Hypothetical Failure of the Khassa Chai Dam and Flood Risk Analysis for Kirkuk, Iraq

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Abstract

Many of Iraq's high-hazard dams lack an Emergency Action Plan, which should include a flood inundation map to show which downstream areas would be flooded if the dams were to fail. This article presents the results of the simulation of a hypothetical 2D dam break for the 58 m high Khassa Chai dam in Kirkuk, Iraq, using HEC-RAS 2D 5.0.7 software. The Khassa Chai dam is situated 7.4 kilometers north of Kirkuk. The simulations revealed that the dam-break flood will affect eight major bridges and the majority of Kirkuk city's metropolitan neighborhoods. Within an hour, the floodwaters will reach the city's center. The flood hazard map revealed that if the Khassa Chai dam fails, many people, vehicles, and structures will be at danger. The findings of this paper can be used to identify evacuation routes and refuge sites as well as build suitable warning systems in order to limit the risk for fatalities if the Khassa Chai dam fails. Moreover, as the effect of modelling bridges downstream of failed dams has not been explored yet, to the knowledge of the authors, eight bridges have been modeled. It was concluded that ignoring bridges in such a large dam break model will not affect the results significantly, which saves the time of data collection and model development.

1. Introduction

Dams are hydraulic structures that control floods and store water for a variety of uses, including drinking, agriculture, industry, and electricity generation. Dams, on the other hand, are prone to failure if they are not well designed and constructed. When a dam fails, massive flood waves might result, potentially causing catastrophic damage. This might result in serious property damage and even loss of life downstream of the dam. Between 2000 and 2019, more than 450 notable dam failures occurred around the world, resulting in significant fatalities and economic loss (Cannata & Marzocchi, 2012; ASDSO, 2020). A hypothetical simulation of dam failure events and the subsequent floods can be helpful for dam designers, authorities, and owners to reduce the loss of life and destructive events that can occur in the downstream area (Pierce et al., 2010; Albu et al., 2019). Furthermore, establishing Emergency Action Plans (EAPs) necessitates accurate forecasting of downstream inundation levels and the arrival timing of flood waves at a specific place (Wahl, 1997; Pierce et al., 2010; Xiong, 2011). Artificial Neural Networks (ANNs), Neuro-Fuzzy Inference Systems (ANFISs) or both, have been employed in various pieces of literature to assess flood risk for areas downstream of dams (Tien Bui et al., 2016; Ghose, 2019; Sahoo et al., 2020). These machine learning methods have demonstrated their ability to predict flood-prone locations through a training and testing process, but they require large data sets that are typically unavailable and must be determined using hydraulic models. Hydraulic models like HEC-RAS, on the other hand, have been used successfully all over the world to analyze the downstream effects of probable dam failures (Yochum et al., 2008; Gee, 2012; Raman & Liu, 2019; Kilania & Chahar, 2019; Kyaw, 2020). The River Analysis System (RAS) was developed by the US Army Corps of the Engineers' Hydrologic Engineering Center (HEC) to assist engineers in river flow analysis and floodplain mapping. To reduce the risks of loss of life and property damages from dam failures, dam safety communities in many countries recommend developing EAPs for all dams with high and significant hazard potential (National Dam

Safety, 2009). The Khassa Chai dam is classified as a high-hazard dam because it is only 7.4 kilometers upstream of Kirkuk, a highly populated city. As a result, a hypothetical dam-break scenario for the Khassa Chai dam is crucial. The goal of this work is to use the HEC-RAS 2D 5.0.7 software to simulate a hypothetical failure of the Khassa Chai earth dam and analyze the consequences of the associated flood wave.

The paper is organized into four main sections following this introduction. Section 2 presents the materials and methods adopted in this study. Section 3 presents the results obtained from the HEC-RAS 2D dam-break model in terms of flood inundation and flood arrival time as well as the hazard classification. Finally, the paper presents its main conclusions in Section 4.

