



## Research Article

# A Framework for Hydraulic Simulation and Risk Analysis of Embankment Dam Break

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**Abstract**

Dams play a key role in supplying water demands, recharging aquifers, and controlling floods, and it is important to accurately study dam break as it could release a huge amount of water and impose catastrophic downstream losses and casualties. An advanced simulation of dam break allows for informing managers of possible losses and casualties to make efficient decisions and effectively manage the crisis. This study presents hydraulics analyzes of the dam break of Tabarakabad and Chahchaheh embankment Dams in Razavi Khorasan Province, Iran. The dam break parameters, flood routing, depth mapping, velocity mapping, primary flood arrival time, and submergible zones were studied for three dam break scenarios, including overtopping, piping, and instantaneous break (sabotage). Numerical analyses were performed in Mathematica environment. The combination of the numerical results and the BREACH model allow for identifying the worst gradual dam break situation through an iterative process and performing unsteady flow analysis in HEC-RAS. Furthermore, the computer code would allow for implementing analyses to determine the most important dam output hydrograph using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). In addition, flood maps under different scenarios were compared between minimum roughness and maximum roughness, discussing the hydraulic results. For risk analysis, a descriptive-analytical (quantitative-qualitative) method was proposed, and a questionnaire was designed. The proposed methodology, which was consistent with passive defense approaches, was implemented with the help of relevant experts and practitioners to assess, and analyze the dam risks through the developed computer code. Finally, the dam break parameters, flood routing under the aforementioned scenarios, flood mapping, and a draft of the necessary measures were provided. It was found that Tabarakabad Dam had a larger degree of risk than Chahchaheh Dam, and its break would impose serious damage to the adjacent villages and the city of Quchan. However, the efficient operation of Chahchaheh Dam could strongly contribute to stabilization and avoiding break floods. The arrival time of dam-break flood wave to Quchan city was calculated 1 h and 30 min to 2 h, while the arrival time of dam-break flood wave to Chahchaheh Village was calculated 45-60 min after gradual break signs.

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### 1- Introduction

Increased human activity and interventions in the environment have increased floods in basins and subjected dams to intensified incoming floods (Amini et al. 2009; Sammen et al. 2017; Wang et al. 2018; de Paiva et al. 2020; Hu et al. 2020; Kostecki and Banasiak 2020; Urzică et al. 2020; Kouzehgar et al. 2021; Liu et al. 2021; El Bilali et al. 2022; Abdulrahman 2022). This endangers the stability of dams. The break of an embankment dam could arise from different phenomena, overtopping (overflowing and the inability of the spillway to discharge the overflow) and piping (the internal erosion of the dam into pipes in the dam body, embankment slope sliding, liquefaction, and shock waves induced by soil mass sliding into the reservoir) (Wahl, 2004). Zhang et al. (2009) analyzed a total of 1065 broken embankment dams and reported that overtopping and technical defects accounted for nearly 80% of the break cases, as shown in Fig. 1.

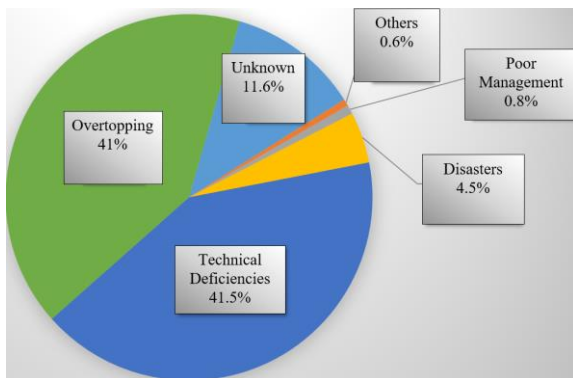


Figure 1. Embankment dam break causes

They also classified the possible dam break causes, as shown in Fig. 2. Although these break causes were reported for embankment dams, some of them hold for other dams.

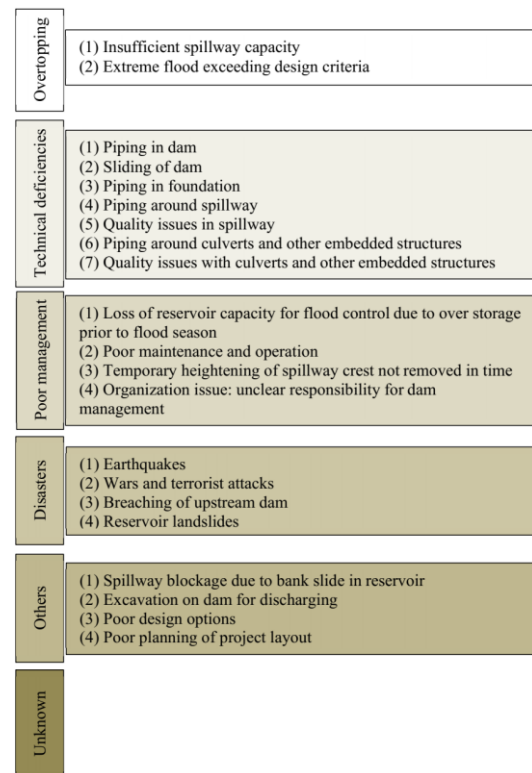


Figure 2. Classification of embankment dam break causes (after Zhang et al. 2009)

Chang et al. (2011) introduced a non-grid numerical model using the governing equations of shallow water flows in open channels with dry and wet beds to analyze dam break. Zhang et al. (2009) studied 1065 broken embankment dams and found that overtopping and technical defects accounted for nearly 80% of the break cases. Today, a total of approximately 600 dams are operating in Iran. Despite extensive research on the construction sites of dams, sophisticated structural calculations, and large financial resources in the construction of such hydraulic structures, dam break is still likely to occur. Dam break occurs gradually or suddenly and leads to a huge, uncontrollable discharge of water toward downstream. Large and destructive floods, earthquakes, intensive leakage from dams or piping, internal erosion in different layers of the dam, and liquefaction are explanations for dam break. Dams have been considered as essential infrastructures by enemies during foreign military attacks. Therefore, the analysis of dam break consequences is a crucial topic in crisis management and water engineering. Maharajan and Takahashi (2014) demonstrated that heterogeneous embankments were more likely to break than homogeneous ones. It is important to study the liquefaction probability of embankment

dams as they mostly consist of different soils. [Heydari \(2020\)](#) proposed an emergency measure plan to cope with the instantaneous break of the Shahr Chay Dam in the vicinity of the Urmia Megacity, Iran. They employed HEC-RAS to simulate dam break under piping and overtopping scenarios and utilized ArcGIS to determine the downstream flood-prone areas. They proposed an effective evacuation plan for people and organizations in each region based on the land use and residing population through the estimated flood arrival time in order to avoid chaos in the event of a dam break. [Amini et al. \(2021\)](#) analyzed the effects of dam break on the downstream using HEC-RAS and GIS to develop a decision-making framework for the safe operation of two sequential dams (Vahdat Dam in the upstream of Zhavveh Dam) in Kurdistan Province, Iran. They optimized the storage of the dams to evaluate downstream stability and introduce a decision-making model for safe dam operation. Piping and overtopping dam break scenarios were examined based on the discharged water quantity. It was found that the break of the upstream dam would break the downstream dam in most cases, and a safe water level was determined for the safe operation of the dams. [Al-Fugara et al. \(2023\)](#) analyzed flood-prone areas in the Al Wala Valley in the governorate of Madaba in Jordan through analysis of the Al Wala Dam under two scenarios: a Clear Day scenario and a Probable Maximum Flood (PMF) scenario. The HEC-RAS was used to analyze flood wave propagation using peak discharge estimated HEC-HMS results. They presented the simulation results of the flood drainage geometry and inundated zones. [Khosravi et al. \(2023\)](#) proposed a model to predict dam break peak outflow by coupling two standalone (random tree, instance-based k-nearest neighbors learning) and new ensemble machine learning algorithms. . Three different input scenarios are used to find the most effective combination of input variables. They stated that machine learning models provide substantially better performance than the empirical equations. [Yang et al. \(2023\)](#) used a stratified sampling Monte Carlo method is proposed to simulate uncertain overtopping breach flood of embankment dams. According to the case study results, though parameters have been controlled in a limited range, the flood routing results in the early stage of dam overtopping failure present greater uncertainty. [Haile et al. \(2024\)](#) simulated flood inundation effects of Midimar dam break on the

