



Estimated Hydraulic Simulation of The Collapse of The Derna Valley Dams (2023); Numerical Analysis of The Causes of Disaster and The Inevitability of Collapse Under Extreme Climatic Conditions

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محاكاة هيدروليكية تقديرية لانهايار سدود وادي درنة (2023)
تحليل عددي لأسباب الكارثة وحتمية الانهيار في ظل ظروف مناخية قصوى

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Abstract:

This study analyzes the causes of the collapse of the Wadi Derna dams, which occurred on Monday, 11 September 2023, and explains the factors that magnified the disaster. Using data compiled from previous researches on local dams behavior and hydraulic conditions, the study approximates hydraulic simulation models to identify the drivers of failure and to interpret the mechanisms involved. It also evaluates whether preventive measures could have averted—or substantially mitigated—the catastrophe. The hydraulic simulations indicate that cyclone rainfall exceeded by more than fourfold the precipitation level required to trigger flooding in the wadi. As a result, the generated runoff volume increased to more than eight times the dam's storage capacity. Field investigations and direct observations support the identification of five key elements responsible for severe human and material losses: (i) high flow velocity combined with a short travel time to the city center, leaving minimal opportunity for survival; (ii) flood-wave height that inundated buildings and people inside; (iii) flow impact force capable of displacing infrastructure from foundations and driving it toward the sea; (iv) heavy sediment transport, with deposition estimated to cover approximately one third of the city; and (v) synergistic interactions among these factors. Model results show that flow velocities arising from the upper catchment (≈ 765 m above mean sea level) reached about 22 m/s (≈ 79 km/h). The post-failure wave height was estimated at roughly 25 m, with the wave reaching the city center within approximately 10 minutes. The associated impact force was estimated at about 1190.2 tonnes, and sediment loads at approximately 28,641,600 tonnes of clay and silt. The study concludes that failure cannot be explained solely by maintenance negligence or monitoring limitations. Even under optimal construction and condition, the dam system would likely not have withstood a cyclone delivering unprecedented rainfall; at best, the failure process might have been delayed by a few additional hours rather than fully prevented.

Keywords: Derna, Storm Daniel, Dam collapse, Runoff estimation, Sedimentation, Impact force

المخلص

تُحلل هذه الدراسة أسباب انهيار سدي وادي درنة، الذي وقع يوم الاثنين 11 سبتمبر 2023، وتوضح العوامل التي زادت من حدة الكارثة. وبالاستناد إلى بيانات مُجمّعة من أبحاث سابقة حول سلوك السدود المحلية والظروف الهيدروليكية، طوّرت الدراسة نماذج محاكاة هيدروليكية لتحديد مسببات الانهيار وتفسير الآليات المرتبطة به. كما تقيّم الدراسة ما إذا كانت التدابير الوقائية كافية لتجنب الكارثة أو التخفيف من آثارها بشكل جوهري. وتشير عمليات المحاكاة الهيدروليكية إلى أن الأمطار الناجمة عن الإعصار تجاوزت بأكثر من أربعة أضعاف مستوى الهطول اللازم لحدوث فيضان في الوادي؛ ونتيجة لذلك، ارتفع حجم الجريان السطحي المتولد ليتجاوز ثمانية أضعاف السعة التخزينية للسد. وتدعم التحقيقات الميدانية والملاحظات المباشرة تحديد خمسة عناصر رئيسية مسؤولة عن الخسائر البشرية والمادية الجسيمة، وهي: (1) السرعة العالية للتدفق مقترنة بقصر الزمن اللازم للوصول المياه إلى وسط المدينة، مما أتاح فرصاً ضئيلة جداً للنجاة؛ (2) ارتفاع موجة الفيضان التي غمرت المباني ومن بداخلها؛ (3) قوة الصدم للتدفق القادرة على اقتلاع البنية التحتية من أساساتها ودفعها نحو البحر؛ (4) النقل الكثيف للرواسب، حيث قُدِّرَت مساحة الترسيب بما يعادل ثلث مساحة المدينة تقريباً؛ و(5) التفاعلات التراكمية والمتضاعفة بين هذه العوامل. وتُظهر نتائج النماذج أن سرعات التدفق القادمة من منطقة التجميع العليا (على ارتفاع 765 متراً تقريباً فوق متوسط مستوى سطح البحر) بلغت حوالي 22 متراً/ثانية (أي ما يعادل 79 كم/ساعة). وقُدِّرَ ارتفاع الموجة بعد الانهيار بنحو 25 متراً، حيث وصلت الموجة إلى وسط المدينة في غضون 10 دقائق تقريباً. كما قُدِّرَت قوة الصدم المصاحبة بنحو 1190.2 طناً، وكمية الرواسب بنحو 28,641,600 طن من الطين والغرين. وتخلص الدراسة إلى أن الانهيار لا يمكن تفسيره بمجرد الإهمال في الصيانة أو قصور أنظمة المراقبة؛ فحتى في ظل ظروف إنشائية وحالة فنية مثالية، لم يكن من المرجح أن يصمد نظام السدود أمام إعصار جلب معدلات هطول أمطار غير مسبوقة؛ إذ كان من الممكن -في أحسن الأحوال- تأخير عملية الانهيار لبضع ساعات إضافية بدلاً من منعها تماماً.

