ORIGINAL RESEARCH ARTICLE | UHD JOURNAL OF SCIENCE AND TECHNOLOGY

Cascading Overtopping-Induced Dam Failures in a Transboundary Basin: Hydrodynamic Modeling from Gawshan to Darbandikhan Dam

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ABSTRACT

This study investigates the cascading failure potential of a multi-dam system in the transboundary Diyala (Sirwan) River basin, spanning Iran and Iraq. Using a two-dimensional hydrodynamic model developed in Hydrologic Engineering Center's River Analysis System 6.6, the study simulates overtopping- and piping-induced breach scenarios at Gawshan Dam and assesses their propagation through downstream reservoirs including Zhave, Daryan, and Hirwa, culminating at Darbandikhan Dam. The results highlight the formation of a compound flood wave that exceeds crest elevations, particularly under overtopping scenarios, leading to overtopping failure at Darbandikhan Dam despite emergency discharge operations. Scenario 1, representing full reservoir conditions and sequential overtopping failure, was identified as the most severe. The model outputs show a rise in water surface elevation from 485.0 m to 495.5 m within 412 min at Darbandikhan Reservoir, causing structural overtopping. Extensive inundation impacts both Iranian upstream settlements and Iraqi downstream communities, submerging over 20 villages and 80 km^2 of agricultural land. The findings underline the need for transboundary coordination, reservoir reoperation protocols, and updated Emergency Action Plans to mitigate the risk of cascading dam failures in seismically active regions.

Index Terms: HEC-RAS, Dam Failure, Inundation Map, Flood Hazard Map, Flood Disaster

1. INTRODUCTION

A dam is an engineered barrier constructed across a river to retain and supply water for various uses, including irrigation, hydropower, flood control, water supply, recreation, and navigation [1]. As noted by M. Zagonjolli [2], the global count of dams exceeds 800,000, built primarily to serve these functions. However, the accumulation of vast water volumes behind these structures can pose significant hazards to populations living downstream.

Access this article online

DOI:10.21928/uhdjst.v9n2y2025.pp251-265	E-ISSN: 2521-4217 P-ISSN: 2521-4209

Although dams offer substantial advantages to society, they also introduce serious risks. A dam's structural failure may lead to uncontrolled water release, potentially resulting in catastrophic flooding and extensive environmental destruction. Such dam-break floods tend to be more devastating than natural flood events, often causing fatalities, economic losses, ecological damage, sediment displacement, terrain deformation, and psychological trauma in affected communities. Worldwide, floods account for approximately 40% of deaths resulting from natural disasters.

Historical data indicate that dam failures affect all structural types. According to Costa [3], embankment dams have failed primarily due to piping (38%), overtopping (35%), foundation failure (21%), and other causes (6%). In addition, failure rates are high during the first 1–5 years and between 20 and

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Received: 20-07-2025 Accepted: 25-09-2025 Published: 13-10-2025

50 years after dam commissioning, accounting for 31% and 22% of failures, respectively [4].

Research based on over 1065 failures of earthen dams highlights overtopping and piping as the leading causes. Spillways, downstream slopes, and foundations are key points vulnerable to overtopping, whereas piping threatens the dam body as a whole [5]. Most dam failures are preceded by observable warning signs such as the development of a breach. Once a breach forms, it triggers a flood wave originating from the water stored upstream [6]. Therefore, it is essential for downstream residents to be informed about such threats, as early awareness can prevent costly damages or enable mitigation efforts [7]. The prediction of breach outflow hydrographs and their routing is central to dam breach studies [8]. Critical elements in such analyses include the shape of the flood hydrograph and the length of the river section affected [7]. Reliable flood prediction supports the development of emergency preparedness plans to reduce risks to life and property [9]. Accurate modeling of dam-break floods and downstream propagation is typically carried out using hydraulic simulation tools [10], [11].

Common modeling tools include DAMBRK [4], MIKE developed by DHI [12], and the Hydrologic Engineering Center's River Analysis System (HEC-RAS) from USACE [13]. Moreover, the physically based model Dam Break-Institute of Water Resources and Hydropower Research has also been utilized in breach studies [14]. Among these, HEC-RAS stands out for its widespread use in dam failure research [15]-[24]. For instance, HEC-RAS was employed to calculate flood depths downstream of Um Al-Khair Dam and compared against observed water levels during the breach event [25].

Combining hydraulic modeling, GIS tools, and risk assessment frameworks enables the identification of flood-prone regions following dam breaches. These methods integrate spatial data, flood depths, and velocities to evaluate hazard levels [22], [26], [27]. HEC-RAS is often used to simulate dam failure timing and geometry, incorporating peak discharge values. To achieve this, cross-sectional data are imported through digital elevation models (DEMs) and HEC-GeoRAS. For example, Sharma and Mujumdar [19] applied HEC-RAS, HEC-GeoRAS, and GIS to study the Ajwa Dam breach after heavy rainfall, deriving critical outputs such as peak water levels, downstream discharge, flow velocities, and inundation mapping.

The border between Iran and Iraq is seismically active, housing major hydraulic structures such as Gawshan and Daryan Dam (Iran) and Darbandikhan Dam (Iraq) within the Diyala River basin. A Mw 7.3 earthquake on November 12, 2017, caused structural impairments to Darbandikhan Dam [28], revealing its susceptibility to seismic events and underscoring the risk of cascading upstream dam failures. Consequently, Darbandikhan Dam is now operated below its rule curve to minimize potential damage from sudden upstream inflows.

This study focuses on modeling the hydrodynamic consequences of hypothetical upstream dam failures specifically Gawshan, Zhave, Daryan, and Hirwa on Darbandikhan Dam using HEC-RAS 6.6. The analysis investigates flood wave movement, peak discharge values, and inundation extent across a range of breach scenarios. The primary objectives are as follows: (1) To evaluate Darbandikhan Dam's structural response to incoming flood waves, and (2) to identify scenario-specific vulnerabilities to guide the development of Emergency Action Plans (EAPs) and support adaptive strategies in reservoir management.

2. MATERIALS AND METHODS

2.1. Study Area

The study area is situated within the Diyala (Sirwan) River Basin, encompassing a transboundary river system shared between Iran and Iraq. This region includes a cascade of major dams Gawshan, Zhave (Java), Daryan, Hirwa, and Darbandikhan, each contributing critically to water resource management, hydropower production, and flood control. The interconnected nature of these structures makes the basin highly sensitive to cascading dam failure scenarios. A general overview of the study area and dam locations is presented in Fig. 1. The Darbandikhan Dam (Fig. 2), in particular its considerable height, substantial reservoir volume, and critical location upstream of major population centers including the cities of Kalar and Diyala, greatly amplifies the potential consequences of failure. This positioning greatly amplifies the consequences of a potential dam failure, underscoring the necessity for comprehensive risk evaluation and effective emergency response strategies. The dam is located roughly 65 km southeast of Sulaimani City and around 230 km northeast of Baghdad. Built between 1956 and 1961, Darbandikhan is an embankment dam serving multiple functions such as irrigation, hydroelectric power generation, and flood control.

