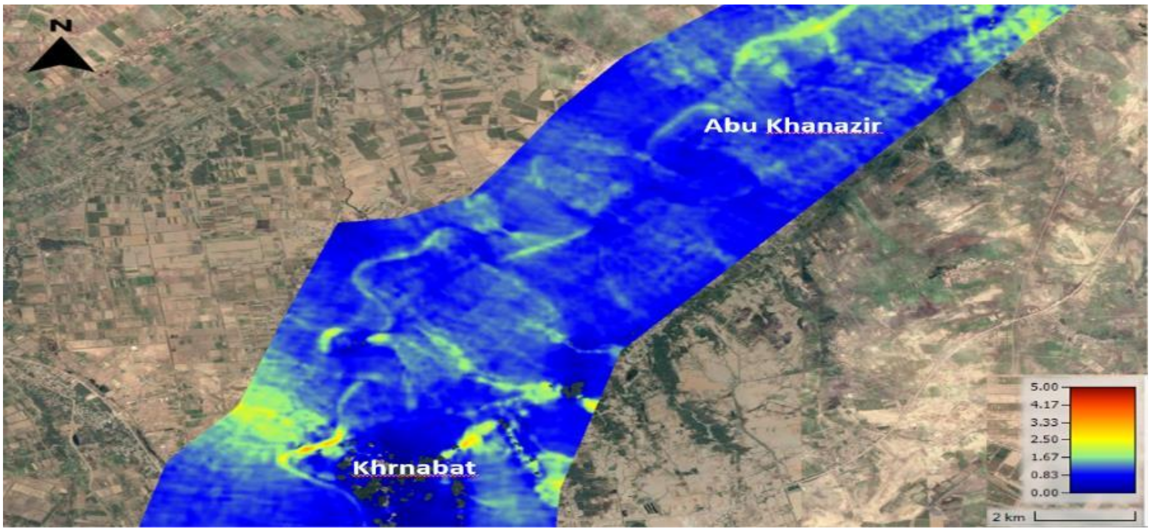

Figure 9. Velocity distribution (Abu Khanazir, khrnabat)

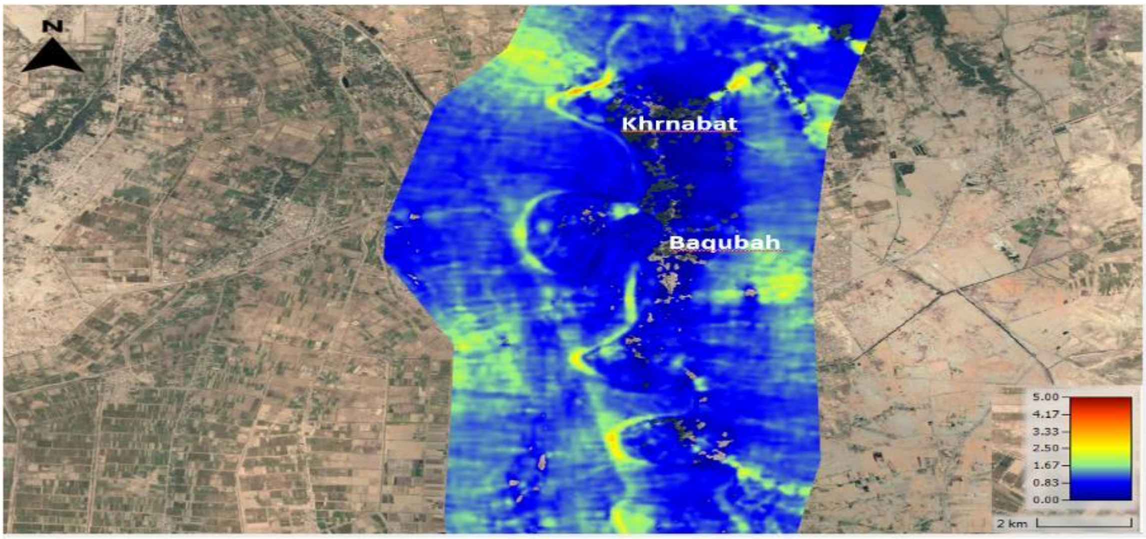

Figure 10. Velocity distribution (Khrnabat, Baqubah)

