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AN ASSESSMENT OF THE FAILURE OF THE WADI DERNA DAMS AND LESSONS FOR ENHANCING DAM SAFETY

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The United Nations Educational, Scientific and Cultural Organization contributes to peace and security by promoting international cooperation and knowledge sharing in education, sciences, culture, communication, and information. The UNESCO Intergovernmental Hydrological Programme (IHP) founded in 1975, is the only intergovernmental cooperation programme of the UN system dedicated to water research and management, and related education and capacity development. The IHP addresses national, regional, and global water challenges, by supporting the development of sustainable and resilient societies.

The Netherlands aims to be highly active, knowledgeable, and relevant in the international approach to water and climate-related disasters. The Ministry of Foreign Affairs and the Ministry of Infrastructure and Environment have initiated the Disaster Risk Reduction & Surge Support (DRRS) Programme. Administered by The Netherlands Enterprise Agency (RVO), the DRRS aims to prevent and reduce the impact of water and climate-related disasters worldwide and increase the resilience of affected areas and populations.

The International Commission on Large Dams is a non-governmental organization that brings together experts and professionals from around the world to share knowledge and advance the science and practice of dam engineering and management. ICOLD develops and promotes guidelines and best practices for the design, construction, operation, and maintenance of dams. It has today 106 country members represented by national committees and a total of around 25,000 professionals of the dam industry.

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It builds on the Rapid Damage and Needs Assessment carried out by the World Bank Group, the United Nations, and the European Union in the immediate aftermath of Storm Daniel, an assessment carried out by the Embassy of the Netherlands to Libya, the Netherlands Enterprise Agency, the World Bank and the International Commission on Large Dams of the dam failures in the months following the failures of the Derna and Abu Mansour dams, and a parallel set of consultations carried out by UNESCO, with support from the International Commission on Large Dams, in November 2023 and January 2024.

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The Disaster Risk Reduction and Surge Support (DRRS) Programme was initiated by the Netherlands Government to prevent and reduce the impact of water- and climate-related disasters worldwide and increase the resilience of affected areas and populations. Through DRRS, water experts are deployed to mitigate fall-outs of water-related disasters with a swift response or to support in improving resilience. Every DRRS intervention is tailor-made and the programme operates in all disaster management cycle phases: mitigation, preparedness, response and recovery.

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UNESCO's *IHP-IX* strategy promotes an integrated, adaptive approach to managing large rivers and dam infrastructure amid global change. It emphasizes ecohydrology and sediment management to improve river basin governance and ensure reservoir function, water quality, and dam safety. Demonstration projects, like *Friends-Water* and *ICIREWARD*, highlight nature-based solutions. It advances real-time hydrological monitoring through remote sensing and platforms like *IHP-WINS* and FRIEND-Water. IHP-IX also supports research on extreme events, early warning systems, and adaptive dam operations. Frameworks like *CRIDA* and IFI guide climate-resilient, risk-informed management, aligning science, data, and ecology for sustainable water governance.

Acronyms

AWS	automatic weather stations
cm	centimeter
CRIDA	Climate Risk Informed Decision Analysis
DEM	Digital Elevation Model
DRSS	Disaster Risk Reduction and Surge Support
EWS	Early Warning System
FRIEND-WATER	Flow Regimes From International Experimental and Network Data
FSL	Full Supply Level
GDP	Gross Domestic Product
GFDRR	Global Facility for Disaster Reduction and Recovery
GWSP	Global Water Security and Sanitation Partnership
ha	Hectares
ICIREWARD	International Center for Interdisciplinary Research on Water Systems Dynamics
ICOLD	International Commission on Large Dams
IHP-WINS	Intergovernmental Hydrological Programme's Water Information Network System
IHP	Intergovernmental Hydrological Programme
IMERG	Integrated Multi-satellitE Retrievals for GPM
inSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
km	kilometers
km^2	Square kilometers
LIDAR	Light Detection and Ranging
LNMC	Libya National Meteorological Center
m	Meters
m^3/s	Cubic meters per second
Masl	Meters above sea level
MCM	Million Cubic Meters
Medicane	MEDIterranean hurricane
mm	Millimeters
NCM	National Coordination Mechanism
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RDAN	Rapid Damage and Needs Assessment
SCS	Soil Conservation System
TC	Tropical Cyclones
UNESCO	United Nations Organization for Education, Science and Culture
WRD	World Register of Dams

Executive Summary

Storm Daniel and the failure of the Derna and Abu Mansour dams in September 2023 resulted in catastrophic consequences for the people of Libya. While such dam failures are typically low-probability events characterized by the sudden, uncontrolled release of water, they can have catastrophic consequences, as evidenced by the damages and losses resulting from Storm Daniel. These are estimated to be US$1.65b, equivalent to 3.6 percent of Libya's GDP, with the flood resulting in more than 4,000 reported fatalities and more than 10,000 individuals unaccounted for as of January 2024, and at least another 34,000 people displaced from their homes.

This report aims to provide an independent assessment of the probable failure modes associated with the collapse of the dams in Wadi Derna. The consequences associated with the failure of the Derna and Abu Mansour dams are among the most significant dam failures in the world. Given this context, the outcome of this assessment is intended to provide important lessons for the reconstruction of Derna, insights to enhance the safety of dams and downstream communities in Libya, while also contributing to efforts by the international dam safety community to improve the design, construction and operation of dams and the management of risks associated with dam failures.

The approach to the assessment relied on the analysis of original design reports, studies conducted from 2002 to 2004, videos, satellite images and photographs, eyewitness reports, facts in the public domain, and expert elucidation. A series of expert consultations and peer reviews were carried out to assist with available data and information, to review the different potential failure modes, identify national priorities related to dam safety and confirm the proposed recommendations. There was little information available on the behavior of the dams since studies in 2003/4 and it was not possible to visit the dam sites in the aftermath of the disaster. Given this context, it is important to note that this analysis may be revised following the availability of new elements, even after the publication of this report.

The Derna and Abu Mansour dams were constructed along Wadi Derna in the 1970s, primarily to control flooding and protect the city of Derna. They were also intended to recharge the aquifers, with the Abu Mansour dam also providing water for irrigation. The wadi drains around 575 km^2 and is roughly 75 kms long, flowing east from an altitude of 765 meters before heading north-east to the city of Derna. Long term annual precipitation averages 278 mm, ranging from 448 mm in 2018 to 130 mm in 1955, with strong seasonal signals averaging 67 mm in December and less than 1 mm in June, July, and August. Total annual runoff was estimated at 8 millions of cubic meters (MCM) during the design phase, although the hydrological characteristics exhibit significant temporal variability and flood events are characterized by short duration, very high maximum discharge values and proportionally smaller volume flood waves in relation to the maximum water discharge. Both dams were designed to protect against flood events up to a 1,000-year return period.

The Derna Dam (also called Belad Dam) was a 45m high, rockfill embankment dam with a clay core located about 1 km upstream of the city of Derna with the catchment area above the dam around 575 km^2. The reservoir was designed to store 1.15 MCM and the dam to carry a flood discharge of 350 m^3 per second over a morning glory shaft type-spillway set at an elevation of 41 masl. The dam crest was 100 m long and 7 m wide at elevation 45.0 masl, with a wave protection wall on the upstream side and railing on the downstream. The intake tower and discharge conduit represented one unit located on the left side above a curving tunnel excavated through the abutment. A valve shaft was set upstream of the overflow shaft, with three 400 mm diameter upper outlets for the irrigation supply and one 1000 mm diameter bottom outlet pipe that combined in a 1000 mm steel pipe set in a trench concreted into the base of the overflow tunnel under the dam.

The Abu Mansour Dam (also called Bu Mansur Dam or Mansur Dam) was a 73 m high, rockfill embankment dam with a clay core located about 11 km upstream of the Derna Dam with the catchment area above the dam around 476 km^2. The reservoir was designed to store 23.7 MCM and the dam to carry a flood discharge of 170 m^3 per second over a morning glory shaft type-spillway set at an elevation of 224.50 masl. The dam crest was 322 m long and 7 m wide at elevation 228 masl, with a wave wall on the upstream side and a railing on the downstream. The bedrock is composed of marly limestones covered by a quaternary deposit made of alluvium and conglomerates with variable cementation. This formation has a permeability coefficient of 2.3x10-1 to 4.3x10-2 cm per second and the foundation was grouted to depths from 20 to 41 m to reduce seepage. At the base of the core was a square-section comprised of 3m wide concrete blocks arranged in steps of various heights that followed the line of firm rockhead in the base of the clay-core-filled trench with battered sides that cut through the alluvium and any soft or very permeable or broken rock. The foundation below these blocks was reportedly grouted to depths of 20 to 34 m. A valve tower was set just upstream of the overflow shaft of the morning glory spillway, with three 600 mm diameter upper outlets for irrigation supply and one 1,200 mm diameter bottom outlet for dewatering that combined beneath the dam in a 1,200 mm diameter steel pipe set in a trench connected to the base of the overflow tunnel.

Serious issues were observed with both dams during construction and in the early years of operation. Abnormal settlement occurred and continued, with water infiltration observed through and beneath the dams during periods of high water. The greatest settlement was observed at the Abu Mansour Dam, particularly in its middle section. Subsequent investigations revealed cracks and cavities within the interior of both dams. A series of studies undertaken between 2002 and 2004 concluded that both dams were under stress and that the runoff and peak floods were underestimated. Furthermore, it was observed that the updated flood passage through the city of Derna was problematic. Recommendations were made on multiple occasions, including after the construction of the dams and again in 2004, to reinforce the dams. However, these recommendations were not implemented due to a range of factors, including a deterioration of the security situation and an ensuing period of political instability.

The extreme rainfall caused by Storm Daniel resulted in extensive flooding that affected Greece, Bulgaria, Türkiye, and Libya. Libya's National Meteorological Agency reported 414 mm at a monitoring station in Al-Bayda and 170 mm in the city of Labraq in 24 hours; well in excess of the long-term average precipitation for September which is estimated at 1.46 mm for Derna. However, estimating average rainfall over the catchment is difficult and there is considerable uncertainty around the spatial and temporal distribution of precipitation, with satellite-based measurements showing consistently lower rainfall intensity. While estimates vary significantly based on the source, it can be safely concluded that the amount of precipitation was most probably in the order of 150 to 300 mm. This rainfall intensity is estimated to have a frequency of occurrence of once every 200 or 500 years.

Storm Daniel's west-east path represents the worst-case scenario for the accumulation of runoff in Wadi Derna. The heavy rainfall covered the entire catchment in quantities, and with an intensity, that were much larger than the infiltration capacity. While the actual magnitude of the resulting storm-driven flood volumes depends on the assumptions used in generating the rainfall estimates and runoff coefficient, the flood volume with 150 mm of rainfall across the catchment is estimated to be in the order of 25 to 30 MCM, with 300 mm resulting in a flood volume estimated around 90 to 100 MCM. This assumes the same coefficient across the catchment for events of different return periods and so likely underestimates the peak flow and volumes for higher magnitude events which would result in ground saturation and most of the additional flow as runoff.

The failure of the Derna and Abu Mansour dams is likely due to the culmination of a range of factors stemming from the original design and triggered by extreme precipitation. An evaluation of various potential failure modes suggests that both dams collapsed due to overtopping resulting from higher runoff than the flood volume in the reservoir. This was likely exacerbated by the limited capacity of the morning glory spillway, with a very high probability that overflow occurred between 100 and 150 mm. While both dams were designed to withstand a 1,000-year return period, the hydrological data available during design phase was limited, resulting in restricted statistical reliability, and what was considered at the time as a 1-1,000 year event is estimated today to have a frequency of occurrence of once every 200 or 500 years.

The safety threshold of each dam was too low due to an outdated and inadequate design. This was not adapted to modern standards and updated design conditions, and was exacerbated by severe settlement observed at both the Derna and Abu Mansour dams. Neither dam had an emergency spillway, so were not designed for overload conditions, and dam inspections were not sufficient to identify and prevent possible damage. Despite inspections carried out in 1985 and 1994 identifying severe settlement, deemed to be well above normal behavior, the integrity of both dams was not considered compromised and the 1994 recommendation to lower the water level in the Derna Dam to a maximum of 35 meters was not feasible. Inadequate dam operation management in the days prior to and during the event does not seem to have contributed to the failures. Furthermore, it is unlikely that the rehabilitation work recommended in 2003/4 would have prevented the failure of both dams given the magnitude of the flood event.