الكلمات المفتاحية: درنة، العاصفة دانيال، انهيار السد، تقدير الجريان السطحي، الترسيب، قوة الصدم.

Introduction

History has witnessed numerous dam failure incidents that have resulted in profound human and material catastrophes. The collapse of the Banqiao Dam in China in 1975 ranks among the deadliest, with death toll estimates reaching approximately 230,000 [6]. The collapse of the two Derna Valley dams on September 11, 2023, is considered the second-largest disaster of its kind worldwide, with unofficial estimates placing the death toll at over 50,000. This collapse occurred as a direct consequence of Storm Daniel, an exceptionally rare subtropical Mediterranean cyclone that originated from a low-pressure system over the Mediterranean Sea in early September 2023 and subsequently intensified before making landfall in northeastern Libya. The storm produced torrential rainfall and catastrophic flooding, and is regarded as the deadliest Mediterranean tropical-like cyclone in recorded history. As it approached the coast of northeastern Libya, wind speeds reached approximately 120 km/h, while total rainfall accumulated to roughly 240 mm over a 25-hour period, with localized totals exceeding this figure [3] equivalent to an entire year's average rainfall. This resulted in massive flooding that led to the failure of the two main dams along Wadi Derna, causing unprecedented destruction to infrastructure and loss of life.

Research Objective

This paper seeks to analyze the events and impacts arising from the Derna Valley flood and the collapse of its two dams on September 11, 2023, in order to address three fundamental questions:

- How did the disaster unfold from a hydraulic and hydrological standpoint?
- Why did it result in human and material losses of such unprecedented magnitude?
- Could it have been avoided or its impacts mitigated?

Specifically, the research aims to provide quantitative and analytical engineering answers, relying on an approximate numerical hydraulic simulation based on available data.

Problem statement

To move beyond descriptive answers and toward rigorous numerical analysis, six main research questions were formulated, grounded in the hydrological and morphometric data of the Wadi Derna basin and the hydraulic design of the dams (particularly the Bou Mansour Dam):

1. What was the magnitude of the runoff that triggered the flood?
2. What was the height of the flood wave that reached the upper floors of buildings?
3. What impact force uprooted buildings, bridges, and roads from their foundations?
4. What volume of sediment did the flood carry, covering nearly one-third of the city?
5. What was the amount of rainfall that triggered the flood in the valley?

6. What was the velocity of water descending from the basin's peak (at an elevation of approximately 765 m above sea level)?

These questions were addressed by constructing hydraulic simulation models using the Python programming language, based on fundamental approximate equations (given the unavailability of detailed data for certain hydrological elements). This approach enabled the testing of multiple scenarios and hypotheses to explain the mechanism of the failure and the extent of its impacts.

STUDY AREA

The Wadi Derna basin is located in the eastern part of the Green Mountain (Jabal al-Akhdar) region, between latitudes 32°34'–32°48' N and longitudes 21°38'–22°59' E, bordered to the west by the towns of Al-Bayda and Al-Fayidiyah. The basin's highest elevation reaches approximately 765 m above sea level at its western end, from which it descends eastward and then northward to discharge into the Mediterranean Sea through the center of Derna city. The basin covers an area of approximately 576 km², with a length of about 70 km, an average width of 8 km, and a perimeter of 238 km. The natural storage capacity of the basin is estimated at approximately 23 million m³ [1]. Map 1 illustrates the location of the valley.

