Future Technology
Open Access Journal
ISSN 2832-0379

May 2025| Volume 04 | Issue 02 | Pages 01-10

Journal homepage: https://fupubco.com/futech

https://doi.org/10.55670/fpll.futech.4.2.1

Future Publishing LLC

Article

Emergency action plan for Haditha dam failure scenario, Al-Anbar, Iraq

Yasameen Hameed[1], Redvan Ghasemlounia[2], Thamer Ahmed Mohammed[3]*, Abdulwahab Al-Ansi[4]

[1]Engineering Management, Institute of Graduate Studies, Istanbul Gedik University, Istanbul, Türkiye
[2]Civil Engineering, Faculty of Engineering, Istanbul Gedik University, Istanbul, Türkiye
[3]Department of Water Resources, College of Engineering, University of Baghdad, Baghdad, Iraq
[4]Department of Civil Engineering, Faculty of Engineering, University of Science and Technology, Sana'a, Yemen

ARTICLE INFO

Article history:
Received 10 January 2025
Received in revised form
18 February 2025
Accepted 03 March 2025

Keywords:
Haditha Dam, Risk factor, Failure, Emergency response plan

*Corresponding author
Email address:
tthamer@gmail.com

DOI: 10.55670/fpll.futech.4.2.1

ABSTRACT

Dams are essential structures that regulate and manage water for human activities such as irrigation, power generation, flood control, and water supply. However, building and operating dams involve inherent risks that can lead to catastrophic consequences in case of failure, such failures can threaten the environment and populations downstream. Haditha Dam, Al-Anbar Governate, Iraq has been chosen as a case study due to its unique geological conditions (existence of limestone formations prone to karstification) and susceptibility to terrorist attacks. In this research, the risk factor for Haditha Dam is categorized as extremely high risk, with a Total Risk Factor (TRF) of 36. An emergency action plan that includes three possible failure scenarios has been proposed. Based on the flood maps, there is an urgent need for evacuation planning and the designation of safe and unsafe zones in the cities downstream of Haditha Dam to mitigate the consequences of a potential failure of the Dam. This plan aims to address immediate flood inundation, minimize loss of life, and manage the damage that could occur to infrastructure. As part of the emergency response strategy, an evacuation program has been proposed to protect lives and reduce the impact on affected populations.

1. Introduction

Dams are critical engineering infrastructures designed to regulate and utilize water resources for diverse purposes, including water supply, hydroelectric power generation, flood control, and irrigation. They play a pivotal role in supporting human activities by providing water for agricultural, industrial, and domestic use. Furthermore, dams contribute to the regulation of river flow, helping to alleviate the impacts of both droughts and floods. Despite the significant benefits dams offer, their construction and operation can potentially result in environmental and catastrophic consequences, particularly for downstream populations in the event of failure. Dam failures pose serious threats to human lives, property, and the surrounding environment. Ensuring the safety and security of communities residing downstream of the Haditha Dam is of utmost importance, Although the Haditha Dam is designed with strong systems and monitoring mechanisms, no infrastructure is completely immune to risks. Natural disasters, extreme weather events, human errors, or even acts of terrorism could compromise the dam's structural integrity, potentially leading to its failure.

1.1 Dam safety

The impact of hydropower operations on embankment dam safety was investigated by comprising two main components. Firstly, a three-dimensional finite volume model generated with ANSYS-CFX simulates a vertical Francis turbine at the Mosul hydropower plant; the resulting pressure patterns from the turbine operation are then analyzed with the dam body's stability under various conditions, such as different flow rates and reservoir levels. Secondly, a three-dimensional finite element model of the Mosul dam is simulated using ANSYS software, and the water pressure patterns from the turbine operation are incorporated into the dam model to assess its stability, considering different reservoir levels [1]. A control program is developed based on the principal stress data collected from hydropower plant operations, aiming to minimize stress on the dam body and increase its operational lifespan.

Abbreviation
ANSYS-CFX: Analysis system software used for fluid turbomachinery problems
SEEP/W: A model for seepage prediction in earth dams
a.s.l.: Average sea level
JCMC: Joint Coordination and Monitoring Center
TRF: Total risk factor.
RFc: Risk factor for capacity of the reservoir.
RFh: Risk factor for the height of the dam.
RFer: Risk factor for evacuation requirement

Improvements to the turbine operating system to mitigate the stress on the studied dam body and enhance dam safety were suggested [2-5]. The flux rates on the safety of dams in Iraq were simulated using the SEEP/W model. Many studies have been conducted on the impact of the maximum water level in the reservoir of Hemrin Dam in Iraq on seepage, pore water pressure, phreatic line, and stability of the downstream slope of the dam by using SEEP/W and SLOPE/W [6, 7]. The same methodology was followed for the Kongele Earth dam in Iraq [8]. Seepage in Shirin Dam, Iraq, was analyzed using the SEEP/W model, and results suggested that The core in an earth dam can reduce seepage by 99% [9]. Many studies investigated the effects of dimensions, geometry, and side slopes of earth dam zones on seepage rates, including different seepage control methods. The effect of various characteristics of the dam shell and core materials on the dam experimental and numerical models were conducted to assess the safety factor of the dam body and foundation before and after sealing. Additionally, the impact of dam height on stability was analyzed using the Plaxis 3D finite element program. Results indicate good agreement between measured data and computational outputs and highlight the tested measures' effectiveness in improving dam safety [10-14].