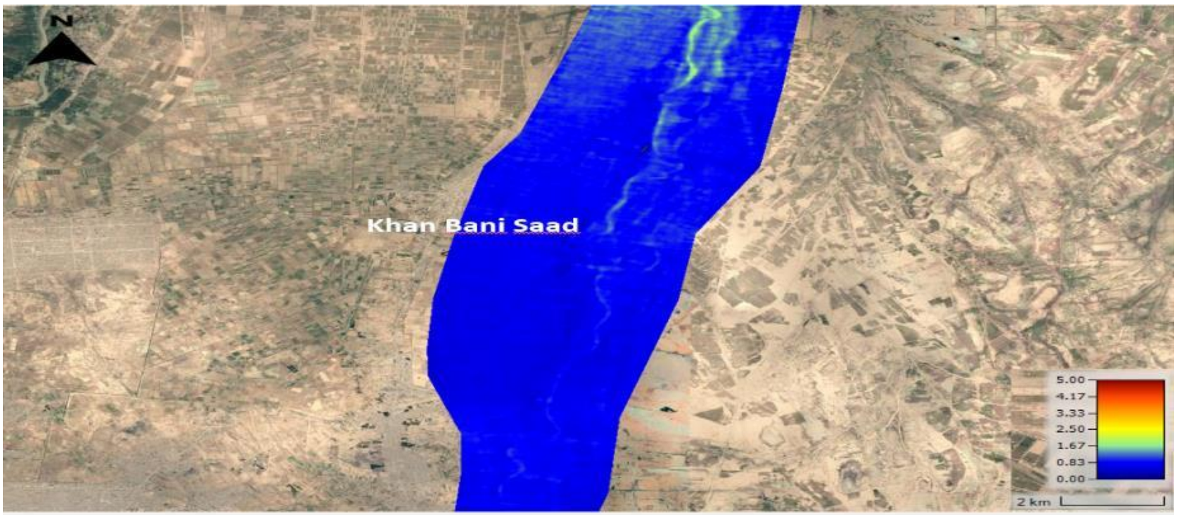

Figure 11. Velocity distribution (Khan Bani Saad)

Figure 12. Velocity distribution (Al-Baladiyat, Baghdad Al-Jadida, Al-Zaafrania, The Confluence of Tigris and Diyala River

4.2. Water depth distribution

Similar to the velocity distribution of the flood wave, the variation and distribution of water depth along the studied reach for different selected locations have been estimated and presented in Figures (13 – 18). According to these Figures, the maximum water depth was located at Diyala weir which was about 66.88m above sea level it arrives after 3 hours after the dam failure and the flood wave began and then gradually decreased until it reached the area the confluence of the Diyala River with the Tigris River after 52 hr from the failure of the dam. Additionally, Figure 20 explains the comparison between the water depths along the different selected locations.

Table 2 shows the results of the maximum discharge, water level, and arrival time after the overtopping dam failure for the most important areas or cities prone to flooding which were obtained through the (HEC- RAS 6.1) program