downstream areas of Adwa town, located in Tigray regional state, northern Ethiopia using HEC-HMS and HEC-RAS. They showed that both overtopping and piping failure scenarios for probable maximum flood condition of Midimar reservoir represents a significant threat to downstream areas in an event of dam break. The present study focused on hydraulic simulation and risk analysis of the dam break of Tabarakabad and Chahchaheh dams in Iran. The dam break hydraulics, model the unsteady flow, the downstream vulnerability, and risk analysis were considered. Although piping is the most probable break scenario for embankment dams, the hydraulics of instantaneous break, overtopping, and piping was compared and discussed. Flood mapping was carried out for minimum roughness and maximum roughness.

## 2- Methodology

### 2-1- Case study

The Tabarakabad dam is an aggregate embankment dam with a vertical clay core and a maximum elevation of 50 m from the bottom of the reservoir. It is located 21 km northeast of the city of Quchan and 1.5 km downstream of Tabarakabad village. It was constructed on a sub-branch of the Atrak River to supply and regulate the water demand of farmlands and a portion of the long-term drinking water demand of Quchan, control floods, and recharge aquifers. Chahchaheh Dam is an aggregate embankment dam with a clay core with a basin area of nearly 646.5 km<sup>2</sup>. It was primarily aimed at storing water from Chahchaheh River, developing agriculture in the region, and preventing river water loss into Turkmenistan. It is located near Chahchaheh Village on Chahchaheh River in the vicinity of the Turkmenistan border. This river flows 77 km and drains into the Karakum Desert.

Although meteorological parameters do not directly affect the behavior of embankment dams, precipitation and temperature variations may play a key role in the evaluation of the pore water pressure. Therefore, it is important to estimate precipitation and temperature in the dam area. [Figs. 3 and 4](#) report the average precipitation and temperature for different months based on the Climate Change Knowledge Portal (CCKP) of the World Bank (WB) for Tabarakabad and Chahchaheh dams, respectively. As can be seen, Tabarakabad Dam has a cold and arid climate, and the flood risk is maximized in April. Chahchaheh Dam, however, experiences lower precipitation than Tabarakabad

Dam.

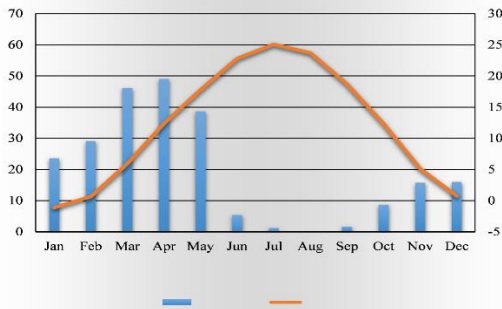


Figure 3. Average precipitation and temperature for Tabarakabad Dam in different months

### 2-2- Hydraulic analysis of dam break

A rapidly varied unsteady flow appears once a dam breaks. Hyperbolic equations govern such flows in shallow areas. The simpler forms of the continuity and momentum equations are given by the Saint-Venant equations as (Akan, 2011; Akbari and Barati 2012; Akbari et al. 2012; Barati et al. 2012 and 2013; Ghandehary and Barati 2018):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\beta QV)}{\partial x} + \frac{\partial Q}{\partial t} + gA \frac{\partial y}{\partial x} + gAS_f - gAS_0 = 0 \tag{2}$$

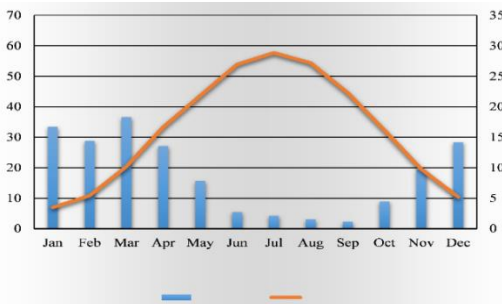


Figure 4. Average precipitation and temperature for Chahchaheh Dam in different months

where  $Q$  ( $m^3.s^{-1}$ ) is the flow rate,  $A(m^2)$  is the cross-sectional area of the flow, and  $x$  (m) and  $t$  (s) represent the space and time, respectively. Furthermore,  $S_0$  is the bed slope,  $S_f$  is the energy grade line slope (energy gradient),  $\beta$  is the momentum modification factor,  $g$  ( $m.s^{-2}$ ) denotes the gravitation acceleration, and  $y$  (m) is the flow depth. The present study exploited the HEC-RAS model, which allows for two-dimensional flow simulation and introducing topographic maps in the latest versions. Floods arising from instantaneous

dam break would result in a rapidly varied unsteady flow which could have two different flow rates at a given flow depth (i.e., a flood rise flow rate and a flood decline flow rate). To simplify the equations, they were solved by assuming a momentum modification factor of 1 and a prismatic section. Also, the bed slope was assumed to be negligible, leading to almost a bed-perpendicular depth equal to the normal flow depth. The dam break parameters could include the depth, width, and slope of the break walls, break onset time and development, peak flow rate, and break flood hydrograph. An instantaneous and complete break assumption applies to concrete dams; however, such an assumption is somewhat inefficient for embankment dams as they break gradually. Two scenarios of gradual break are possible: (1) overtopping (overflow over the crest, as shown in Fig. 5) and (2) piping (voids forming in the dam, as shown in Fig. 6).

The dam break parameters would be determined. To this end, not only were software analyses employed, but also a mathematical model was implemented in the form of a computer code based on previous reports. The gradual break of embankment dams was simulated using the BREACH model based on hydraulic, hydrological, erosion, and sediment transport principles using the dam materials and hydraulic and hydrological parameters (Fread, 1988).