1.2 Failure modes and causes of earth dam failure

The most common causes of failure for homogeneous earth dams, zoned earth dams, earth dams with diaphragm, and earth dams with concrete slabs at the upstream face had been extensively studied and categorized as failure due to overtopping, seepage, and piping. Overtopping occurs when water flows over the dam crest and causes erosion of the embankment and slope stability and failure, while the collapse of channels and pipes resulting from internal erosion due to the removal of soil particles by seepage causes dam failure. The failure of large dams such as the Teton Dam and Baldwin Hills Dam in the USA and Malpasset Dam in France necessitate the preparation of an effective emergency plan for the protection of downstream areas [15, 16]. The analysis of dam failures is of paramount importance for engineers as it provides crucial information on failure modes informing causes. In addition, it enables them to take preventive measures in the development located downstream. Data on failed earth dams play a vital role in the improvement of maintenance and inspection practices. besides, it will help in the consideration and implementation of the new required preventive measures that increase dam safety [17]. Studying historical dam failures is an essential practice for learning from past challenges and improving engineering practices; by analyzing both failures and successes, engineers can gain valuable insights into the design, construction, and maintenance of dams [18, 19]. In the case of the Tawila Dam failure in North Darfur, Sudan, the author explained that the leading causes of the dam failure were sediment deposition, erosion, excessive deformation of the foundation, high silting rate, and seepage of water leading to piping through the existence of loose sandy soil in the foundation [20]. Similarly, the failure of the Ivex Dam in north-eastern Ohio, USA, resulted from a combination of factors, including a significant hydrologic event triggered by a 70-year rainfall event, inadequate spillway design, lack of an emergency spillway, loss of permanent pool capacity due to sedimentation, and poor dam maintenance leading to seepage and piping [21, 22]. Examples of significant dam ruptures that have led to substantial loss of life have been provided, such as the Vajont dam rupture in Italy in 1963, the Johnstown dam rupture in Pennsylvania in 1889, and the Machhu II dam rupture in India in 1974. These examples highlight the devastating consequences of dam failures and highlight the urgent need for effective risk management practices to prevent such tragedies in the future [23]. The importance of anticipating dam failures through evaluations of age, storage capacity loss, and management history has been studied, including the vulnerability of older dams with inadequate spillway design and the lack of emergency spillways due to storage capacity loss caused by sedimentation [24]. Notably, the failure they discuss was caused by seepage piping near the masonry spillway-earthen dam contact, leading to the breach of the dam and the rapid release of 38,000 m^3 of impounded water and sediment [22, 24]. The Oroville Dam crisis in February 2017 highlighted the significance of resilience processes and adaptive decision-making in managing dam safety [25]. Four key resilience processes have been identified: sensing, anticipation, adapting, and learning. These processes play vital roles in effectively managing and responding to disruptions and crises of the Oroville Dam. The processes involve continuous monitoring of the dam and spillways (sensing), preparing for potential disruptions, developing contingency plans (anticipation), emergency repairs and evacuation plans (adapting), and analyzing the causes of the crisis for future improvements (learning). Also, they argued that considering adaptive decision-making in both the development and resolution of the crisis is crucial for a comprehensive understanding [24]. Table 1 shows the dam failures that occurred around the world between 1975 and 2011. The main causes of the dam failure were different from overtopping due to flood to piping due to seepage [25].

Table 1. Causes of dam failure between 1975-2011 [25]

Cause of Failure	Number of Dam Failures	Percentage of Dam Failure
Flood or Overtopping	465	70.9%
Piping or Seepage	94	14.3%
Structural	12	1.8%
Human Related	4	0.6%
Animal Activities	7	1.1%
Spillway	11	1.7%
Erosion/Slide/Instability	13	2.0%
Unknown	32	4.9%
Other	18	2.7%
Total number of dam failures	656	

It is important to mention that High-Energy Facilities (HEFs) are attractive targets for terrorists due to their importance and interconnectedness, which can lead to significant environmental damage, loss of life, and property damage. Cyber-attacks, physical attacks, and insider attacks are the three types of attacks that could be carried out against HEFs. Understanding these attack vectors is crucial in developing effective strategies for prevention and response [27]. Regarding recent events, the Nova Kakhovka dam in Ukraine was subjected to a physical attack, resulting in its explosion during the ongoing war. Figure 1 illustrates the dam before and after the failure, while Figure 2 shows one of the inundated areas downstream. The catastrophic failure of the Derna dams, notably the Bu Mansour Dam and Al Blad Dam, during Storm Daniel on September 11, 2023, was a multifaceted disaster influenced by several critical factors. Firstly, the unprecedented intensity of Storm Daniel produced runoff that vastly exceeded the dams' design capacities, highlighting a severe underestimation of potential storm impacts.

Figure 1. Aerial photographs of the Nova Kakhovka dam, Ukraine, before and after failure (Google Earth accessed on 15 December 2022)

Secondly, design and maintenance issues were identified, with investigations suggesting significant flaws in the Bu Mansour Dam's design that compromised its integrity under extreme conditions. Thirdly, the rapid overtopping and subsequent breach of the dams underscored their inability to manage such extraordinary volumes of water, leading to structural failures. Additionally, the absence of adequate emergency planning and historical neglect of the dams' vulnerabilities- evidenced by previous damage and inadequate resource management- exacerbated the disaster's impact [28]. Structural weaknesses and erosion due to water overflow and seepage were identified as direct causes of the collapses. These factors, combined with insufficient preparedness for such extreme weather events, culminated in a tragic loss of life and significant displacement, underscoring the urgent need for revaluation of dam safety protocols and emergency response strategies in similar regions [29, 30]. Based on previous literature and to avoid such a catastrophic event in western Iraq, Haditha Dam was selected as a case study because of its unique geological conditions, primarily characterized by limestone formations undergoing active and ongoing karstification, the process of karstification leads to the formation of karst landscapes such as caves, submerged surface rivers, and karstic slopes. This process causes the erosion of carbonate rocks, such as limestone, due to water saturated with carbon dioxide, resulting in the formation of unique and complex geographical structures. Karst formations embody prominent features in nature and pose challenges for risk management, Understanding the impact of karst formations can be an essential part of assessing the risks of dam failure and developing emergency plans to deal with potential emergencies. Given its geological conditions, preparing an Emergency Action Plan for Haditha Dam is paramount. Large voids caused by limestone formations could jeopardize its safety and may affect its safety.