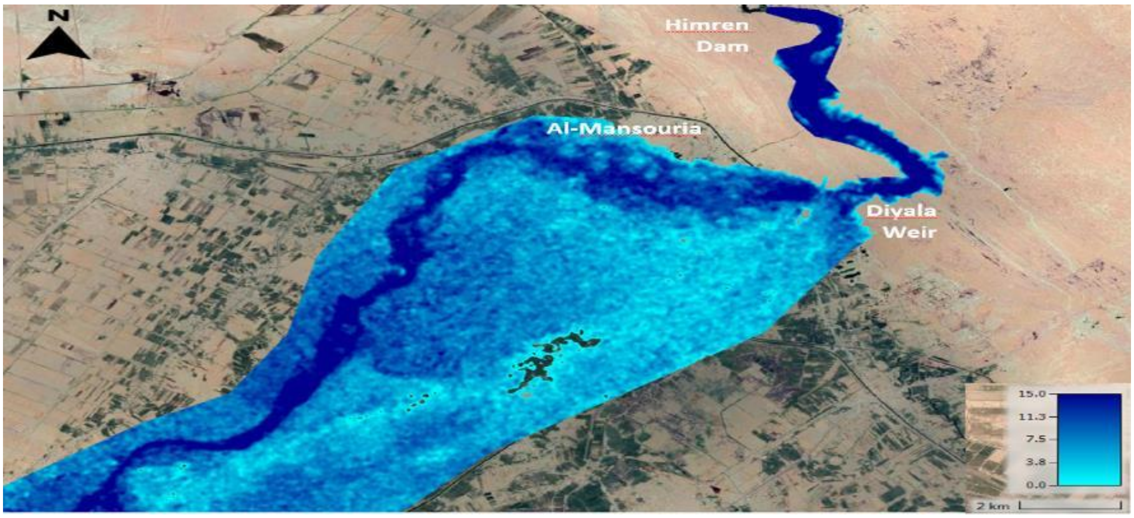

Figure 13. Water Depth distribution (Himren Dam, Diyala Weir, Al-Mansouria)

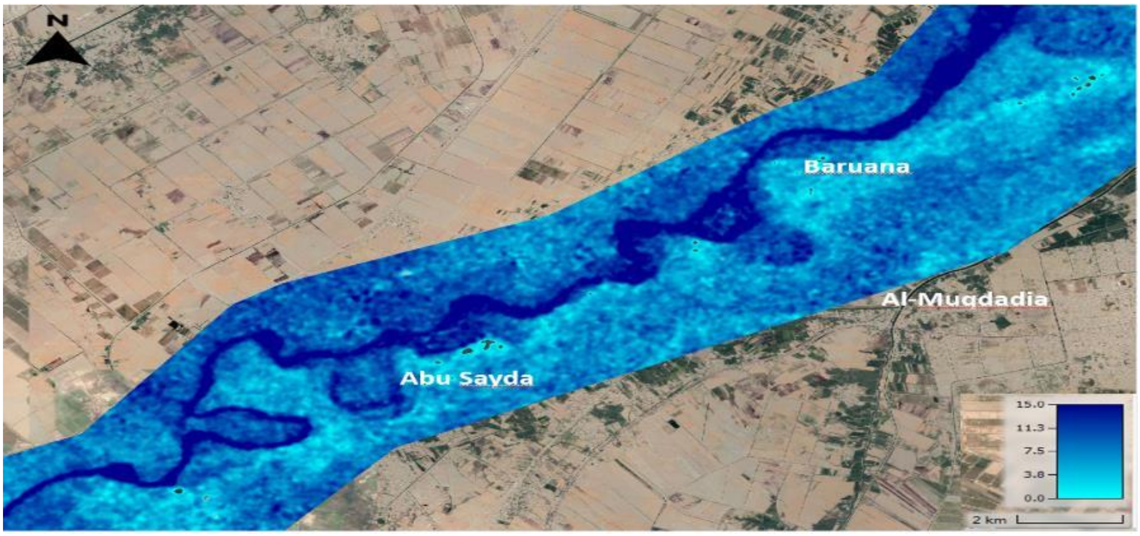

Figure 14. Water Depth distribution (Baruana, Al-Muqdadia, Abu Sayda)