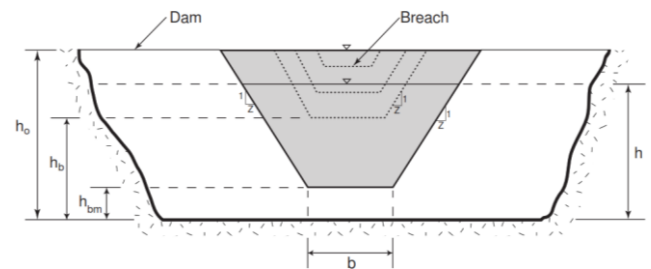


Figure 5. Overtopping dam break parameters (after Fread, 1984)

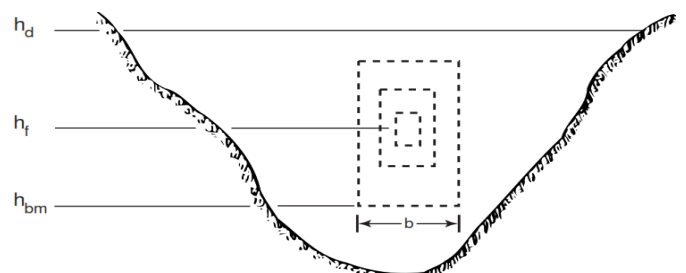
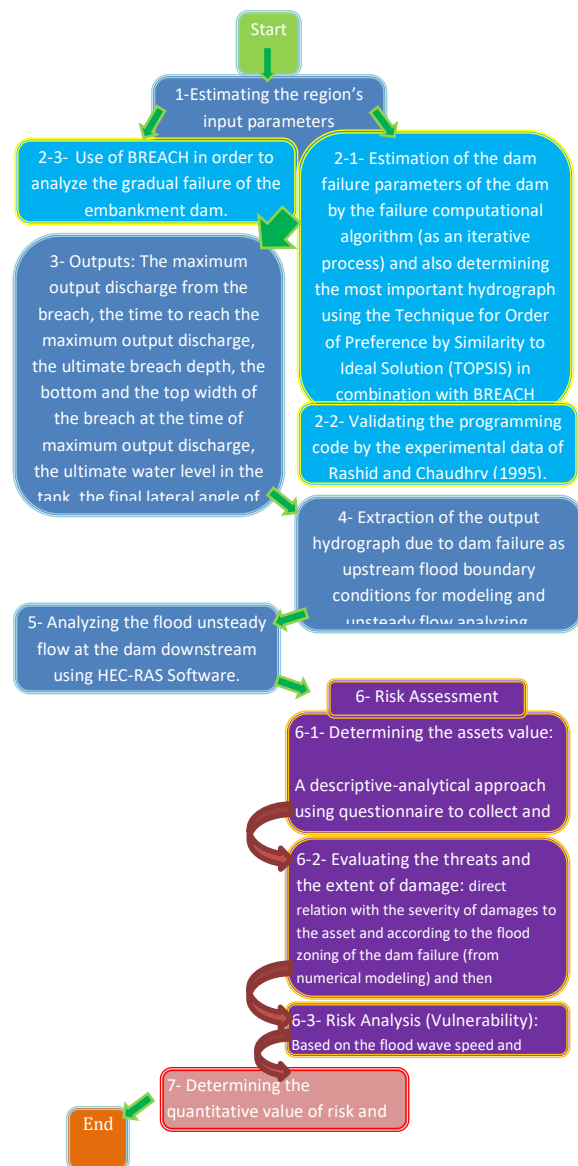


Figure 6. Piping dam break parameters (after Fread, 1984)

The BREACH model allows for inputting data such as the incoming flow hydrograph, river area-elevation curve, tail-water cross-section, and spillway discharge curve and outputting the dynamic visualization of break stages and tables. The outputs also include the peak flow rate, flood maximization time, ultimate breach depth, the top width and bottom width of the breach at the time of the peak flow rate, ultimate reservoir elevation, ultimate lateral breach slope, and the failure time. To simulate the dam break-induced flow, it is required to use the break outflow hydrograph as boundary conditions. Then, unsteady flow analysis is performed via conventional efficient numerical methods. Considering the poor probability of instantaneous embankment dam break, the present study analyzed overtopping and piping break scenarios. The break computation algorithm includes an iterative process as the flow within the break channel is associated with the bottom level and width of the break channel. These parameters are dependent on the flow rate and sediment transport capacity, which are, in turn, dependent on the break flow dimensions and intensity. A Mathematica code was employed to determine the break parameters of embankment dams (for piping and overtopping breaks) without limitations on inputting the reservoir area-elevation curves, stage-discharge curve relation, and tail-water cross-section. The model would output the dam break hydrograph to be used in unsteady flow analysis. It should be noted that the erosion process in the model includes downstream erosion, upstream erosion, and complete break for overtopping and involves downstream erosion, upstream erosion, top material fall, and complete break for piping.



**Figure 7.** Flowchart of hydraulic analysis and risk analysis of dam break

To analyze the unsteady flow and predict its performance in floodways, hydrological flood routing was used to evaluate flow rate variation as a function of time in a given location (Barati, 2011; Barati, 2013; Badfar et al. 2021; Atashi et al. 2023 a, b, c). It requires detailed information on rivers and various hydrometer stations. HEC-RAS was utilized in this respect. The geometric parameters, including the tail-water cross-section, dam shape, and break type, analysis mode (i.e., whether steady or unsteady), boundary conditions, initial conditions, and analysis parameters would be introduced to HEC-RAS to model dam break. The

initial conditions include the water flow rate and depth downstream of the dam. The upstream boundary conditions include dam break-induced flood for possible scenarios and are obtained from BREACH. The downstream boundary conditions are defined in a location very distant from the dam such that the flow depth is equal to the normal depth of the given cross-section. It should be noted that instantaneous dam break is modeled by simulating the reservoir and introducing volume-elevation and area-elevation curves of the downstream unsteady flow. Fig. 7 illustrates the hydraulic analysis process of dam break.

### 2-3- Risk analysis and passive defense considerations

Several scientific techniques, such as risk assessment and analysis, are available to identify the threats, damages, and consequences of infrastructural risks. These techniques include the assessment and analysis of risks (i.e., identifying and analyzing vulnerabilities) and finding efficient solutions to eliminate the risk or control it when it cannot be eliminated (risk control). From a passive defense perspective, risk assessments should be performed for (1) assets (the economic value of assets), (2) threats (and then loss quantification), and (3) vulnerabilities. Finally, the quantity of the risk represents the situation of the case study.

The present study implemented risk analysis using two approaches: (1) risk zone mapping is carried out downstream of the dams using passive defense in a qualitative-quantitative procedure and (2) downstream casualties of dam break are estimated. In the descriptive-analytical approach, literature review, documentation, and online database searching were employed to classify the assets and identified hazards and complete the classifications. Then, based on passive defense expert views and questionnaires (collecting quantitative data), qualitative variables are translated into quantitative variables. It should be noted that the novelty of the present work includes bridging the numerical analysis to the risk assessment. Descriptive parameters are used in most conventional methods in passive defense engineering to evaluate threats and risks, and possible incidents are typically not simulated numerically; however, it was possible to bridge numerical simulation and risk estimation in the present study as it would simulate floods due to dam break and estimate maximum flood zones. A

comprehensive approach was adopted for risk analysis and assessment. In this approach, once GIS maps have been implemented for the three aforementioned fields, the risk is formulated as:

$$R = T V u C \quad (3)$$

where R denotes risk value, T is the threat score, Vu is the vulnerability score, and C denotes the score of the consequence of losing the element under study (i.e., asset value). To determine high-risk areas, it is required to calculate the product of the scores in each GIS layer and provide a representation of the high-risk points (risk zone mapping). The present study divided assets into five groups, including farmlands (as the main means of income in the areas under study), infrastructural facilities of industries, mines, and factories, roads, residential areas (including rural or urban buildings), and population centers (e.g., universities and stadiums). These groups differed for the dams in terms of both value and area. The assets were determined for the case-study areas using satellite images, as shown in Figs. 8 and 9. The population centers were weighted based on the residing population downstream of each dam using weight coefficients derived from the questionnaires as representing the importance of assets. Experts working at consultation service companies and Khorasan Regional Water Company and relevant academics would respond to the questionnaires.