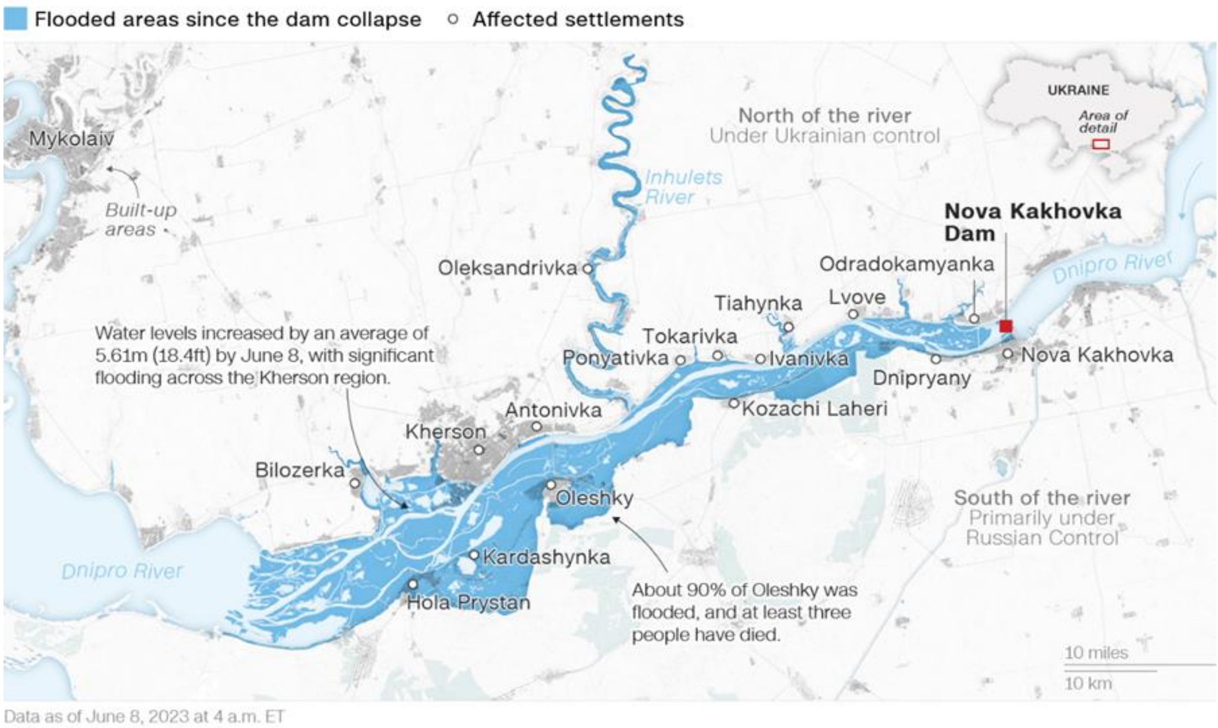

Figure 2. The inundation of residential areas downstream of the Nova Kakhovka dam

Another reason for the selection of Haditha Dam is that it is susceptible to terrorist operations, having been previously targeted by ISIS terrorist groups. Additionally, it is situated downstream of the Tabqa Dam in Syria. It is well-known that Syria is a country facing security instability. This study aims to prepare an integrated emergency action plan to minimize the loss of life and the potential for property damage due to the failure of the Haditha Dam. The plan focused on all the densely populated areas downstream of the dam.

2. Methodology

An emergency action plan is developed specifically for this purpose to ensure the Haditha Dam's safety and minimize the potential impact of dam failure. Haditha Dam is a mega structure that plays a key role in supplying water for various purposes. Figure 3 shows the flow chart for various activities included in the research methodology.

2.1 Study area

Haditha Dam is an earth-fill dam constructed on the Euphrates River, Al-Anbar governorate, Iraq. Geologically, the Haditha Dam is situated on various layers of limestone beds from the Euphrates and Ana formations, characterized by fissures, cracks, and nearly isolated sinkholes. Despite the prolonged development and collapse of sinkholes, they are relatively less hazardous [31]. Figure 4 shows a typical cross-section of the Haditha dam with the major materials. The construction of the Haditha Dam, initiated in 1977 and completed in 1988, represents a hallmark of international collaboration, primarily between the Soviet Union and the Iraqi Government under the Technical and Economic Cooperation Treaty.

