DAM BREAK ANALYSIS USING HEC-RAS: CASE STUDY OF WADI ABU SHEIH, EGYPT

تحليل إنهيار السدود باستخدام HEC-RAS: دراسة حالة لوادي أبو شيح ، مصر

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ABSTRACT

Although it is a low probability, the collapse of flash flood protection dams in arid areas cause dramatic disasters. Such event is extremely unpredictable, so it is necessary to estimate probable flood characteristics over inhabited areas. Analyses of dam break consider the parameter of dam breach to quantify and route the outflow hydrograph due to dam break. Several dam failure simulation models are used to predict dam failure shape and timing, HECRAS being one of the best known. Three cascade flash flood mitigation dams in upper Egypt were breached in 2014 but the details of the event weren't recorded. In this paper, we investigate the application of HEC-RAS 2D in dam break analysis as an early warning system, emergency action plans, and flood mapping implementation tool. That is a powerful tool to understand the complexity of these events and its consequences. HEC-RAS 2D is used to build a hydrodynamic model for a dam breaching case, its reservoir and the downstream flooding zone. The results include flood extent, dam's outflow hydrograph, flow depth and velocity over the inundated delta, and arrival time. After completing this work, further studies for other failing scenarios are required to achieve complete understanding of that disaster.

KEYWORDS

Dam break analysis, Breach parameters, Flood routing, Flood inundation.

الملخص

على الرغم من أن انهيار السدود حدث نادر، إلا أنه يسبب كوارث مأساوية لا سيما في المناطق القاحلة. إنه من الصعوبة بمكان أن يتم التنبؤ الدقيق بهذه الحوادث ومن ثم السيول الناجمة عنه. تعتمد دراسات انهيار السدود على توقع آلية انهيار السدود بالإضافة إلى تحليل حركة السيل الناتج عبر منطقة خلف السد. ويعتبر برنامج HEC-RAS أحد أشهر البرامج في هذا المجال. وفي هذا البحث تم استخدام هذا البرنامج لمحاكاة حادثة انهيار أحد السدود في صعيد مصر في عام ٢٠١٤ حيث انهارت ثلاثة سدود متتالية وللأسف لم يتم تسجيل قياسات تفاصيل الحدث. في هذه الورقة، نحقق في تطبيق HEC-RAS 2D في تحليل انهيار السدود ومدى ملائمة هذه المنهجية في وضع خطط إدارة مخاطر السيول الفجائية. وتبين أن البرنامج يوفر الكثير من المخرجات سواء على شكل جداول أو خرائط زمنية مما يوفر بيانات كثيرة وأداة قوية لفهم هذه الظاهرة المعقدة. وتشمل النتائج خرائط الأراضي التي تعرضت لمياه السيل، وهيدروغراف التدفق الخارج من السد، تغير عمق وسرعة السيل فوق الأراضي المغمورة خلال فترة السيل، ووقت وصول المياه لكل المنشأ المهددة. ويوصى الباحث باختبار تطبيق أنظمة الاستشعار عن بعد كبديل لتوفير بيانات عن نتائج السيول التي لم يتثنى قياسها أثناء الحادثة في ٢٠١٤. وفيما يخص منطقة الدراسة فيجب عمل دراسات أكثر تعقيدا لتشمل كل الاحتمالات الممكنة التي صاحبت انهيار الثلاث سدود في عام ٢٠١٤.

الكلمات المفتاحية

تحليل إنهيارات السدود، ترسيم خرائط إمتداد السيول، تحليل حركة السيول الفجائية

DOI: 10.21608/furp2022.2022.1814

1. INTRODUCTION

Extreme rainfall and resulting flash flood events are a frequent phenomenon in the arid watersheds of the Middle East countries. Small embankment dams are the main flash floods' hazard mitigate structural measure in these areas. But, the failure of such dams causes a very rapid flood wave with an extremely short time, even instantaneous causing widespread devastation. Therefore, It is important to include dam failure analysis into dam design studies, which is unfortunately neglected in most of the time. This paper tests HEC-RAS 2D in simulation of a flood event happened in southern Egypt in 2014 due to dam breach. with the aim of mapping the expansion of the flood, calculate flood characteristics and evaluate resultant damage.

The aim of this study is to show the importance of integrated of dam break hazard assessment and the expected outputs. Although the embankment dams have a lot of advantages, especially the low cost, they have a high rate of failures compared to concrete dams. Failure here means any damage from initial seepage to complete collapse. But usually, failure is used to describe a hole or gap in the dam body (Morris, Hassan, Kortenhaus, & Visser, 2009).
The three main causes of embankment dams failure are hydraulic, seepage and structural failures. Among all failures causes mentioned in **Error! Reference source not found.**, overtopping is the most common reason of breaching of those embankment dams (Saberi, 2016).