2. Materials And Methods

The HEC-RAS 2D program, Version 5.0.7, was utilized in this study to model dam-break flooding and subsequently delineate several hazard regions downstream of the Khassa Chai dam. Fig. 1 depicts the methodology's flowchart.

2.1 Breach Prediction Models

According to (Gee, 2012), the location, magnitude, and formation time of the breach are the most unpredictable input parameters in dam failure analysis. The breach parameters can be estimated using a variety of regression equations. Von Thun and Gillette (1990) as cited in (US Army Corps of Engineers, 2014), Froehlich (1995, 2008, 2016a), Xu & Zhang (2009), and Pierce et al (Pierce et al., 2010) are the most widely used regression equations. Several dam-break related literature have employed the aforementioned equations (Gee, 2012; Abdulrahman, 2014; Brunner, 2016; Psomiadis et al., 2021). The features of the Khassa Chai dam (i.e., dam size, storage volume, etc.) are within the range of the data used to generate the mentioned regression equations; thus, the regression equations used in the aforementioned literature are considered appropriate for this case study.

Seventy-five percent of the data utilized to derive most of the above-mentioned regression equations came from low dams with a height of less than 15 meters(Wahl, 2004; Brunner, 2016). As a result, the results of these equations will be less accurate for high dams than for low dams. The results of each of the above-mentioned regression equations are shown in Table 1. It should be noted that the Xu and Zhang (2009) equation for breach development time incorporates more of the initial erosion phase and post erosion period than what is commonly used in HEC-RAS for the critical breach development time. This equation, in general, will result in longer breach development durations than the other equations given above(US Army Corps of Engineers, 2014).

Table 1
The results of breach parameters from the different regression equations.

Method	Breach Average Width (m)	Side Slope Z	Breach Bottom Width (m)	Breach Top Width (m)	Breach Development Time (hrs)
Froehlich (1995)	275.44	1	224.44	326.44	1.014
Froehlich (2008)	107.37	0.7	71.67	143.07	0.86
Froehlich (2016a)	102.8	0.6	72.2	133.4	0.87
Von Thun and Gillette (1990)	182.4	0.5	156.9	207.9	0.89 or 0.69
Xu & Zhang (2009)	80.3		49.35	111.25	8.65

The regression equations in Table 1 cannot accurately estimate the breach size based on past case studies for dams; they either underestimate or overestimate (Wahl, 2004; Gee, 2009, 2012). However, modeling results and breach inundation mapping for many dam-break case studies have shown that selecting an inappropriate set of equations had a significant impact on flood depths and inundation extents as far as a few kilometers downstream from a dam, but as the model progressed downstream, it converged on the actual breach inundation (Yochum et al., 2008; US Army Corps of Engineers, 2014; Shih et al., 2018). In comparison to the other researchers, Froehlich (2016a) has developed the equations based on more data. However, the equation of Froehlich (2008) will be used in this study because their results are very similar to Froehlich (2016a), but they produce somewhat higher flood than Froehlich (2016a).

2.2 Flood Hazard Mapping

In emergency management analysis or EAP development, flood hazard or exposure to flooding risk is critical (Ouma & Tateishi, 2014). The majority of studies in this field (Graham, 1999; Maijala et al., 2001; AEMH, 2014; DRIP, 2018) link flood severity to flood depth, velocity, damage factor (depth $\times$ velocity), warning time, and other factors. Smith et al. (2014) described a strategy for dividing flood areas into distinct zones based on varying combinations of the parameter $D \times V$, taking into account the associated impacts of floods on people, cars, and buildings. As a result, combined curves (see Fig. 2) have been created to break down flood impacts into hazard classifications linked to various susceptibility levels as detailed in Table 2. Table 3 shows the limit of the above classification.

Table 2
Combined hazard curves – vulnerability thresholds (Smith et al., 2014) .

Hazard Vulnerability Classification	Description
H1	Generally safe for vehicles, people, and buildings.
H2	Unsafe for small vehicles.
H3	Unsafe for vehicles, children, and the elderly.
H4	Unsafe for vehicles and people.
H5	Unsafe for vehicles and people. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure.
H6	Unsafe for vehicles and people. All building types are considered vulnerable to failure.