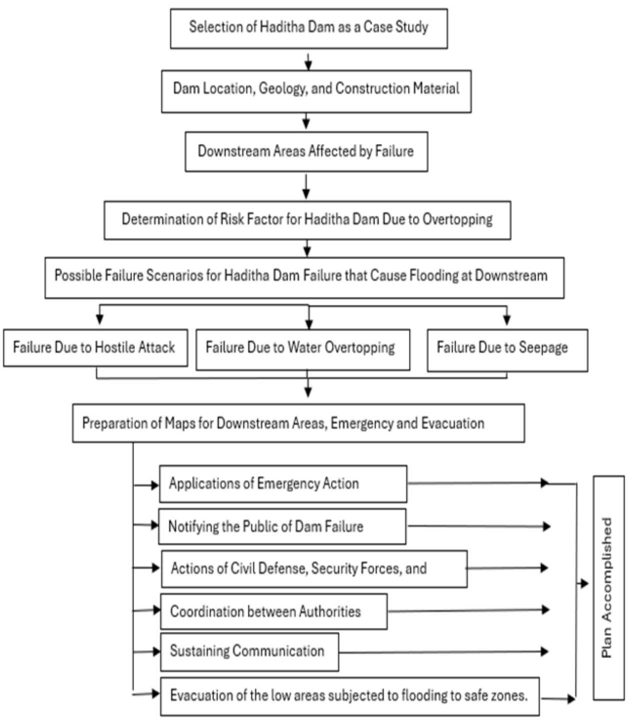

Figure 3. The flow chart summarizes the research methodology activities

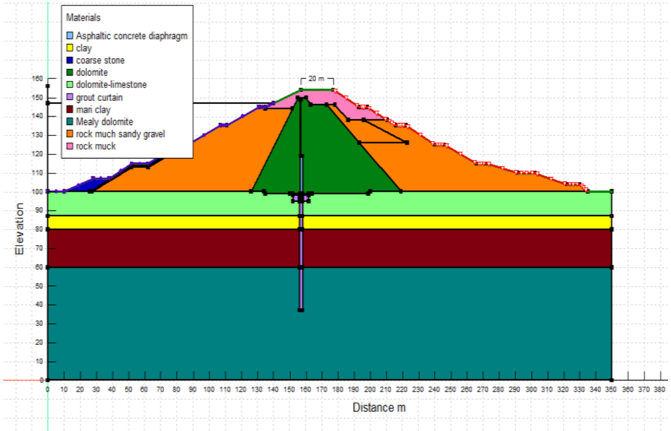

Figure 4. Typical cross-section of Haditha dam with the major materials

The dam's strategic location and construction were the outcomes of thorough geological and topographical analyses, resulting in a multi-faceted structure that spans over 9 km, featuring a complex amalgamation of materials, including sand, gravel, reinforced concrete, and rock-mass revetments. With a crest level of 154 meters above sea level and a width of 20 meters, the Haditha Dam serves multiple functions, including flood control, irrigation, and hydroelectric power generation, making it a critical component of Iraq's infrastructure. Its capacity to generate 660 megawatts of power and its role in river flow regulation and flood management underscore its significance to the country's water resource management and energy production. The Haditha Dam project, through its innovative approach and the synergy of international expertise, embodies the essence of engineering ingenuity and sustainable development in addressing the intricate demands of water resource management and power generation in Iraq.

2.2 Downstream areas affected by failure

The cities around the dam and directly affected by dam failure are Haditha, Baghdadi, Heet, Ramadi, and Fallujah. These cities are considered major cities and are located near the Euphrates Riverbanks. The total population of these cities is estimated to be one and a half million. The population will be severely affected by dam failure due to overtopping or breach. Table 2 shows the affected cities from the dam failure.

Table 2. The affected cities by the dam failure

City	Population	Distance from Haditha Dam (Km)
Haditha	120,000	7
Heet	100,000	76
Ramadi	570,000	168
Fallujah	500,000	250

2.3 Estimation of risk factor

The risk factor calculation method used in this research is that proposed by ICOLD (International Committee On Large Dams). The total risk factor for Haditha Dam can be calculated based on the available data and based on Tables 3 and Table 4 and Eq. (1) [32].

$$TRF = RFc + RFh + RFer + RFpdd \quad (1)$$

where TRF is the total risk factor, RFc is the risk factor for the capacity of the reservoir, RFh is the risk factor for the height of the dam, RFer is the risk factor for evacuation requirement, and RFpdd is the Risk factor for potential downstream damage. Table 3 indicates the potential risk rating in the ICOLD method.

Table 3. The potential risk rating is given in the ICOLD method

Risk Factor	Contribution to risk (weighting points)			
	Extreme	High	Moderate	Low
Capacity (hm³)	>120 (6)	120-1 (4)	1-0.1 (2)	< 0.1 (0)
Height (m)	> 45 (6)	45-30 (4)	30-15 (2)	< 15 (0)
Evacuation Requirements (# of persons)	>1000 (12)	1000-100 (8)	100-1 (4)	None (0)
potential downstream damage	High (12)	Moderate (8)	Low (4)	None (0)

Table 4. Risk classes based on the total risk factor

Total Risk Factor	Risk Class	Risk Rating
0-6	I	Low
7-18	II	Moderate
19-30	III	High
31-36	IV	Extreme

2.4 Possible failure scenarios for Haditha Dam

This study will consider three scenarios and an emergency response plan is prepared for this purpose.

2.4.1 Dam failure due to hostile attack

The scenario begins with the failure of the dam's foundations, leading to a gradual erosion of the dam towards the left of the power station. Ultimately, this failure resulted in a catastrophic collapse with a width of 420 meters downstream from the dam's body (these findings were derived from the utilization of a Digital Elevation Model (DEM) for the study area). The angle of this collapse is 34 degrees to the left of the valley's direction, and the erosion continues downward until it reaches an elevation of 100 meters above sea level.

2.4.2 Dam failure due to overtopping

Overtopping occurs when the water level in the dam's reservoir exceeds the dam's crest elevation, which means that the dam is facing a potentially catastrophic situation where the water level in the reservoir rises above the crest elevation of the dam, which is for Haditha Dam at an elevation of 155 meters above sea level.

2.4.3 Dam failure due to geological problems, including seepage

The Haditha Dam was constructed on various limestone beds from the Euphrates and Ana formations. These beds contain fissures, cracks, and almost isolated sinkholes. However, it took a significant amount of time for the sinkholes to develop and collapse, leading to a settlement in the dam. Hence, the dam requires constant monitoring to prevent seepage issues that will directly affect its safety. So, the failure will start with the dam's foundations, leading to the dam's gradual erosion towards the power station's left. Ultimately, this failure results in a catastrophic collapse. In this study, the River Analysis System software (HEC-RAS) Version 6.6 was used as a tool to simulate the possible scenarios for the Haditha Dam break and the resulting flood wave and inundation along the Euphrates River downstream. Two-dimensional (2D) unsteady flow encroachment analysis is adopted, and the procedure of creating encroachment regions is used. The floodway encroachment analysis can be based on 1D, 2D, or combined 1D/2D models with a mix of encroachment methods. However, for portions of the 2D model domain, Encroachment Regions are the only method to control the floodway analysis. For unsteady flow, HEC-RAS solves the full, dynamic Saint Venant equation by using an implicit, finite difference method. The simulation examines critical factors such as peak discharge, the timing of the flood wave's arrival, and the maximum water levels at various locations within the cities along the Euphrates River immediately following the dam's hypothetical failure. These findings are based on a Digital Elevation Model (DEM) of the study area.

2.5 Proposed emergency response plan

It is a systematic plan that identifies potential emergencies in the dam and categorizes the actions and steps that must be followed to mitigate human and material losses. Emergencies in dam operations are defined as unexpected situations that threaten the overall dam facilities, properties, and lives downstream, necessitating immediate measures. For Haditha Dam, there are three emergency levels (Level III- imminent failure emergency, Level II- potential failure emergency, Level I- non-emergency), and the primary purpose of pre-defined emergency levels is to provide clear external communications of project conditions and project owner/operator incident management activities. The emergency level helps to define the primary goal of emergency response, such as to intervene to prevent the breach, to communicate that a breach or high flow is occurring, and to expedite evacuation by government authorities.