The assessment concludes that there were likely two independent failure events. The Derna Dam likely failed first, with a partial failure around 11:00pm on the evening of September 10, 2023, followed by a separate event with the failure of the Abu Mansour Dam at around 02:40am on the morning of September 11, 2023. This resulted in two flood waves through the city of Derna, with the flood wave due to the failure of the Derna Dam estimated to have been in the order of between 1,500 and 5,000 m^3 per second, with the flood wave due to the failure of the Abu Mansour Dam estimated to be in the order of 7,000 m^3 per second, exceeding the 1,000 m^3 per second capacity of the city's drainage channel. With high velocities (3-8 m per second), this water inundated even larger portions of the city, causing more destruction and loss of human lives.

The tragic failure of the dams in Wadi Derna highlights the need to assess the safety of other dams in Libya. Dams play an important role in water management in Libya and Ministry's list indicates that Libya had 18 dams (total storage capacity of approximately 390 Mm^3). A screening using remote sensing carried out as part of this assessment has identified another 14 dams not included in the original register. While none of these are estimated to above 15m high, some potentially impound more than 3 MCM, and could thus be considered large dams. A preliminary estimate of the population and infrastructure exposed downstream of all 28 dams was carried out to provide a rapid, high-level assessment of the potential consequences in the event of another dam failure. Several dams rank as presenting a very high risk and should be subject to an immediate evaluation, particularly those aiming at urban areas flood protection. This should include a more detailed determination of the downstream population at risk, a review of the design criteria and outlet/spillway characteristics, along with the early warning systems and emergency preparedness plans in place.

The tragic failure of the Derna and Abu Mansour dams provides important lessons for the reconstruction of Derna, assuring the safety of dams and downstream communities in Libya and informing efforts by the international community to improve the safety of dams. Eight specific and actionable recommendations are proposed. These are structured around three core elements that firstly acknowledge the uncertainties in this assessment and provide for additional or updated assessments in the event of new information, secondly highlight opportunities to inform the reconstruction efforts and to leverage the tragedy to build back better, while thirdly outlining measures for strengthening the national systems for ensuring the safety of dams and downstream communities. These include:

1. *Carry out a more detailed assessment of the 2023 flood event* as more data, information, and investigations become available and develop an hydraulic model that can inform design conditions for reconstruction measures aimed at building back better.

2. *Carry out a more detailed assessment of the dam failures* as new data, information, and investigations become available, ideally based on site visits and field investigations, to evaluate overtopping erosion, internal erosion, micro- and macro-instability and provide further insights to support the evaluation of the most probable failure modes and contributing factors.

3. *Improve Emergency Preparedness* by investing in hydro-meteorological observations, real-time monitoring and forecasting; preparing detailed flood risk maps and risk-informed development plans; developing preparedness and emergency response plans; upgrading equipment and facilities for emergency response and strengthening capacities for response and recovery; and, organizing community level awareness campaigns, supplemented by measures to reinforce the institutional and regulatory framework for disaster and climate risk management.

4. *Determine the acceptable level of protection for Derna City* through a participatory, adaptative planning and management approach that considers the probability of occurrence associated with specific hazards, and the potential casualties and damage to infrastructure, in order to minimize the potential loss of life, economic losses and that can accommodate changes in socio-economic conditions over time.

5. *Determine appropriate interventions for building back better* by revisioning a new urban redevelopment plan using climate resilient, inclusive principles that would include structural and non-structural measures to accommodate future peak discharges and improve the liveability and quality of life for the people of Derna.

6. *Develop a Regulatory Framework for Dam Safety Assurance* to guide a uniform approach to assuring the safety of dams and downstream communities across Libya based on a review of the existing organizational roles and responsibilities, the legal and regulatory elements governing the planning, design, development, implementation, operation and maintenance and that captures the legal, institutional, technical, and financial realities.

7. *Launch a National Dam Safety Program* to reduce the probability of dam failures and the potential loss of human life and economic losses by identifying priority investments using a risk informed decision making framework, carrying out inspections for all medium- to high-risk dams, developing and socializing emergency preparedness plans and early warning systems, and implementing a capacity enhancement program to improve the safety of dams and downstream communities.

8. *Implement a Communications and Stakeholder Engagement Plan* to disseminate the results of this assessment in order to: (i) inform the development of a shared vision for reconstruction and an agreed level of protection for Derna; (ii) provide an informed basis for managing risks associated with other dams in Libya, address the restoration of trust and ensure enhanced resilience; as well as (iii) inform the international community and provide clarity regarding the events that lead to the failure of the Derna and Abu Mansour dams.

The assessment and recommendations contained herein are intended to inform recovery and reconstruction efforts that are inclusive, coordinated and help to build a more resilient future for people in Libya. By providing an objective, independent assessment of the potential failure modes it is hoped that this report will help Libyan stakeholders move towards conceiving, planning, and implementing an efficient and effective recovery program through a coordinated national platform. Libya can come out of this disaster, stronger and more resilient, by converting adversity into an opportunity for building back better and contributing towards a resilient, inclusive, and sustainable recovery for people in Libya.

1. Introduction and Approach

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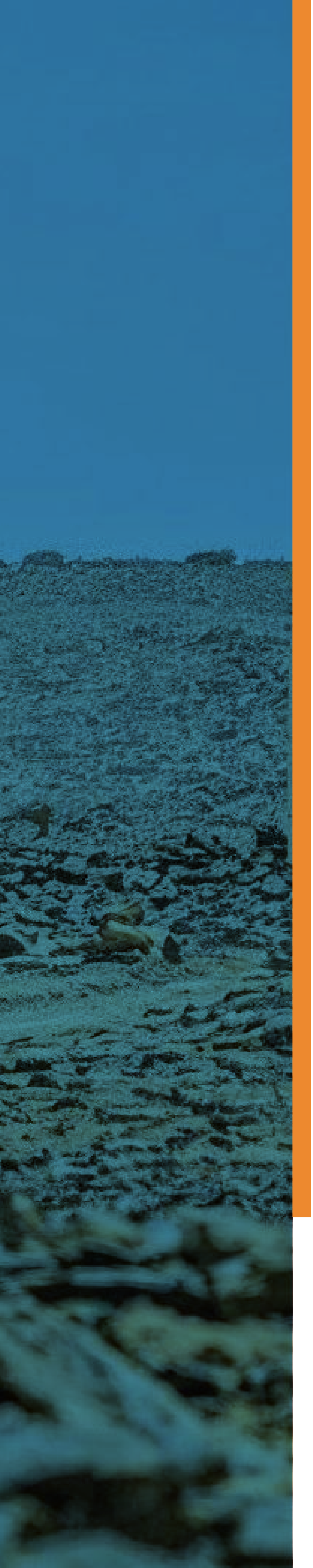

1 Dam failures are typically low-probability, unpredictable events, that often have catastrophic consequences, as evidenced by the failure of the Derna and Abu Mansour dams due to Storm Daniel.

2 Damages and losses associated with Storm Daniel have been assessed at US$1.65b, equivalent to 3.6% of GDP, and initial reconstruction estimates in excess of US$1.8b, with fatalities exceeding 4,000 people, more than 10,000 people unaccounted for and 34,000 people displaced across Libya.

3 This assessment is intended to provide an independent assessment of the potential failure modes of the Derna and Abu Mansour dams that can provide lessons for the reconstruction of Derna, insights to enhance the safety of dams and downstream communities in Libya, while also contributing to international efforts to improve the management of risks from dam failures.

On Sunday, September 10, 2023, a devastating natural disaster unfolded in eastern Libya when Storm Daniel wreaked havoc with heavy rains and fierce winds. The storm initially hit Greece, Bulgaria, and Türkiye with major flooding and acquired quasi-tropical characteristics as it moved towards the coast of Libya, where the storm's initial impact was felt across Libya's coastal cities in the northeast, including Benghazi, Susa, and Al-Marj. However, the most catastrophic event occurred during the night of September 10 to September 11, when two dams upstream of the coastal city of Derna, situated on the Wadi Derna, tragically failed. This led to the near instantaneous release of millions of cubic meters of water downstream, resulting in flash flooding that inundated the river's floodplain and caused extensive destruction of Derna, a city inhabited by approximately 120,000 people.

The flood resulting from the failure of the Derna and Abu Mansour dams caused the complete destruction of entire neighborhoods, some of which were reported to have been swept into the Mediterranean Sea. The damage to buildings and infrastructure was severe, numerous roads were rendered impassable and the livelihoods and social fabric of the city changed forever. As of January 23, 2024, the death toll reportedly exceeded 4,000, with more than 10,000 individuals still unaccounted for, and at least 34,000 people displaced from their homes (UN OCHA 2023). Effective post-disaster reconstruction would benefit from coordinated efforts among all Libyan stakeholders. The hope is that the need for a joint response and the desire to avoid further such disasters might incentivize positive developments in the political dialogue.

In the immediate aftermath of the devastating flood event, the World Bank Group, the United Nations, and the European Union, jointly carried out a Rapid Damage and Needs Assessment (RDNA: World Bank, United Nations, and European Union. 2024). This was supported by the Global Facility for Disaster Reduction and Recovery and the State and Peacebuilding Fund, with technical support for the assessment of the failures of the Derna and Abu Mansour dams provided through collaboration with the Embassy of the Netherlands to Libya, the Netherlands Enterprise Agency and the International Commission on Large Dams (ICOLD).[1] A parallel set of consultations were carried out by UNESCO in November 2023 and January 2024. The former targeted the needs assessment in the culture sector, while the latter were done as part of a fact-finding mission carried out with international experts designated by the ICOLD to identify national and subnational needs and priorities and assess the status of the Derna and Abu Mansur dams.

The RDNA provides a comprehensive analysis of sectoral damages, economic losses, and recovery needs arising out of the disaster. It covered 12 sectors and 7 cross-cutting areas.[2] Damages and losses are estimated at US$ 1.03 and US$ 0.62 billion, respectively, and impacted approximately 1.5 million people – 22 per cent of Libya's population – living in the coastal and inland cities that were hardest hit. The US$ 1.65 billion in estimated damages and losses accounts for 3.6 per cent of Libya's GDP in 2022. The damages and losses were estimated through various remote-sensing based data acquisition and triangulation tools, corroborated through ground information where possible following a globally established and recognized methodology. This has been applied in numerous post-disaster and conflict contexts to assess damages, losses and needs towards informing recovery and reconstruction planning.

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[1] This was executed as part of the MoU between the World Bank and the ICOLD.

[2] These sectors encompass Social Sectors (Housing, Education, Health, Poverty, and Social Protection, and Jobs), Productive Sectors (Agriculture and Financial), Infrastructure Sectors (Energy, Transport, Telecommunications and Digital Development, Water and Sanitation, and Water Resource Management, and Municipal Services), as well as Cross-Cutting Sectors (Environment, Impact on Women and Men, Governance and Public Institutions, Disaster and Climate Risk Management, and Social Sustainability and Inclusion).

Early-stage reconstruction and recovery needs have been estimated at around US$ 1.8 billion. The greatest impact has been on housing, the environment, Libya's cultural heritage, as well as the transportation and water sectors. Housing was severely hit, with more than 18,500 houses estimated to have been destroyed or damaged, equivalent to seven per cent of the country's housing stock. The RDNA estimates 70 per cent of the needed reconstruction costs would be for infrastructure, with the largest component being for the housing sector. Total damage to the water sector is estimated at between US$ 127 million and US$ 146 million and is driven almost exclusively by the complete destruction of the Derna and Abu Mansour dams.

Dam failures, such as those of the Derna and the Abu Mansour dams, are typically low-probability, unpredictable events, that often have dramatic consequences. Catastrophic dam failures are characterized by the sudden uncontrolled release of water. Such failures can result in extremely adverse consequences, including large-scale loss of human life and significant economic and environmental impacts as evidence by the failure of the dams in Wadi Derna. While the overall failure rate of dams globally is around 1 percent, the failure ratio to the number of dams has decreased from 1.42 percent between 1900 and 1925 to 0.12 percent since 2000 (Figure *1.1*a: ICOLD 2019a). However, the failure ratio related to the age of construction has shown an increase since the year 2000 (Figure *1.1*b: ICOLD 2019a) with most dams failing in the first five-years of construction (Figure 1.2: ICOLD 2019a).

The improvements observed in the safety of dams are considered to have benefited from the wider dissemination of knowledge on risks and lessons derived from dam failures. These lessons have helped inform improvements in technical investigations, design, and construction techniques, along with advances in oversight mechanisms and dissemination through organizations such as ICOLD (ICOLD 1973, 1995, 2019). Within this spirit, the objective of this joint assessment is to delve deeper into the potential failure modes of the dams in Wadi Derna with the aim of deriving lessons that can help inform the reconstruction efforts and avoid such tragedies in the future. In doing so, it is hoped that these lessons can contribute to ensuring that dams are built and operated safely, efficiently, economically, and are environmentally sustainable and socially equitable.