Table 1. Classification of earthen dam breach causes source: (Sinha, 2020)

Hydraulic	**Seepage**	**Structural**
over topping	Piping through foundations	Foundation slide
Erosion of upstream face	Piping through the Dam body	Slide in Embankments
Erosion of downstream face	Sloughing	
Erosion of the down stream toe		

Dams failure mechanism is the movement of soil particles when the shear stress of the stored water is higher than the resistance of the soil. The failure or breaching of earth dams takes from minutes (the worst) to few hours (the least bad). Dam's erosion resistance depends on soil type and construction implementation.
Cohesion-less dams, such as rock-fill dams, seepage occurred on dam's downstream face. Where dam's eroded material are removed rapidly layer by layer. Conversely, cohesive embankments aren't usually exposed to seepage in downstream slopes due to the low permeability of its material. But, breaching starts at the dam's downstream toe and spread upward till the crest. Piping is another failure mechanism, where soil particles are removed due to channels formation and growing inside dams leaving holes and discontinuity in soil particles (Xu and Zhang, 2009) .
There are different approaches to analyze dam breaching and predicting the outflow hydrograph and the flood propagation through downwards to determine breaching

consequences on downstream areas. The necessity of accurate and detailed dam breaching analysis increases if vulnerable areas are close to the dam (Fread, 1996).

The hydraulics evaluation includes a breach analysis to determine the area that would be affected if the dam were to breach. Such analysis require the application of dam breach models. By modeling dam breach scenarios, the down stream area could be classified into zones according to the expected damage degree. Singh (1996) emphasized the necessity of analyzing downstream hazards for each dam since the dam's failure mechanism depends on the individual characteristics of each dam besides the cause of failure.

Although there is no agreement to classify the risk of dam failure, it is common to make three classes; the area just downstream the dam is not allowed to create any structure is called prohibitive zone, the second class is called restrictive zone, where damages are expected but not severe. Last zone is the warning zone, where danger is not critical so warning and evacuation systems are enough.

The entire failure process could be divided into two phases. The initiation phase and the development phase. In the initiation stage of breaching, the outflow from the dam is low with small overtopping. While during the development phase, the outflow and erosion occur rapidly (Xu and Zhang, 2009).

Any assessment of the peak flow and potential hazard from a dam failure depends on good estimation of a dam breach location, dimensions, and development time. So, the breach dimensions and development time must be estimated for every failure scenario that will be evaluated.

The most common breach parameter are (Breach depth, Breach width, Breach side slope, breach initiation time and breach formation time). A dam breach often has a trapezoidal shape, see **Error! Reference source not found.**, (Brunner, 1995).

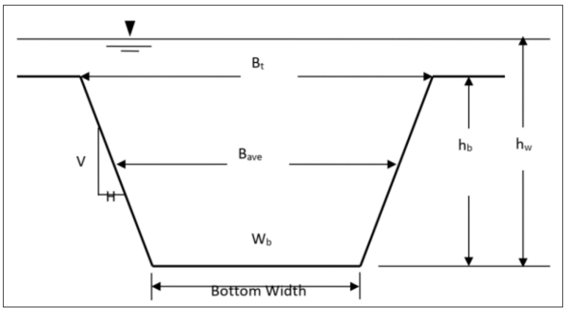


Figure 1. Description of the breach parametersyear)

Dam breaching could be assumed started by a ‘V’ shape of (2V:1H) and grow to be a trapezoidal (2V:1H). And the broad-crested weir equations are assumed represent the flood flow above the dam and the breaches. On the other hand, it is extremely difficult to predict the shape of piping failure (Singh, 1996).

Once an initial breach (or notch) is formed, it will continue expanding according to the duration of overtopping. The breaching process is very complex, so, it is very difficult to accurately predict the location, extend rate, and final final extent dimensions. Determining the consequences of dams failure is determined by dam breach analysis (Sawai et al., 2019).

There are many methods of varying difficulty and accuracy for predict dam breach studies. The simplest method, but the lowest certain, is estimating the breach based on historical dam failure events. Other methods (i.e., parametric models) statistically analyze historical breaches to generate mathematical relations between peak flow during dam failure and breach and reservoir characteristics (such as reservoir volume, breach width). Third approach is the semi-physically based models, which uses breach geometry and/or the erosion rates to produce flow hydrogrph during dams breaching. Last approach is the physically based models, these tools produces outflow hydrographs in high accuracy but with long processing time (West et al., 2018).

Among all available dam breach analysis approaches, the semi-physically approach is selected for this study, we need the whole hydrograph due to overtopping as well as piping failure breaches for earthen dams. Therefore, HEC-RAS is selected because it is free, well documented, frequently updated, and its learning curve is reasonably steep.

1.1. Dam break analysis using HEC-RAS

Since its introduction in 1995, HEC-RAS has grown to become one of the most extensively utilized floodplain modeling tools. HEC-RAS is capable of simulating steady, progressively variable, and unstable flow. Engineers use HECRAS to simulate floodplain hydraulics, evaluate existing conditions, determine the correct hydraulic structure design, and assess the structure's impact.

HEC-RAS is developed to model overtopping and piping failures of earth dams. And it simulates the routing of flood wave downstream using unsteady flow equations. Finally, it maps flood inundation and all its variables using its GIS tool (i.e., RAS-Mapper) (Brunner, 2021). Simulating dam failure using HEC-RAS require information about the dam, spillway, and the expected breach (as listed in Table 3).

Dam break analysis using HEC-RAS consists of three main processes. These are, Routing the Inflow Flood through upstream Reservoir; define the Dam Breach Characteristics; and modeling Flood Routing in dam’s Downstream area.

HEC-RAS allows defining geometry in the study area using cross-sections, two-dimensional flow area, or storage area. Their combination allows users to represent the dam and its upstream and downstream areas using one of six combinations. The most relevant one to this research is representing the whole flow area as 2D flow area, while build the dam using SA/2D connection.