Table 3
Combined flood hazard curves – vulnerability thresholds classification limits (Smith et al., 2014).

Hazard Vulnerability Classification	Classification Limit (D * V)	Limiting Still Water Depth (D)	Limiting Velocity (V)
H1	$D*V \leq 0.3$	0.3	2.0
H2	$D*V \leq 0.6$	0.5	2.0
H3	$D*V \leq 0.6$	1.2	2.0
H4	$D*V \leq 1.0$	2.0	2.0
H5	$D*V \leq 4.0$	4.0	4.0
H6	$D*V > 4.0$	-	-

2.3 Study Area

The Khassa Chai dam is a zoned earth dam with a central clay core and relatively flat sloped shells. The dam's height and crest length are 58 meters and 2360 meters, respectively. As depicted in Fig. 3, the dam is constructed on the Khassa Chai river near the village of Kuchuk, about 7.4 kilometers north of Kirkuk. The dam's construction began in 2005 and was finished in November of 2010. The dam's features are shown in Table 4. In 2008, the city of Kirkuk had a population of 1,050,000 people (Cracknell et al., 2008). The Khassa Chai river, a 70-kilometer tributary of the Zaghaitun, flows through Kirkuk, dividing the city into two sections as it approaches from the northeast. The river finally empties into the reservoir of the Al-

Azim dam. Within the city center, there are eight main bridges on the Khassa Chai river distributed over less than 20 km. Several subsidiary bridges for people and small cars have also been built on the river. Furthermore, there are several high-density residential neighborhoods, administration bureaus, hospitals, and agricultural areas on both sides of the river as well as a huge military airfield and a university (University of Kirkuk).

Table 4
Khassa Chai dam properties.

Properties	Values
Maximum Dam Height	58 m
Dam Length	2360 m
Crest Width	13 m
Crest Elevation	498 masl
Spillway Crest Elevation	491 masl
Spillway Length	108 m
Dam Type	Zone Earth Dam
Reservoir Capacity @ Normal Pool Level	$80 \times 10^6 \text{ m}^3$
Upstream Side Slope	1:3
Downstream Side Slope	1:2
Clay Core Side Slopes	1:1 both upstream & downstream

2.4 Hydraulic Modeling

Using one-dimensional (1D) modeling software, many dam failures have been modeled (Pilotti et al., 2006; Yochum et al., 2008; Pilotti et al., 2011; Gee, 2012; Abdulrahman, 2014). Due to advancements in programming, the researchers have recently shifted to the 2D modeling of flood risk assessments (Vionnet et al., 2006; Mignot et al., 2006; Mandlbürger et al., 2009; Schubert & Sanders, 2012; Rangari et al., 2019; Shustikova et al., 2020). The hypothesis failure of the Khassa Chai dam was modelled using HEC-RAS 2D in this study. In this study, the HEC-RAS 2D program was chosen over the 1D software due to its superior performance, particularly in flat terrain (Altinakar et al., 2008).

Depending on whether existing bridges in the downstream area are taken into account, two alternative types of dam-break models will be simulated to account for the effects of bridges on simulation results. It

has been noted that in some research, bridges were not included in dam-break simulation modeling (Altinakar et al., 2010) without providing any information on the effects of not-included bridges in the modeling on the generated flood. In addition, (Li Changzhi et al., 2014) ignored four existing bridges located downstream of the dam in the simulation, claiming that flooding would worsen if these bridges were included, as the bridges have the capacity to affect flood levels. Thus, two separate models will be built to show the influence of bridge modeling on flood level and flood extent. In the first, the eight bridges together with the Khassa Chai river valley will be taken into account, while in the second, the bridges will be ignored. It should be highlighted that modeling eight bridges in HEC-RAS 2D takes time in addition to the time required for data collecting. As a result, it is planned to show how including bridges in the model affects the results just as much as it affects the length of time it takes to collect data and create the model.

In addition, a non-dam-break flood model based on a 100-year return period flood will be developed to distinguish between dam-break and non-dam-break consequences on the dam's downstream.