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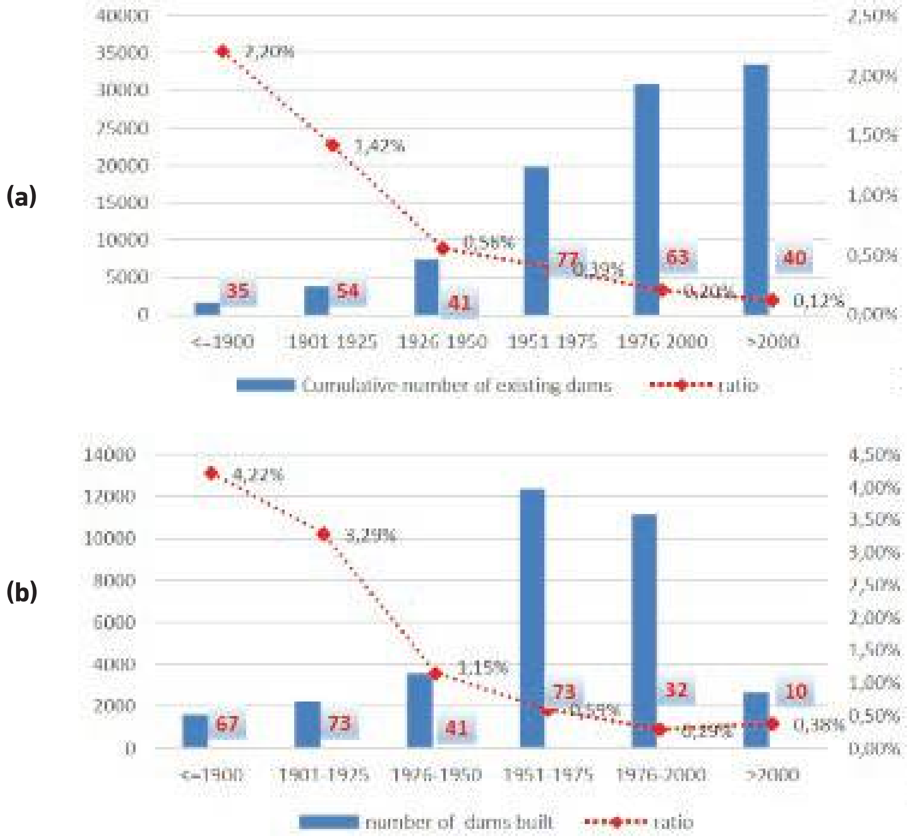
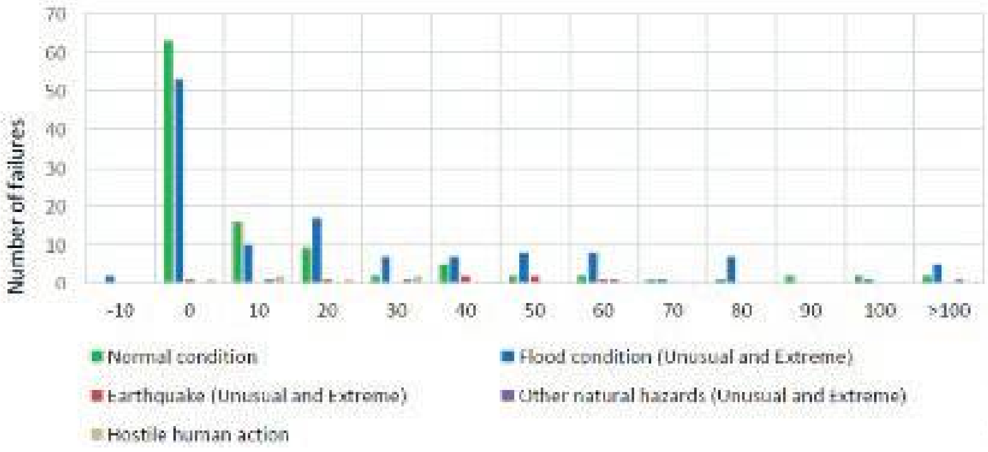
FIGURE 1.1. **Dam failures by time periods and ratio with existing dams (a) over time and (b) with year of construction.**

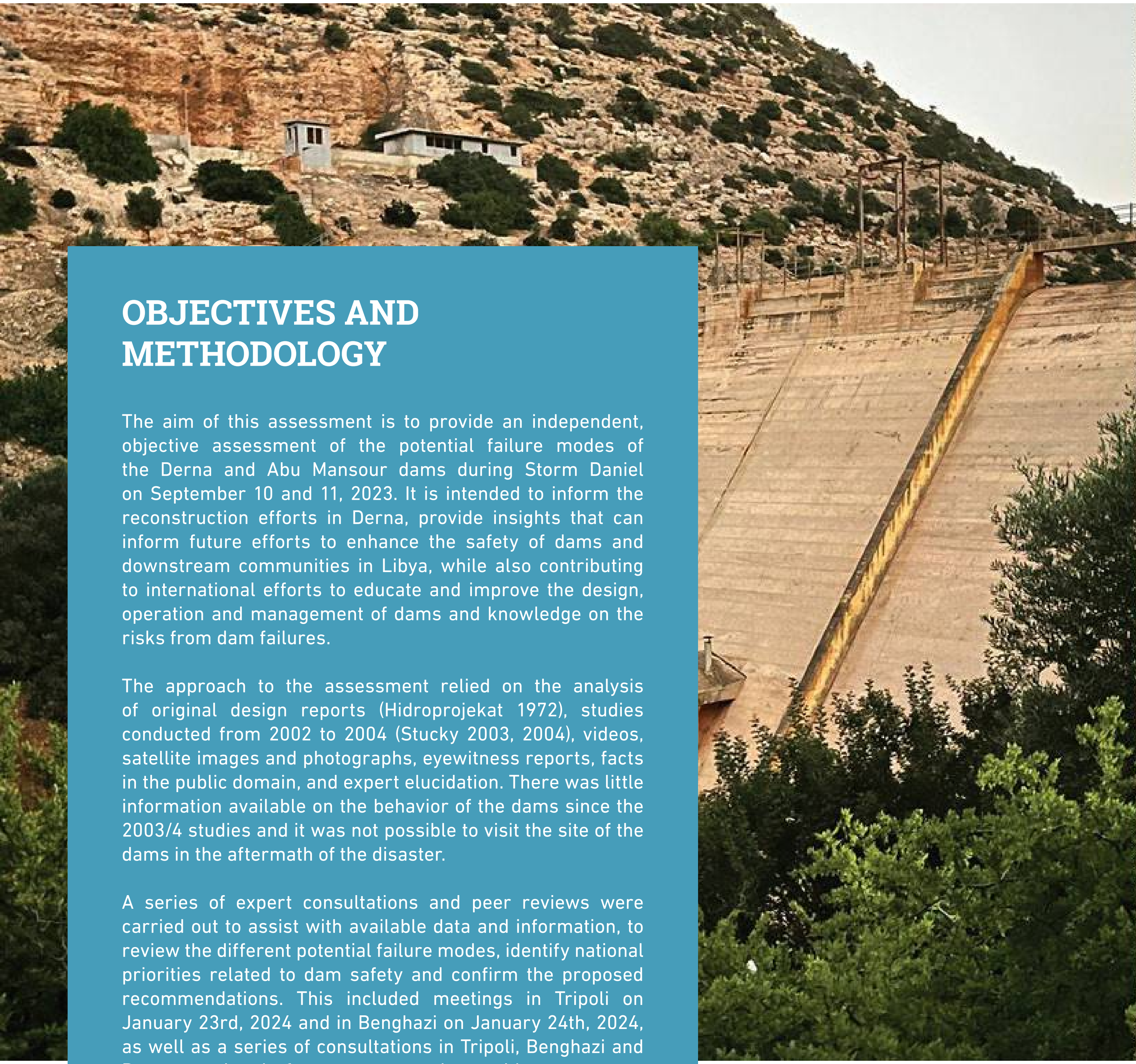


Source: ICOLD 2019a

FIGURE 1.2. **Dam failures with age after construction.**



Source: ICOLD 2019a



OBJECTIVES AND METHODOLOGY

The aim of this assessment is to provide an independent, objective assessment of the potential failure modes of the Derna and Abu Mansour dams during Storm Daniel on September 10 and 11, 2023. It is intended to inform the reconstruction efforts in Derna, provide insights that can inform future efforts to enhance the safety of dams and downstream communities in Libya, while also contributing to international efforts to educate and improve the design, operation and management of dams and knowledge on the risks from dam failures.

The approach to the assessment relied on the analysis of original design reports (Hidroprojekat 1972), studies conducted from 2002 to 2004 (Stucky 2003, 2004), videos, satellite images and photographs, eyewitness reports, facts in the public domain, and expert elucidation. There was little information available on the behavior of the dams since the 2003/4 studies and it was not possible to visit the site of the dams in the aftermath of the disaster.

A series of expert consultations and peer reviews were carried out to assist with available data and information, to review the different potential failure modes, identify national priorities related to dam safety and confirm the proposed recommendations. This included meetings in Tripoli on January 23rd, 2024 and in Benghazi on January 24th, 2024, as well as a series of consultations in Tripoli, Benghazi and Derna on the draft assessment, along with expert peer review by the partners.

Given this context, it is important to note that this analysis may be revised following the availability of new elements, even after the publication of this report. Should conditions allow, an inspection of the site of the Derna Dam and the remains of Abu Mansur dam would help to confirm or review the probable scenario of their failure.

2. Dams in Libya and Wadi Derna

1 Dams play an important role in Libya's water security and flood protection, despite the arid conditions and natural scarcity of water.

2 The Derna and Abu Mansour dams were constructed in the 1970s to control floods and protect the city of Derna, recharge the aquifers and provide water for the Fataya Agricultural Project.

3 Studies undertaken between 2002 and 2004 concluded that: (i) both dams were under stress and (ii) the runoff and the peak floods are underestimated, making a series of recommendations for urgent rehabilitation measures.

2.1 DAMS IN LIBYA

Libya faces significant challenges in managing its water resources due to its arid climate and limited water availability. The country relies on four main sources of water, including: (i) intermittent surface water along ephemeral wadis; (ii) shallow groundwater; (iii) deep aquifer groundwater; and, (iv) desalinated seawater. However, the majority of water resources in Libya come from non-renewable groundwater, which is distributed across five main groundwater basins, including Al-Jafara, Al-Jabal Al-Akhdar, Al-Hamada Al-Hamra, Murzuq, and Al-Kufra. With little to no recharge taking place, the country's ancient aquifers provide more than 80 percent of the total water demand and is the primary source of potable, industrial, and irrigation water supply.

Dams play a crucial role in water management in Libya. The portfolio is typically recognized as including 18 dams (Table 2.1), with 14 large dams registered with the World Register of Dams (WRD) (Map 2.1). However, the ICOLD WRD includes the Megenin IV Dam, along with the Megenin IV1 Dam that is not included in the national count. In the absence of permanent surface water, these have been constructed on the main wadis, primarily to control periodic floods, but also to divert water for irrigation projects, and recharge local groundwater aquifers. The Dams Department within the Ministry of Water Resources is responsible for studies and research on dams and reservoirs, as well as their technical supervision, operation, and maintenance. In the absence of dedicated legislative provisions for ensuring the safety of dams and downstream communities, these activities are governed by Law No. 3 of 1982 regulating the exploitation of water resources.

Libya's aging portfolio is increasingly susceptible to the impacts of climate change and changing hydrology. The average age of the large dams in the portfolio is over 40 years, with three of the 14 large dams in the ICOLD WRD more than fifty years old. While the total design capacity of dams in the portfolio is estimated at about 390 million cubic meters (MCM), the average annual volume of water stored is about 61 MCM (GWA 2012). The 14 large dams account for nearly 98 percent of the total storage capacity, with more than 50 percent of this capacity in three dams. Reflecting the variability of the ephemeral systems, the average annual amount of water stored is roughly 15 percent of the design capacity, exhibiting similar wide variation with Wishka Dam averaging 5 percent and only two dams, the Mourkos and Ben Gawad dams, estimated to reach full supply level on average every year.