Two Earth dams were constructed on this valley in 1972 by the Yugoslav company "Hidroprojekt":

- **Al-Bilad Dam:** located 2 km south of the city, with a height of 40 m, a crest length of 100 m, upstream and downstream slopes of 1.4:1 and 1.5:1 respectively, and a storage capacity of 1.2 million m³.
- **Bou Mansour Dam:** located 13 km south of the city, with a height of 75 m, a crest length of 380 m, a base width of 158.1 m and a crest width of 7 m, the same slopes as Al-Bilad Dam, and a storage capacity of approximately 22.5 million m³, founded on limestone strata.

Both dams remained in service for approximately 51 years before their failure due to the storm [4]. Photo 1 shows Bou Mansour Dam prior to its collapse.



Map 1: illustrates the location of the valley (Source: Google Earth)



Figure 1: shows Bou Mansour Dam prior to its collapse

Study data

The research relied on the SCS-CN model applied by Ashour (2022) in his study estimating the runoff depth of the Wadi Derna basin using Geographic Information Systems. The SCS method—the American Soil Conservation Service method—is used for basins lacking gauging stations (the condition of most Libyan basins), and is based on curve numbers (CN) that reflect the interaction of land cover, soil type, antecedent moisture, and land use. The study demonstrated the following:

- The weighted curve number (CN_w) for the basin was 85 over 55% of its area (318.4 km²), and 74 over 22.5% (128.22 km²).
- The rainfall thresholds triggering runoff were: 27.92 mm (dry soil), 11.72 mm (normal moisture), and 5.1 mm (wet soil).
- The overall curve number for the basin was 81.3, indicating low permeability and high runoff potential.
- The model demonstrated good accuracy, estimating the runoff of the 1986 flood at 14.8 million m³ compared to 13 million m³ reported by the General Water Authority, and estimating the runoff of the 1959 flood at 53.36 million m³.
- 70% of the basin's soils belong to Hydrologic Soil Group D (poorly drained), and 30% to Group C (moderate to low infiltration), which increases flood risk.
- The dominant soil type is red ferruginous soil (clayey, rich in calcium carbonate and iron oxides), characterized by high water-retention capacity and an infiltration rate of 0.96 m/day [5].
- The average annual runoff of the basin was estimated at approximately 138.5 million m³, based on a 40-year rainfall average (1960–2000).

The morphometric study by Al-Jumaili (2008) pointed to notable contradictions: it reported that the basin's elongated (rectangular) shape—combined with its high relief ratio (12.6 m/km)—reduces flood risk, whereas the low drainage density (0.11 stream/km²) and sinuosity coefficient (1.38) indicate rugged terrain and slow wave arrival, contradicting the actual flow velocity observed during the disaster. The study also noted that the prevailing winds are northwesterly, while northeasterly winds are rare, and that westerly and southwesterly winds recur during winter, which affects rainfall distribution.

Research methodology

This study adopts a quantitative analytical methodology based on numerical hydraulic simulation, aimed at addressing three principal dimensions:

- The hydraulic mechanism by which the disaster occurred.
- The causes of the unprecedented human and material losses.
- The extent to which the disaster could have been avoided under the prevailing conditions.

To move beyond descriptive answers toward rigorous engineering analysis, six quantitative research questions (presented in the previous section) were formulated to serve as the primary inputs for the models. The research relied exclusively on data available from prior studies and technical reports related to the Wadi Derna dams, given the absence of direct field measurements during the storm. Due to this shortage of detailed data (such as the dynamic characteristics of the failure, the temporal and spatial distribution of rainfall, and the instantaneous soil

properties), all models were designed using empirical and approximate equations, with the aim of producing numerical estimates that reflect the approximate magnitude of the physical phenomena rather than precise values—some of which were verified through visual observation (such as flood-mark heights) or eyewitness testimony (such as wave arrival time)—in order to understand the scale of the disaster in an explanatory, rather than a strictly measurement-based, sense.

Simulation tool

The hydraulic simulation was carried out using the Python programming language, owing to its flexibility in rapidly testing multiple scenarios and assumptions. Specialized scientific libraries (NumPy, SciPy, Matplotlib) were employed to perform numerical computations and plot the results, relying on simplified equations due to the unavailability of detailed data on runoff, sedimentation, and instantaneous hydraulic dynamics (Kalkan & Sehitoglu, 2022). All outputs are approximate estimates rather than absolute values, and are valid within the scope of the assumptions adopted.