2.5. Terrain Data

On May 15, 2020, the Alaska Satellite Facility (ASF) downloaded the ALOS PALSAR DEM for the research area in GeoTIFF format with a resolution of 12.5m × 12.5m. The dataset was chosen because it has a finer spatial resolution than the other DEMs that are freely available. The dataset was retrieved on June 16, 2007. This indicates that the data was obtained prior to the dam's construction. As a result, full dynamic wave routing can be used to represent the reservoir area, which is more accurate than the storage area technique (US Army Corps of Engineers, 2014).

According to (Ngula Niipele & Chen, 2019), the ALOS DEM can efficiently extract the drainage networks of a complex study area. Also, (Shawky et al., 2019) studied the accuracy of SRTM (Global) GL1 DEM V003 28.5 m, ALOS DSM 28.5 m, and PALSAR DEMs 12.5 m and 28.5 m. The results showed that PALSAR DEM 12.5 m-derived channel networks/orders achieved the highest horizontal accuracy compared to those derived from LiDAR DTM 12.5 m.

2.6 Dam-Break Scenarios

According to (Zhong et al., 2011) and other relevant literature, overtopping is responsible for around 35% of all dam failures, whereas seepage or piping and bank slope instability are the second and third most common causes, respectively. Therefore, the following two scenarios are commonly explored in dam-break simulations (National Dam Safety, 2009; ICOLD, 2011):

1. Dam failure due to piping or internal erosion during fair weather conditions with the reservoir at normal pool level and regular inflow. Due to the element of surprise, a fair-weather dam-break failure is widely regarded as having the greatest potential for human life loss.
2. Dam failure due to overtopping during flood conditions (bad weather). Because the downstream residents is "on alert," failure during flood conditions will often result in flooding downstream areas with

less possibility for human life loss.

The second scenario (overtopping scenario) is thought to be very unlikely for the Khassa Chai dam due to its comparatively large reservoir volume, compared to its small catchment area and its large ungated spillway capacity. As a result, only the first scenario (fair-weather) is taken into account while simulating the dam failure at Khassa Chai.

2.7 Model Setup

The model domain for the Khassa Chai dam is divided into two computational domains: one to determine the reservoir geometry upstream of the dam and the other to around 22.0 km downstream of the dam. At the upstream boundary, a zero-inflow condition was determined, while at the downstream boundary, a normal flow condition was assumed with a slope of 0.005 based on the site's prevailed slope. A dynamic Courant stability criterion was established using adaptive time-stepping. As initial conditions, a dry bed is assumed downstream of the dam, and the normal pool level is specified upstream. The dam's largest cross-section is near the deepest part of the valley, where the breach is located.

In terms of bed roughness, a Manning roughness (n) polygon was created in ArcMap 10.4.1 using supervised classification (Fig. 4) and exported to HEC-RAS 2D for dam-break analysis.

Four land cover categories have been considered to represent the modeled area, as indicated in Table 5, based on Landsat 7 image analysis and site visits. The Manning coefficient values were chosen using data from the US Army Corps of Engineers (Brunner, 2016).

In this analysis, an orifice coefficient of 0.8 was chosen with an initial piping elevation of 440 m, exactly at the dam's foundation contact, as it achieves a worse flood than any other level (Awal et al., 2011).

Table 5
Land cover types (Brunner, 2016).

Land Cover	Selected Manning n value	Allowable range of (n) Values
Developed area (High Intensity)	0.2	0.12-0.2
Barren Land	0.03	0.023-0.03
Shrub/Scrub	0.07	0.07-0.16
Water Area	0.04	0.025-0.05