The identification of threats is directly associated with the intensity of asset losses. Since the present study modeled dam break-induced floods and carried out flood mapping, the areas under potential threats would be determined using numerical simulation. The areas that would be flooded were identified as potential threats using GIS maps after flood mapping. The vulnerability of assets downstream of the broken dam is dependent on the flood velocity and wave height. These parameters were calculated along the floodway after analyzing dam break-induced floods, scoring vulnerabilities accordingly.

### 3- Results and Discussion

To model piping or overtopping, geometric data and physical parameters of the case-study dams were collected, as listed in Table 1.

The other parameters were set to default values in the BREACH model. The data of the downstream sections were extracted from satellite information and relevant maps. The area-elevation and volume-

elevation curves were derived from the hydrometric data, as shown in Fig. 10.



Figure 8. Assets downstream of Tabarakabad Dam



Figure 9. Assets downstream of Chahchaheh Dam

Table 1. Input parameters of the break models of Tabarakabad and Chahchaheh Dams

Input Parameters	Part	Symbol	Unit	Tabarakabad Dam	Chahchaheh Dam
Internal friction angle	Core materials	AFRC	degree	24	26
	Shell materials	AFRS	degree	41	40
Coherence coefficient	Core materials	COHC	ton/m <sup>2</sup>	2	3
	Shell materials	COHS	ton/m <sup>2</sup>	-	2
Specific weight	Core materials	UWC	ton/m <sup>2</sup>	1.78	1.8
	Shell materials	UWS	ton/m <sup>2</sup>	2.1	2.1
The ratio of the horizontal to vertical length of the downstream slope	Shell materials	ZD	-	1.65	2.0
The ratio of the horizontal to vertical length of the upstream slope	Shell materials	ZU	-	1.8	2.1
The averaged ratio of the horizontal to vertical length of the core slope	Core materials	ZC	-	0.25	0.2
The Dam downstream slope	-	SM	ton/m	0.011	0.018
Crest width	-	WC	m	10	10
Crest length	-	CRL	m	193.5	250
Spillway width	-	SPW	m	15	22
Spillway bottom level	-	HSP	m	1513.5	577
Dam crest level	-	HU	m	1523.5	586
The bed level on the downstream side	-	HL	m	1480	544
Maximum bottom opening at the time of failure	-	BMX	m	80	100
Design flood	-	PMF	m <sup>3</sup> /s	1211	1317
Flood peak time	-	Tpic	hour	5	5

### 3-1-1- Analysis of instantaneous dam break

For instantaneous dam break, it is assumed that the flow depth remains unchanged and the wave velocity is zero in the broken part of the dam. For a

given reservoir volume, the hydrograph of the discharge rate has two regions. In the first region, the flow rate is constant. Due to the discharge of water, the water storage and elevation of the reservoir decrease over time until the reservoir elevation becomes  $4.9y_0$ , and the discharge rate declines. To model this scenario in HEC-RAS, the

relationship between the reservoir and two-dimensional space was exploited, assuming only a few seconds of dam break duration. The subsection “unsteady flow analysis” provides the flow depth and velocity results of this scenario.

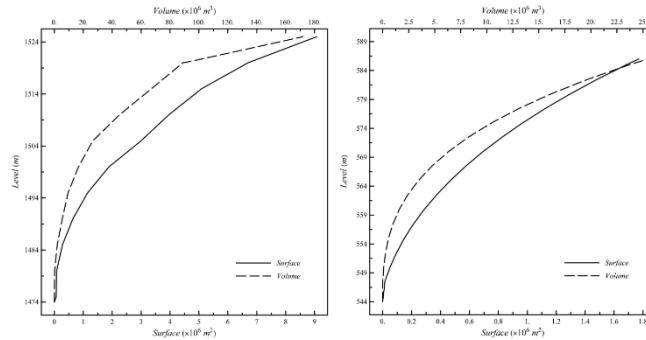


Figure 10. Area-elevation and volume-elevation curves of (a) Tabarakabad and (b) Chahchaheh Dams

### 3-1-2- Analysis of piping dam break

For the piping dam break scenario, it was assumed that the reservoir had no inflow at the time of break. Furthermore, the reservoir volume is a sensitive parameter in the analysis. Since piping is more probable and destructive at higher reservoir elevations, the normal elevation was considered for the piping break scenario. Moreover, piping may occur in the dam structure at different depths, leading to different peak flow rates and peak times at different piping conditions. Thus, the piping phenomenon was coded and simulated for different piping break conditions to identify the most

important hydrographs of piping for unsteady flow analysis. The scenario was simulated using the developed code in BREACH for the two case-study dams at 100 different elevations, ranging from the spillway bottom level to an elevation 25% of the distance between the dam bottom and spillway bottom. The completion of piping would require a certain water height on the break location. It was found that only 65 and 84 of the studied elevations enabled the completion of piping in Tabarakabad and Chahchaheh Dams, respectively, as shown in [Figs. 11](#) and [12](#) – hollow circles represent the peak flow rate time of each hydrograph.

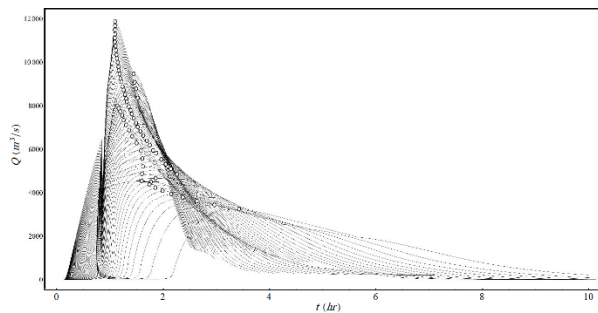
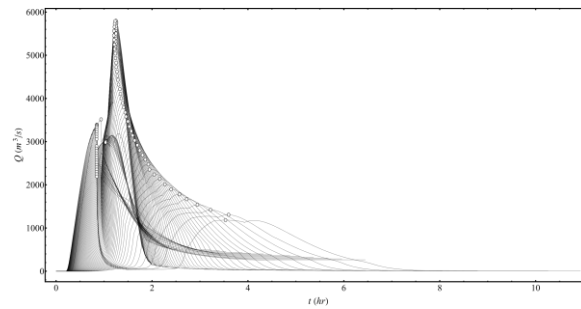


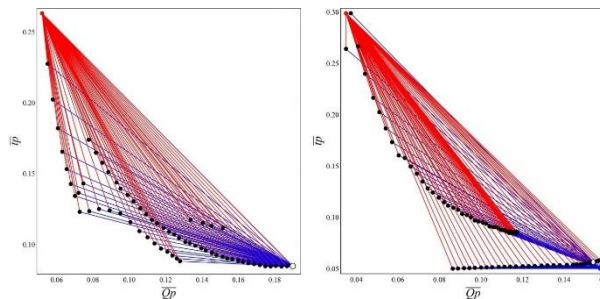
Figure 11. Piping break simulation of Tabarakabad Dam for 65 elevations



**Figure 12.** Piping break simulation of Chahchaheh Dam for 84 elevations

Interestingly, the minimum peak flow rate time and maximum peak flow rate did not necessarily occur in the same hydrograph. Therefore, to determine the most important hydrograph, TOPSIS

was employed based on the two main criteria, i.e., peak flow rate time and peak flow rate with the same weight coefficient, as shown in [Fig. 13](#).