The water storage upstream of the dam can be modeled as a storage area, or a 2D Flow Area. The most accurate technique to simulate upstream reservoir storage, elevations, and outflows of long narrow reservoirs is unsteady Full Dynamic Wave Routing method.

Breach information includes dam breach location, dimensions, development time, etc (see **Error! Reference source not found.**). The most important characteristics controlling the outflow of the failed dam are location, dimensions, and development time. In HEC-RAS, user can enter all breach information or enter the relation between flow velocity and breach expanding relationship. The most uncertain information are the failure time and breach width, so multiple guidelines give accepted ranges of these variables (see (Brunner, 2014, p. 15)).

Table 2. Breach parameters used in HEC-RAS. Source (Brunner, 1995)

Failure Location	**center-line stationing of the breach in the dam**
Failure Mode	**over-topping or piping**

Shape	**bottom elevation, bottom width, left and right side slopes H:V**
Time	**breach development time**
Trigger Mechanism	**Certain water level**
Weir and Piping Coefficients	**coefficients used to compute flow.**

Flood prone areas can be modeled using either cross-section or 2D flow area. The first one is suitable with relatively narrow streams and low computation capacity is available. The other is better for alluvial fans with complex terrain but needs powerful and long computation but it gives detailed results (Brunner, 2014).

1.2. Literature Review

The main concern of dam failure and dam release analysis in Egypt studies is concerned with old Aswan dam, High Aswan Dam & Grand Ethiopian Renaissance Dam (Helwa et al., 2020; Sadek, 2010; Soliman et al., 2014).

(Mhmood et al., 2022) used HEC-RAS to predict the flood propagation wave downstream of Haditha Dam in Iraq. They developed a one-dimensional model simulated a hypothetical overtopping failure and estimate the expected flood risk. They expect that two-dimensional flood breach models produces more accurate risk maps.

A more complicated study is provided in (Mehta et al., 2022). They used HEC-RAS to build both a one-dimensional and two-dimensional unsteady flow model to simulate both piping and overtopping failure.

Several criteria for assessing potential hazard have been developed around the world. In (Psomiadis et al., 2021), the multiplication of water depth and flow velocity, is selected as appropriate criteria for estimating flood intensity downstream of failed dams. Where intensity of more than 2 m2/s is considered endangers human lives.

El Bilali et al. (2021) utilized HEC-RAS and HEC-LifeSim together to evaluation two alternative evacuating processes according to their impact on the resultant flood risk especially the potential life loss

Abdulrahman (2021) estimated the arrival time of the leading edge of a dam-break-induced flood wave using HEC-RAS. Also they identified evacuation routes, refuge sites, and the amount of time available before highways and other evacuation routes are flooded in the study area.

HEC-RAS-2D allows simulating dam-break flood propagation over large flatten urban areas. For example Azeez et al., (2020) studied a historic dam failure in Saudi Arabia that flooded Jeddah city. Breach parameters are estimated from dam failure videos and images taken during and after the event. The model underestimated but with high correlation the water depth.

2. TECHNIQUES AND METHODS

2.1. Study Area and Data Collection

Wadi Abo Sheih is one of the main watersheds in Eastern Desert of Egypt of typical arid to semi-arid climate. It is located between latitudes 26º 30' and 26º 44' N and longitudes 33º 20' and 33º 30' E. The wadi has an area of 1388.2 square kilometers, that flows to an alluvial fan of about 120 Km2. This fan has special importance due to the presence of villages, farms. National roads, and infrastructures.

The flood protection study of the catchment was done in year 2000 and was updated later on 2003. These studies contain site visits, meteorological and hydrological analysis, and designing flood mitigation structures. The proposed structures (see Figure 2) were implemented.

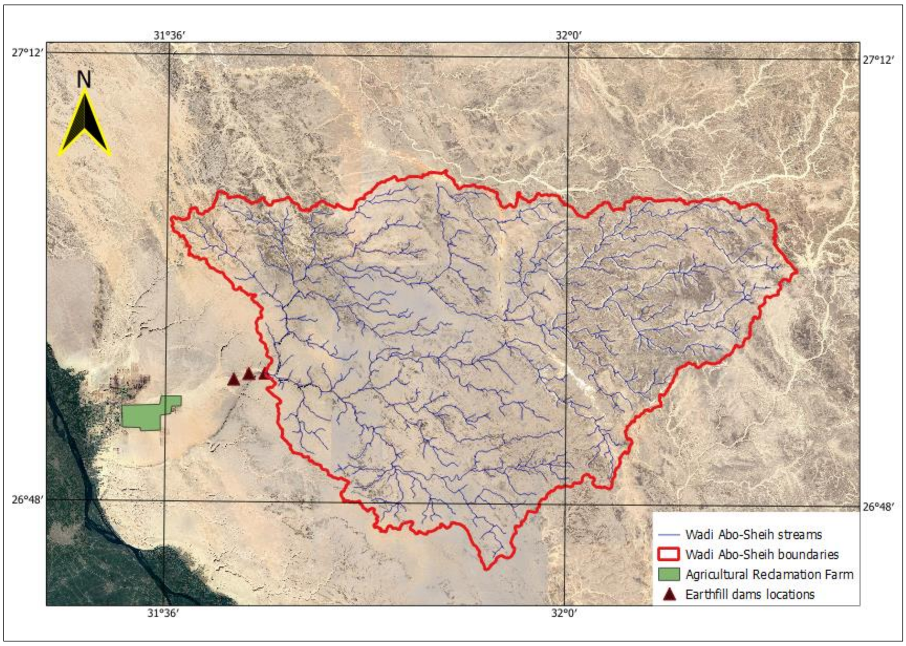


Figure 2. Location map of the study area [Wadi Abo-Sheih]