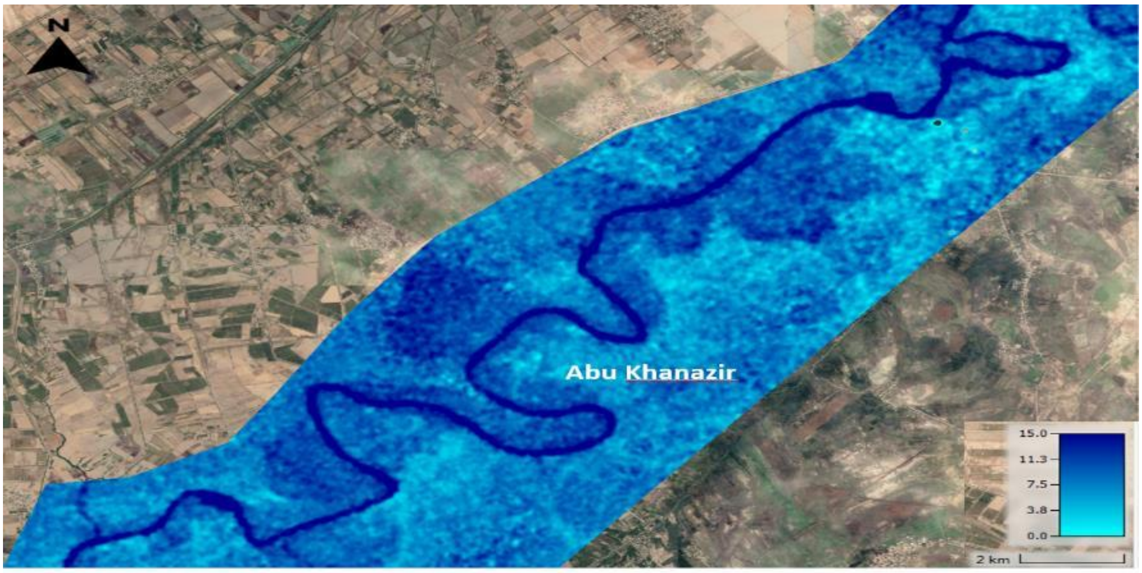

Figure 15. Water Depth distribution (Abu Khanazir)

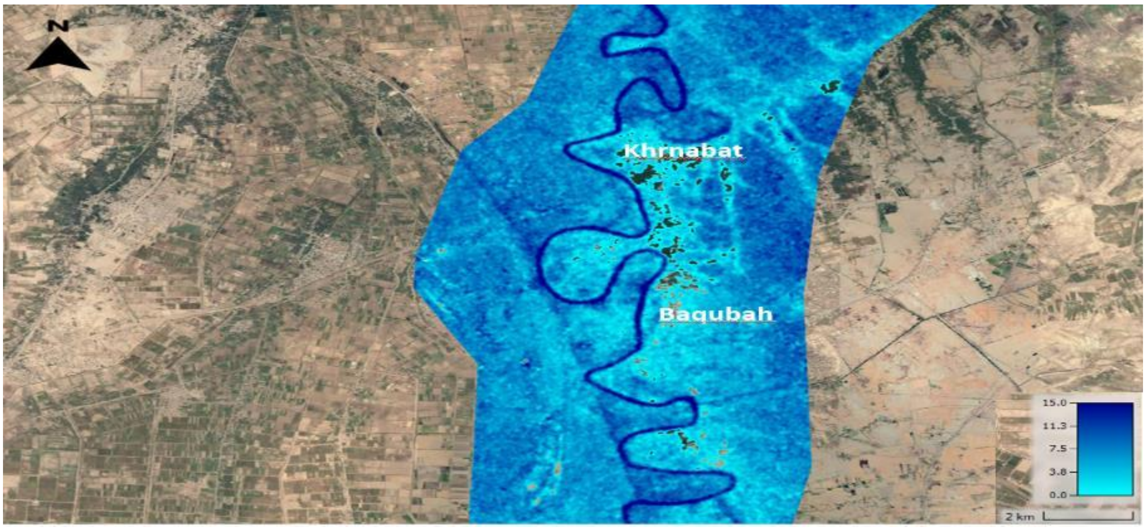

Figure 16. Water Depth distribution (Khrnabat, Baqubah)