2.5.1 Emergency response plan downstream of Haditha Dam

Step 1: Event Detection and Evaluation - The Emergency Action Process begins by identifying any events or unusual conditions near the dam through observations made by project personnel and landowners and the evaluation of instrumentation data gathered from monitoring devices and sensors that provide information about the dam's condition. During the initial stage of the Emergency Action Process, project personnel conduct regular inspections, ranging from weekly to 24-hour inspections during high pool levels, to identify any abnormalities. If any abnormalities are detected, they are reported to supervisors or managers. Various methods, such as observations, evaluation of instrumentation data, and forewarnings of potential events, are used to detect events. Signs of distress, such as seepage, movement, or structural changes, are thoroughly investigated.

Step 2: Emergency Level Determination - Once the event is detected, the emergency level needs to be determined, which involves assessing the severity of the situation and classifying it into one of the predefined emergency levels. The dam Project Manager, in consultation with engineers, determines the emergency level.

Step 3: Notification and Communication - After determining the emergency level, the next step is to notify and communicate the situation to the relevant stakeholders and authorities in charge. This includes internal reporting and external communication to downstream populations and government authorities. Stakeholders for Level III and Level II Emergency:

- Government of Iraq – Ministry of Water Resources
- Governor of Al-Anbar Province
- Ministry of Interior
- Ministry of Defense
- Director of Water Resources in Anbar Province
- Director of Police in Anbar Province
- Joint Coordination and Monitoring Center (JCMC)
- Stakeholders for Level I (non-emergency): Government of Iraq – Ministry of Water Resources

Step 4: Emergency Actions – in this step, the needed actions and emergency procedures are implemented based on each level of emergency level as follows:

Level III (Imminent Failure Emergency)

- Quick decision-making and notification are crucial.
- Multiple communication channels are utilized.
- Local authorities lead evacuation efforts.
- Continuous communication with local authorities is maintained.

Level II (Potential Failure Emergency)

- Notifications and communication tools are activated.
- Project personnel assess dam conditions.
- Investigation and corrective actions are initiated.
- Level I (non-emergency)
- Dam inspection is conducted following the monitoring plan.
- Conditions are analyzed, and corrective actions are recommended.

Step 5: Resolution and Follow-up - The final step of the emergency response plan involves resolving the emergency and following up on the actions taken. Once the emergency response plan is activated and the emergency is resolved, the termination responsibilities include the following:

- The Dam Manager declares the termination based on input from MWR and support.
- Inspection is conducted to ensure no threat remains.
- Records are compiled and distributed to relevant stakeholders.

This comprehensive process ensures a systematic and effective approach to emergency planning for Haditha Dam.

3. Results and discussion

3.1 Estimation of risk factor

By following the specifications provided by the International Commission on Large Dams (ICOLD) and using the equation to calculate the risk factor, we can determine the level of risk associated with Haditha Dam. The Haditha Dam is 57 meters high and 8,700 meters long, with 8.2 billion cubic meters and by applying Eq. (1), the value of TRF was found to be 36. According to the classifications mentioned in Table 3, Haditha Dam falls under the extreme category.

3.2 Description of the situation after failure

The Haditha Dam holds an extreme risk of failure, which could lead to catastrophic consequences due to its strategic location, substantial population, and infrastructure that depend on its stability. The impact of its failure would not only be limited to the immediate vicinity but also affect regions downstream. The repercussions of a dam failure would be severe and can be summarized as follows:

Immediate Flood Inundation: The failure of the Haditha dam would release an immense volume of water stored in the reservoir (estimated to be $8x10^9$ m^3), causing a rapid and massive flood downstream. Communities located near the dam would be inundated almost instantly. Table 5 and Figure 5 show the results obtained from the hydraulic model based on the failure scenario of Haditha Dam.

Table 5. The results of the peak time, discharge, and elevation of the flood wave

Location	Peak Time (hour)	Discharge (m^3\s)	Elevation m (a.s.l)
Haditha	8	173350	131
Heet	13	122053	79.56
Ramadi	18	100582.7	55.08
Fallujah	28	64754.37	47.04

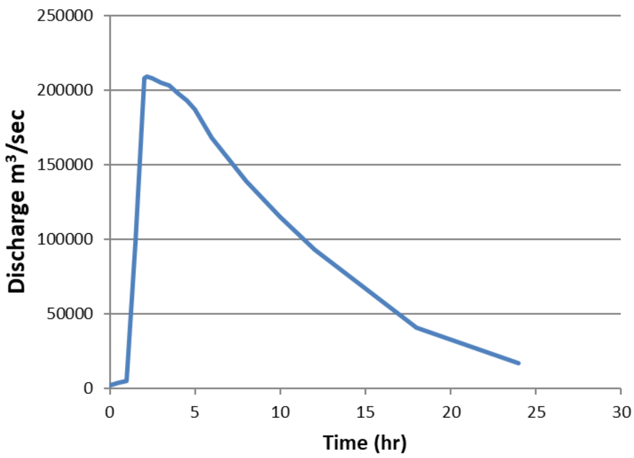

Figure 5. The hydrograph of the dam failure in cities downstream of Haditha Dam during the failure

The loss of Life and Injury: The unexpected flooding caused by the dam could catch approximately a million people downstream off guard, which could potentially lead to a significant loss of life and injuries. Those who are not able to evacuate in time or are trapped in low-lying zones would be particularly vulnerable. Infrastructure Damage: Critical infrastructure such as roads, bridges, power lines, and communication networks would suffer extensive damage or destruction, hindering rescue and relief efforts and exacerbating the crisis. Displacement of Population: Communities downstream of the dam would face displacement due to flooding. This would strain resources and infrastructure in areas accommodating refugees, leading to humanitarian challenges. Environmental Impact: The floodwaters would carry debris, pollutants, and sediment, causing environmental degradation downstream, contaminants from agricultural areas, industrial sites, and urban centers could pollute water sources and harm ecosystems. Impact on Agriculture: Agricultural land along the riverbanks would be submerged, leading to crop loss and damage to livestock, especially since almost all the cities downstream of Haditha Dam have agriculture activities. Economic Disruption: The economic impact would be profound, with damage to infrastructure, agriculture, and businesses leading to loss of livelihoods and reduced economic activity. Recovery and rebuilding efforts would require significant financial resources and time. The process would be lengthy and resource-intensive. All the catastrophic damage mentioned above can be avoided by having an Emergency Action Plan; by applying the emergency action plan and following the evacuation procedures, the casualties can be reduced to the least possible amount.