Estimation of the runoff volume causing the flood

The calculation of the total runoff volume (V) generated by Storm Daniel was based on the SCS-CN method, previously applied to the Wadi Derna basin by Ashour (2022), which demonstrated its validity by comparing its results with the 1959 and 1986 floods and with data from Elost & Masoud (2015). The following equations were used:

$$\frac{Q \times A}{1000} \quad (1)$$

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (2)$$

$$S = \frac{25400}{CN_w} - 254 \quad (3)$$

where:

- V : total runoff volume (m^3).
- Q : runoff depth (mm).
- A : basin area (m^2) = 576,000,000 m^2 .
- P : rainfall depth (mm) = 400 mm (based on meteorological data).
- CN : weighted curve number = 81.3 (according to Ashour, 2022).
- S : maximum potential retention after runoff begins (mm) = 58 mm.

The value of V was calculated by substituting the values stated above, noting that the result represents an estimate of the total runoff volume, without simulating the temporal distribution of rainfall or the effect of progressive soil saturation, due to the absence of the relevant hydrological data.

Estimation of flood wave height and velocity following dam failure

To simulate the height (h_{wave}) and velocity (v) of the flood wave resulting from the failure of Bou Mansour Dam followed by Al-Bilad Dam, fundamental energy equations were employed, under the assumption that the failure was instantaneous and that the water depth behind the dam was equal to the full dam height (75 m). Given the absence of data on the initial breach velocity (v_0) and the initial breach height (h_0), a wide range of hypotheses for these two variables was tested using Python code, based on the energy conservation equation:

$$V = \sqrt{2g(h - h_0)} \quad (4)$$

$$h = \frac{v_0^2}{2g} \quad (5)$$

where g is the acceleration due to gravity (9.81 m/s^2) and h is the water depth prior to failure (75 m). The scenario most consistent with eyewitness testimony regarding the wave's arrival time at the city center (approximately 8–10 minutes) and its height (reaching upper floors of buildings) was selected. These results are highly approximate and rely on the assumption of ideal flow with no friction, yielding upper-bound values.

approximate estimation of the hydrodynamic force acting on structures (impact force)

The impact force (I) acting on buildings and bridges was calculated using the simplified momentum equation (impact law) for a moving fluid:

$$I = 0.5 \times \rho \times (V)^2 \times A \quad (6)$$

where:

- ρ : water density (assumed at 1,500 kg/m³ for sediment-laden water, compared to 1,000 kg/m³ for clear water).
- V : flow (wave) velocity.
- A : frontal cross-sectional area of the building or obstructing object (ranging between 10 and 150 m²).

This equation is purely approximate, as it does not account for terrain factors, the shape of objects, non-uniform pressure distribution, or the damping effect of debris; however, it provides a numerical indication of the magnitude of destructive force within an assumed range.

Estimation of the volume of transported sediment

Given the absence of measurements of sediment concentration during the flood, a simplified mass-balance equation (derived from King's equation, neglecting the flow-path length factor and the delay coefficient) was used to estimate the quantity of silt and clay transported during the first hour of the flood:

$$Q_s = \frac{K \times V \times C}{(1 + DL)} \quad (7)$$

where:

- Q_s : quantity of sediment (in tons)
- K : a factor depending on soil and terrain characteristics
- A : area of the flowing region (in km²)
- V : flow velocity (in m/s)
- C : concentration of solid material in the water (in tons/m³)
- D : sedimentation delay coefficient
- L : length of the flow path (in km)

Due to the unavailability of detailed data, Walter's equation (the Wash Load Equation) was employed—a simplified equation that can be used to estimate the quantity of sediment carried by floods in rivers and natural channels. This equation relies on simple assumptions and is considered an approximate estimate, with potentially limited accuracy in cases involving complex contributing factors. The use of Walter's equation for sediment estimation is appropriate in situations where detailed data are unavailable, or when a quick, approximate estimate is required. This equation typically takes the form of King's equation (7), in which the flow-path length (L) and the delay time coefficient (D) are neglected. The equation assumes that sediment is homogeneous and uniformly distributed over the area of the flowing region.

Additionally, the mass-balance equation can be used to calculate the hourly quantity of sediment carried by the flood, whereby the sediment quantity is calculated based on the total volume of debris transported in the water during the flood period. Factors such as the concentration of debris in the water, the cross-sectional flow area, and the flood duration must be taken into account. Sediment concentration (density) was assumed to range between 1,200 and 2,700 kg/m³. The cross-sectional flow area was assumed to be 170 m (the width of the valley channel) with a depth of only 1 m. The resulting value was multiplied by 24 hours to obtain a total estimate of the sediment that covered the city, with the understanding that this method assumes a homogeneous distribution and continuous flow at a constant velocity throughout the period—a considerable simplification intended solely to provide an approximate picture of the enormous volume of sediment involved.