In March 2014, a storm of rainfall over Wadi Abo Sheih. The generated flash flood caused partial damage to the three small earth dams in the main stream of that wadi (Water Resources Research Institute, 2014) . Unfortunately, the mechanism and order of damage weren’t recorded, so, any simulation of that event will be hypothesized. Therefore, analyzing all alternative failure possibilities is quite a long and complicated study.

This research partially deals with one of the collapse scenarios (**Error! Reference source not found.** to **Error! Reference source not found.**). The expected outputs will be useful and has a significant contribution in future complete studies.

Figure 3. Satellite view of the dam before failure

Figure 4. the dam after failure. outline of the dam (green line). boundaries of the collapse (black dotted line)

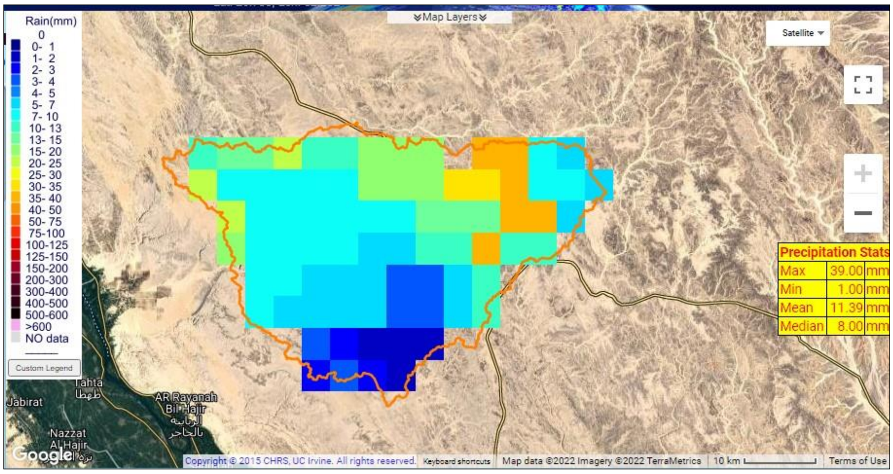
Figure 5. There is a partial collapse of the right shoulder with a length of about 20 m, as well as a collapse of 50 m in the left shoulder. Also, some traces of overtoping

2.2. Methodology

A hydrodynamic dam breach model is introduced here to revisit what happened in Wadi Abu Shieh in 2014 after protection dams were failed. A complete study of all possible failure scenarios of the three dams requires very sophisticated and elongated research, so only a part of the catastrophic event is discussed here. The target is to calculate and map flood characteristics (depth, velocity, and arrival time) within the delta of the wadi. Among the hydrodynamic modeling tools that support flood breach analysis, the HEC–RAS computer program was selected because it is free, popular and easy to use.

The storm happened in 09 March 2014 were recorded in the few rain-gauges found in upper Egypt and also is provided by satellite-based rainfall estimation algorithms (Figure 6). A rainfall-runoff model was built to the watershed using HEC-HMS, hence the resultant hydrograph is estimated. This hydrograph represents the upstream boundary condition that floods the reservoir, dam and the delta.

The terrain of whole simulated area (i.e., reservoir and flooding zone) were geometrically represented using a single 2D flow area. As shown in Figure 7 a 2D flow area with a cell size resolution of 100 meters by 100 meters is created. Calculation cells were condensed near the dam resulting in a computational mesh with 28130 cells to allow accurate application of the shallow water equation. The Manning value for the flow area is set to 0.3. The Upstream boundary line exists four kilometers above the dam, while the downstream boundary line extends along a main irrigation channel.



Precipitation Stats		
Max	39.00	mm
Min	1.00	mm
Mean	11.39	mm
Median	8.00	mm

Figure 6. Storm of 9 March 2014 as estimated by PERSIANN-Cloud Classification System