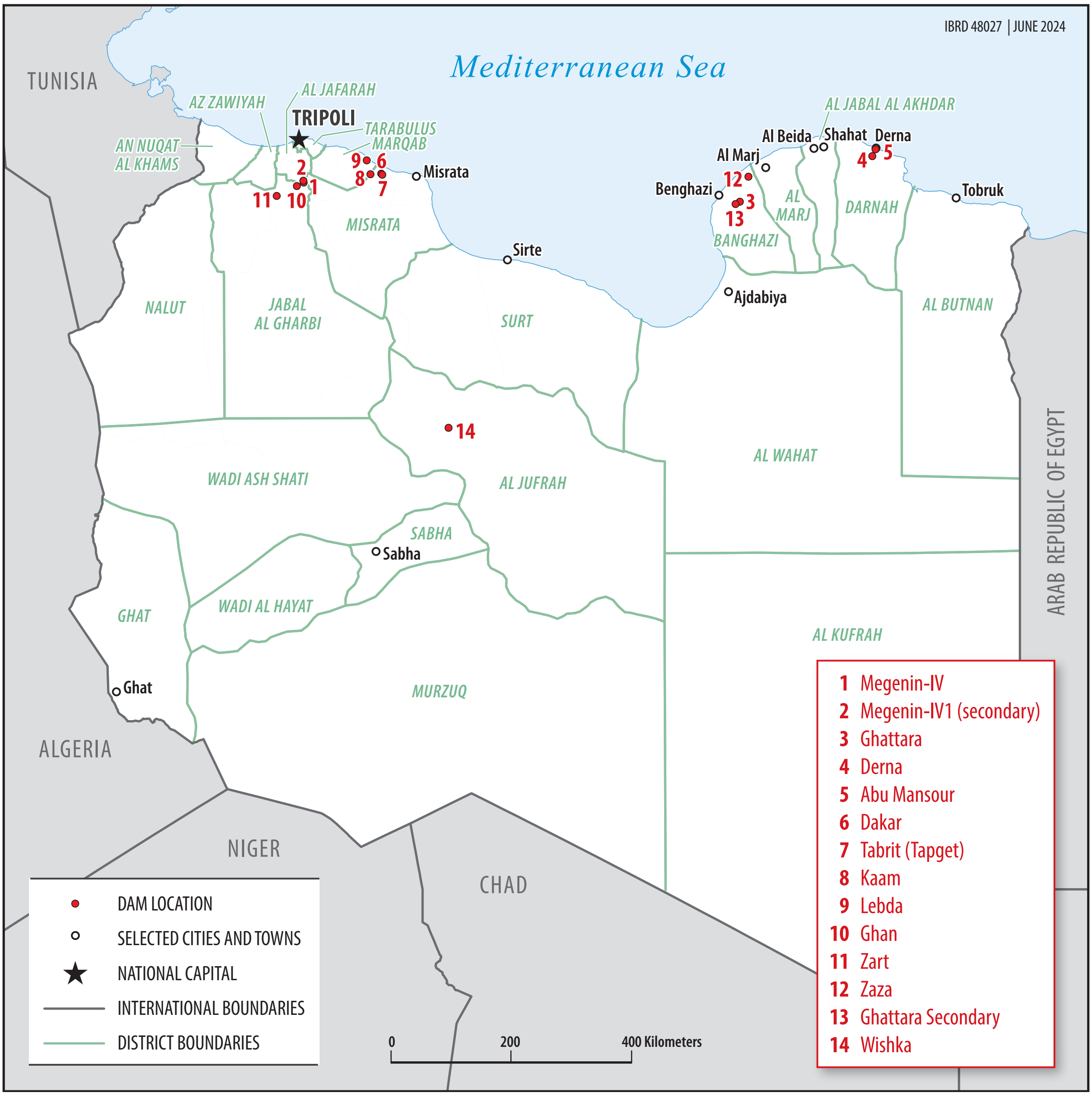
All of the dams in the portfolio are earth and rockfill embankment dams, with the exception of the Wadi Zaza Dam. Earthfill dams are mostly made up of compacted earth with a core in the middle made of low permeability material, such as clay to stop water passing through the dam, a permeable part growing gradually outward, called a filter, on the two sides covering the core, and the shell on the upstream and downstream heels. Rockfill dams are mainly made from deposited and compacted rockfill, with an impermeable core or an impermeable layer on the upstream face of the dam to prevent seepage through the porous core.

TABLE 2.1. Characteristics of the dams portfolio in Libya.

No.	Dam name	Year	Location	Dam Type	Height (m)	Design Capacity (MCM)	Purpose
1	Megenin-IV	1972	Tripoli	Earthfill	42	58	Irrigation agricultural project (3,000 ha), flood protection for the city of Tripoli
2	Megenin-IV1 (secondary)	1972	Tripoli	Earthfill	30		
3	Ghattara	1973	Benghazi	Earthfill	55	135	Drinking water and agricultural project in Beneina and Benghazi
4	Abu Mansour	1978	Derna	Earthfill	73	23.70	Flood protection for city of Derna, aquifer recharge and Fataya Agriculture Project
5	Derna	1978	Derna	Earthfill	40	1.15	
6	Dakar	1978	Zletin	Earthfill	19	1.60	
7	Tabrit (Tapget)	1978	Zletin	Earthfill	24	1.60	
8	Kaam	1979	Khoms	Earthfill	50	111	Irrigation of Kaam agricultural project (5000ha) and water to the industrial region of Kaam
9	Lebda	1982	Khoms	Earthfill	33	5.20	Protection of Lebda Cultural City
10	Ghan	1982	Gharian	Earthfill	80	30	Provision of 2 MCM per year of drinking water from Gherian to Kekat; supply bottled water factory in Ghan with 8 l/sec; protect Hayrat agricultural project
11	Zart	1982	Gharian	Earthfill	32	8.60	Protection of Abu Sheiba Agricultural Project
12	Zaza	1984	Benghazi	Gravity Concrete	38	2.00	
13	Ghattara Secondary	2005	Benghazi	Earthfill	34	1.50	Drinking water and agricultural project in Beneina and Benghazi
14	Wishka	2006	Hun / Waddan	Earthfill	25	3.65	
15	Mourkos		Ras Hilal		14	0.15	Provision of water to small-scale farms
16	Ben Gawad		Ben Gawad		12	0.34	Provision of drinking water to nearby areas
17	Garef / Giaaref		Sert		12	2.40	
18	Al Zahawia / El Zahaweya		Sert		11	2.80	
19	Al Zeed / El Zayd		Sert		13	2.60	

Source: World Register of Dams (1-14), Abdudayem and Scott (2014) and GWA (2012)

MAP 2.1. **Location of large dams in Libya.**



1	Megenin-IV
2	Megenin-IV1 (secondary)
3	Ghattara
4	Derna
5	Abu Mansour
6	Dakar
7	Tabrit (Tapget)
8	Kaam
9	Lebda
10	Ghan
11	Zart
12	Zaza
13	Ghattara Secondary
14	Wishka

Source: Original for this publication

The Derna and Abu Mansour dams, located in the Wadi Derna system, were designed and built from 1973 to 1977 mainly to control flooding and protect the city of Derna following a series of major flood events (Hidroprojekat 1985a and 1985b). The dams were also intended to recharge the aquifers and provide irrigation water for the Fataya Agricultural Project located eastward of Derna, through pipelines pumping water from the dam reservoirs. In 1941, during World War II, a deluge swept away tanks and soldiers stationed on the outskirts of Derna. There were also major floods in 1956, 1959, 1968 and 1986. Studies for the dams were launched after the 1959 flood, which was the worst in terms of damage and fatalities until the 2023 flood disaster. The dams were designed to protect the city Derna from flood events up to a 1,000-years return period event, with the onset of overflow occurring around 500 m^3 per second, which corresponds to a return period of approximately 50 years, and it is likely that the dams protected the city from flood damage on numerous occasions between the end of construction in 1977 and the collapse in 2023.

2.2 DERNA DAM

The Derna Dam (also called Belad Dam) was an embankment dam located on the Wadi Derna about 1 km upstream of the city of Derna (Table 2.2). The total catchment area upstream of the dam was reported to be 575 km^2, including the catchment area of the Abu Mansour Dam, and the design height was 40 m from the foundation. The reservoir was designed to store 1.15 MCM up to its Full Supply Level (FSL) at elevation 41 masl, almost entirely within the wadi itself, giving a long and thin reservoir shape. According to the initial design, the dam crest was at elevation 45 masl and the crest length was 100 m (Figure *2.1*). The normal freeboard was 4m (45m minus 41m). The crest was 7 m wide with a wave protection wall on the upstream side and a railing on the downstream. The road across the crest had effectively become part of the public road network and carried considerable traffic.

The Derna Dam was a rockfill dam with a slender section clay core. The upstream slope of the rockfill was hand-placed to form a smooth rip-rap surface at a slope of 1V:1.5H. The downstream slope had two intermediate berms at elevation 25 masl and 35 masl, and the rock fill was similarly finished to slopes of 1V:1.4H. The dam shoulders made of compacted rockfill are sitting on the quaternary deposit. The core was formed of clay vertically below the crest roadway with side slopes of 10:1. Coarse and fine filters 1 m wide were placed on either side of the core. At the base of the core was a grouting/inspection gallery running the entire length of the dam, following the line of the rock head beneath the alluvial material.

The bedrock of the Derna Dam site is composed of marly limestones dating back to the Eocene / Oligocene. It is composed of fine-grained to microcrystalline limestone featuring sometimes chalky facies, including cherts and bituminous substances. There is evidence of karstification

TABLE 2.2. General features of Derna dam.

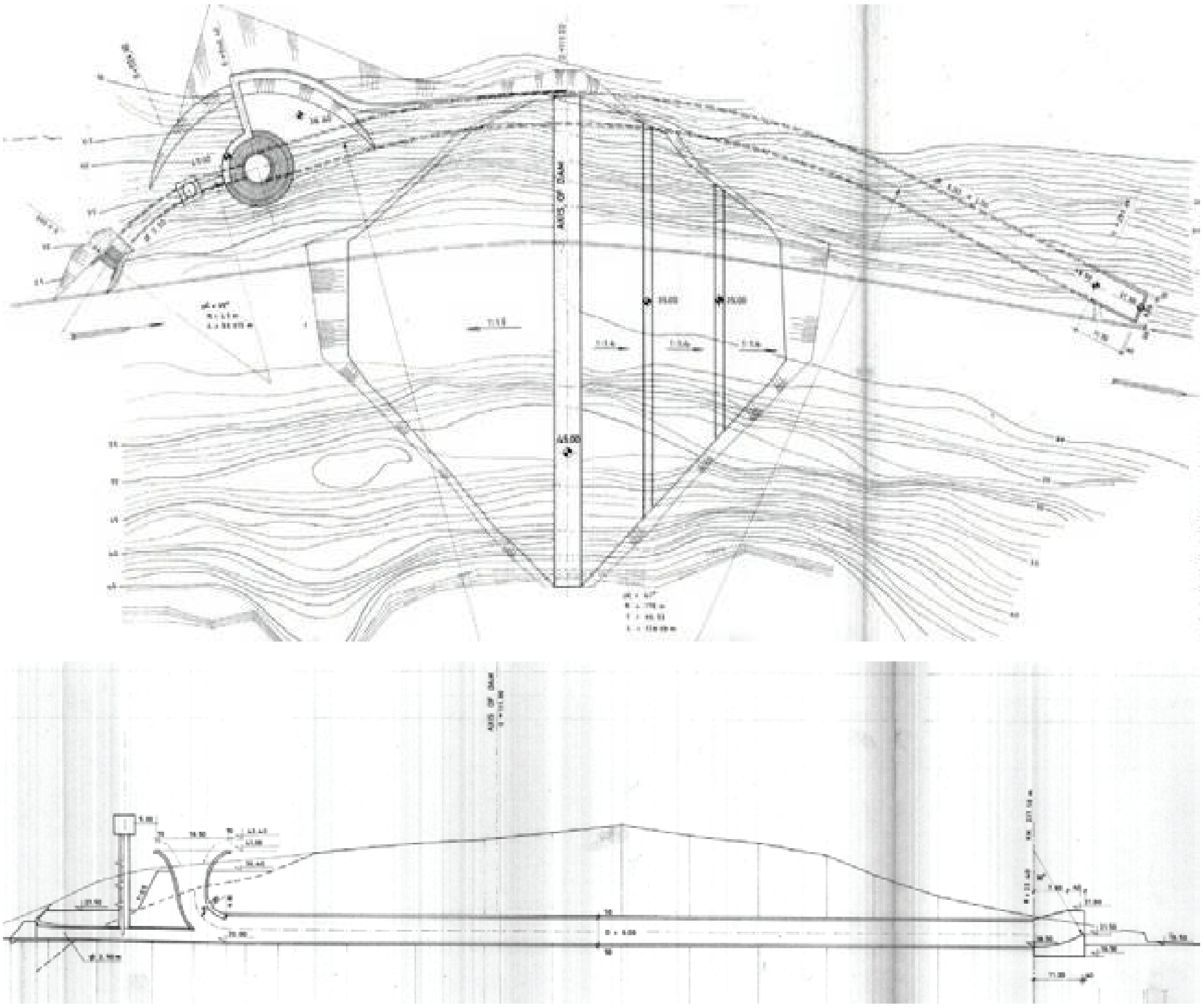
Dam Characteristic	Measurement Unit
Catchment Area (including Abu Mansour reservoir)	575 km^2
Maximum height of the dam on the foundation	40 m
Maximum height of the dam on the wadi bed	26 m
Length at the crest (45.00 masl)	100 m
Maximum foundation width (US/DS)	110 m
Crest elevation - No camber is reported	45 masl
Storage (max) in 1985	1.15 MCM
Spillway capacity	350 m^3/s
Maximum overflowing height	43.40 masl
Spillway edge elevation	41.00 masl
Discharge conduit elevation	21.00 masl

Source: Original compilation for this report.

and dolomitization of the limestone (Stucky 2003a & 2003b). A quaternary deposit made of alluvium and conglomerates with variable cementation covers the bedrock in the wadi bed. The foundation below the grouting gallery was grouted to depths from 20 to 41 m almost entirely in middle hard to very hard limestones to reduce the seepage under the structure.