The reservoir is mainly supplied by four tributaries: The Tanjaro and Zalm rivers from Iraq, and the Sirwan and

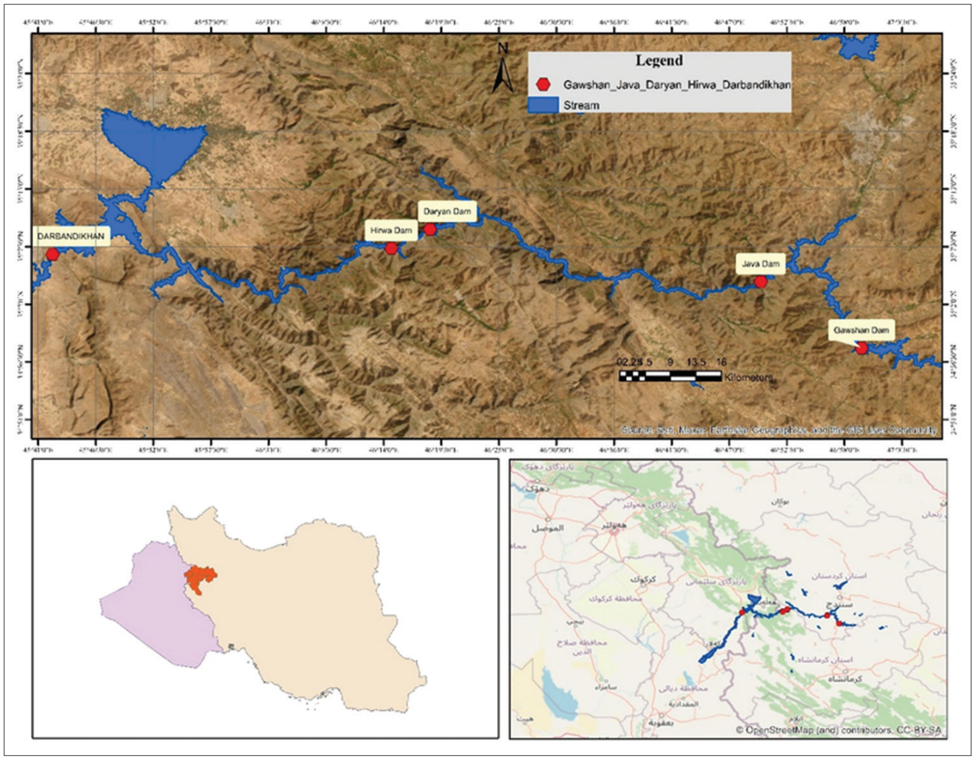

Fig. 1. Map of Stream Gawshan to Darbandikhan.

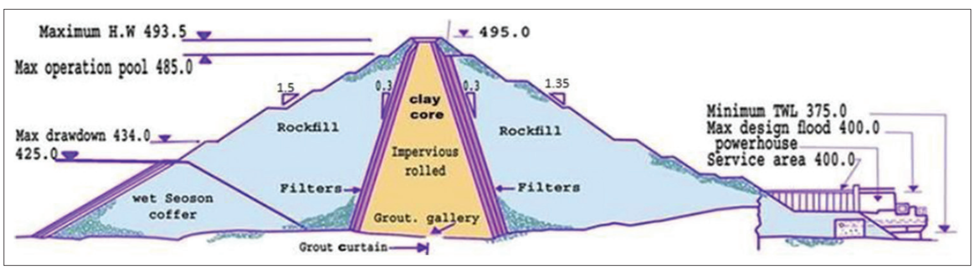

Fig. 2. Maximum cross section of the Darbandikhan Dam (Adopted from the Darbandikhan Dam Directorate).

Zmkan rivers flowing from Iran. The dam rises to a height of 128 m and spans 445 m along its crest. Originally, its reservoir had a total capacity of (3.0×10^9 m^3), which has since declined to (2.55×10^9 m^3) due to sediment buildup over six decades of operation. This includes (2.05×10^9 m^3) of usable (active) storage and (0.50×10^9 m^3) categorized as inactive storage. The spillway system comprises a gated chute with three outlets, collectively capable of handling up to 11,400 m^3/s during peak flow events. The reservoir itself spans an area of 113 km^2 and is part of a catchment that drains 17,850 km^2. At its highest operational level, the water surface can reach an elevation of 485 m, ensuring optimal water retention and distribution. The dam's power station uses three Francis turbines, each with a maximum discharge capacity of 113 m^3/s, and a minimum flow release of 63 m^3/s through the turbine gates.

Gawshan Dam is an embankment-type structure positioned near Kamyaran in Iran's Kurdistan Province, constructed to regulate the flow of the Gaveh River, a tributary of the Sirwan River Fig. 3. Its precise location is marked by the geographic coordinates (34°57'48"N) and (46°59'40"E), as illustrated in Fig. 4. The dam's construction commenced in 1992 and was completed in 2004 [29]. It is currently managed by the Iran Water and Power Resources Development Company. With a total reservoir storage capacity of 550 million cubic meters, Gawshan ranks among the largest hydraulic infrastructure initiatives in western Iran. It plays a key role in the region's water and energy management by supplying 183 million cubic meters annually for agricultural irrigation and 63 million cubic meters to meet the municipal water needs of Kermanshah. The dam is also equipped with hydroelectric generation facilities, producing up to 11 megawatts of electricity. In addition, a 21-km-long diversion tunnel was constructed to deliver water at a rate of 30 cubic m/s, enabling irrigation across 31,000 ha of productive farmland. Due to its location and multifunctional design, Gawshan Dam serves as a key asset in regional water allocation, agricultural development, and energy production [30].

Zhave (Java) Dam located in Iran's Kurdistan Province Fig. 5. Zhave Dam sits at the geographic coordinates of (35°04'N) and (46°50'E), with its crest reaching an elevation of 1320 m

Fig. 3. Gawshan Dam.

above sea level. It is situated approximately 6 km downstream from the junction where the Gheshlagh and Gavehrood rivers meet two rivers that originate in the eastern highlands of the Sirwan River Basin. Their confluence forms the Zhave River, which flows southwestward through the region [32]. The Zhave Dam Reservoir stretches upstream into the main channels of both contributing rivers, thus offering substantial hydrological regulation over the sub-basin. Further upstream, the Gavehrood River is also regulated by Gawshan and Soleyman Shah dams, which contribute to managing the flow entering the Zhave system. By controlling inflow from these upstream sources, Zhave Dam plays a key role in regional flood mitigation and water resource storage [33].