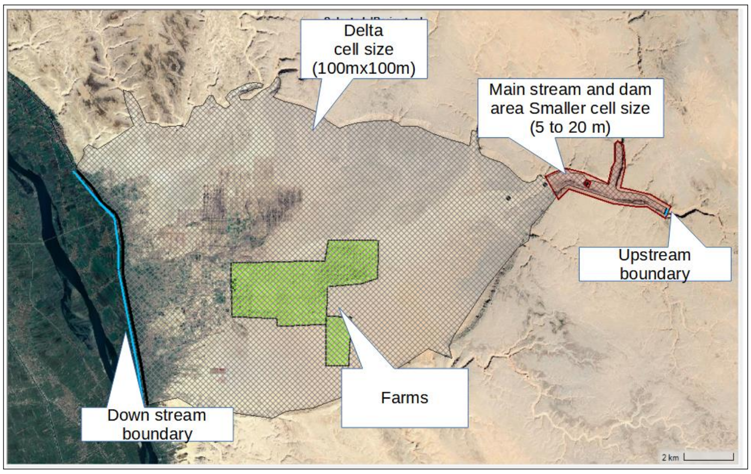
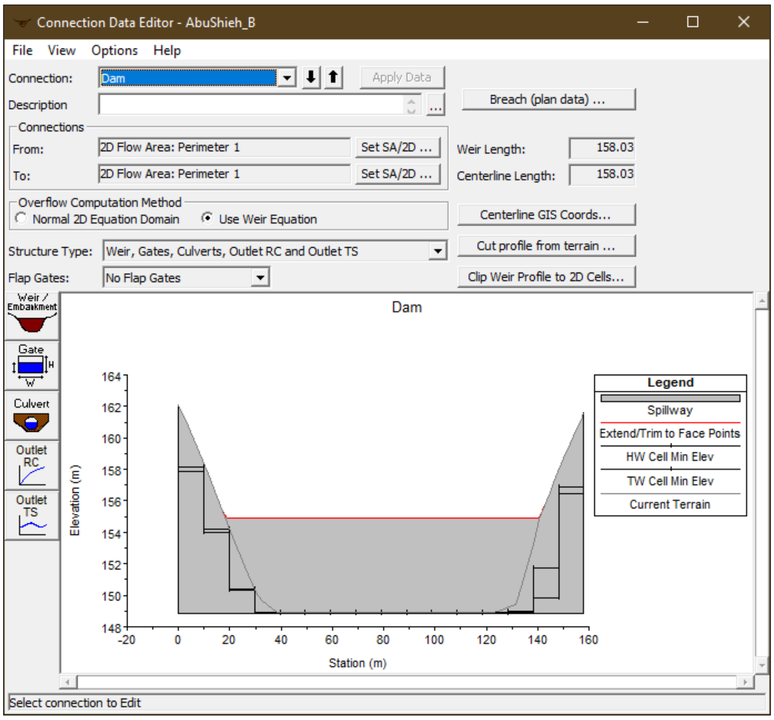


Figure 7. Geometry and boundaries of the study area

The dam (M1) was defined in the model using SA/2D Conn tool, then 'weir/embankment' tool was used to define a six meters height dam as shown in Figure 8.

When it comes to define the breach characteristics, unfortunately, HEC-RAS allows only one breach for each dam, while two breaches (as in 2014) are obtained. So, the set-up of the dam breach was to represent the dam as two adjacent SA/2D Conn. Figure 9 and Figure 10 show dam structure and other breach data (as listed in previously in **Error! Reference source not found.**). Breach formation times are assumed according to (Brunner, 1995, pp. 13–18).



Connection Data Editor - AbuShieh_B

Connection: Dam

Description:

Connections

From: 2D Flow Area: Perimeter 1

To: 2D Flow Area: Perimeter 1

Weir Length: 158.03

Centerline Length: 158.03

Overflow Computation Method

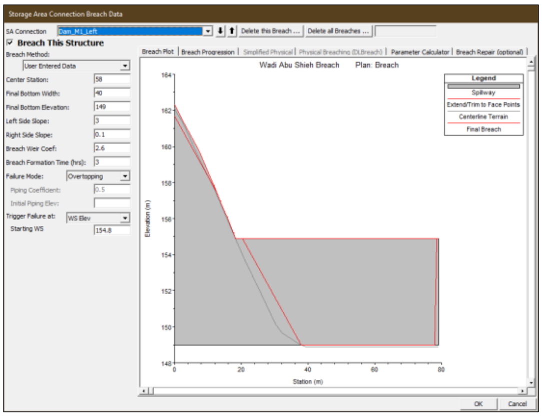
○ Normal 2D Equation Domain ● Use Weir Equation

Structure Type: Weir, Gates, Culverts, Outlet RC and Outlet TS

Flap Gates: No Flap Gates

Select connection to Edit

Figure 8. A cross section at dam location, and dam is added as a weir.



Storage Area Connection Breach Data

SA Connection: Dam_M1_Left

☑ Breach This Structure

Breach Method: User Entered Data

Center Station: 58

Final Bottom Width: 40

Final Bottom Elevation: 149

Left Side Slope: 3

Right Side Slope: 0.1

Breach Weir Coef: 2.6

Breach Formation Time (hrs): 3

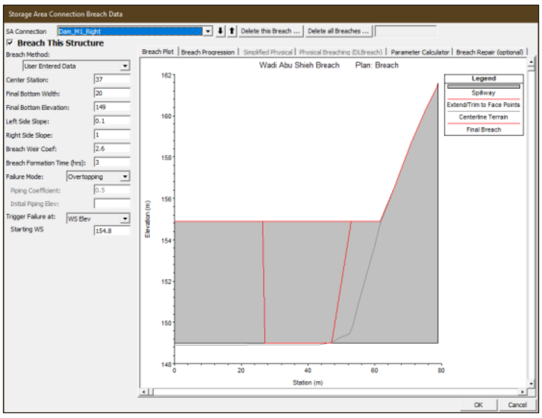
Failure Mode: Overtopping

Piping Coefficient: 0.5

Initial Piping Elev:

Trigger Failure at: WS Elev

Starting WS: 154.8



Storage Area Connection Breach Data

SA Connection: Dam_M1_Right

☑ Breach This Structure

Breach Method: User Entered Data

Center Station: 37

Final Bottom Width: 20

Final Bottom Elevation: 149

Left Side Slope: 0.1

Right Side Slope: 1

Breach Weir Coef: 2.6

Breach Formation Time (hrs): 3

Failure Mode: Overtopping

Piping Coefficient: 0.5

Initial Piping Elev:

Trigger Failure at: WS Elev

Starting WS: 154.8

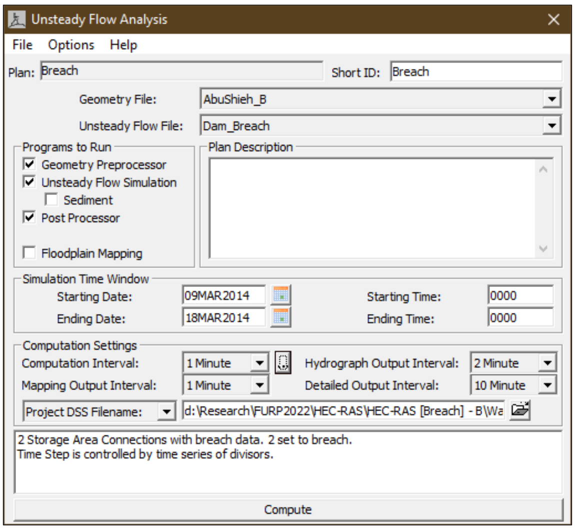
Figure 9. breaching data of the left porting of the dam

Figure 10. breaching data of the right porting of the dam

The simulation period starts in 09 of March to 13 March 2014. Those five days should be enough to empty the reservoir and flood wave to completely path through the downstream area. The general computation interval of 1 minute is selected by shorter time steps were added to achieve accurate representation of the sudden failure (as shown in Figure 11 and Figure 12).

3. RESULTS AND DISCUSSIONS

There are several methods available to view HEC-RAS outputs, mainly graphical or tabular format. Graphical outputs such as georeferenced maps allow visualizing not only flood characteristics but also know what on earth will be affected with it. For example Figure 13 displays the maximum spatial extent of dam-break flood, the flood path, affected area are shown. On the other hand, tabular results gives very detailed information about each structure or pixels within the 2D flow area. Figure 14 shows that outflow reached its peak of 737.876 m^3/s after 28 minutes from the beginning of the reach.



Plan: Breach
Short ID: Breach
Geometry File: AbuShieh_B
Unsteady Flow File: Dam_Breach

Programs to Run
☑ Geometry Preprocessor
☑ Unsteady Flow Simulation
☐ Sediment
☑ Post Processor
☐ Floodplain Mapping

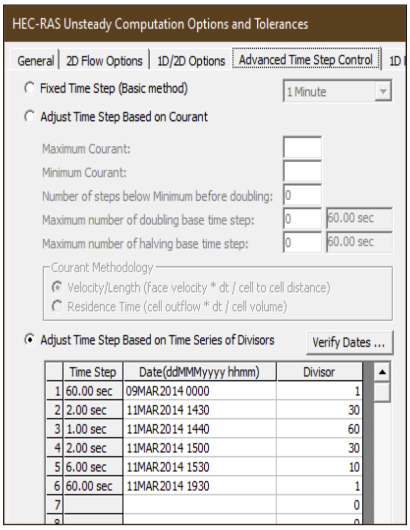
Plan Description

Simulation Time Window
Starting Date: 09MAR2014
Ending Date: 18MAR2014
Starting Time: 0000
Ending Time: 0000

Computation Settings
Computation Interval: 1 Minute
Hydrograph Output Interval: 2 Minute
Mapping Output Interval: 1 Minute
Detailed Output Interval: 10 Minute
Project DSS Filename: d:\Research\FURP2022\HEC-RAS\HEC-RAS [Breach] - B\Wa

2 Storage Area Connections with breach data. 2 set to breach.
Time Step is controlled by time series of divisors.

Figure 11. computation options of the unsteady dam breach model



○ Fixed Time Step (Basic method) 1 Minute
○ Adjust Time Step Based on Courant
Maximum Courant:
Minimum Courant:
Number of steps below Minimum before doubling: 0
Maximum number of doubling base time step: 0 60.00 sec
Maximum number of halving base time step: 0 60.00 sec
Courant Methodology
● Velocity/Length (face velocity * dt / cell to cell distance)
○ Residence Time (cell outflow * dt / cell volume)
● Adjust Time Step Based on Time Series of Divisors

	Time Step	Date(ddMMMyyyy hhmm)	Divisor
1	60.00 sec	09MAR2014 0000	1
2	2.00 sec	11MAR2014 1430	30
3	1.00 sec	11MAR2014 1440	60
4	2.00 sec	11MAR2014 1500	30
5	6.00 sec	11MAR2014 1530	10
6	60.00 sec	11MAR2014 1930	1
7			0