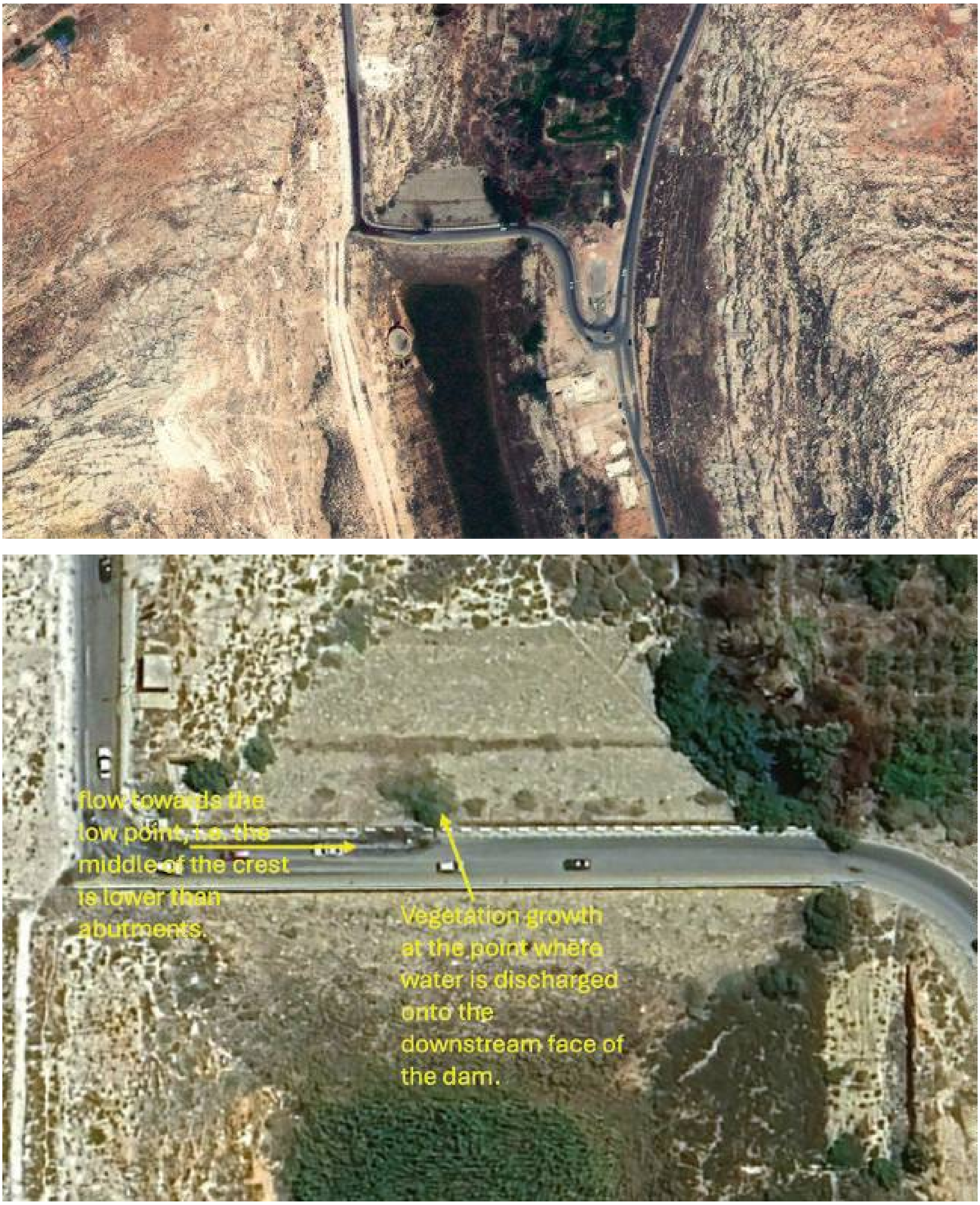
The Derna Dam was equipped with a morning-glory-type overflow spillway, designed to carry a discharge of 350 m3 per second with an 18 m diameter set at an elevation of 41 masl. The intake tower and the discharge conduit represent one unit located on the left side of the valley above a curving tunnel excavated through the abutment that was presumably used for diversion. A valve shaft was set upstream of the overflow shaft, connecting to the same diversion tunnel at its base. It was provided with three 400 mm diameter upper outlets for the irrigation supply and one 1000 mm diameter bottom outlet pipe. These joined to run under the dam in a 1000 mm steel pipe set in a trench concreted into the base of the overflow tunnel.

FIGURE 2.1. Details of original design drawings of the Derna Dam.



Source: Hydraulic Model Studies, Institute for Development of Water Resources, Beograd, August 1972

PHOTO 2.1. **The Derna Dam on June 18th, 2023.**



Source: World Bank / IPSOS.

2.3 ABU MANSOUR DAM

The Abu Mansour Dam (also called Bu Mansur Dam or Mansur Dam) was an embankment dam located on the Wadi Derna about 11 km upstream of the Derna Dam (Table 2.3). The catchment area above the dam was reported to be 476 km^2, and the design height was 73 m from the foundation. The reservoir was designed to store 23.7 MCM at its Full Supply Level (FSL) of 224.50 masl. The dam crest was 322 m long, and its elevation was 228 masl according to the initial design (Figure *2.2*). A quaternary deposit made of alluvium and conglomerates with variable cementation covers the bedrock in the wadi bed. This formation has a permeability coefficient of 2.3x10-1 to 4.3x10-2 cm3 per second. The foundation below the grouting gallery was grouted to depths from 20 to 41 m almost entirely in middle hard to very hard limestones to reduce the seepage under the structure. The spillway was set at elevation 224.50 masl, so that the normal freeboard was 3.5 m (228 minus 224.5). The crest was 7 m wide at elevation 228 masl, according to the design drawings, with a wave wall on the upstream side and a railing on the downstream. The road across the crest was paved but did not serve as part of the public road network and did not carry significant traffic.

The Abu Mansour Dam was a rockfill dam with a slightly inclined upstream clay core with a slender section. The upstream slope of the rockfill was hand-placed to form a smooth rip-rap surface set to a slope of 1V:1.5H. The downstream slope had three intermediate berms at elevation 192.0, 204.0, and 216.0 masl and the rock fill was finished to a slope of 1V:1.4H. The core was formed of clay from borrow pits and had a vertical downstream face and an upstream face set at a slope of 4:1. Coarse and fine filters 1 m wide were placed on either side of the core.

TABLE 2.3. General features of the Abu Mansur dam.

Dam characteristics	Measurement Unit
Catchment Area	476 km^2
Maximum height of the dam on the foundation	73 m
Maximum height of the dam on the wadi bed	50 m
Length at the crest (45.00 masl)	322 m
Maximum foundation width (US/DS)	160 m
Crest elevation - No camber is reported	228 masl
Berms elevation	216, 204, 192.00 masl
Storage (maximum) in 1985 at el. 224.50 masl	23.7 MCM
Spillway capacity	170 m^3/s
Maximum overflowing height	226.00 masl
Spillway edge elevation	224.50 masl
Discharge conduit elevation (Wadi bed ≈178 masl)	179.00 masl

Source: Original compilation for this report.

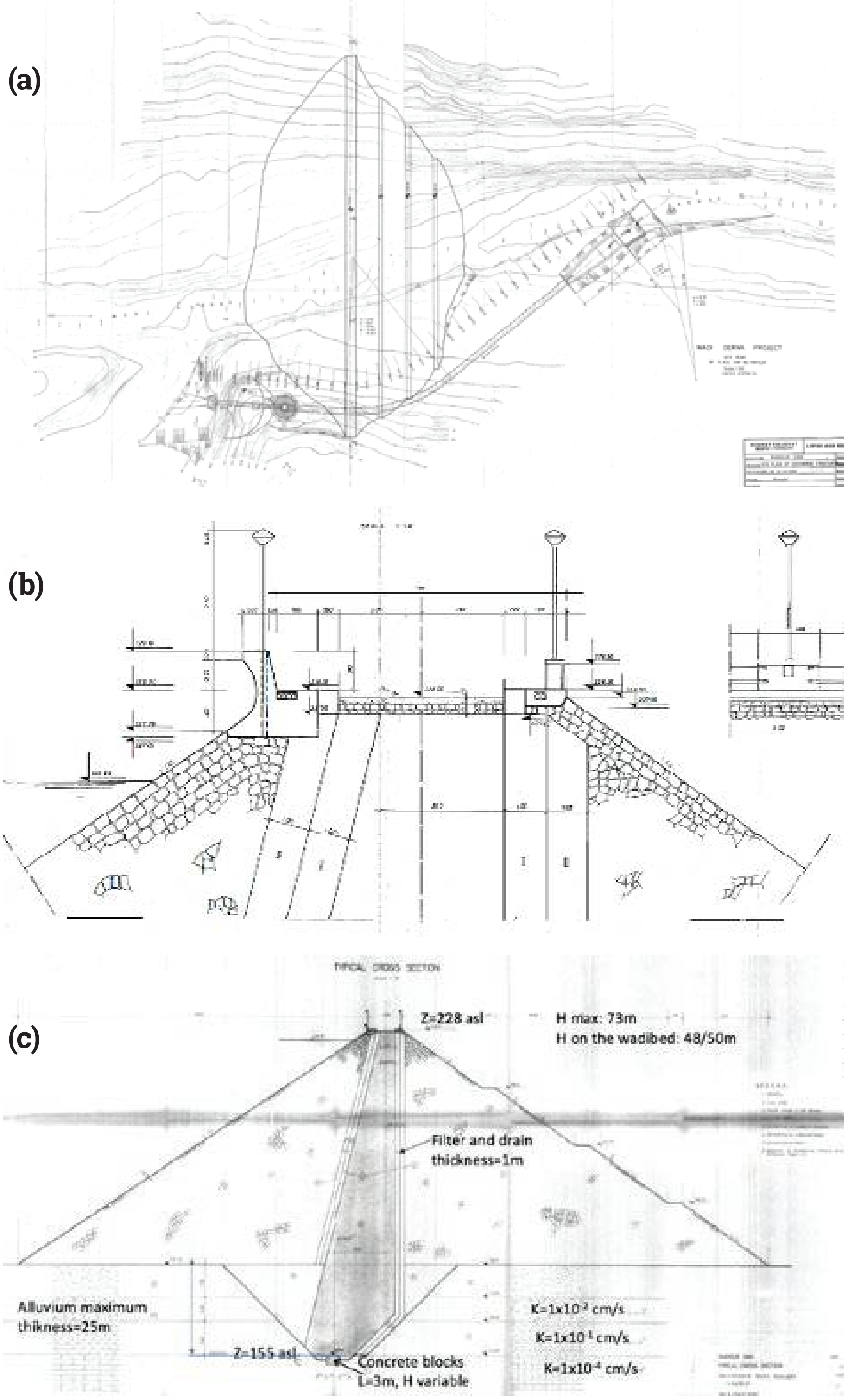
A square-section comprised of 3m wide concrete blocks was arranged in steps of various heights at the base of the core, slightly upstream of the centerline, reaching about 5m where the flanks are steep. It followed the line of firm rockhead in the base of the clay-core-filled trench with battered sides (1:1) that cut through the alluvium and any soft or very permeable or broken rock. The foundation below these blocks was reportedly grouted to depths of 20 to 35 m. According to the geological cross section that shows the grout curtain drillings (Hidroprojekat 1972g), this reached (7) limestone, soft, very porous and (4) limestone with marl and marly limestone, light, gris, hard and porous. A karstic void measuring approximately 20 meters in width and 3 to 4 meters in maximum height has been identified within this formation.. It is important to note that part of the core is sitting on "conglomerate, strongly jointed broken and very porous" (Hidroprojekat, 1972).