Estimation of the rainfall threshold triggering the flood

To determine the rainfall threshold that would trigger a flood in the valley under similar conditions, a simple relationship was used combining the basin's natural storage capacity ($V_c = 22.5$ million m³) and the runoff coefficient derived from Storm Daniel:

$$V = \frac{V_R}{A.C} \quad (8)$$

where A is the basin area. This relationship is highly approximate and does not substitute for fully integrated hydrological models; however, it allows for a comparison between the actual rainfall depth (400 mm) and the approximate threshold, in order to illustrate the substantial gap between them.

Estimation of downslope flow velocity from an elevation of 765 m

Numerous equations are used to calculate the flow velocity of floodwaters or fast-moving water in rivers and valleys. Among the most widely used is Manning's equation, which is employed to estimate flow velocity in rivers and natural channels. To calculate the velocity of floodwater descending from a given elevation, the energy equation can also be used, based on the principle of conservation of energy between the initial and final elevations of the floodwaters.

Torricelli's energy equation was used to estimate the theoretical velocity of water as it descends from the highest point of the basin (approximately 765 m above sea level) to the base of the valley, neglecting friction and energy losses:

$$v = \sqrt{2gh} \quad (9)$$

where h is the elevation difference (m). This equation yields an upper-bound velocity (in reality lower, due to friction and channel sinuosity), but it helps explain the enormous destructive capacity of the accelerating flow.

By testing different values of elevation (h), the corresponding flow velocity can be determined accordingly.

Estimation of reservoir filling time and time to flood onset

The theoretical time required for the dam reservoir to fill completely was calculated, assuming a continuous inflow at rate (Q) (as derived in Section 6.7), using the following equation:

$$V = \frac{V_F}{Q} \quad (10)$$

where V is the cumulative flood volume. This simplified relationship reveals the discrepancy between the theoretical filling time and the actual time to failure, which is attributable to the smaller effective storage capacity (due to sediment accumulation) and to the structural weakness of the dams—underscoring the approximate nature of the model.

Methodological summary

All equations and models used in this study are approximate estimates, developed in the context of a scarcity of detailed field data. They aim to provide a numerical picture consistent with field observations and eyewitness testimony, in order to understand the physical dimensions of the disaster rather than to precisely calculate true values. The use of Python code enabled the testing of a wide range of hypotheses, which strengthens the reliability of the qualitative interpretation, even though the quantitative values remain subject to revision as more accurate data become available.

Results

All results presented in this chapter are based on simplified mathematical models and empirical equations, given the absence of instantaneous hydrological and hydraulic measurements during the storm. These values are therefore approximate estimates intended to provide a quantitative picture of the magnitude of the physical phenomena accompanying the disaster, rather than absolute or precise values. They are valid within the scope of the assumptions outlined for each section.

Runoff volume generated by the storm

The total runoff volume (V) resulting from the rainfall of Storm Daniel (assuming a rainfall depth of $P = 400$ mm) was calculated using the SCS-CN model, in accordance with Equations (1), (2), and (3), based on the weighted curve number (CN) and the basin area ($A = 576$ km²) derived from the study of Ashour (2022).

The results showed that the runoff volume reached 194 million m³, exceeding the design storage capacity of the valley basin (22.5 million m³) by more than eightfold. Table 1 presents a comparison between the model's results for this storm and previous results for less severe storms, confirming the enormous difference in water quantities.

Table 1: Comparison of Calculated Runoff Volumes for Different Rainfall Scenarios

No.	Rainfall (mm)	Water Volume in Valley (Mm ³)	Runoff (Mm ³) (Al-Osta, 2015)	Runoff (Mm ³) (Ashour, 2022)
1	60	34.56	9.1	12.6
2	70	40.32	13.5	16.8
3	90	51.84	22.3	25.9
4	110	63.36	34	35.66
5	120	69.12	39.7	40.6
6	400	230	—	194

Characteristics of the flood wave resulting from the dam failures

The enormous runoff volume (194 million m³) led to the failure of Bou Mansour Dam first, followed by Al-Bilad Dam, generating a flood wave that swept through the valley channel. Using the energy equations (4) and (5), and testing a wide range of hypotheses for the initial breach velocity (v_0) and breach height (h_0), the results were then

compared against eyewitness testimony (the wave reaching the city center, located 14 km away, within 8–10 minutes, and rising to the upper floors of buildings). The scenario most consistent with these observations was selected, yielding the following results:

- Wave velocity: approximately 22 m/s (i.e., ~79 km/h).
- Wave height: approximately 25 m upon reaching the city center.
- Arrival time: approximately 8–10 minutes from the moment of failure.