As illustrated in Fig. 6, Daryan Dam is positioned upstream of Darbandikhan Dam along the Sirwan River in Paveh County, Kermanshah Province, Iran. The dam lies approximately 55.8 km away from Darbandikhan Dam in a straight-line distance. Construction activities commenced in 2009, and the dam became operational by the end of 2015 [34]. With a structural height of 169 m, the primary objective of the dam's development was the generation of hydroelectric power, with a capacity of 210 megawatts. The reservoir created by Daryan Dam spans an area of 10 km^2, reaching a maximum width of 800 m. Its total storage volume is 316.3 million cubic meters, of which 281 million cubic meters are designated as active storage.

Shown in Fig. 7, Hirwa Dam is a concrete diversion structure built in 2018. It is located around 8 km downstream of the

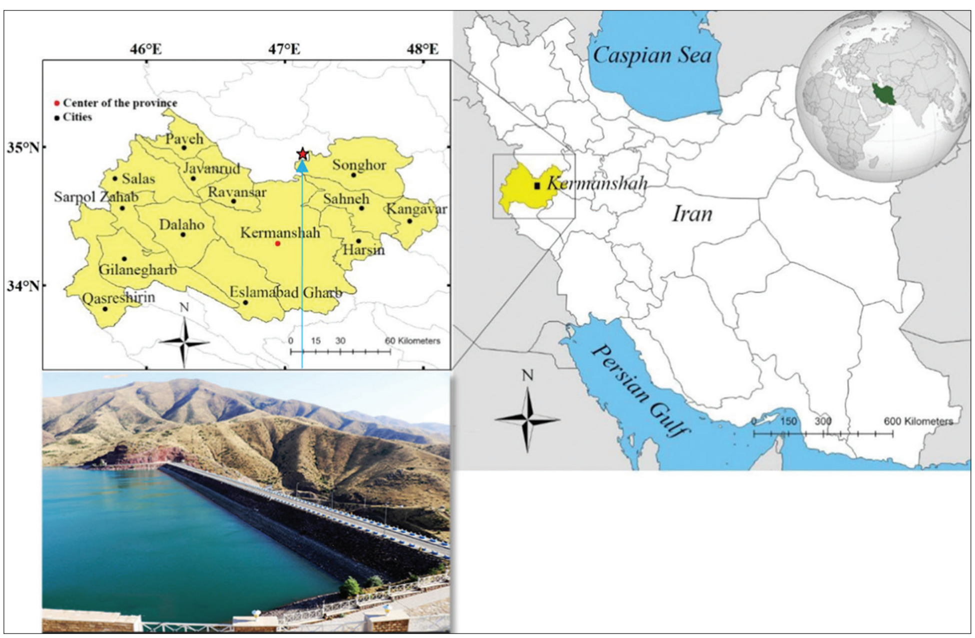

Fig. 4. Iran map and the study area (Kermanshah province, Gawshan dam) [31].

Fig. 5. Zhave Dam.

Fig. 6. Upstream view of Daryan dam [31].

Fig. 7. Hirwa Dam looking upstream.

Daryan Dam, in Hirwa Village, Paveh County, Iran. This dam plays a key role in managing the outflow from Daryan Dam before its diversion into the Nowsud Tunnel, thereby ensuring consistent water delivery for both irrigation and hydroelectric power generation. Hirwa Dam has a height of 45 m and a total storage capacity of 12 million cubic meters [35].

Considering the strategic importance of the interconnected dam system in the region, this research concentrates on the cascading failure risks associated with the Gawshan, Zhave, Daryan, and Hirwa dams. It specifically models breach scenarios to evaluate their downstream hydrodynamic consequences on the Darbandikhan Dam. A sequential failure of these upstream dams could severely compromise the structural stability, flood management capability, bank protection, and overall operational performance of the Darbandikhan Dam.

2.2. Problem Statement

Gawshan Dam, situated on a principal tributary of the Sirwan River, is the largest and most critical storage reservoir in the upper Sirwan basin. Due to its considerable impoundment capacity, a hypothetical failure, particularly one triggered by overtopping or piping due to seismic disturbance, would generate an exceptionally high-energy flood wave that no downstream reservoir, including Zhave, Daryan, or Hirwa dams, could effectively withstand. The scale of this outflow would likely initiate a cascading sequence of structural failures, amplifying the flood wave as it moves downstream and ultimately threatening the stability of Darbandikhan Dam, one of many vital infrastructures for hydropower, irrigation, and water supply in Iraq.

This hydrodynamic threat is compounded by the fact that the region lies within a seismically active zone as seismic map, as shown in Fig. 8.

The Mw 7.3 earthquake of November 12, 2017, which caused notable structural damage to Darbandikhan Dam [28], underscores the potential for seismic events to trigger or exacerbate dam failures. Earth-fill dams such as Gawshan are particularly vulnerable to combined seismic loading and elevated reservoir levels, which may lead to slope instability, foundation movement, or overtopping-induced breach. In response to these risks, Darbandikhan Dam is currently operated below its designated rule curve to provide buffer capacity for absorbing sudden upstream inflows. While this precautionary strategy enhances flood resilience, it also introduces trade-offs in terms of reduced water storage for hydropower generation, agricultural irrigation, and municipal supply.

These operational limitations highlight the urgent need to determine a safe and sustainable reservoir level that balances hazard mitigation with resource utilization. Despite the severity of these scenarios, there remains a notable lack of quantitative research on the cascading impacts of Gawshan Dam failure on the broader Sirwan River system. This study aims to fill that gap by employing 2D hydrodynamic modeling using HEC-RAS 6.6 to simulate breach scenarios at Gawshan Dam and assess their downstream effects, particularly on

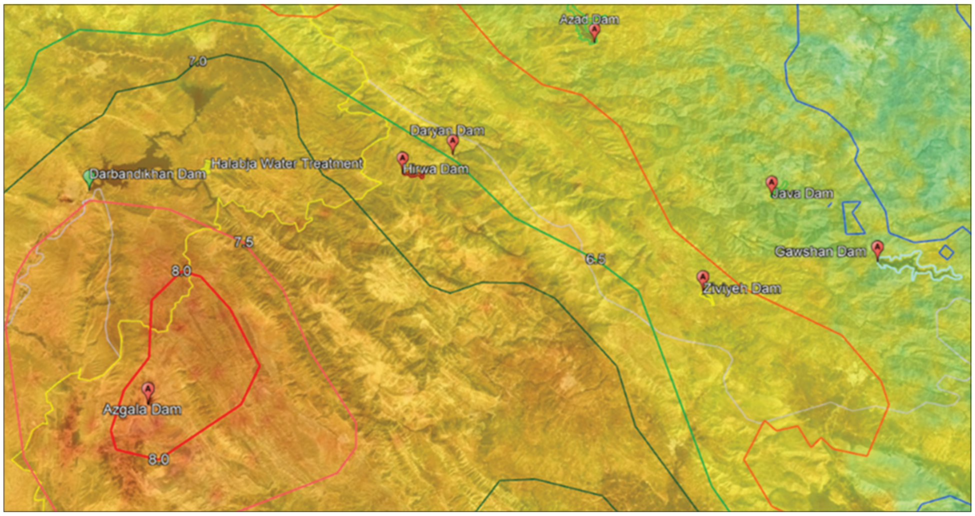

Fig. 8. Seismic map of the study area.