The Abu Mansour Dam was equipped with a morning-glory-type overflow spillway, designed to carry a discharge of 170 m^3 per second at an elevation of 226 masl. The relatively limited capacity was presumably designed to store most of the flood volume given the Abu Mansour Dam reservoir was relatively large. The spillway was built on the right abutment above a curving tunnel through the abutment presumably used initially as a diversion channel. A valve tower was set just upstream of the overflow shaft of the morning glory spillway, connected to the same diversion tunnel as its base (see Photo 2.2). It was provided with three 600 mm diameter upper outlets for irrigation supply and one 1200 mm diameter bottom outlet for dewatering. These combined to run beneath the dam in a 1200 mm diameter steel pipe set in a trench connected to the base of the overflow tunnel. At the downstream end, the pipe discharged in the tail bay.

PHOTO 2.2. **The Abu Mansour Dam in June 2023.**

Source: World Bank / IPSOS

FIGURE 2.2. **Details of original design drawings of the Abu Mansour Dam: Layout (a), Crest arrangements (b) and Typical Cross Section (c).**



Source: Final design drawings: Hidroprojekat (1972).

2.4 EARLY INDICATIONS OF IMPENDING ISSUES

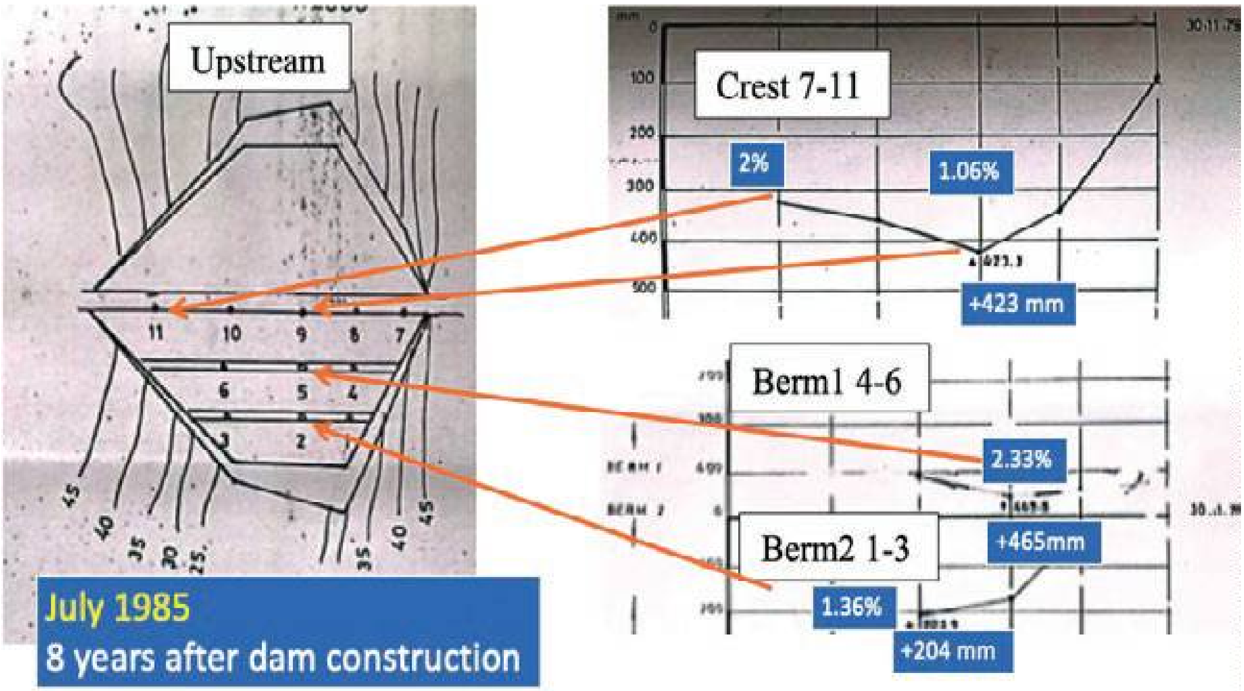
The Derna Dam was completed two years before the Abu Mansour Dam and initially filled in 1979. While the Abu Mansur dam initially filled in 1981, there are indications that the dam began to hold back floods as early as October 1978 (Hidroprojekat 1985a and 1985b). This notwithstanding, early operation and maintenance reports indicate that both dams were not ready for normal operation due to various technical reasons and that certain deficiencies and shortcomings had not been rectified at the time of the hand-over for both dams in July 1985 (Hidroprojekat 1985a and 1985b). Among the various issues, neither of the dams were connected to the power grid, and there is no indication that the hydromechanical components (i.e., bottom outlet gates) could be operated without electricity.

The teams in charge of the surveillance for both dams were not in place during the first years of operation, considered the most critical period in the life of the dams. It was noted at the time that "*regular measurements and observations on the dams were not done until the second half of 1982 when a technician was appointed to deal with the maintenance of these dams. A technical control program was prepared containing schedule of the required measurements and observations with the aim to give information for the dams' behavior and status*" (Hidroprojekat 1985a). It was further noted that "*data do not come on time, which delays their analysis within the Maintenance Team*" with recognition of the need to improve communication with Derna and the other remote sites so that important information would be provided in a timely manner.

2.4.1. Settlement

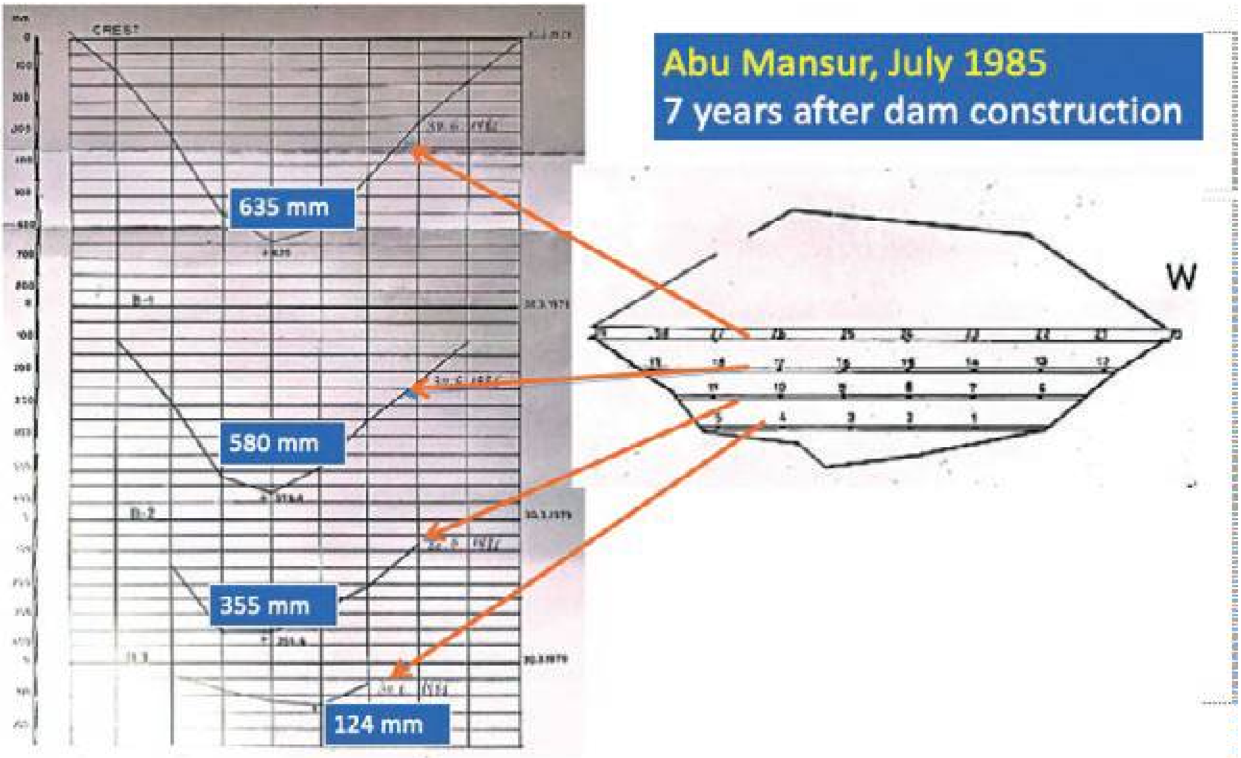
Excessive settlement of the embankments was reported for both dams during 1984-85, the first year of operation (Hidroprojekat 1985). The Derna Dam exhibited settlement of the crest and the two berms (Figure 2.3), while the Abu Mansour Dam experienced first settlements and associated foundation problems of 40-75 mm per year in the period 1976-1990, lowering the level of the dam crest (Stucky 2003). The topographical survey carried out in 2004 (Stucky 2004a) shows settlement reached a maximum of 635 mm at the crest (0.87 percent of the total height of the embankment), 580 mm at B1 (1.5 percent), 355 mm at B2 (1.4 percent), and 124 mm at B3 (0.9 percent) (Figure 2.4, Figure 2.5 and Table 2.4). For the berms, the embankment height corresponds to that of the rockfill which is founded on the alluvium. Peak settlement at the crest roughly doubled between 1985 and 2004, with a significant part of the crest settling manifested during the 1986 storm event, reaching 1.2 m at the crest and 0.6 to 0.9 m at the downstream face by 2004 (Photo 2.3). It is likely that the settlement of the embankment has continued over time, especially during flood periods, as was the case in 1986. In 2011 the water level rose to almost 219 masl (volume stored 15 MCM), which was of ≈2m higher than the level reached in 1986 (Ashoor & Eladawy 2024). This increase is expected to lead to further erosion and subsidence.

FIGURE 2.3. The settlement of the crest and the two berms in Derna dam.



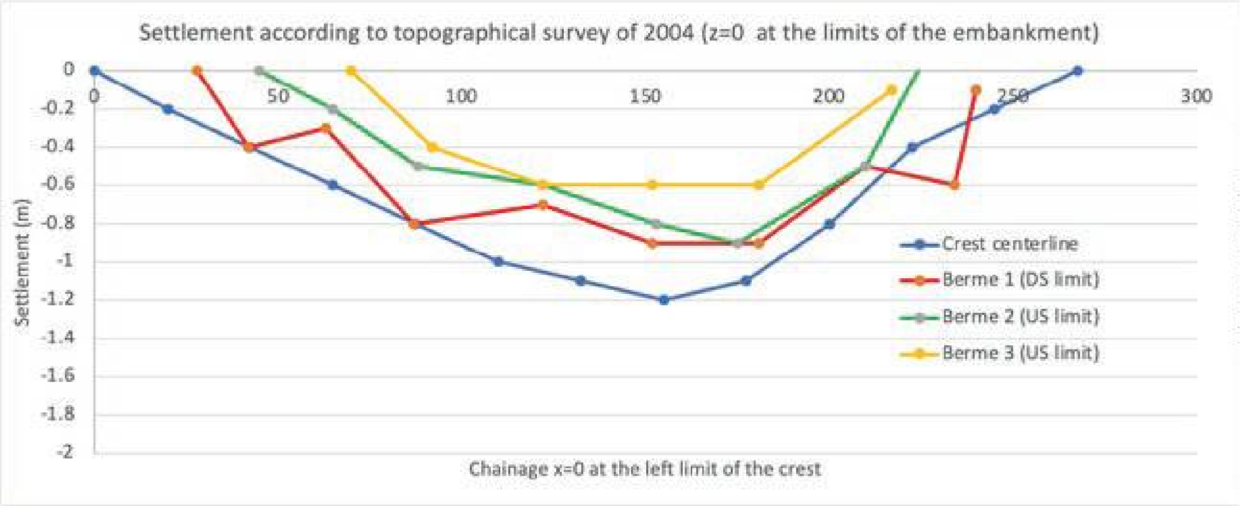
Source: Hidroprojekat (1985b).

FIGURE 2.4. Abu Mansur dam settlement measurement (30 June 1985).



Source: Monitoring report July 1985.

FIGURE 2.5. Settlement of the Abu Mansour Dam according to the topographic survey in 2004 (z=0 at the limits of the embankment).



Source: Original for this publication based on Stucky 2003g.

TABLE 2.4. Abu Mansur settlement surveyed in 2004 as percentage of the height of the embankment.