3.3 Evacuation program

The evacuation program involves the efforts of authorities in charge to evacuate people at risk downstream of the dam to the safe zones (the areas with a high level). Figure 6 displays the flood path with dark blue colour and areas with elevations above 140 m (a.s.l) marked in green. The HEC-RAS model results indicate that if the Haditha Dam were to experience failure due to hostile attack or seepage, the elevation of the flood wave in Haditha city (with a total population of 120,000) would reach 131 m (a.s.l). In case of failure due to overtopping, the elevation would reach 134 m (a.s.l). People should evacuate to these higher areas in such scenarios. Conversely, the low zones marked in red should be avoided in the downstream areas during a Haditha Dam failure.

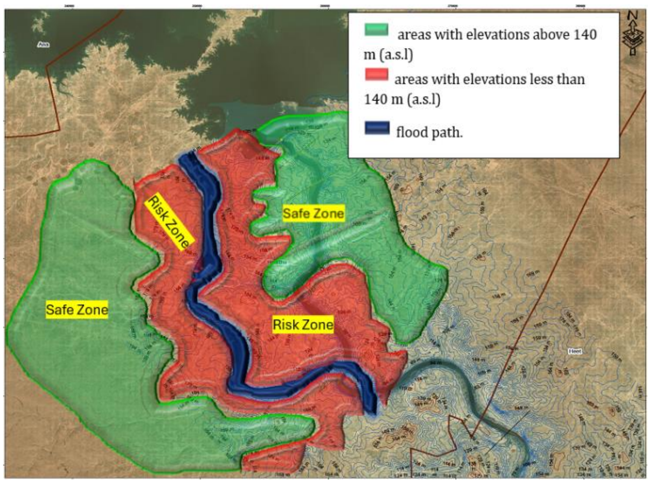

Figure 6. High and low zones of Haditha City

Figure 7 displays the flood path with a dark blue color and areas with elevations above 84 m (a.s.l) marked in green. The HEC-RAS model results indicate that if the Haditha Dam were to experience failure due to hostile attack or seepage, the elevation of the flood wave in Heet City (with a population of more than 95,000) would reach 79.56 m (a.s.l). In case of failure due to overtopping, the elevation would reach 81.32 m (a.s.l). People should evacuate to these higher areas in such scenarios. Conversely, the low zones marked in red should be avoided in the downstream areas during a Haditha Dam failure.

Figure 8 displays the flood path with a dark blue color and areas with elevations above 56 m (a.s.l) marked in green. The HEC-RAS model results indicate that if the Haditha Dam were to experience failure due to hostile attack or seepage, the elevation of the flood wave in Ramadi City (with a population of more than 570,000) would reach 55.08 m (a.s.l). In case of failure due to overtopping, the elevation would reach 55.95 m (a.s.l). People should evacuate to these higher areas in such scenarios. Conversely, the people living in the low zones marked in red should be evacuated immediately after the failure of the Haditha Dam. Figure 9 displays the flood path with a dark blue color and areas with elevations above 49 m (a.s.l) marked in green. The HEC-RAS model results indicate that if the Haditha Dam were to experience failure due to hostile attack or seepage, the elevation of the flood wave in Fallujah City (with a population of more than 500,000) would reach 47.04 m (a.s.l). In case of failure due to overtopping, the elevation would reach 48.88 m (a.s.l). People should evacuate to these higher areas in such scenarios. Conversely, Conversely, the people living in the low zones marked in red should be evacuated immediately after the failure of Haditha Dam.