Darbandikhan Dam. The research focuses on flood wave routing, peak discharge propagation, and structural loading under various breach conditions. The outcomes are intended to support the development of EAPs, enhance cross-border risk communication, and inform adaptive reservoir management under extreme climate and seismic uncertainties.

2.3. HEC-RAS

This study employed HEC-RAS version 6.6, along with its updated 6.7 Beta release, to perform detailed hydrodynamic modeling. Both versions were sourced from the official platform of the U.S. Army Corps of Engineers (www.hec.usace.army.mil). HEC-RAS is a robust and extensively adopted hydraulic simulation tool capable of modeling both one-dimensional and two-dimensional unsteady flow conditions [36]. Its intuitive graphical interface supports a variety of functions, including dam breach analysis, sediment transport, water quality modeling, and the hydraulic design of in-channel and lateral infrastructure such as spillways, culverts, sluice gates, and weirs.

In this research, the breach scenario of Gawshan Dam was simulated using the 2D flow module of HEC-RAS, which provides a more spatially detailed view of flood wave behavior across complex terrain. While offering greater precision in modeling flood propagation dynamics, 2D simulations demand more advanced computational resources and meticulous preprocessing of topographic and boundary condition data. The technical specifications and structural properties of the modeled dams essential for defining breach parameters and flow hydraulics are summarized in Table 1.

2.4. Terrain Data

To support the hydraulic modeling in this study, a DEM with a spatial resolution of approximately 30 m (1 arc-second) was acquired from the USGS Earth Explorer portal (https://earthexplorer.usgs.gov). This elevation data, derived from the Shuttle Radar Topography Mission and made publicly available by the USGS on September 23, 2014, was processed within ArcMap after being converted into a Triangulated Irregular Network. All geospatial processing was conducted using the (WGS 1984 UTM Zone 38N) coordinate system to ensure consistency in horizontal referencing. Covering the geographic range between (34°N to 35°N) latitude and (45°E to 46°E) longitude, the dataset offers a reliable elevation profile suitable for detailed floodplain delineation and hydrodynamic modeling. Since the DEM predates the construction of the Gawshan Dam, a fully dynamic wave routing approach was adopted to simulate the reservoir's hydraulic response with greater accuracy than static storage-area methods, following guidelines from [37].

2.5. Breach Prediction Models

Analyzing dam failure scenarios is inherently complex due to the uncertain nature of key parameters such as breach location, breach dimensions, and the time required for breach formation, all of which significantly influence the resulting flood hydrograph [38]. To address these uncertainties, researchers have proposed numerous empirical and regression-based models aimed at estimating breach characteristics.

Among the most frequently utilized models are the equations introduced by Von Thun and Lawrence [39], which have been cited and adapted in several studies, including those by

Brunner [36], Froehlich [40], [41], Xu and Zhang [42], and Pierce [43]. These models have gained widespread application in dam breach assessments [38], [44], [45], especially due to their compatibility with diverse dam types and failure conditions. The Gawshan Dam, when evaluated for its structural profile and hydrological setting, demonstrates characteristics consistent with the assumptions underlying these regression models. Therefore, the breach equations from these established studies are considered reliable and suitable for application in the present simulation. Additional studies, such as those by Wahl [7], Wu *et al*. [8], also emphasize the importance of selecting breach parameter equations that reflect dam-specific conditions and site characteristics.

2.6. Assessment of the Flood Hazard

In flood modeling, water depth and flow velocity are regarded as the two most critical parameters influencing flood hazard evaluation. According to the classification developed by Mihu-Pintilie *et al*. [46], these variables serve as the primary indicators for assessing flood severity, as outlined in Table 2. This classification system has been adopted in the current study to support the analysis and categorization of flood hazard levels across the affected region.

2.7. Dam Failure Scenarios

To assess the downstream consequences of potential upstream dam failures on Darbandikhan Dam, four distinct failure scenarios were formulated and analyzed. These scenarios differ based on the mode of failure, initial reservoir levels, and the resulting cascading impacts on downstream hydraulic structures. The initial reservoir volumes and elevations used in the modeling are summarized below:

- Gawshan Dam (overtopping): 550 million m^3 plus an additional 80 million m^3 from overtopping inflow
- Gawshan Dam (piping failure): 550 million m^3
- Daryan Dam (overtopping): 316.3 million m^3
- Zhave Dam (at full capacity): 172 million m^3
- Hirwa Dam (in all cases): 12 million m^3.

Darbandikhan Dam – full condition: 2.55 billion m^3 at an elevation of 485 m, according to the most recent bathymetric survey conducted by the Darbandikhan Dam Directorate, the current live storage at the normal operation elevation of 485 m a.s.l. is 2,550 million m^3.

Darbandikhan Dam – semi-full condition: 2.05 billion m^3 at an elevation of 480 m. According to the operational rule curve Fig. 9, during wet seasons, the reservoir water level is maintained at 480 m, and based on the most recent survey conducted by the Dam Directorate, the corresponding storage at this elevation is 2,050 MCM.