**Figure 13.** TOPSIS results for (a) Tabarakabad and (b) Chahchaheh Dams

TOPSIS seeks to find a solution from a set of solutions that has the highest similarity to the ideal solution and lowest similarity to the worst solution. The peak flow rates and peak flow rate times were normalized based on TOPSIS. In [Fig. 13](#), the blue lines represent the distance between the best solution and the obtained solutions (solid circles), while the red lines stand for the distance between the solutions and the worst solution. In addition, the white circle is the best solution. The worst piping break was found to occur at an elevation of 22.12 m from the bottom in Tabarakabad Dam and 20.17 m in Chahchaheh Dam. Fig. 14 depicts the TOPSIS-derived hydrographs of Tabarakabad and Chahchaheh Dams for piping. To validate the coded model, the numerical models were compared to BRCH-J. The coded model and BREACH model were found to be in good agreement, and the slight differences between the models are attributed to different assumptions and time steps. Hence, BRCH-J was employed to implement hydraulic analyses.

The subsection “unsteady flow analysis” provides the flow depth and velocity results of Tabarakabad and Chahchaheh Dams in the piping break scenario.

### 3-1-3- Analysis of overtopping break

Tabarakabad and Chahchaheh Dams were designed based on the probable maximum flood (PMF). Thus, the analysis of overtopping required a new scenario for overtopping. This could be possible in two ways. First, the inflow of the reservoir should be calculated using hydrological models. These models require data of meteorological stations, basin, statistical models, and basin bottom topography. This results in an inflow rate with a lower probability than PMF and a higher magnitude. Second, it is required to consider a defect in the hydraulic system of the spillway such that the spillway could discharge only half of the reservoir inflow. The second way was selected since it required no statistical data and emphasized the importance of the embankment dam structures containing no defects. The inflow rate of the reservoir was assumed to be PMF, and the flood time was considered to be the same as the peak flood time reported in previous hydrological studies. According to [Fig. 10](#), the reservoir area and volume substantially increase at elevations near the crest. The BREACH model revealed that Tabarakabad Dam would not be endangered at an incoming flood time of 5 hours even when the spillway discharged

only 50% of the inflow. It was also found that overtopping was likely to occur at a flood time of 25 hours. Thus, overtopping has a very poor probability in Tabarakabad Dam. Despite its negligible probability, overtopping was investigated for Tabarakabad Dam in the present study. For Chahchaheh Dam, on the other hand, an inflow rate as large as PMF for 5 hours (i.e., peak flood time)

and a spillway discharging 50% of the inflow (the spillway on the verge of overflow) were found to induce overtopping. To avoid overtopping, the effective operation of the spillway is more circuital for Chahchaheh Dam than for Tabarakabad Dam. Likewise, the developed code and BREACH model were compared to validate the proposed model for the overtopping scenario, as shown in Fig. 15.

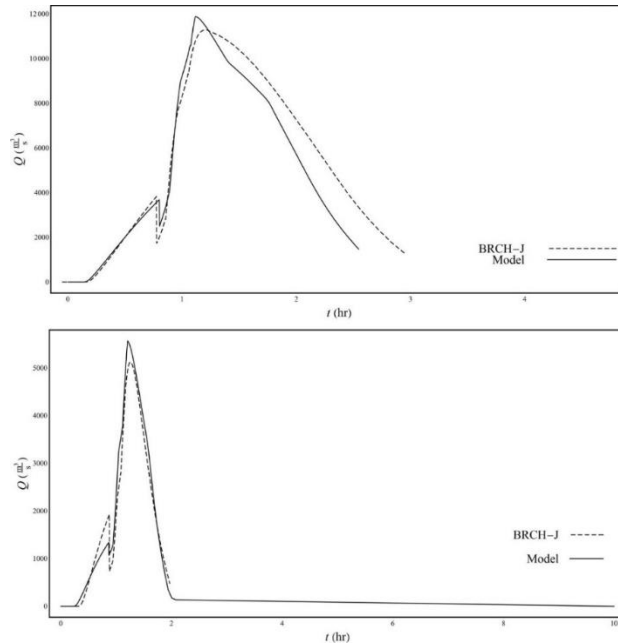


Figure 14. Hydrograph of the proposed scheme and the validation by comparison to BREACH model for the piping of (a) Tabarakabad and (b) Chahchaheh Dams

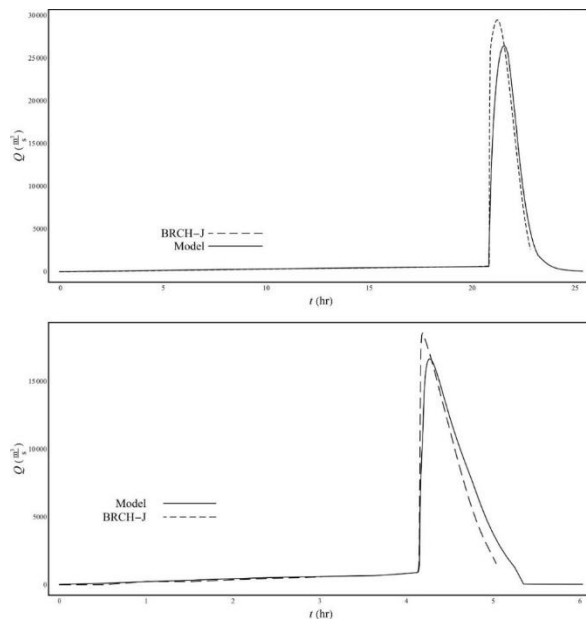


Figure 15. Hydrograph of the proposed scheme and validation by comparison to the BREACH model for the overtopping of (a) Tabarakabad and (b) Chahchaheh Dams

According to [Fig. 15](#), the proposed code and BREACH model were found to be in good agreement. The BREACH model was selected as the efficient hydrograph of overtopping. The subsection “unsteady flow analysis” provides the flow depth and velocity results of the overtopping scenario.

### 3-2- Unsteady flow analysis and flood mapping

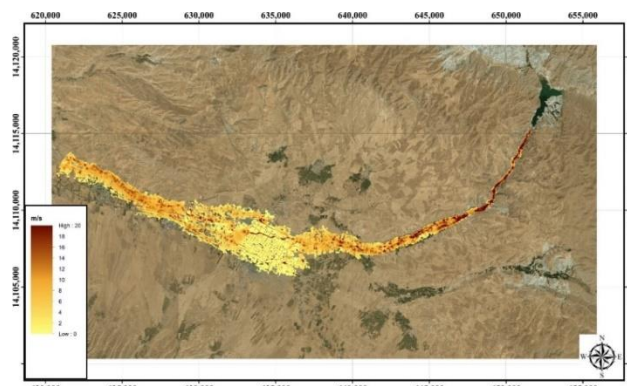
To simulate the unsteady flow induced by dam break, input data would be required, including cross-section geometry, roughness, initial conditions, and boundary conditions. The geometric data of cross-sections (the topography of the region) were extracted from satellite images. Roughness is a determinant of flow depth and velocity. However, it is difficult and costly to accurately estimate roughness for rivers and downstream surfaces, and continuous examinations are required. Since the flow bed downstream of the dams consisted of a set of materials and the roughness size was uncertain in the event of dam break, it would be reasonable to consider minimum roughness and maximum roughness. A minimum roughness of 0.02 and a maximum roughness of 0.07 were assigned. Furthermore, it was assumed to be 10 for residential areas with flood-prone buildings. The upstream boundary conditions included the output hydrograph of the broken dam in the overtopping and piping scenarios; for the instantaneous dam break scenario, a set of reservoir characteristics and a frictional slope as large as the ground slope downstream of the dam were the boundary conditions, while the absence of water flow in the river downstream of the dam was the initial condition. To implement two-dimensional flow analysis in HEC-RAS, the topographic data derived from satellite images were introduced to the model. Then, the flow cross-sections were meshed, applying roughness, boundary, and initial conditions. For example, maximum velocity map for minimum roughness and maximum depth map for maximum roughness in the overtopping scenario of Tabarakabad Dam were presented in [Figs.16](#) and [17](#), respectively. According to the results, the maximum flow velocity occurred to be 20 m/s near the dam approximately 15 km from the city, and the velocity sharply declined in the inundation area. It is worth noting that the maximum velocity area