Table 2 presents the relationship between the assumed initial breach velocity and breach height, and the resulting wave velocity and height. It is notable that the initial breach velocity has a limited effect compared to the effect of the initial breach height on the final characteristics of the wave.

Table 2: Estimated Flood Wave Velocity and Height under Different Breach Scenarios

Breach Velocity (m/s)	Breach Height (m)	Water Height Before Failure (m)	Wave Velocity (m/s)	Wave Speed (km/h)	Wave Height (m)
From 1 m/s to 100 m/s	10	75	35	126	65
	20		33	118	55
	30		28	101	45
	40		26	94	35
	50		22	79	25 (Matching Scenario)
	60		17	61	15
	70		10	36	5
	75		0	0	0

Impact force of the water current

The impact force (I) acting on buildings and structures was estimated using the simplified momentum equation (6), based on the selected wave velocity (22 m/s) and the assumed water density (1,500 kg/m³ for sediment-laden water, and 1,000 kg/m³ for clear water, for comparison). Different values of the obstructed cross-sectional (Building facades) area were tested, taking into account that typical building facades in the area range between 20 and 30 m².

The results showed that the average impact force ranged between 7,935 kN and 11,902 kN (equivalent to 793.5 to 1,190.2 tons) for sediment-laden water. Assuming clear water instead (an unrealistic assumption in the context of the flood) reduces the force to approximately two-thirds of this value. Table 3 summarizes the results.

Table 3: Estimated Impact Force (kN) by Cross-Sectional Area and Water Density (at a velocity of 22 m/s)

Cross-Sectional Area (m ²)	Impact Force at $\rho = 1500 \text{ kg/m}^3$ (kN)	Impact Force at $\rho = 1000 \text{ kg/m}^3$ (kN)
10	3,967.500	2,645.000
20	7,935.000	5,290.000
30	11,902.00	7,935.000
40	15,870.000	10,580.000
100	39,675.000	26,450.000
150	59,512.500	39,675.000

Volume of transported sediment

The quantity of sediment (silt and clay) carried by the flood was estimated using the simplified mass-balance equation (7), assuming a flow cross-section 170 m wide (the width of the valley channel) and only 1 m deep, with a constant flow velocity of 22 m/s. A range of sediment densities (1,200–2,700 kg/m³) was tested.

The results showed that the quantity of sediment transported per hour ranged between 734,400 tons and 1,652,400 tons, with an average of 1,193,400 tons/hour. Assuming the flood persisted for 24 hours, the total quantity of sediment that covered parts of the city is estimated at approximately 28.64 million tons (Table 4). This estimated value reflects the enormous volume of solid material accompanying the flow, which contributed to increasing the density and destructive power of the fluid, as well as to the burial of low-lying areas.

Table 4: Estimated Quantity of Transported Sediment (tons/hour) at Different Densities

Sediment Density (kg/m ³)	Sediment Quantity (kg/hr)	Sediment Quantity (ton/hr)
1,200	734,400,000	734,400
1,500	918,000,000	918,000
2,000	1,224,000,000	1,224,000
2,500	1,530,000,000	1,530,000
2,700	1,652,400,000	1,652,400
Average	1,193,400,000	1,193,400
Sediment Quantity / 24 hours	28,641,600,000	28,641,600 tons

Estimation of the rainfall threshold triggering the flood

To determine the amount of rainfall that would trigger a flood in the valley under normal conditions, the mass-balance logic between the reservoir volume and the runoff coefficient was applied.