Figure 12. Advanced Time step control options of the unsteady dam breach model

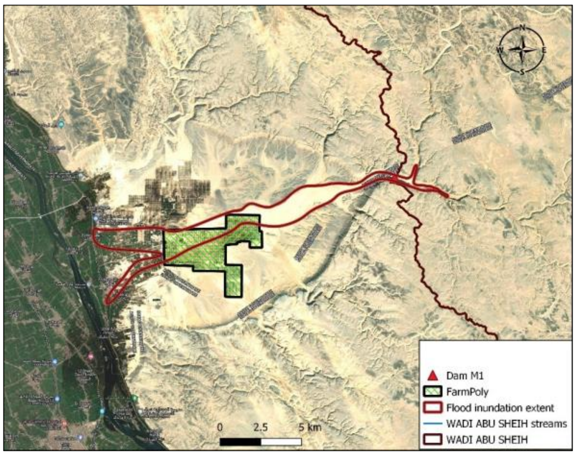


Figure 13. the spatial extent of flash flood cased by dam (m1) failure

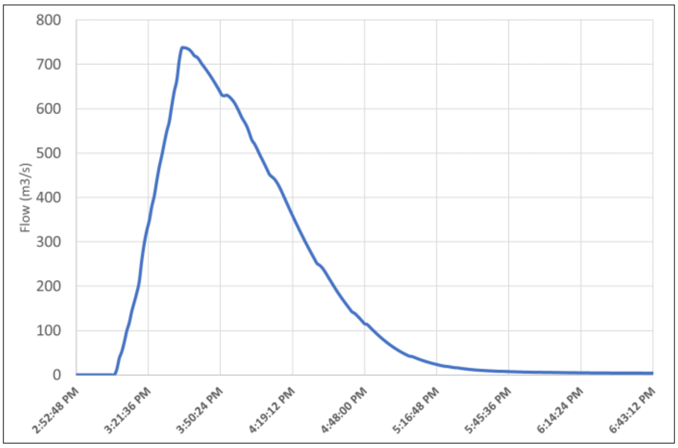


Figure 14. Dam M1 Breach Outflow during day March, 11

The most typical graphical output is height and velocity maps of the water's surface. Shown in Figure 15 is the water accumulated in front of the dam, where water level raised about six meters to the crest level. By the beginning of dam failure, water starts to flow out of the breaches (as shown in Figure 2). Detailed information on water level variations due to flow from the two breaches are shown in Figure 3 and Figure 4

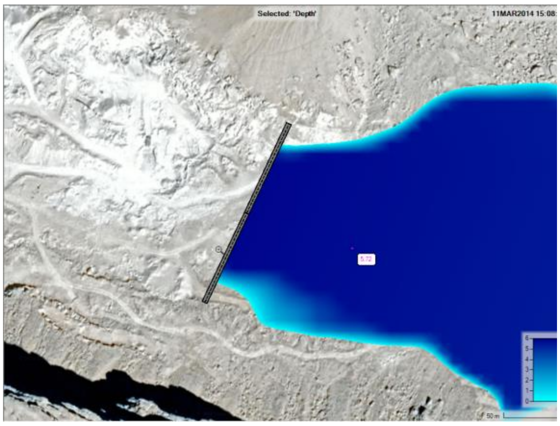


Figure 1 Reservoir is filled before the breach

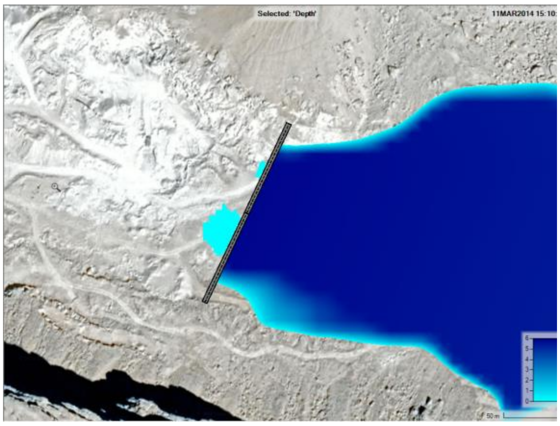


Figure 2 Breaching process started

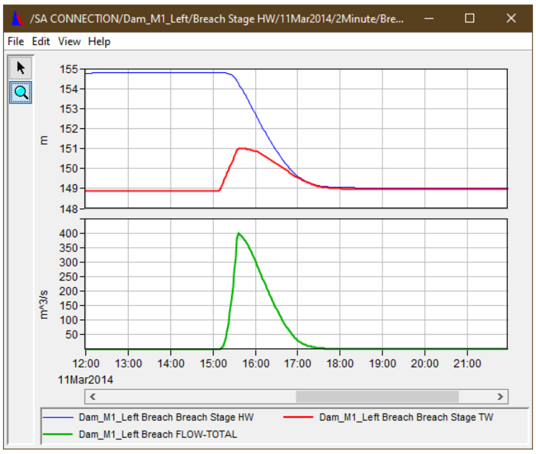


Figure 3 the changes in water level and flow rates due to the left breach

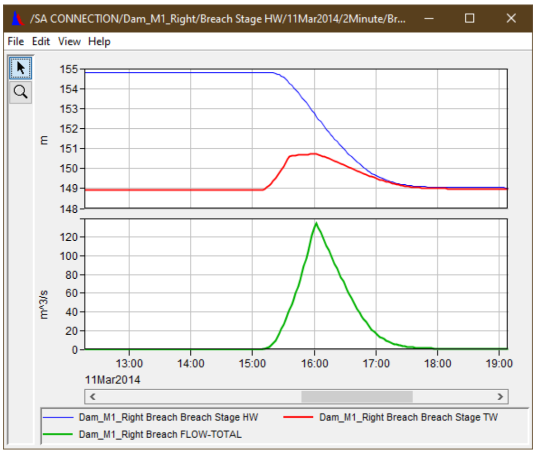


Figure 4 the changes in water level and flow rates due to the right breach

Another useful output from HEC-RAS is mapping the highest values of water surface depth and velocity during the simulation period (see Figure 19 and Figure 20). So, value in these maps may not occurred simultaneously, the importance of such map is to show the worst anywhere. Figure 19 shows water depth high in both upstream (before the breaching) and downstream (during the breaching). Figure 20 shows the highest velocity distribution. It is clearly that peak velocity, hence flow, go through the left breach (50 m wide) not the right breach (10 m wide).