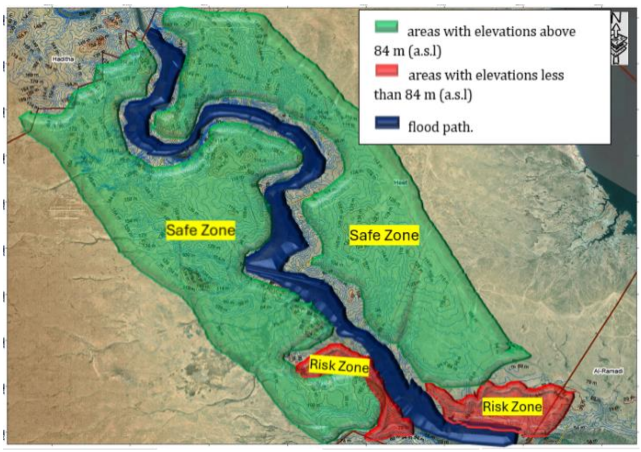

Figure 7. High and low zones of Heet City

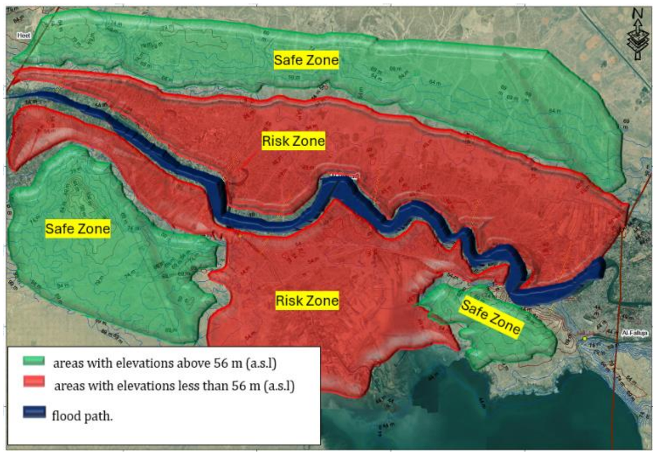

Figure 8. High and low zones of Ramadi City

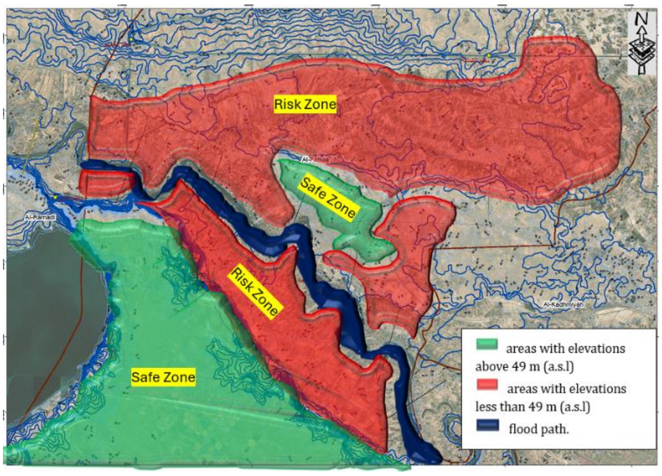

Figure 9. High and low zones of Fallujah City

Maps were prepared based on the inundation areas obtained from the application of the HEC-RAS model. The maps were coloured to show the safe areas in green while the red shows the dangerous areas. In Haditha City (with a population of 120,000), the areas with elevations above 140 m (a.s.l) are marked in green. If the dam fails, the flood wave's elevation would reach 131 m (a.s.l). In case of overtopping, the elevation would reach 134 m (a.s.l). Therefore, people should evacuate to the areas with elevation higher than 140 m (a.s.l) as marked in the maps with green color and avoid low zones marked in red in the downstream areas. In Heet City (with a population of more than 95,000), The flood wave's elevation would reach 79.56 m (a.s.l). In case of overtopping, the elevation would reach 81.32 m (a.s.l). People should evacuate to the areas with an elevation higher than 84 m (a.s.l) as marked in the maps with green color and avoid low zones marked in red in the downstream areas. In Ramadi City (with a population of more than 570,000), The flood wave's elevation would reach 55.08 m (a.s.l). If there is overtopping, the elevation would reach 55.95 m (a.s.l). People should evacuate to the areas with an elevation higher than 56 m (a.s.l) as marked in the maps with green color and avoid low zones marked in red color in the downstream areas. In Fallujah city (with a population of more than 500,000), The flood wave's elevation would reach 47.04 m (a.s.l). If there is overtopping, the elevation would reach 48.88 m (a.s.l). People should evacuate to the areas with an elevation higher than 49 m (a.s.l) as marked in the maps with green color and avoid low zones marked in red in the downstream areas. However, the dam's unique geology, which includes voids caused by limestone formations, poses a risk to its structural integrity. This makes it more susceptible to failure, especially in the event of a terrorist attack, as it has been targeted before. In this research, an emergency action plan was proposed that includes three possible failure scenarios, categories of potential emergencies in the dam, and the actions and steps that must be followed to mitigate human and economic losses. Also, an evacuation program has been suggested as part of the emergency response plan that involves different stakeholders and authorities in safeguarding the population downstream of the dam.

4. Conclusion

The Haditha Dam located in Iraq is a crucial safeguard against potential risks, such as natural disasters, deliberate acts of sabotage by terrorists, or failure due to geological conditions. The dam has a significant storage capacity of around ($8x10^9$ m^3), and most of the cities downstream are located in low areas, making it an essential structure for the region's safety. The authorities in charge have developed an evacuation program to help people at risk downstream of the dam to reach the areas with higher elevations that are considered safe zones.

Acknowledgments

The authors highly acknowledge the cooperation and encouragement that they got from the Ministry of Water Resources, Iraq, Istanbul Gedik University, Turkey, and the University of Baghdad, Iraq.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] H. A. Al-Fatlawi, and A. M. Salih Ameen, "A control program for hydropower operation based on minimizing the principal stress values on the dam body: Mosul dam case study. Journal of Engineering," 29(6), pp.30–45, 2023. https://doi.org/10.31026/j.eng.2023.06.03.

[2] J. D. Pisaniello, T. T . Dam, and J. L. Tingey-Holyoak, "International small dam safety assurance policy benchmarks to avoid dam failure flood disasters in developing countries," Journal of Hydrology, 531, pp.1141–1153, 2015. https://doi.org/10.1016/j.jhydrol.2015.09.077.

[3] A. M. Mehta, C. S. Weeks, and E. Tyquin, "Towards preparedness for dam failure: an evidence base for risk communication for downstream communities," International Journal of Disaster Risk Reduction, vol. 50, no. 11, 2020. https://doi.org/10.1016/j.ijdrr.2020.101820

[4] A. Mohammed, A. Maryam, and N. Odaa, "Analysis of Mosul and Haditha dam flow data," Journal of Engineering, vol. 50, no. 2, 2014. https//doi:10.1016/j.ijdrr.2020.101820

[5] A. S. Abass, and D. Najeeb, "Analysis of seepage through embankment dams as case study (Al-Shahabi Dam) in Iraq," International Journal of Sciences: Basic and Applied Research (IJSBAR), vol. 40, no. 2, pp.7–17, 2018. http://gssrr.org/index.php?journal=JournalOfBasicAndApplied

[6] T. Al-Hadidi and M. Al-Nedawi, "Seepage and slope stability analysis for Hemrin earth dam in Iraq using geo-studio software," Solid State Technology, vol. 63, no. 3, pp. 3434-3448, 2020.