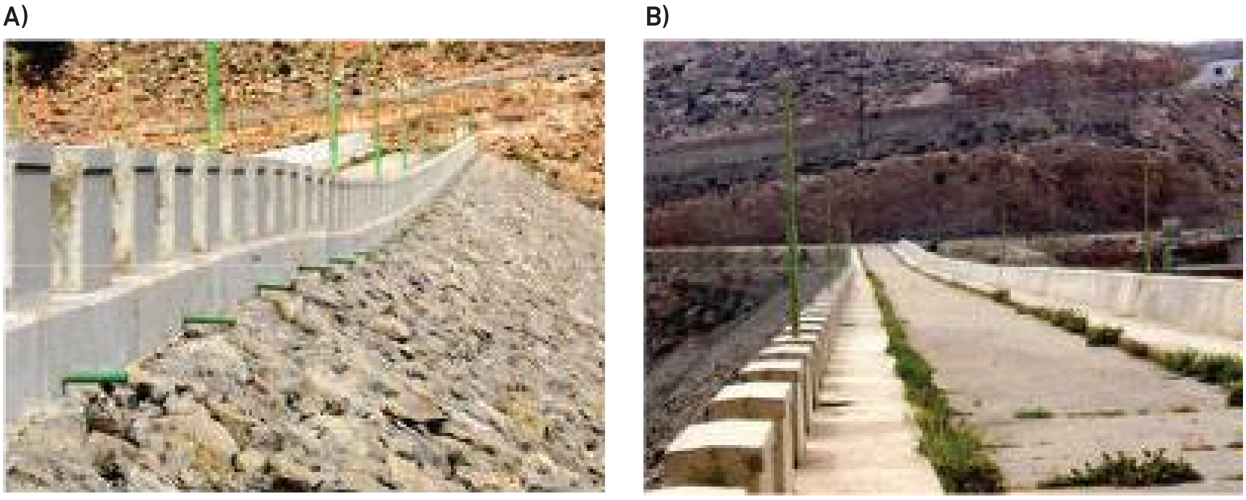
Profile	Embankment height (m)	Settlement (m)	%
Crest	73 (core)	1.2	1.6
Berm 1	38*	0.9	2.4
Berm 2	26*	0.9	3.4
Berm 3	14*	0.6	4.3

Source: Original for this publication based on Stucky 2003g.

Note: (*) these heights correspond to the elevation difference from the wadi bed i.e. 178 masl.

None of the reports from the designer, the contractor, or those involved in the monitoring of the dam until July 1985, question the validity of the settlement measurements (except for point 11, Figure 2.3). It is therefore appropriate to consider that the settlement reflects the actual behavior of the dam. This is supported by the topographic surveys carried out in 2004 that show roughly the same phenomenon. The designer attributed these high magnitude settlements to the "*low quality of the material that composes the embankment*". No information on the testing data from construction (material testing, compaction testing, etc.) has been identified. The only material requirement for the clay in the design drawing is the maximal permeability of 5x10E-9 m per second. However, there is no explanation how this was checked during construction, meaning that there is no guarantee on the application of high-quality clay. Test carried out on the clay in 2004 (Stucky 2004) found a low plasticity (=lean clay), suggesting that the maximal permeability for the clay was optimistic. It is unusual to observe a settlement of this magnitude near the banks, where the embankment is not so thick and founded directly on bedrock, and of a similar scale as the central sections. In such instances, the primary cause can only be settlement of the foundation and/or erosion of the embankment. This is consistent with the significant seepage observed, as described below, the development of sinkholes and voids in the dam foundation left by the eroded materials.

PHOTO 2.3. **Vertical deformation as seen from the right abutment of the Abu Mansour Dam (a) and horizontal deformation as seen from the left abutment (b).**



Source: Stucky 2003b

While there is no information on the dam behavior since the 2004 topographic survey, satellite data provides some insights. Vertical deformation measurements from Sentinel 1 interferometric synthetic aperture radar (inSAR) show a linear deformation of -5 mm per year of the crest of the dam during the period of October 2016 until October 2018 (Figure 2.6).[3] An analysis of LIDAR data suggests that the crest level before the Abu Mansour Dam collapsed was likely between 226.5 to 227.5 m above sea level and not 228.9 masl as per the original design specifications, suggesting continued settlement of more than 2m (see Figure 2.7).[4] While there is a margin of error associated with satellite derived data, the observed settlements have resulted in a 'V-shape' of the dam in which the crest was lower than the dam sides, thus reducing the volume needed for overtopping.[5]

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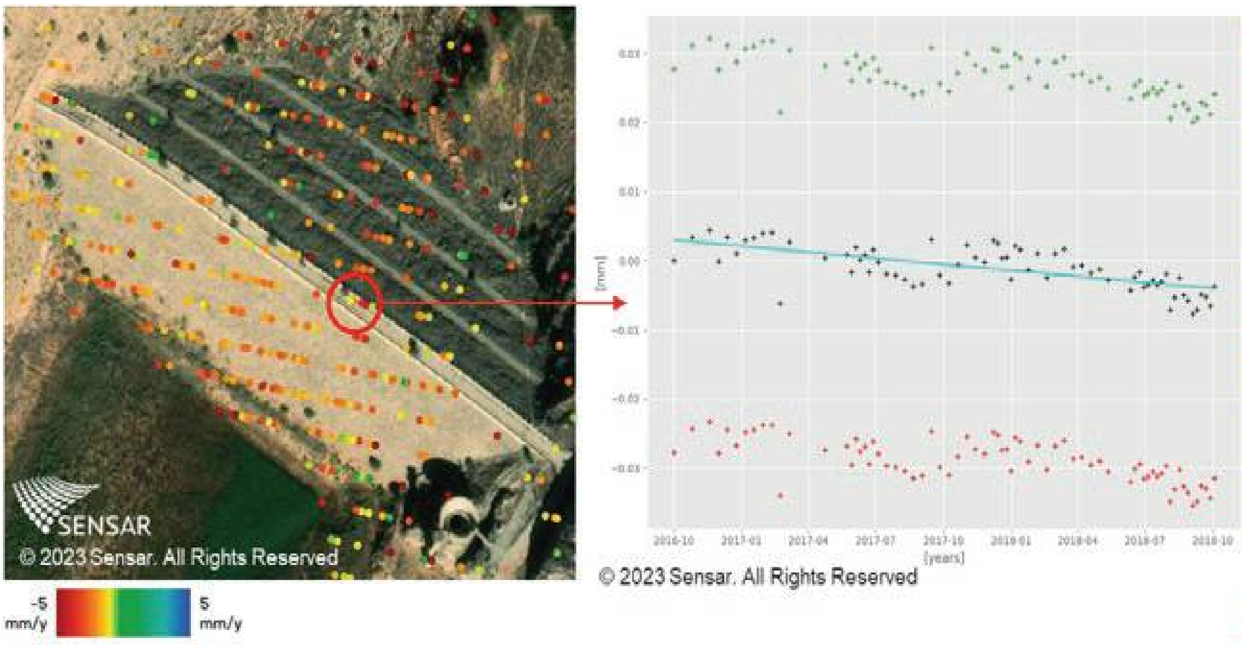
3 Measurements were conducted through the PS-inSAR methodology for which the precision is typically within 1/10th of the wavelength (<5.5 mm per observation) by Sensar B.V., a firm specialized in subsidence and inSAR measurements of infrastructure.

4 Data was extracted from a NASA operated LIDAR altimeter (Icesat2 ATL03) acquired between 2020 and 2022. Three overpasses of the LIDAR tracks created a section of the Abu Mansour Dam. ATL03 reports height measurements each 0.7 m (with an estimated dispersion footprint of 17 m diameter). This is expected to produce height estimates with an approximate mean absolute error of 0.45 m. Averaged photon heights each 10 m, obtaining an approximated crest height of 226.6 m at 117 m from the left bank, and 227.2 m at 50 m from the left bank.

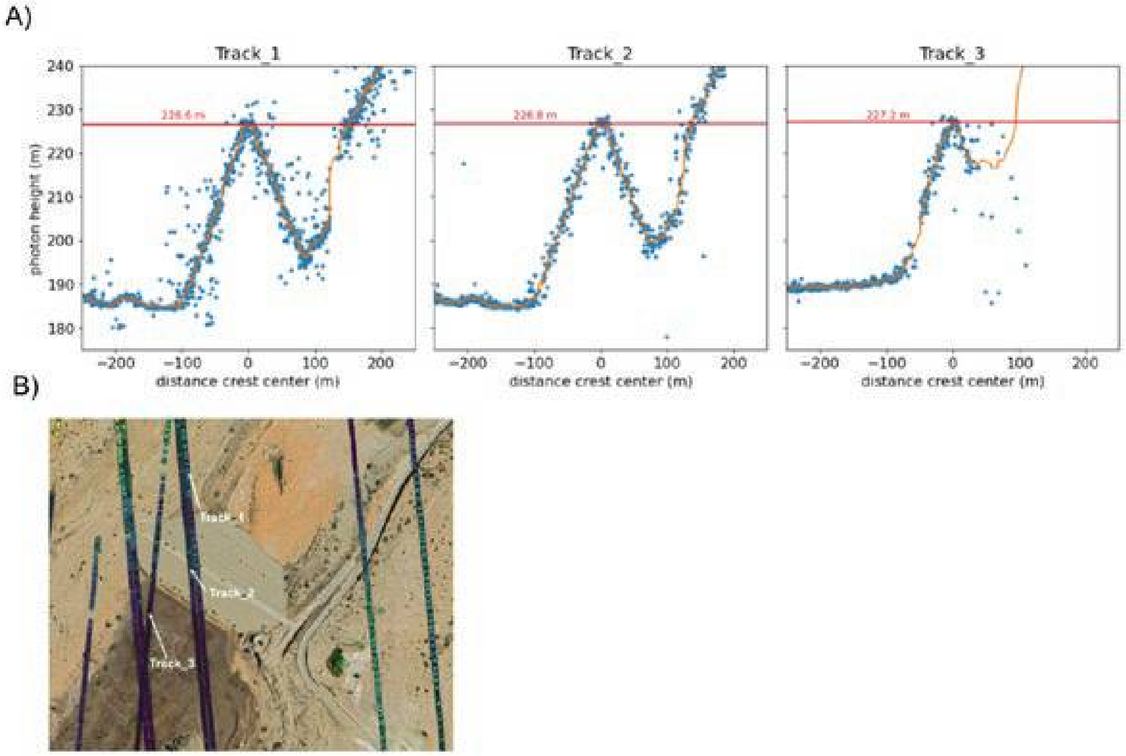
5 This is in line with the observation of no erosion of the hill slopes next to Abu Mansour Dam (post failure). Such erosion would have been expected in case of overtopping a dam with a normal longitudinal profile (higher in the middle of the crest and decaying towards the banks).

FIGURE 2.6. Single-stack inSAR measurements of the Abu Mansour Dam, Sentinel 1 2016-2018.



Source: Original for this publication based on Sensar dam scan.

FIGURE 2.7. LIDAR altimetry: (a) Elevation at crest level of different sections of the dam; and, (b) footprint of the three different tracks over the Abu Mansour Dam.

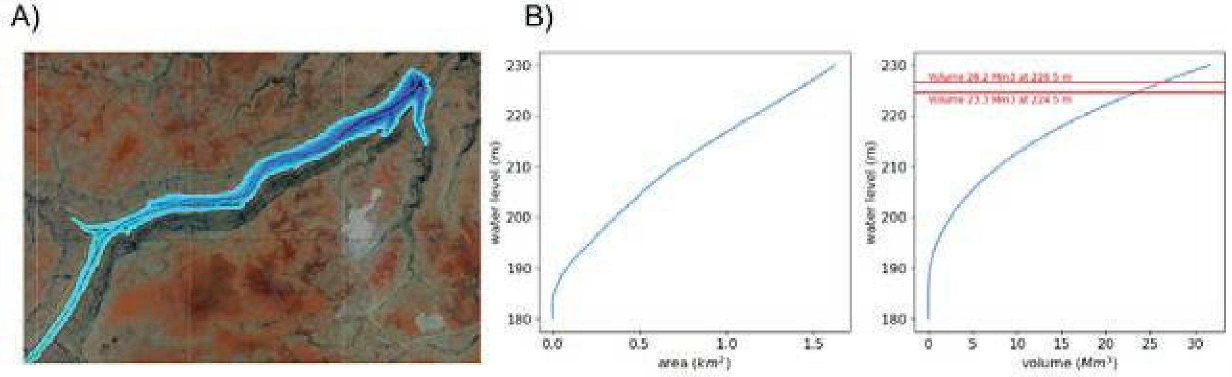


Source: NASA Icesat2, ATL03 photon heights

Note a) data acquired at Track_1: 12-04-2020, Track_2: 08-07-2022 and Track_3: 01-10-2022

Using the satellite data, the hypsometric curve of the Abu Mansour reservoir (Area-Elevation and Volume-Elevation) was estimated based on the best available digital elevation model (Copernicus GLO30 DEM) (Figure 2.8). This was done by integrating the DEM's contour lines in the reservoir's basin (with a 1 m discretization). This resulted in an estimated 23.3 MCM of volume at spillway level (224.5 m) and 26.2 MCM at near-crest level (226.5 m). The Copernicus GLO30 DEM was computed from the TanDEM-X mission (-band radar observations taken between 2011-2015). The very high-slope of the Wadi Derna in which the Abu Mansour Dam is located might result in DEM errors on the order of 25 m, which may transfer to the hypsometric curve. Nevertheless, these estimates were later validated (Stucky 2003), who also reported a volume of 23.7 MCM at the level 224.5 masl based on a 2003 topographic survey of Abu Mansour Dam.