The simulated failure scenarios are defined as follows:

- Scenario 1: An overtopping-induced failure at Gawshan Dam causes the collapse of Zhave, Daryan, and Hirwa dams, while Darbandikhan remains at full capacity (elevation 485 m)
- Scenario 2: Initiation of piping failure at Gawshan Dam triggers successive failures of Zhave, Daryan, and Hirwa dam, with Darbandikhan reservoir at full storage (elevation 485 m)
- Scenario 3: An overtopping event at Gawshan results in the failure of the same three downstream dams, while

TABLE 1: Gawshan, Zhave, Daryan, Hirwa, and Darbandikhan dams' properties

Items	Gawshan Dam	Zhave Dam	Daryan Dam	Hirwa Dam	Darbandikhan Dam
Dam type	Rock-fill dam	Concrete dam	Rockfill dam	Concrete dam	Rockfill dam
Height	123	86	169 m	45 m	128 m
Crest width	15 m	4.5 m	15 m	4.5 m	17 m
Reservoir capacity	550 million m^3	172 million m^3	316.3 million m^3	12 million m^3	2.55 billion m^3

TABLE 2: Classification flood hazard evaluation

Hazard level	Flood depth (m)	Flow velocity (m/s)	Hazard vulnerability classification	Description
Low	<0.5	0–2	H1	Flood does not pose hazard to people and on-foot evacuation is not difficult.
Medium	0.5–1	0–2	H2	Flood water poses hazard for infants and on-foot evacuation of adults becomes dicult; evacuation becomes more complicated.
High	1–2	0–2	H3	Flood depth can drown people; people may be safe inside their homes.
Crisis	2–5	0–2	H4	People are exposed to flood hazard even inside their homes and evacuate toward the roof of their homes is suggested.
Catastrophic	>5	2–4	H5	Built-up structures like homes may get covered by the flood; people may get drowned even if they evacuate toward the roof of their homes.

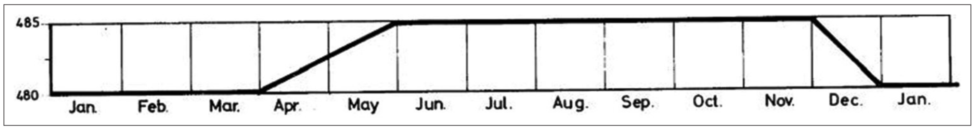

Fig. 9. Darbandikhan reservoir operational rule curve (adopted from Darbandikhan dam directorate).

Darbandikhan is operating below maximum storage (elevation 480 m)

- Scenario 4: Piping failure at Gawshan leads to the cascading failure of Zhave, Daryan, and Hirwa dams, under semi-full conditions at Darbandikhan (elevation 480 m).

These scenarios aim to capture the variation in downstream flood dynamics and structural response under different breach mechanisms and storage levels, thereby supporting the development of robust emergency response plans and reservoir operation strategies.

3. RESULTS AND DISCUSSION

3.1. Scenario Characterization

To analyze the cascading dam failure risks within the study area, four initial breach scenarios were constructed involving Gawshan, Zhave (also referred to as Java), Daryan, and Hirwa dams. These scenarios were formulated to capture two key failure modes: Overtopping and piping across two storage states: Full supply level (FSL) and semi-full level. Among these, two representative scenarios were selected for detailed hydraulic evaluation based on their severity, relevance to real-world dam management practices, and their potential to cause extreme downstream flooding and instability at Darbandikhan Dam.

- Scenario 1: Overtopping Cascade at Full Capacity

Sequence: Gawshan (overtopping) → Zhave (overtopping) → Daryan (overtopping) → Hirwa (overtopping) → Darbandikhan (at FSL: 2.55 billion m^3, Water Surface Elevation (WSE) = 485 m)

This scenario reflects the worst-case cascade, with all upstream dams breaching due to overtopping while Darbandikhan remains at full reservoir capacity.

It is designed to examine peak inflow volumes, minimum flood arrival times, and the structural load limits of the downstream dam.

- Scenario 2: Mixed Failure Under Full Storage

Sequence: Gawshan (piping) → Zhave (overtopping) → Daryan (overtopping) → Hirwa (overtopping) → Darbandikhan (at FSL: 2.55 billion m^3, WSE = 485 m)

This scenario combines internal erosion at Gawshan Dam with overtopping failures at the downstream dams. The objective is to assess how variation in initial breach mechanisms influences the shape of the flood hydrograph, wave travel time, and the resulting stress imposed on the Darbandikhan reservoir and dam body.

3.2. Peak WSE Analysis

Table 2 presents a comparison of peak WSEs at six strategically important locations during flood propagation: The Iraq–Iran border, marking the point where breach outflows begin entering Darbandikhan Reservoir. The immediate upstream zone of Darbandikhan Dam reflects the attenuated wave impact after storage buffering. By analyzing the differences in peak WSE at these locations, the reservoir's capacity to absorb and dampen incoming flood waves can be evaluated. Higher values recorded at the border indicate the initial magnitude of the flood wave, whereas lower elevations near the dam body reveal how much energy and volume were mitigated by the reservoir's geometry and storage.

This comparative analysis is essential for determining:

Emergency drawdown requirements, design thresholds for structural reinforcement, and response trigger in the EAP under varying failure conditions.

3.3. WSE Rise and Flood Arrival Dynamics

A comparison between the breach hydrographs produced for piping and overtopping failures at Gawshan Dam revealed only slight variations in both peak discharge and total flood volume. As a result, Scenario 1, which simulates the overtopping failure, has been selected for further hydraulic analysis due to its potential to generate the most critical downstream flood impacts and heightened risk of structural stress on Darbandikhan Dam.

In Scenario 1, the cascading failure sequence begins with the overtopping-induced breach of Gawshan Dam, which occurs while all upstream reservoirs Gawshan, Zhave (Java), Daryan, and Hirwa are operating at full storage capacity. The downstream Darbandikhan Reservoir is similarly assumed to be at its maximum level, with an initial WSE of 485.0 m.

Following the initial breach, the flood wave of Gawshan Reservoir after failure propagates rapidly through the cascade system. It arrives at Zhave Dam approximately 52 min after the failure of Gawshan Dam, inducing structural failure at Zhave 67 min post Gawshan breach. The compound flood surge then continues its path, reaching Daryan Dam at 172 min and causing overtopping failure at 187 min.

The wave subsequently reaches Hirwa Dam at 190 min, where it also results in overtopping-induced failure due to the dam's limited retention capacity. The cumulative floodwaters from the four failed dams, Gawshan, Zhave, Daryan, and Hirwa then traverse the transboundary river system, arriving at the Iraqi border approximately 270 min after the initial breach event.

On entering Iraq, the flood wave impacts the Darbandikhan Reservoir within 280 min, where rapid inflow begins elevating the reservoir level. Modeling results indicate that the WSE at Darbandikhan rises from the initial 485.0 m to 495.5 m by 412 min after Gawshan Dam's failure. This significant elevation surpasses the dam crest level (495.0 m), resulting in overtopping by approximately 0.5 m. Such an event poses a critical threat to the structural integrity of the dam, with the potential to trigger a catastrophic downstream flood wave unless immediate emergency response and reservoir drawdown measures are enacted. This chain-reaction failure scenario highlights the severe transboundary hydrodynamic risks posed by overtopping-induced cascading dam breaches and underscores the urgent need for coordinated reservoir operation strategies and real-time flood management protocols.