2.8 Mesh Size

One of the most significant advantages of HEC-RAS 2D modeling is that coarse computational mesh sizes can be used without losing the underlying terrain's details. This is because each cell and cell face of the computational mesh in HEC-RAS 2D modeling is preprocessed to create comprehensive hydraulic property tables based on the underlying terrain. In addition, as compared to other models that use single bed elevation for each cell and cell face, the HEC-RAS 2D can yield more details for a given cell size. The net impact is that the simulation time with larger cells is significantly shorter than with smaller cells, resulting in a faster simulation (Brunner, 2016). A sensitivity study was performed using two models, one with mesh sizes of 12.5 m by 12.5 m (1,330,000 cells) and the other with mesh sizes of 20 m by 20 m (561,000 cells), to assess the effects of mesh size on the results. The change in the inundated area was only 0.3 percent; however, the computational time reduced from 65.01 hours to 9.41 hours. As a result, a coarse mesh of 20 m by 20 m was used in this study.

3. Results

In the next lines, the findings of a hypothetical dam-break simulation using HEC-RAS 2D 5.0.7 software are reported. Two dam-break scenarios were investigated. In the first, the eight main bridges in the inundated area were not taken into account, whereas in the second, they were. There was just a 3.2 percent difference in flood extent between the two scenarios. Water backlog occurs as a result of the bridge restriction during the flood event, which accounts for the minor difference. This small variation in results may lead to the conclusion that disregarding bridges in such big dam-break flood simulation models has little impact on the outcomes. This can be advantageous in situations when fast modeling methods are required.

3.1. The Peak Flood Discharge

The most essential parameters that should be assessed in dam-break risk analysis are the dam-break flood hydrograph and its peak discharge. Table 6 shows the peak breach outflow rates calculated using the HEC-RAS model and regression-based equations. It can be observed from the data that Froehlich (1995), Froehlich (2016b), and Pierce (2010) have very similar results, while the results of Xu & Zhang (2009) revealed a considerable difference. The results of the HEC-RAS and the regression-based equation are likewise significantly different. The findings are not uncommon in dam failure investigations. The regression-based equations are beneficial for reconnaissance-level studies as well as assessing the reasonableness of dam failure outflow hydrographs generated as a result of estimated breach parameters (Wahl, 2001). The prediction interval of Froehlich (1995) is between 0.53 to 2.3, according to Wahl (2004)'s uncertainty analysis. As a result, the peak flood is expected to range between 9042 m³/s to 39238 m³/s. Furthermore, given that 75% of the data used to generate the regression equations came from small dams with heights of less than 15 m, comparable results for the Khassa Chai dam, which stands at 58 m, are improbable.

Table 6
Peak breach discharge.

Method	HEC-RAS 5.0.7	Froehlich (1995)	Froehlich (2016b)	Xu & Zhang (2009)	Pierce (2010)
Flood Discharge (m^3/s)	31095	17060	18916	515815	18025

The peak flow rate decreases as the flood propagates downstream of the dam (Yochum et al., 2008; Álvarez et al., 2017). The National Weather Service's (NWS) Rules of Thumb, which are a quick and easy way to estimate flood depth and discharge in severe dam failure conditions, states (Reed & Halgren, 2011):

- Maximum outflow depth just downstream of the dam is no more than $\frac{1}{2}$ the water height upstream of the dam.
- Peak Flow discharge is reduced by about $\frac{1}{2}$ for every 10 miles (16.1 km) travelled along the river downstream of the dam.
- Flood depth is reduced by about $\frac{1}{2}$ for every 10 miles (16.1 km) travelled along the river downstream of the dam.

The decreases in peak flood discharge along the downstream channel of the Khassa Chai dam were computed to support the foregoing conclusions, as shown in Table 7. Table 7 shows that, when the downstream channel distance increases, the peak flood discharge decreases, and that the results obtained using the NWS rules of thumb method and HEC-RAS 2D are equivalent.

Table 7
Peak flood discharge reduction with distance downstream of the dam using dynamic flood routing in HEC-RAS 2D 5.0.7.