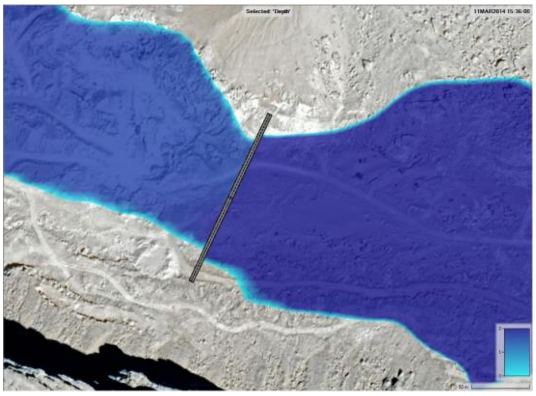


Figure 5 flow depth at moment of maximum flow

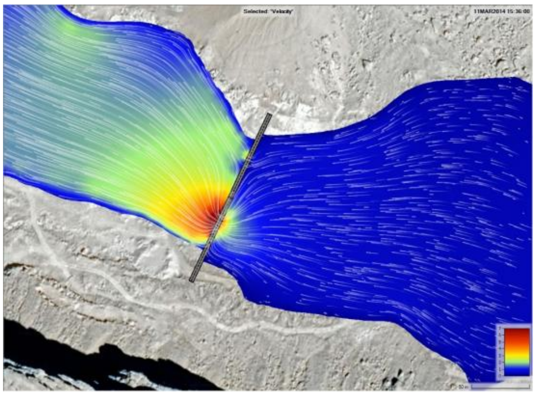


Figure 20 flow velocity at moment of maximum flow

The dam-break models are not only used to identify flood-prone area (Figure 13), but also to assess the hazard involved. Such as mapping the maximum depth and velocity of flood that attach farm in the delta of wadi Abu Sheih (as shown in Figure 21 and Figure 22). These maps demonstrate the part of the farm threatened by flood and also shows that water depth is about one meter while flow velocity is between 0.5 m/s and 2 m/s. similarly, arrive time is calculated to be about two hours after dam breach started.

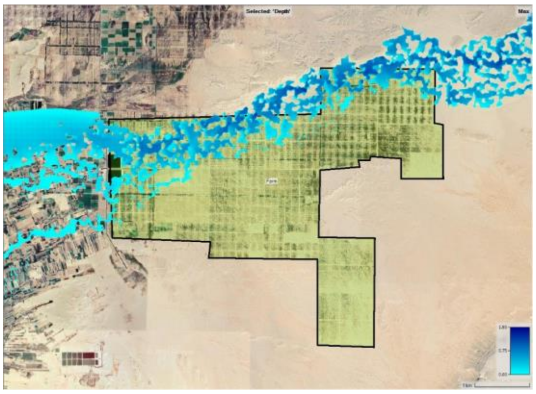


Figure 21 Maximum flood depth

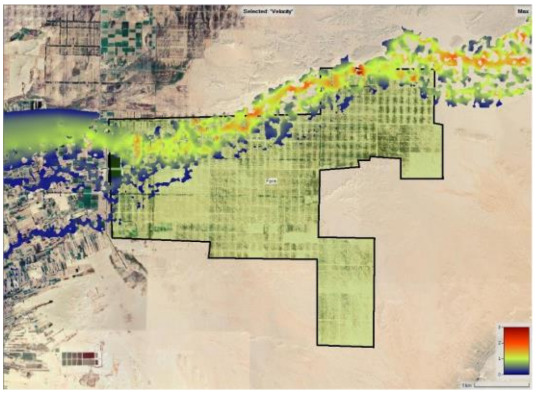


Figure 22 Maximum flood velocity

4. CONCLUSIONS AND RECOMMENDATIONS

Flash floods caused by dam failure cause significant economic loss and even human death. The developed dam failure model using HEC-RAS combined standard model approaches, visual inspection for breach geometry and Manning’s n selection. Generally, the model gave plausible results according to the flooded areas, depth and velocities. It is recommended to consider utilizing remote sensing technologies to calibrate the model.

Considering similar models is highly recommended when planning new urban community, but that required extra detailed site investigation, land survey and data collection.

Results shown that sometimes it enough to provide partial flood mitigation measure which is a promising economic defense alternative.

In this work, only a single failure case is studied (the most upstream dam is totally failed before the failure of the other two dams. It is recommended to consider all other possible scenarios and compare them to stand on the worst scenario or combination of scenarios.

That model calculated flood arrival time, so, we recommend use it to develop flood warning systems.

ACKNOWLEDGEMENTS

I would like to express my very great appreciation to colleagues of the water resources research institute for their valuable comments. And special thanks to Dr. Gamal Kotp for suggesting a suitable study area. I would also like to thank Mr. Zakaria Yacoub for supporting me with photos and notes from his field visit. Lastly, I thank the director, and secretary for providing me with previous studies reports.

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