3.4. Submergence of Rural Settlements and Agricultural Lands Due to Cascading Dam Failures from Gawshan to Hirwa in Iran

The cascading overtopping scenario results in severe upstream flooding, particularly in the valleys located above Daryan and Hirwa dams. The initial failure of Gawshan dam due to overtopping generates a high-velocity flood wave that rapidly propagates through the narrow river valleys, overwhelming the storage capacity of Zhave dam and causing its subsequent failure. The combined discharge from both dams substantially elevates upstream water surface levels and increases flow velocities throughout the interconnected catchments. The flood hazard classification of these impacted villages is shown in Table 3, while the downstream flood depth and hazard vulnerability of affected villages and roads are detailed in Table 4.

TABLE 3: WSE results for each scenarios

Location	Scenario 1 WSE (m) Overtopping	Scenario 2 WSE (m) Pipping
Downstream of Gawshan Dam	1470.57	1466.76
Downstream of Zhave Dam	1290.21	1290.0
Downstream of Daryan Dam	759.8	759.6
Downstream of Hirwa Dam	704.19	704.01
At the Iran-Iraq Border	518.60	516.53
Near Darbandikhan Dam body	495.50	494.66

Hydraulic modeling indicates that over 10 upstream villages situated between Gawshan, Zhave, Daryan, and Hirwa reservoirs are critically affected by the flood wave. In particular, the stretch between Gawshan dam and Hirwa dam located upstream of both Hirwa and Daryan dams contains a concentration of rural settlements where over 2,000 houses are expected to be submerged or severely damaged by the cascading flood wave. Notably, Kwana and Faqia Sleman and Taza Abad Sarpil and Askaran and Palangan which is located and Dewaznaw and Jolandah and Hirwa Villages, Palangan village located just upstream of Daryan Dam Fig. 10, Palangan village is projected to be completely submerged, with approximately 194 houses and an estimated 821 residents inundated under flood depths exceeding 19 m., widespread inundation also impacts surrounding agricultural lands, Dewaznaw and Jolandah village affected by flood submerged under flood water over 30 m, as shown in Fig. 11. Due to the steep topography and narrow shape of the river valleys, the velocity of floodwaters accelerates rapidly during propagation.

In addition, the floodwaters submerge key regional roads that connect upstream villages, effectively severing transport and communication links. This loss of connectivity poses major challenges to emergency response, aid delivery, and long-term recovery, further compounding the social and economic vulnerability of the impacted population.

3.5. Impact on Downstream Areas in Iraq

Beyond Hirwa Dam, the cascading flood wave crosses into northeastern Iraq, triggering severe transboundary hydrodynamic consequences. HEC-RAS simulation results indicate that more than 12 Iraqi villages fall within the projected inundation zone. These predominantly agricultural communities face a high risk of socioeconomic disruption, infrastructure damage, and population displacement. The flood also impacts over 80 km^2 of farmland, particularly in the low-lying plains near Halabja city and across the Said Sadiq and Sirwan districts, posing a serious threat to food security and rural livelihoods in this agriculturally vital region.

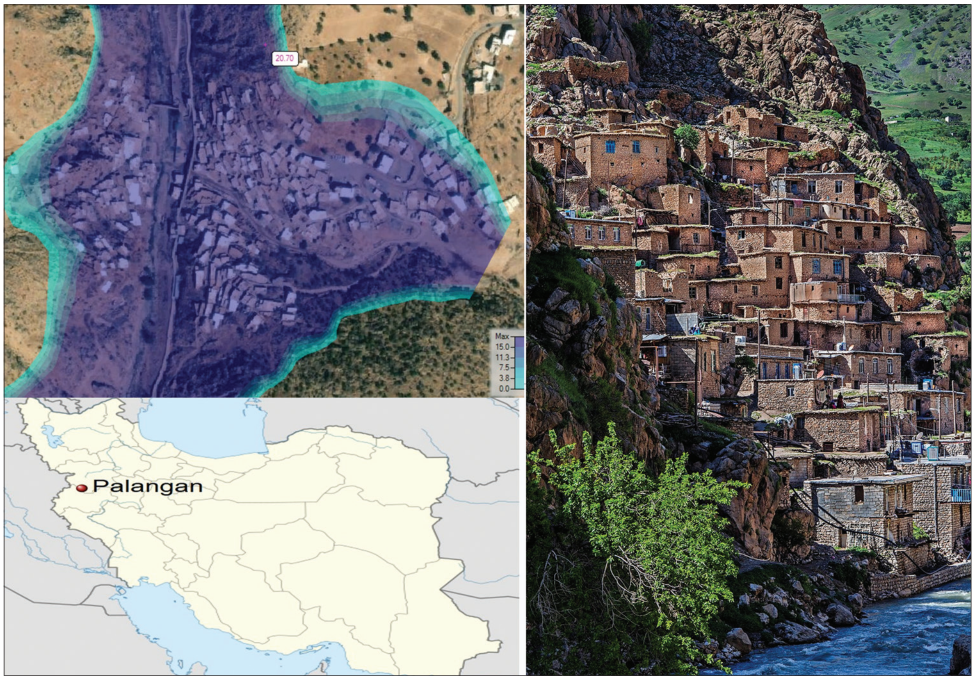

Fig. 10. Palangan Village after flood, submerged.

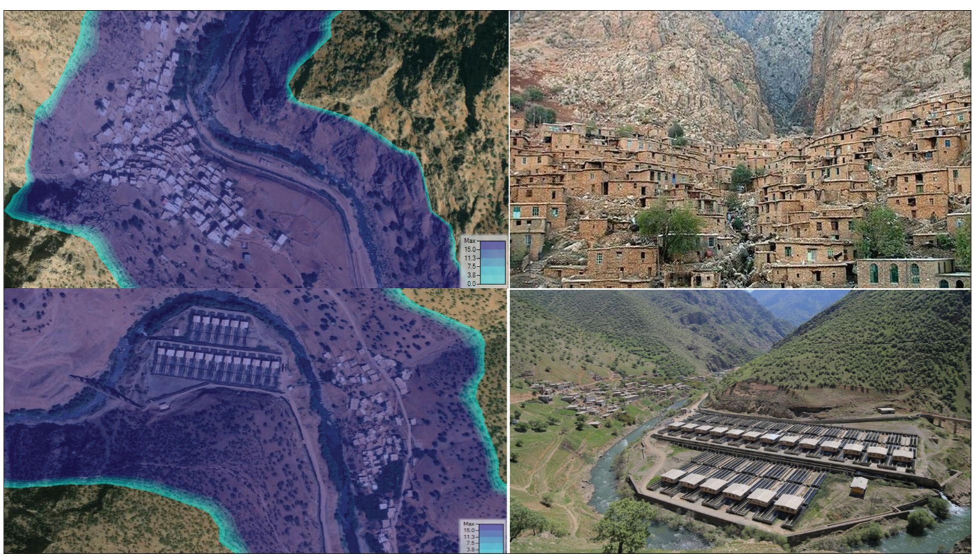

Fig. 11. Dewaznaw and Jolandah Village after flood, submerged.