downstream of the dam was larger in the instantaneous break scenario than in the piping and overtopping scenarios. Likewise, the front height was found to be smaller in the instantaneous break scenario than in the piping and overtopping scenarios, and the maximum depth was calculated to be 36 m in the overtopping scenario. As an example, maximum velocity map for minimum roughness and maximum depth map for maximum roughness in the piping scenario of Chahchaheh Dam were presented in [Figs.18](#) and [19](#), respectively. The maximum velocity was obtained to be 20 m/s for the break of Chahchaheh Dam. The maximum velocity area was larger in the instantaneous break scenario. Furthermore, the maximum front height was found to be 0-20 m. Since the width was small along most of the path, the flow experienced large depths. The maximum depth was smaller for Chahchaheh Dam than for Tabarakabad dam at the same maximum velocity areas since Chahchaheh Dam had a lower water quantity than Tabarakabad Dam (at the normal elevation). As mentioned, piping has a larger probability than overtopping and instantaneous break in embankment dams. Therefore, stabilization and leakage control may significantly minimize the catastrophic consequences of a break in such dams.

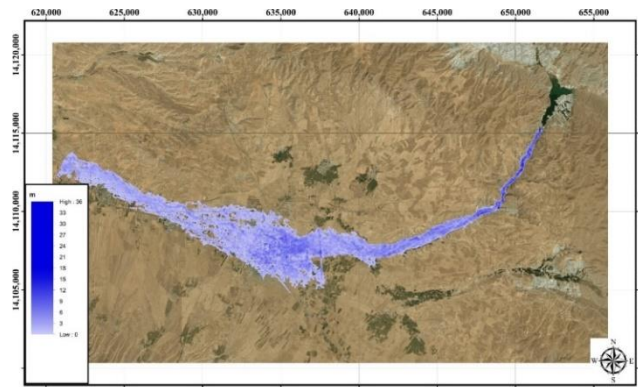
Another important issue in dam break is the analysis of flood arrival time. It was found that the flood would arrive in the city of Quchan in nearly 1 h and 30 min to 2 h with a flood front height of 15-20 m after the break of Tabarakabad. In Chahchaheh Dam, the shortest time of flood arrival was estimated to be 45 to 60 min after gradual break signs. Flood arrival time estimation is important in flood risk and vulnerability analyses, which has been discussed in the “risk analysis” subsection.

### 3-3- Risk analysis

The present study implemented risk analysis based on passive defense via a developed quantitative-qualitative approach and break-caused casualty estimation for risk mapping. Mapping was carried out through a questionnaire to translate qualitative parameters into quantitative. The respondents included water engineering and passive defense experts. It should be noted that some of the respondents had two or more skills in different fields. [Table 2](#) provides the assets downstream of the case-study dams based on the experts.



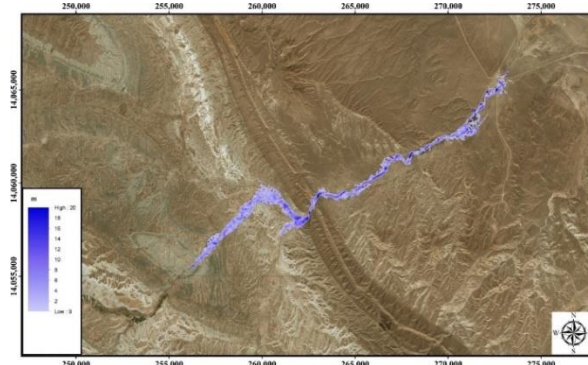
**Figure 16.** Maximum velocity map for minimum roughness in the overtopping scenario of Tabarakabad Dam



**Figure 17.** Maximum depth map for maximum roughness in the overtopping scenario of Tabarakabad Dam



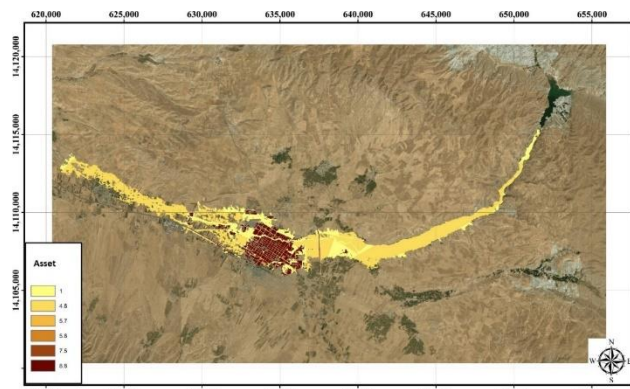
**Figure 18.** Maximum velocity map for minimum roughness in the piping scenario of Chahchaheh Dam



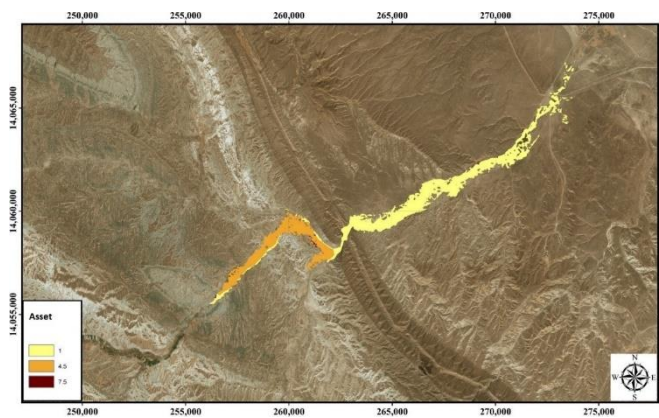
**Figure 19.** Maximum depth map for maximum roughness in the piping scenario of Chahchaheh Dam

**Table 2.** Downstream assets of Tabarakabad and Chahchaheh Dams

Asset	Tabarakabad					Weighted Average Opinions	Chahchaheh					Weighted Average Opinions
	Score						Score					
	2	4	6	8	10		2	4	6	8	10	
Agricultural Land	5	6	8	3	0	4.8	8	6	4	2	2	4.5
Infrastructure, industry, mines and factories	2	6	7	7	0	5.7	16	1	4	1	0	3.1
Communication Roads	0	4	4	8	6	7.5	5	9	6	2	0	4.5
Residential Areas	0	0	4	5	13	8.8	2	1	4	8	7	7.5
Population Centers and Human Forces	3	7	5	3	4	5.8	6	5	4	5	2	5.3



**Figure 20.** Asset value map of Tabarakabad Dam in the piping scenario



**Figure 21.** Asset value map of Chahchaheh Dam in the piping scenario

Figs. 20 and 21 respectively depict the asset value mapping of Tabarakabad and Chahchaheh Dams in the piping scenario.