- Design storage capacity of the basin: 22.5 million m³.
- Runoff coefficient derived from Storm Daniel:

$$C = \frac{Q_{runoff}}{P_{total}} = \frac{194}{230} \approx 0.84.$$

- The theoretical rainfall depth required to completely fill the design reservoir capacity is:

$$P_{threshold} = \frac{V_{reservoir}}{A \times C} = \frac{22,500,000}{576,000,000 \times 0.84} \approx 0.047 \text{ m} = 47.0 \text{ mm}$$

- If, instead, the actual volume of water stored in front of the dam (the "swamp"/backwater area), which does not exceed 14.46 million m³ (as a result of sediment accumulation and the absence of dredging), is taken into account, the threshold decreases to:

$$P_{threshold-actual} = \frac{14,460,000}{576,000,000 \times 0.84} = 0.0298 \text{ m} \approx 30.0 \text{ mm}$$

Comparing this threshold (ranging between 30 and 47 mm) with the actual rainfall of 400 mm, it is evident that the rainfall quantity exceeded the minimum flood-triggering threshold by approximately 8 to 13 times. This enormous difference illustrates the impossibility of containing such a volume of water within the available storage capacity, rendering the flood inevitable regardless of the structural condition of the dams.

Theoretical velocity of the downslope flow from the basin summit

The maximum theoretical velocity of the water as it traveled from the highest point of the basin—at an elevation of approximately 800 m above sea level—toward the base of the valley was estimated using the energy equation (9), neglecting the effects of friction and hydraulic losses. Table 6 presents the theoretical velocity values corresponding to different elevations. The results indicate that the velocity computed at the highest elevation could theoretically reach approximately 451 km/h—a limiting value resulting from the assumption that potential energy is converted entirely into kinetic energy, and therefore does not represent the actual velocity of the flood flow. When the effects of channel roughness, valley terrain, and hydraulic losses are taken into account, the actual flow velocity is estimated at approximately 22 m/s (about 79 km/h). This velocity corresponds theoretically to the conversion of an elevation difference of only about 24.66 m into kinetic energy, according to the energy equation with losses neglected.

This is a very high velocity, capable of generating substantial shear, drag, and impact forces, which may have contributed to the displacement or destruction of structures and bridges located along the flood path—particularly when combined with substantial flow depth and a high load of sediment and debris.

Table 6: Theoretical Flow Velocity at Different Elevations in the Valley

Elevation (m)	Velocity (km/h)
50	112.7
100	159.4
200	225.4
300	276.1
400	318.75
500	356.4
600	390.4
700	421.7
800	450.8

Reservoir response time and time to failure

Assuming a continuous inflow into the reservoir at an average discharge rate (Q), derived in Section 7.1 as the total runoff volume (194 million m^3) divided by the actual storm duration until failure (approximately 12 hours), we obtain:

$$Q = \frac{194,000,000}{12 \times 3600} \approx 4,490 \text{ m}^3/\text{s}$$

Using instead the theoretical time required to fill the design storage capacity (22.5 million m^3):

$$t_{\text{theoretical}} = \frac{22,500,000}{4,490} \approx 1.40 \text{ hr}$$

This is a considerably shorter time than the actual 12 hours, indicating that the runoff process was not sustained at full intensity from the outset, and that the soil absorbed a portion of the water during the initial hours prior to saturation. Furthermore, the actual failure occurred once the effective storage volume (14.46 million m^3) had filled, subjecting the dams to additional pressure, with the actual filling time estimated at:

$$t_{\text{actual}\backslash\text{fill}} = \frac{14,460,000}{4,490} \approx 0.89 \text{ hr} \approx 53 \text{ min}$$

This indicates that the effective reservoir filled very rapidly, and that the failure was relatively delayed (to 12 hours) due to the temporary structural resistance of the two dams; however, the immense pressure made the failure inevitable once the heavy rainfall continued. Accordingly, the theoretical time calculated using Equation (10) depends heavily on the assumed inflow rate, and the results confirm that the limited effective storage capacity was the decisive factor governing the speed with which the disaster unfolded.

Summary of Results: All numerical estimates—despite their approximate nature—confirm that the runoff volume, wave velocity, wave height, impact force, and sediment quantity all exceeded the design limits and natural tolerance of the dams and structures in Wadi Derna by enormous margins (ranging between 4 and 13 times the design thresholds), rendering the disaster an inevitable outcome of extreme natural phenomena, compounded by sediment accumulation, which reduced the effective storage capacity.

Conclusion

This paper aimed to analyze the causes of the collapse of the two Wadi Derna dams on September 11, 2023, and to explain the unprecedented scale of human and material losses, through an approximate numerical hydraulic simulation based on data available from prior studies. The simulation was implemented using the Python programming language, relying on simplified empirical and mathematical equations, given the absence of detailed field measurements during the storm. Accordingly, all numerical values presented in this study are approximate estimates intended to provide a quantitative picture consistent with field observations and eyewitness testimony, rather than to determine absolute values.