Critical infrastructure is similarly threatened. The newly constructed highway linking Halabja to surrounding districts is projected to be overtopped by floodwaters, cutting off essential transportation routes and severely hindering emergency response and post-disaster recovery efforts.

Under the Gawshan Dam overtopping scenario, the situation deteriorates significantly. Following the sequential collapse of upstream dams including Zhave, Daryan, and Hirwa, the flood inflow to Darbandikhan Reservoir intensifies rapidly. As a result, the reservoir level rises from 485.0 m to 495.5 m, exceeding the dam's crest elevation of 495.0 m. Despite the full operation of spillway gates (crest at 485.0 m) and bottom outlets, the discharge capacity proves insufficient. This leads to uncontrolled overtopping and the eventual structural failure of Darbandikhan Dam.

The catastrophic breach of Darbandikhan Dam generates an overwhelming downstream flood wave, exacerbating hydrodynamic risks along the lower Sirwan River corridor. Several populated areas including Kampi Xwarw Fig. 12, Azadi Fig. 13, Eisay Fig. 14, Karashala, Hamid Awa, Panamini Mala Sleman, parts of Kalar Fig. 15, and Kulajo Fig. 16 are projected to be inundated. These regions face immediate threats to life, widespread infrastructure destruction, and long-term disruption to community stability and regional development.

4. DISCUSSION

The cascading failure of dams within a transboundary river basin poses a unique and severe hydrodynamic threat, as evidenced by the simulation results of this study.

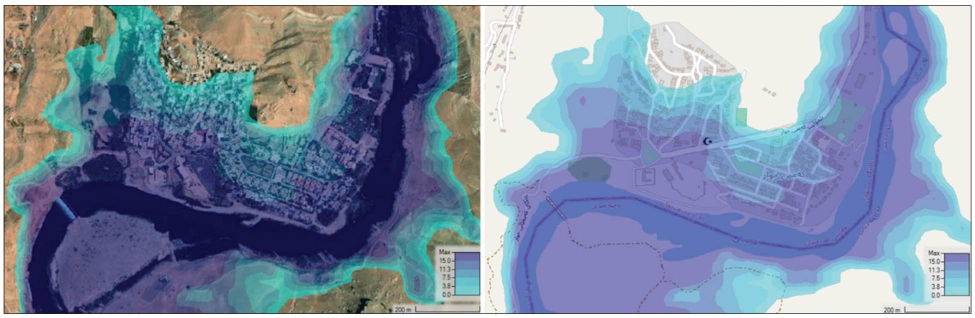

Fig. 12. Kampi Xwarw.

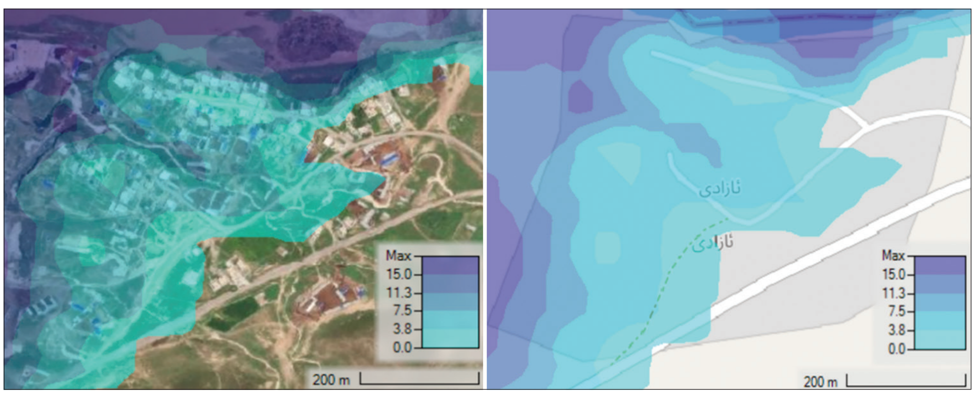

Fig. 13. Azadi.

Fig. 14. Eisay.

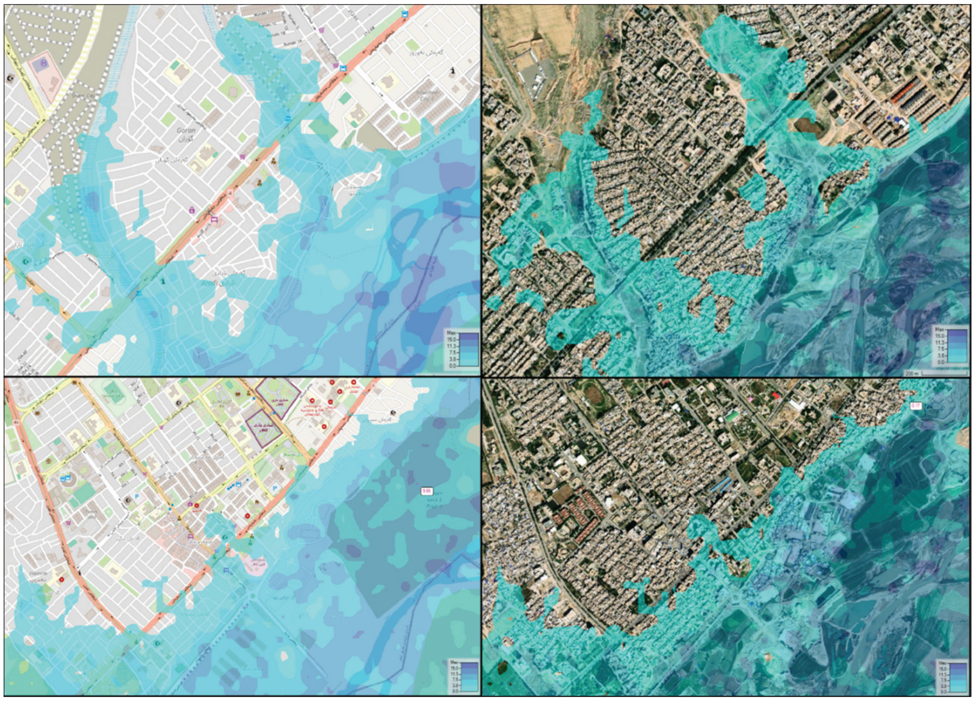

Fig. 15. Kalar.