Downstream distance from the dam	Peak discharge (m^3/s)	Reduction, %
At the dam axis	31095	0
At 8.3 km	27265	12
At 15 km	14939	52

3.2 Inundation Depth Due to the Dam Failure

The inundation area, which delineates the extent of a flood caused by a dam failure, is an essential requirement for emergency response planners. Fig. 5 depicts the maximum flood inundation depth and extent map as a result of the hypothetical failure of the Khassa Chai dam. The results show that most of Kirkuk's urban districts will be submerged by flood water, with maximum inundation depths ranging from 13 to 18 meters at the city's upper parts and 3 to 7 meters at the city's lower parts.

The flood will affect most residential buildings and some significant service buildings, such as the Governorate of Kirkuk, the military airfield, the General Hospital of Kirkuk, and others, as shown in Fig. 5. The dam's failure will also have an influence on the river's eight main bridges as well as the secondary bridges. The city's major public hospital (Azady Hospital) and several residential structures on both banks of the Khassa Chai river, however, will be unaffected by the flood because they are above flood levels and can be used as shelter sites.

The flood depths estimated by HEC-RAS 2D and NWS Rules of Thumb are shown in Table 8. Despite the fact that the results of HEC-RAS 2D and NWS Rules of Thumb are not identical or even close to each other, the NWS Rules of Thumb criterion is preserved as the depth is approximately halved; the depth of floodwater just downstream of the dam (12.9 m) is reduced to 6.8 m (approximately half) at a distance of 16.1 km downstream of the dam.

Table 8
The flow depth estimated by both HEC-RAS 2D and NWS Rules of Thumb.

Method	Depth Just Downstream of the Dam	Depth at 16.1 km Downstream of the Dam
HEC-RAS	12.9 m	6.8 m
NWS	< 25.5 m	< 12.75 m

3.3 Flood Arrival Time

The warning time is one of the most important factors that affects the loss of life and the vulnerability of communities to flooding (Wahl, 1997; Graham, 1999). The breach initiation time, breach formation time, and flood wave propagation time from the dam axis to a population center are added together to give the warning time (Wahl, 1997). Accurate estimations of warning time are crucial when establishing emergency action plans and building early warning systems; the shorter the warning time, the higher the fatality rate.

For emergency responders, the arrival time of the leading edge of a dam-break-induced flood wave is more essential than the peak time because it shows the amount of time available before highways and

other evacuation routes are flooded (National Dam Safety, 2009).

Figure 6 depicts the arrival time of the water caused by the failure of the Khassa Chai dam. The results show that the water will move in about 35 minutes from the dam to the uppermost border of Kirkuk city (i.e., 7.4 km) and that the leading edge of the flood wave will arrive at the population center in about one hour from the start of the breach formation. For such a heavily populated city, this provides a relatively limited time for warning and evacuation for sudden breach (assumed zero breach initiation time).

3.4 Hazard Classification

The level of hazard posed by a flood varies depending on the intensity and volume of the flood; the flood may result in injury or loss of lives as well as property damage. The combined approach of flood hazard can be used to address the degree of vulnerability of people, vehicles, and buildings to dangerous flood scenarios, as described in the flood hazard section. Fig. 7 depicts the danger classification map created by combining the hydraulic model with GIS. As the dam-break flood wave moves downstream, the severity of the flood is mitigated, as shown on the map. However, the hazard classification study given in Fig. 7 shows that extensive urban areas will be exposed to considerable or high hazard flood levels if the Khassa Chai dam fails (i.e. H4, H5 or H6). The percentage of each hazard type is shown in Table 9. Of the total inundated regions, 36%, 25%, and 10% are classed as H6, H5, and H4 categories, respectively, all of which are hazardous to persons and vehicles. Because locations under the H6 and H5 hazards can cause failure and damage to all types of buildings, local authorities should concentrate their efforts in those areas in the event of a flood.

A dam failure poses a significant threat to Kirkuk city. However, the above-mentioned potential consequences provide risk managers with a framework for establishing an EAP for Kirkuk. An EAP will include a list of the specific structures and persons considered as the most vulnerable, particularly in locations with the highest danger levels (i.e., H4, H5, and H6). Because the flood will affect bridges, the evacuation routes should be designed so that bridges are not used to access refuge places. However, as shown in Fig. 7, the flood area in the city's upper parts will be limited to the valley and will not extend beyond it. As a result, the main refuge region can be recognized as the topmost part of the city. Furthermore, because considerable sections in the city's lower parts are not exposed to high-risk floods because their hazard levels are in the H1, H2, and H3 classes, these locations can be recognized as favorable refuges.