The results showed that the rainfall depth generated by the storm (400 mm) exceeded the basin's flood-triggering threshold (ranging between 30 and 47 mm, depending on the effective storage volume) by approximately 8 to 13 times, generating a runoff volume of 194 million m^3 —more than eight times the basin's design storage capacity (22.5 million m^3), and more than thirteen times the actual volume of water stored in front of the two dams (which did not exceed 14.46 million m^3 due to sediment accumulation). This enormous surplus rendered the flood inevitable.

The wave resulting from the failure of the two dams was estimated to have a velocity of approximately 22 m/s (~ 79 km/h) and a height of approximately 25 m, reaching the city center (14 km away) within 8–10 minutes—a timeframe that left no opportunity for escape. The impact force acting on buildings ranged between 793.5 and 1,190.2 tons (depending on the obstructed facade area), while the quantity of sediment (silt and clay) carried by the flood, which covered approximately one-third of the city, was estimated at approximately 28.6 million tons. The maximum theoretical velocity of the water as it descended from the basin summit (800 m) reached approximately 450 km/h, dissipating due to friction to approximately 79 km/h—which helps explain the extraordinary destructive capacity that uprooted buildings and bridges from their foundations.

Although these estimates are approximate in nature, they align closely with field observations in terms of wave velocity, wave height, arrival time, runoff volume, and sediment quantity, which reinforces their credibility as an interpretive tool.

Main Conclusion: The study's principal finding is that the collapse of the two dams was not the result of maintenance neglect, deficiencies in monitoring their structural condition, or design and construction errors—as

might often be assumed—but rather an inevitable consequence of a rainstorm that delivered an unprecedented volume of rainfall, one that far exceeded any design limits or structural capacity. Even had the dams been in the best possible structural condition, they would only have delayed the inevitable failure by a few additional hours, without being able to prevent it. The results further confirm that the accumulation of sediment in the storage basin over decades, without removal, significantly reduced the effective storage capacity and accelerated both the filling of the reservoir and the onset of failure.

Recommendations

Based on the findings of this unprecedented disaster, and the deficiencies in storage and load-bearing capacity revealed by the hydraulic simulation in the face of extreme phenomena, the research recommends adopting an integrated package of preventive, structural, and institutional measures, as follows:

First: Strengthening Monitoring and Early Warning Systems

- Developing meteorological and hydrological monitoring networks in regions prone to storms and flooding.
- Establishing a multi-tiered early warning system based on numerical weather prediction models, enabling the issuance of early warnings to residents and relevant authorities at least 48–72 hours prior to the arrival of severe storms, with clear identification of the areas at greatest risk.

Second: Developing the Infrastructure of Flood-Prone Areas

- Reassessing and reinforcing existing dams, bridges, roads, and buildings located along valley pathways, so that they can withstand the impact and flow forces generated by floods exceeding conventional design scenarios, taking into account climate change and the increasing frequency of extreme events.
- Carrying out regular sediment-removal operations in the storage basins behind dams.

Third: Updating Emergency and Evacuation Plans

- Developing rapid, clearly defined response plans for flood and dam-failure scenarios.
- Conducting regular drills for residents and relevant authorities on the implementation of evacuation plans, to ensure readiness and reduce response time in emergency situations.

Fourth: Community Awareness and Education

- Implementing sustained awareness programs for residents living in valley and dam-adjacent areas, safety behaviors during storms, and how to respond to evacuation warnings.

Fifth: Compliance with International Technical Standards in Dam Design and Management

- The necessity of adhering to local and international standards and regulations throughout all stages of dam construction, operation, and maintenance, most notably the guidelines issued by the International Commission on Large Dams (ICOLD), which cover geotechnical, hydrological, and structural design aspects, in addition to risk-management and safety-assessment standards.
- It is also recommended that relevant international standards issued by the International Organization for Standardization (ISO) pertaining to water-related structures be adopted, such as standards for hydrological design and design-flood estimation, with periodic review of these standards to keep pace with emerging climatic and hydrological changes.
- Emphasis is placed on the necessity of involving independent experts in reviewing designs and maintenance plans, and conducting periodic tests simulating extreme flood scenarios, to verify the dams' capacity to withstand conditions exceeding conventional design limits.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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