TABLE 4: Flood depth and hazard vulnerability classification of affected villages and roads in the downstream region

No.	Village name	Depth of water	Hazard vulnerability classification	Description
1	*Kwana*	Over 20 m	H5	Unsafe for vehicles and people. All building types are vulnerable to structural damage.
2	*Faqia Sleman*	Over 16 m	H5	
3	*Taza Abad Sarpil*	Over 25 m	H5	
4	*Askaran*	Over 6 m	H5	
5	*Sanandaj – Kamiaran Road*	From 17 m to 40 m	H5	
	Mariwan – Kamiaran Road	From 10 m to 78 m	H5	
6	*Palangan*	Over 19.60 m	H5	
7	*Dewaznaw*	Over 30 m	H5	
8	*Jolandah*	Over 50 m	H5	
9	*Dolamrz*	Over 55.40 m	H5	
10	*Zum*	Over 9.0 m	H5	
11	*Kani pl*	Over 12 m	H5	
12	*Pawa – Nowsud Road*	Over 40 m	H5	
13	*Hirwa*	Over 30 m	H5	

The sequential breach of Gawshan, Zhave, Daryan, and Hirwa dams triggered by overtopping or piping produces a compound flood wave that intensifies as it descends through the Sirwan River system. Notably, this flood wave reaches Darbandikhan Dam with minimal attenuation, despite the significant distances involved. The modeling outcomes clearly indicate that the proximity of dams, their full operational levels, and the confined nature of the upstream valleys collectively reduce the capacity for wave dispersion, resulting in the convergence of peak flows at critical downstream locations.

The hydraulic behavior of Darbandikhan Reservoir under these scenarios reveals significant vulnerability. In the most extreme case Scenario 1, which assumes full upstream and downstream reservoir levels the WSE at Darbandikhan rises from 485.0 m to 495.5 m within less than seven hours. This exceeds the dam's crest elevation, leading to overtopping and potential structural failure. Even under less severe breach mechanisms, such as the piping-induced scenario

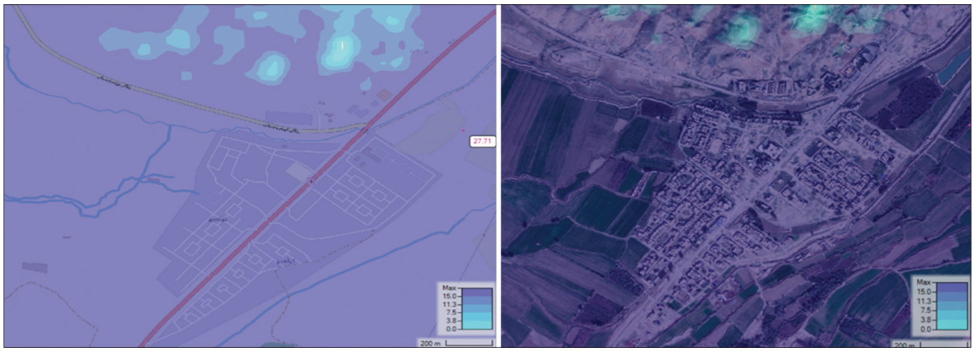

Fig. 16. Kulajo.

(Scenario 2), the WSE still reaches 494.66 m, dangerously close to the overtopping threshold. These findings suggest that the reservoir's current operational rule curve does not provide sufficient buffer capacity for high-magnitude, compound inflow events.

The limitations of Darbandikhan Dam's emergency discharge infrastructure are also evident. Despite full engagement of bottom outlets and spillway gates, the inflow from the cascading breaches overwhelms its outflow capacity. This indicates that the dam's design parameters, while effective under isolated failure or high rainfall conditions, are inadequate in the context of transboundary, compound flood events. The modeling indicates that these systems were never intended to absorb flood waves of this scale and velocity, which originate from multiple upstream sources in rapid succession.

Beyond the hydraulic implications, the human and ecological impacts are profound. In the Iranian portion of the basin, over 10 villages are directly affected by upstream flooding, with flood depths exceeding 30 m in several locations. Entire communities including Palangan, Dewaznaw, and Jolandah are projected to be submerged. The steep terrain and poorly connected road systems limit evacuation options and emergency access. In addition to residential damage, extensive agricultural areas and lifeline infrastructure such as the Mariwan–Kamyaran road are inundated, isolating populations and interrupting essential services. The flood wave's transboundary journey into Iraq further exacerbates the crisis. On arrival, it submerges more than 80 km^2 of agricultural land and affects villages and infrastructure near Halabja, Said Sadiq, and Kalar. The secondary failure of Darbandikhan Dam leads to further destruction along the lower Sirwan River. Urban centers and transportation routes downstream are not designed to withstand this scale of hydraulic load, exposing the systemic fragility of water infrastructure and civil protection systems in both nations.

The overall findings from this study reinforce the importance of cooperative, anticipatory planning. The cascading failure risk in the Sirwan Basin is not a theoretical construct it is a plausible, data-supported scenario that demands immediate attention. Both structural adaptations (e.g., auxiliary spillways and crest raising) and non-structural measures (e.g., early warning systems, revised operational protocols, and bilateral emergency coordination) are required to prevent catastrophic losses in the event of extreme natural or human-induced triggers.

5. CONCLUSION

This study provides the first integrated hydrodynamic simulation of cascading overtopping and piping failures across a transboundary dam network from Gawshan Dam in Iran to Darbandikhan Dam in Iraq. The results reveal that under full reservoir conditions, a sequential overtopping cascade leads to catastrophic consequences downstream, including the overtopping and potential breach of Darbandikhan Dam. Scenario 1, involving maximum water storage and overtopping-driven failures, generated the most critical conditions, with rapid flood wave propagation and insufficient structural mitigation capacity. Both upstream Iranian and downstream Iraqi communities face substantial human, agricultural, and infrastructural losses under these scenarios. These findings underscore the urgency for coordinated risk assessments, early warning systems, and bilateral flood risk governance.

6. ACKNOWLEDGMENT

The authors express greatest appreciation to the Darbandikhan Dam Directorate and the supervisory committee for their significant assistance in supplying crucial data and information necessary to this study.

7. FUNDING

The authors declare that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

8. DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author on reasonable request.

9. CONSENT TO PARTICIPATE

Not applicable. This review article does not involve human participants or personal data requiring consent.

10. CONSENT TO PUBLISH

All authors have read and approved the final version of the manuscript and consent to its submission and publication in UHD journal of science and technology.

11. ETHICS

This article does not contain any studies with human participants or animals performed by any of the authors.

12. COMPETING INTERESTS

The authors declare no competing interests.

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