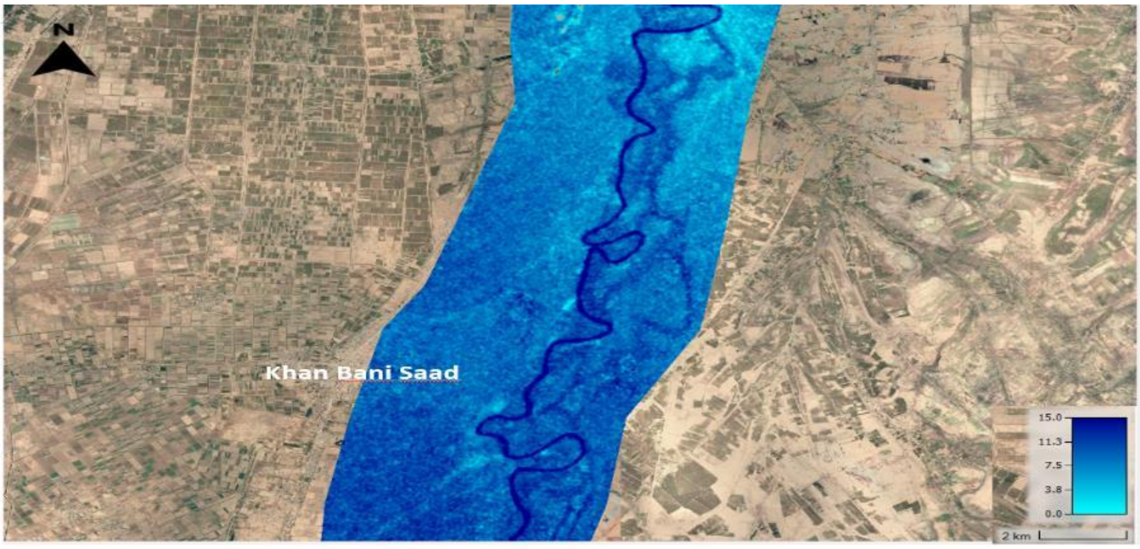

Figure 17. Water Depth distribution (Khan Bani Saad)

Figure 18. Water Depth distribution (Al-Baladiyat, Baghdad Al-Jadida, Al-Zaafrania, The Confluence of Tigris and Diyala River)

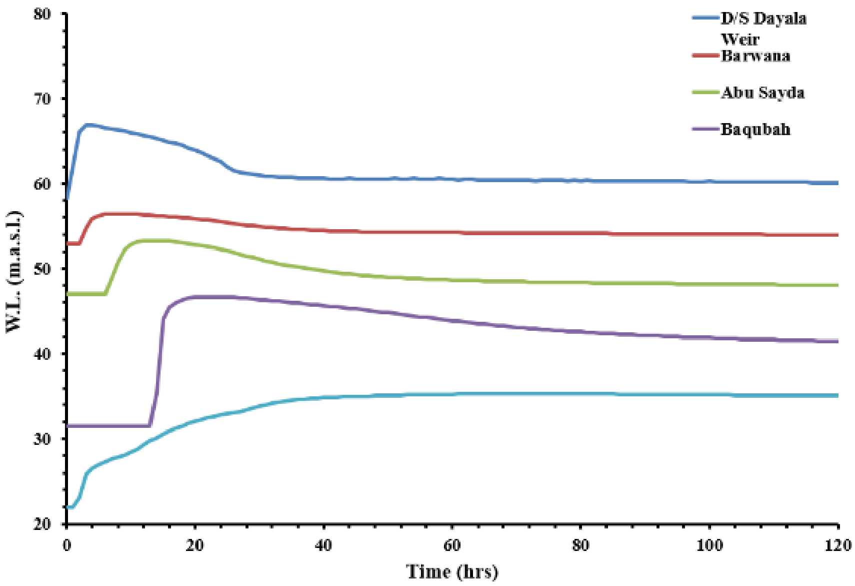

Figure 19. Water level at different locations downstream of Hemren dam

Table 2: The results of the overtopping dam failure

Location	Arrival Time after a dam failure (hr.)	Discharge (m^3/s)	W.L. (m.a.s.l)
Downstream Diyala weir	7.30	85701	79.78
Burwana	12	82788	63.26
Abu Sayda	15	80857	60.6
Baqubah	19	77497	53.25
The confluence of Tigris with the Diyala River	52	59434	50.9

5. Conclusions

Several conclusions can be deducted from the process of dambreak analysis and model construction and application. Below are the most important deductions:

1. The Hemren Dam break is expected to produce outflow hydrographs based on the reservoir's pool level at the breaking time, which poses a clear and threatening danger to the Diyala and Baghdad governorates.
2. Dambreak may occur in different forms or scenarios that vary in peak discharge and formation time depending on the final size of the breach in the dam's body.
3. Estimated flood waves have peak discharges ranging from ($59434m^3/s$) to ($85701\ m^3/s$) that are routed downstream through the main river and irrigation channels across the study area. Peak discharges are expected to reach most of the populated areas within (7.30 in the Diyala weir - 52hr in the confluence with the Tigris River.) from the start of the dambreak.
4. Extreme flooding is expected to affect the study area with significant damage to populated areas in terms of casualties and properties.
5. Diyala River and irrigation systems are incapable of safely conveying the estimated flood waves resulting from of Himren Dam break. Flooding is expected to inundate the overbank areas near the main river and irrigation channels from each side depending on the distance from the dam and the failure scenario.

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