https://solidstatetechnology.us/index.php/JSST/issue/view/46
[7] N. M. Al-Nedawi, "Finite element analysis of seepage for Hemrin earth dam using geo-studio software," Diyala Journal of Engineering Sciences, 13(3), pp.66–76, 2020. https://doi.org/10.24237/djes.2020.13307.
[8] R. Mahdi, and M. T. AI-Hadidi, "The simulation of seepage through the foundations: hilla canal main regulator as case study," E3S Web of Conferences, vol. 427, no. 9, 2023. https://doi.org/10.1051/e3sconf/202342701007
[9] M. T. Al-Hadidi, and S. H. Hashim, "Finite element analysis of seepage for Kongele earth dam using geo-studio software," Journal of Physics: Conference Series, 2021. https://doi.org/10.1088/1742-6596/1895/1/012003.
[10] Zedan, A.J., Faris, M.R. and A. K. Bdaiwi, 2022. Performance assessment of Shirin earth dam in Iraq under various operational conditions. Tikrit Journal of Engineering Sciences, 29(2), pp.61-74. DOI: http://doi.org/10.25130/tjes.29.2.8.
[11] M. M.Aboelela, "Control of seepage through earth dams based on pervious foundation using toe drainage systems," Journal of Water Resource and Protection, vol. 8, no. 12, pp. 1158–1174, 2016. https://doi.org/10.4236/jwarp.2016.812090.
[12] M. G. Jassam, and S. S. Abdulrazzaq, "Theoretical analysis of seepage through homogeneous and non-homogeneous saturated-unsaturated soil," Journal of Engineering, 25(5), pp.52–67, 2019. https://doi.org/10.31026/j.eng.2019.05.04.
[13] S. Bredy, and J. J. andora, "Effect of dam height on the stability of earth dam (case study: Karolinka dam)," Journal of Engineering, vol. 26, no. 3, pp.117–126, 2020a. https://doi.org/10.31026/j.eng.2020.03.10
[14] Z. N. Alzamily, and B. Sh. Abed, "Comparison of seepage trough zoned earth dam using improved light-textured soils," Journal of Engineering, vol. 28, no. 3, pp.32–45, 2022. https://doi.org/10.31026/j.eng.2022.03.03.
[15] M. M. Mostafa, and S. Zhenzhong, "Effect of zones' dimensions and geometry on seepage through zoned earth dams," Journal of Engineering and Applied Science, vol. 70, no. 1, 2023. https://doi.org/10.1186/s44147-023-00223-7.
[16] R. P. Sharma, A. Kumar, A. Kumar, Proceeding of International conference on case histories in geotechnical engineering, Missouri, USA; University of Science and Technology, 2013. https://scholarsmine.mst.edu/icchge/7icchge/session03/
[17] C. Wannous, and G. Velasquez, "United Nations Office for Disaster Risk Reduction (UNISDR)—UNISDR's contribution to science and technology for disaster risk reduction and the role of the international consortium on landslides (ICL)," Advancing Culture of Living with Landslides, pp.109–115, 2017. https://doi.org/10.1007/978-3-319-59469-9_6.
[18] Juliastuti and Setyandito, O., Dam break analysis and flood inundation map of Krisak dam for emergency action plan, AIP Conference Proceedings, Sumatera, Indonesia, 2017. https://doi.org/10.1063/1.5011615.
[19] K. Bharti, M. Sharma, and N. Islam, "Study on the dam & reservoir, and analysis of dam failures: a data base approach," International Research Journal of Engineering and Technology, vol. 7, no. 5, pp. 1661-1669, 2020. https://www.researchgate.net/publication/341378442_Study_on_the_Dam_Reservoir_and_Analysis_of_Dam_Failures_A_Data_Base_Approach
[20] M. Axman, and S. Kročová, "Safety of dams in crisis situations. in: IOP conference series: Earth and Environmental Science," vol. 900, no. 2021, pp. 1-9, 2021. https://doi.org/10.1088/1755-1315/900/1/012002.
[21] M. M. E. Zumrawi, 2013. "Failure investigation of Tawila dam in north Darfur, Sudan," International Journal of Science and Research, vol. 40, no. 5, pp. 963-967, 2013. https://doi: 10.13140/RG.2.2.31096.52488
[22] M. Foster, R. Fell, and M. Spannagle, "The statistics of embankment dam failures and accidents," Canadian Geotechnical Journal, vol. 37, no. 5, pp. 1000–1024, 2000. https://doi.org/10.1139/t00-030.
[23] R. B. Fernandes, A. C. C. Fontenla Sieira, and A. P. M. Filho, "Methodology for risk management in dams from the event tree and FMEA analysis," Soils and Rocks, vol. 45, no. 3, 2022. https://doi.org/10.28927/SR.2022.070221.
[24] S. E. Evans, S. D. Mackky, J. F. Gottckns, and W. M. Gill, "Lessons from a dam failure," The Ohio Journal of Science, vol. 100, no. 4, pp. 121-131, 2000. https://www.researchgate.net/publication/273761656_Lesson_From_a_Dam_Failure
[25] L. X. Hollins, D. A. Eisenberg, and T. P. Seager, "Risk and resilience at the Oroville Dam," Infrastructures, vol. 3, no. 4, pp. 1-17, 2018. https://doi.org/10.3390/infrastructures3040049.
[26] Federal Emergency Management Agency (FEMA). Federal guidelines for inundation mapping of flood risks associated with dam incidents and failures (first edition), FEMA P-946/July 2013.
[27] I. Escuder-Bueno, E. Matheu, L. Altarejos-García, and J.T. Castillo-Rodríguez, Risk analysis, dam safety, dam security and critical infrastructure management, Abingdon, Oxfordshire, UK, 2011.
[28] J. Imran, A. Tanim, M.S. Khan, A. Nahian, and E. Goharian, Rising waters, falling dams: deciphering the Derna flood disaster, Research Square, Preprint, 2023. https://doi.org/10.21203/rs.3.rs-3809203/v1
[29] A. Ashoor, and A. Eladawy, Watch and upgrade or deconstruct and relocate: Derna catastrophe lessons amid the climate-change era of unpredictable flash floods, Research Square, 2024. https://doi.org/10.21203/rs.3.rs-3858769/v1
[30] K. S. Varoujan, N. Al-Ansari, L. H. Abdullah, "Neotectonic activity using geomorphological features in the Iraqi Kurdistan Region," Geotechnical and Geological Engineering, vol. 38, no.1, pp. 4889-4905, 2020. https;//doi: 10.1007/s10706-020-01334-1
[31] C. A. Alvarado Ancieta, "The importance for selecting adequate seismic design parameters for large dams - Andean, Himalayas and eastern Anatolia Mountain range cases," Journal of Earthquake Engineering,

26(3), pp.1194–1208, 2020. https://doi.org/10.1080/13632469.2020.1713933.
[32] Topçu Kütahya, S., Tosun, H. and Topcu, S., An overview on total risk classifications for dams, 2021. https://www.researchgate.net/publication/355444095