According to Figs. 20 and 21, Tabarakabad Dam has a higher asset value than Chahchaheh Dam due to the presence of the city of Quchan with a significant population in the southwest. Tables 4-6 report the expert responses on the threat domain (the distance from the numerical flood zone map), flood wave vulnerability due to the flow velocity, and possible vulnerability due to the flood depth (regardless of the flow velocity), respectively.

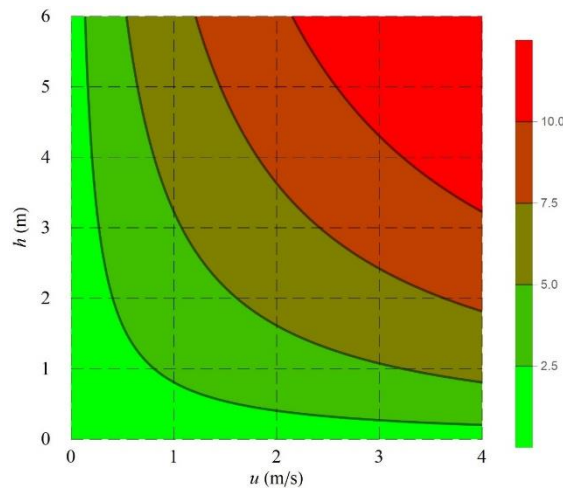
The vulnerability was quantified based on Table

3 for four computational layers, as shown in Fig. 22.

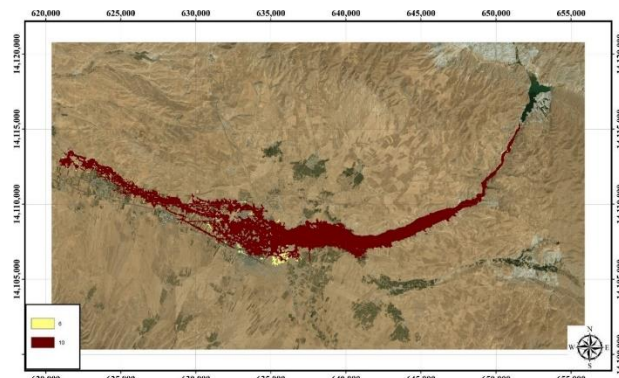
The identification of threats is directly associated with the quantity of damage to assets. Considering the modeling carried out for dam break-induced flood mapping, the zones under potential threats were identified using numerical simulations. Once flood mapping had been completed, the flooded zones were determined as potential threats using GIS maps. Figs. 23 and 24 represent threat maps for Tabarakabad and Chahchaheh Dams in the piping scenario.

**Table 3.** Threat coefficients and Damage coefficients due to the velocity and depth

Number of Layers		2	3	4	5	6	7	Number of Layers		2	3	4	5	6	Number of Layers		2	3	4	5	6															
Distance (m)	5	0	0	0	0	0	0	Velocity (m/s)	0.25	0	1	0	0	1	Depth (m)	1	4	4	1	1	2															
	10	0	2	5	0	0	0		0.5	0	1	3	2	1		2	1	0	4	0	0															
	25	1	2	2	1	1	2		1	1	1	4	1	0		3	0	1	1	2	0															
	50	0	1	0	0	0	0		1.5	0	3	2	1	0		4	0	0	0	1	0															
	100	1	0	1	2	0	0		3	0	0	0	0	0		5	0	0	0	0	0															
	200	0	0	0	1	0	0																													
Average Number of Selected Layers	4.14 Maximum Effective Distance (m)						140.455 Average Number of Selected Layers						4 Maximum Velocity						2.58 Average Number of Selected Layers						3.68 Maximum Depth (m)						5					



**Figure 22.** Vulnerability curves based on the velocity and depth



**Figure 23.** Threat map of Tabarakabad Dam in the piping scenario

Once the questionnaire responses had been concluded, experts and practitioners were invited to a meeting to improve the proposed methodology. The suggestions proposed in the meeting included:

- Concerning threats, it was suggested that minimum and maximum roughness sizes be considered downstream of the dam to more

accurately reflect the uncertainty assessed by the respondents in numerical analyses. Therefore, the second part of the questionnaire was replaced with mathematical calculations and numerical simulations to adopt the roughness uncertainty approach.

- To improve the vulnerability index, a set of

studies conducted in the northeast of Australia (Queensland) was proposed by [Smith et al. \(2014\)](#). They estimated the flood vulnerability for various velocities and depths and provided flood vulnerability curves (as with the present work). This would enhance accuracy in the estimation of possible damages. Queensland vulnerability criteria and vulnerability curves based on the velocity and depth are available in [Smith et al. \(2014\)](#).

The results indicated that the piping and overtopping scenarios showed no significant difference in risk mapping. [Fig. 25](#) represent the

vulnerability map of Tabarakabad Dam in the overtopping scenario as an example. The downstream was found to have a high risk zones for populations, vehicles, and buildings. However, the vulnerability area was larger for Tabarakabad Dam than for Chahchaheh Dam due to the city of Quchan downstream of the dam.

The risk maps of the dams were obtained for different scenarios through the proposed approach (Eq. (3)), and risk quantification, threat scoring, vulnerability scoring, and asset scoring were carried out, as shown in [Figs. 26-27](#) for the overtopping scenario for example.