Table 9
Percentage of each hazard type in the inundated area.

Hazard Classification	Percentage of Area	Description
H1	0.12	Generally safe for vehicles, people, and buildings.
H2	0.01	Unsafe for small vehicles.
H3	0.16	Unsafe for vehicles, children, and the elderly.
H4	0.10	Unsafe for vehicles and people.
H5	0.25	Unsafe for vehicles and people. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure.
H6	0.36	Unsafe for vehicles and people. All building types considered vulnerable to failure.

3.5 Non-Dam-Break Flood inundation Depth

As previously stated, a non-dam-break model will be created to demonstrate the differences in the impacts of both the dam-break and non-dam-break floods. The flood maximum inundation depth map developed using a 100-year return period flood is shown in Fig. 8. The highest flood depth, as shown in Fig. 8, is 5 *m*, which is quite modest when compared to the dam breach generated flood depth (i.e., 18 *m*). Furthermore, the inundated areas are primarily limited to the Khassa Chai river valley, with the exception of some locations in the city's lower parts, where some parts of both sides of the river valley will be inundated by flow depths of less than 1 *m*.

4. Conclusions

In this study, HEC-RAS 2D 5.0.7 software was used to simulate the potential failure of the Khassa Chai dam and its effects. The purpose of the modeling was to identify vulnerable and non-vulnerable locations downstream of the dam as well as the risk level to which they would be exposed. Inundation depth maps and wave arrival time maps were produced as part of the simulation findings. The hydraulic model was also integrated with ArcGIS, resulting in the creation of a flood hazard map based on flood depth and flow velocity data. The flood hazard zones are identified and divided into six categories. According to the findings, most parts of urban areas will be vulnerable to flooding, with around 36% and 25% of them classed as H6 and H5 hazard zones, respectively, posing a risk to people, cars, and structures. A H4 zone covers around 10% of the inundated region, making it dangerous for people and vehicles. It has also been discovered that, in addition to residential buildings, the flood wave will affect many administrations, services, governmental buildings, and all bridges to varying degrees due to the failure of the Khassa Chai dam. The flood wave will hit the center of Kirkuk in less than an hour, leaving little time for warning and evacuation, and posing a significant challenge for flood risk management. In addition, the uppermost

section of Kirkuk city, as well as some parts of the lower end, have been classified as refuge locations. Furthermore, it is recommended not to utilize the bridges to access the refuge sites because they are at great risk of flooding.

Despite the presence of eight bridges along the 20-kilometer flood path, the results showed that the bridges had a very small impact on the flood extent, indicating that in urgent cases, it may be possible to ignore bridges modeling in large dam-break flood simulations (i.e., saving data collection and model development times) without significantly affecting the results.

The results demonstrated that the NWS Rules of Thumb cannot be fully adopted as a replacement for the hydraulic model in terms of flood depth downstream of the dam since the results are not comparable to those of the HEC-RAS 2D mode. The simulation findings can give local authorities crucial information regarding the flood severity and depth for the entire research area. The information contained in the resulting maps can be used to determine the best evacuation routes, refuge areas, and establish early warning systems in order to reduce potential fatalities.

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Code availability (Not applicable)

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Figures

Figure 1

Flowchart of the Methodology.

Figure 2

Combined flood hazard curves (Smith et al., 2014).

Figure 3

Study area.

Figure 4

Land cover generated in ArcGIS 10.4.1.

Figure 5

Map showing the maximum depth of inundation due to a hypothetical failure of Khassa Chai dam.

Figure 6

Map showing flood arrival time due to the hypothetical failure of Khassa Chai Dam.

Figure 7

Map showing hazard levels produced due to failure of Khassa Chai dam.

Figure 8

Inundation depth map for non-dam break flood using 100 years return period.