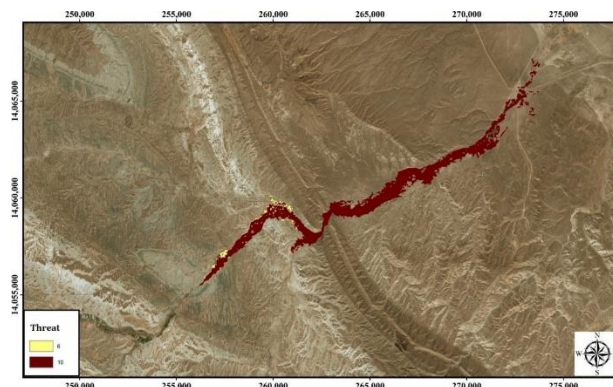


Figure 24. Threat map of Chahchaheh Dam in the piping scenario

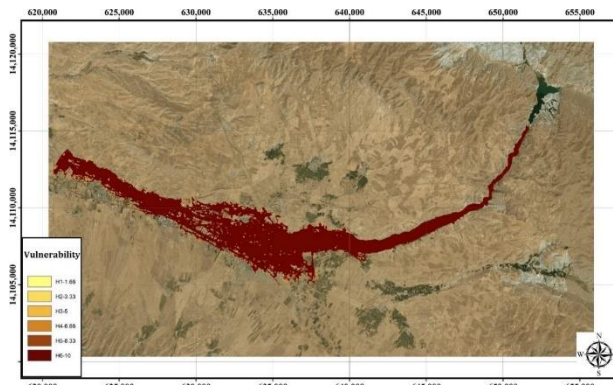


Figure 25. Vulnerability map of Tabarakabad Dam in the overtopping scenario

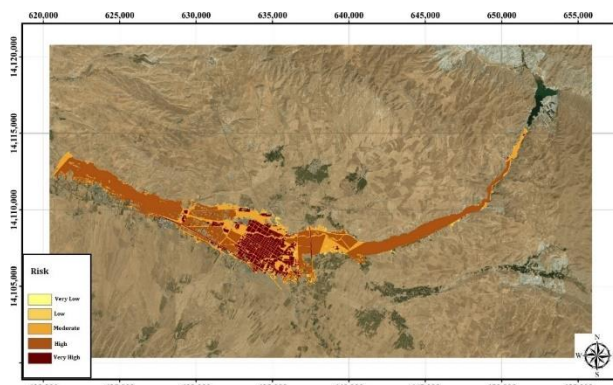


Figure 26. Risk map of Tabarakabad Dam in the overtopping scenario

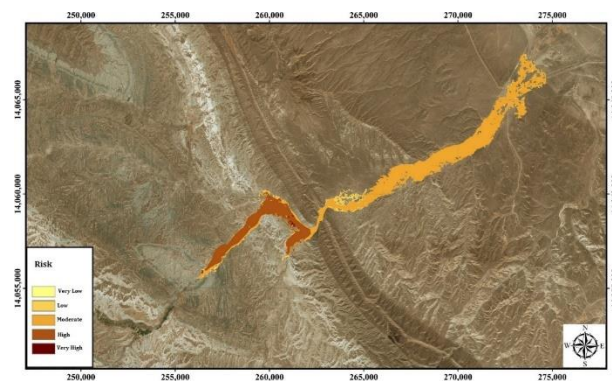


Figure 27. Risk map of Chahchaheh Dam in the overtopping scenario

It was concluded that Tabarakabad dam was found to have a lower risk of instantaneous break than of piping and overtopping since its risk of (maximum depth) was lower in the instantaneous break scenario than in the piping and overtopping scenarios. This is also the case with Chahchaheh Dam, except that not only the areas near the dam were at risk, but also some other areas downstream of the dam (eastern areas) were found to be at a relatively low level of flood risk. Hence, more details on the vulnerable areas are provided below.

To analyze the risk and vulnerability, three outputs of each scenario were employed. First, the flood arrival time after the break was studied as it plays a key role in prompt measures and enables relevant authorities to minimize casualties. Second, the maximum flow depth was analyzed in the final mapping. Third, the maximum flow velocity was calculated and discussed in the dam break process. Drawing on these outputs and a questionnaire, the assessment of risks downstream of the dams was carried out using the proposed approach. Tabarakabad Dam was found to have a much lower probability of overtopping than piping. Stabilization and leakage control could minimize the catastrophic consequences of piping. Furthermore, the flood mapping of Tabarakabad Dam in different scenarios estimated that the flood front would arrive in the city of Quchan in 1 h and 30 min to 2 h after the break. Thus, there would be enough time to prevent casualties. Since several villages exist around Tabarakabad Dam, all the casualties are expected to occur in these villages. Floods would destroy all the farmlands and gardens around Tabarakabad Dam since the flood front height would be nearly 15-20 m. The numerical results indicate that the buildings in the city of Quchan and roads would undergo serious damage due to the downstream bed topography. According to the risk maps, two zones

could help avoid casualties: (1) the northern part of Quchan and (2) the southern part of Quchan on the mountain feet. However, the flood would block the connection between the northern and southern parts of the city, and it is important to select settlement zones that could allow for providing relief to the affected population. Hence, it is recommended that crisis management authorities gather the population of Quchan in the south (around the Gojeh and Sarab Villages) and construct wider and more accessible roads. The measures that should be implemented to minimize possible losses and casualties include:

- Evacuating the villages around Tabarakabad Dam in case of piping dam break signs;
- Rapidly informing the citizens of Quchan to evaluate the city toward the south; the residents of the northern part of Quchan need to move to the Quchan Stadium.
- Stabilization and leakage control should be implemented by the Water Facilities Maintenance and Operative Office of Khorasan Regional Water Company.
- Loudspeakers should be deployed across the city of Quchan to warn the citizens of possible crises

For Chahchaheh Dam, the downstream river bed does not have sufficient capacity for the flood due to the dam break. Hence, a large area downstream of the dam would be flooded. Chahchaheh Dam was found to be likely to undergo overtopping, unlike Tabarakabad Dam. The assets that would be damaged in the event of the break of Chahchaheh Dam include farmlands and Chahchaheh Village. The northern part of Chahchaheh Village would be completely submerged. The minimum flood arrival time was numerically calculated to be 45-60 min after gradual break signs. This time seems to be sufficient to rescue the population of Chahchaheh Village. The measures that should be implemented

to avoid casualties include:

- Moving the population of Chahchaheh Village to the south on mountain feet until flood declines.
- The spillway should be regularly checked to ensure its effective functionality.
- The stability and possible leakage of the dam should be sufficiently monitored; in the case of a leakage, the reservoir elevation should be promptly reduced by opening the bottom outlet gate.

#### 4- Conclusions

The present study adopted novel methods and evaluated different break scenarios of Tabarakabad and Chahchaheh Dams to determine the dam break hydraulics, model the unsteady flow, evaluate the downstream vulnerability, and carry out a risk analysis. A numerical model (computer code) was developed in Mathematica, which is applicable to other dams. In combination with the BREACH model, the proposed model enabled the identification of the worst gradual dam break scenario and was employed to analyze the unsteady flow arising from dam break in an iterative process. Moreover, the proposed computer code allows for analyses to determine the most important hydrograph through TOPSIS. The flood arrival time and flooded zones were found based on the flood velocity and depth results. Although piping is the most probable break scenario for embankment dams, the hydraulics of instantaneous break, overtopping, and piping was compared and discussed for Tabarakabad and Chahchaheh Dams. Flood mapping was carried out for minimum roughness and maximum roughness. The flood arrival time in the city of Quchan was obtained to be 1 h and 30 min to 2 h after the break of Tabarakabad Dam, while the flood arrival time of Chahchaheh Dam was estimated to be 45-60 min after gradual break signs. However, the flood front height was calculated to be approximately 15-20 m for both dams, imposing serious damage to the adjacent farmlands, gardens, and buildings. Drawing on the modeling and hydraulic analysis results, the dam break hazards were identified and evaluated. Apart from huge financial losses, dam break imposes a serious threat to the lives of populations residing downstream of the dam. Casualties of a break event are maximized when the residents of high-risk areas are not aware of the break and cannot have a chance to save their lives

or the authorities lack sufficient knowledge and preparedness to cope with threats in crises. Considering the break-induced flood velocity, there would be a very short time to warn the residents of high-risk areas. Therefore, dam break and high-risk zone identification have long been of great interest to researchers. The proposed method and computer code can also be applied to other dams. The instantaneous break, piping, and overtopping scenarios were simulated for the dams, and it was found that Tabarakabad Dam was much less likely to undergo overtopping than piping. Stabilization and leakage control could significantly diminish the catastrophic piping consequences of Tabarakabad Dam. According to the flood maps of different break scenarios, a break-induced flood would destroy all the farmlands and gardens downstream of Tabarakabad Dam. Although there would be sufficient time to rescue the population of Quchan, the villages around Tabarakabad Dam are expected to undergo casualties. The numerical results suggest that most buildings in the city of Quchan and a number of roads would experience serious damage due to the downstream bed topography. The safe areas to rescue the population of Quchan in the event of dam break were identified. In contrast to Tabarakabad Dam, Chahchaheh Dam was found to be likely to undergo overtopping. There would be enough time to rescue the population of Chahchaheh Village, based on the estimated flood arrival time.

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#### *Competing interest*

*The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

#### *Authors contribution*

*A.R.K. conceived the study and drafted the manuscript; R.B. supervised the work and provided resources and data curation, validated the data, and reviewed and edited the manuscript; A.F., H.S. and M.M. provided data curation and reviewed and edited the manuscript.*

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