FIGURE 2.8. (a) Contour lines at the Abu Mansur reservoir as computed by the GLO30 DEM, (b) Hypsometric curve of the reservoir along with volumes estimated at spillway level (224.5 masl) and a water level of 226.5 masl.



Source: Original for this publication.

2.4.2. Seepage

Major seepage through the foundations was also observed during the early operational years. Seepage at the Abu Mansur dam reached around 13 m^3 per second during the 1986 flood, under a head of less than 40 m, and with a whitish colour observed, indicating possible transport of material out of the dam structure. Since both dams are built on similar bedrock, it is likely that the foundations of the Derna Dam were subject to similar erosion which created voids. Further evidence of the high rate of seepage flowing through the Derna Dam were the existing three funnel-shape sinkholes on the upstream left-hand side at elevation 25.00 masl (Hidroprojekat 1985a). In 1985, two of the sinkholes were treated by plugging while the third was still undergoing silting and further treatment by concrete plugging and injections. It was implicitly assumed that seepage occurs only through the foundation, and that the dam body was watertight. Nothing is mentioned about possible downstream resurgences and whether they release clean or dirty (colored) water. There is also no indication of whether seepage rates had been increasing over time.

While a system of piezometers were arranged for controlling the seepage flow under the dam and to inform the level of the saturation line within the dam body, the sites had not been provided with the necessary devices for direct measurement of the seepage flow. The amount of the seepage was estimated indirectly from the reservoir losses and the piezometer observations. Percolation was considerable due to the geological conditions and a self-sealing, or self-clogging, of the foundation by sediments was slowly taking place, particularly at the banks which are very steep, and the water quickly seeps in depth (Hidroprojekat 1985b). Given the geological context of the site, it is questionable to count on the reservoir siltation for the clogging of the seepage paths, as can be inferred from the auscultation reports.

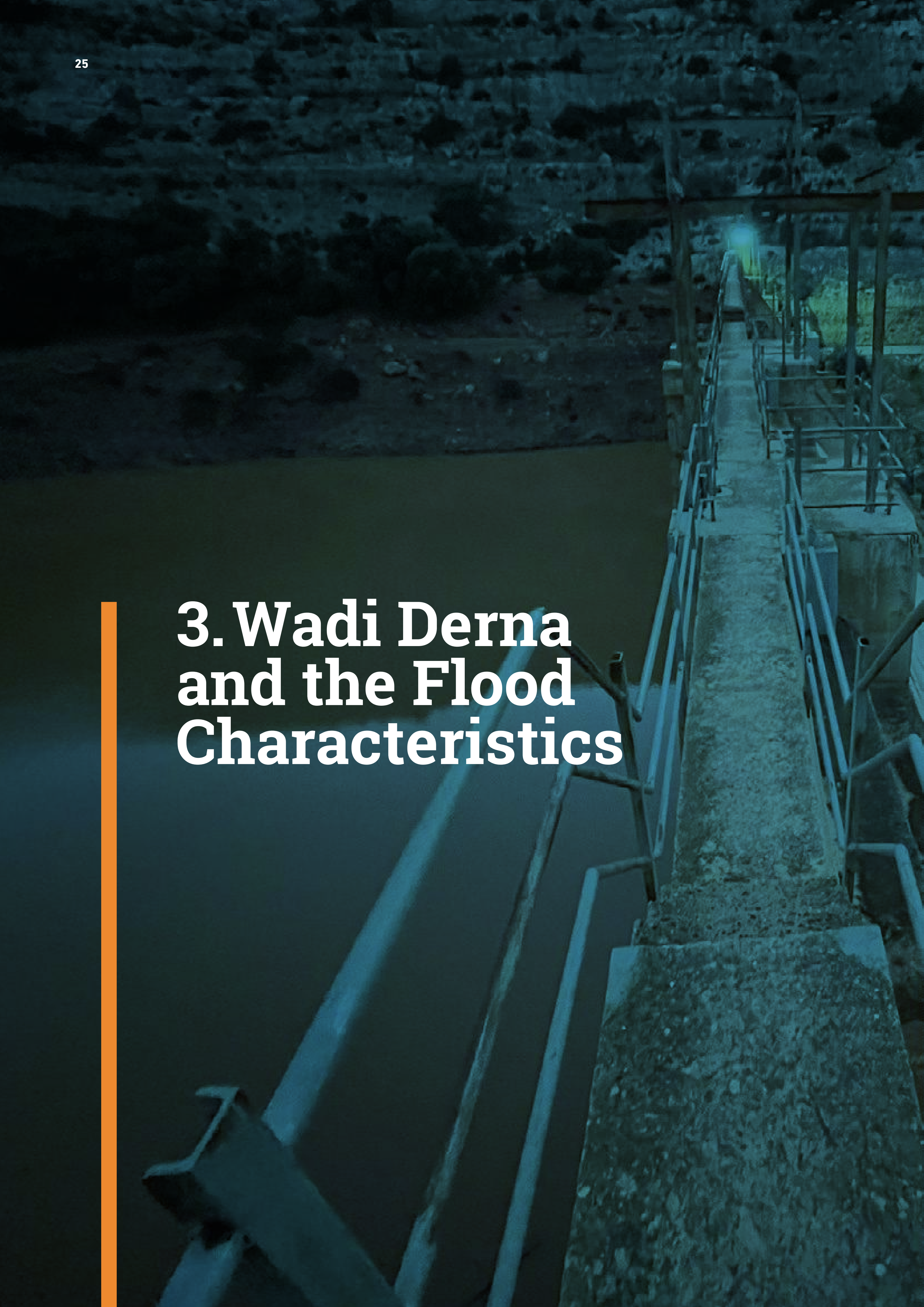
Given these conditions, it is plausible that the safety of both dams was compromised from the onset of their commissioning and early years of operation, therefore posing a potential hazard to the city of Derna. The design reports clearly highlighted the fact that the observed settlements were far greater than could have been expected, and that operation of the Derna Dam should be limited to elevation of 30 masl (i.e., 11 m below the spillway) (Hidroprojekat 1985a, 1985b). No explanations were given for these settlements, which would normally reflect a major anomaly likely to compromise the safety of the dams. Given the hydrological context of the Wadi Derna, characterized by the occurrence of flash floods, it was unrealistic to expect to control the water level at an elevation of 30 masl in the Derna dam, as recommended by the designer, particularly as the spillway crest is located at elevation 41.0 masl, the discharge (spill) capacity is low and the reservoir is very small compared to the flood inflow, even if it is only that of the intermediate catchment.

2.4.3. Proposed rehabilitation measures

A series of studies undertaken between 2002 and 2004 (Stucky) concluded that both dams were under stress and that the runoff and peak floods were underestimated. These studies made a series of recommendations for urgent rehabilitation measures to improve the safe operation of the dams, including the following:

- Adding a new spillway at the Abu Mansour Dam with a capacity of 430 m^3 per second, in addition to the existing spillway with a capacity of 170 m^3 per second (total discharge capacity of 600 m^3 per second).
- Incorporating a new spillway at the Derna Dam with a capacity of 315 m^3 per second, alongside the existing spillway with a capacity of 350 m^3 per second (total discharge capacity of 665 m^3 per second).
- Construction of a new dam upstream of the Derna Dam, 900 meters away, with a height of 15 meters, to trap sediments.
- Increasing the height of the Abu Mansour Dam by 6.5m.
- Injection of the dam body core with a cement grout.
- Lining the front slope of the dam with asphalt concrete, including the construction of a new drainage tunnel and the closure of the old tunnel.
- Implementation of an additional spillway above the dam crest.

Furthermore, it was observed that the updated flood passage conditions through the city of Derna was problematic (Stucky 2004). A firm was subsequently brought in to provide another assessment and again concluded that the dams needed rehabilitation measures to reinforce safety. Subsequently another firm was contracted in 2007 to carry out maintenance on the two existing dams and to build a third dam but completed just over a fifth of the work before a period of political instability and insecurity following the uprisings of the Arab Spring and the fall of the Gadhafi regime. As a result, the recommendations for strengthening the safety of the dams were not implemented.



3. Wadi Derna and the Flood Characteristics

1 Wadi Derna is situated in the north-eastern part of Libya and comprised of four distinct sub-basins characterized by short periods of intense and spatially variable precipitation.

2 Significant uncertainty exists around estimates of precipitation during Storm Daniel, exacerbated by paucity of functional hydro-meteorological stations and data.

3 While estimates vary significantly, it can be safely concluded that the precipitation intensity during Storm Daniel was in the order of 150-300 mm, with a return period of 200 to 500 years.

4 The estimated flood volumes range reflect the uncertainty around precipitation estimates and range between 25 to 30 MCM for 150 mm precipitation and around 90 to 100 MCM for 300 mm precipitation.

3.1 THE CHARACTERISTICS OF WADI DERNA

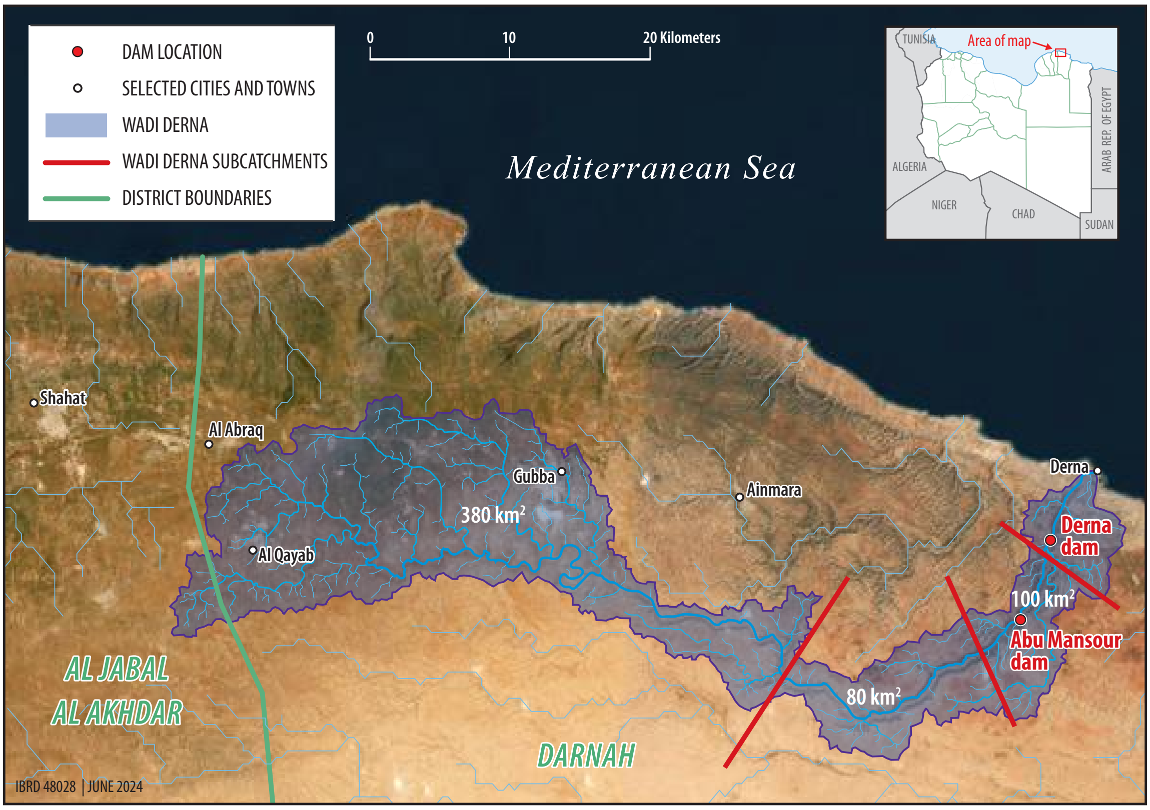
The Wadi Derna catchment covers an area of roughly 575 km^2 in the north-eastern part of Libya (Map 3.1). The wadi is around 75 kilometers in length, averaging approximately 8 kilometers in width, and flows from a height of around 765 meters in the Jebel Akhdar mountains in the western part of the catchment, draining to the east before heading north-east to the port city of Derna (Hidroprojekat 1972; Ashoor 2022). The average slope is around 1.1 percent, with the catchment generally characterized by high permeability and high karstic losses. Vegetation is very sparse and characterized by small bushes and shrubs that limit runoff and results in losses due to evapotranspiration, with agriculture limited to those areas with fertile soils.

The catchment is characterized by an elongated shape that includes four sub basins (Map 3.1; Hidroprojekat 1972; Ashoor 2022). The upper part of the basin constitutes about 60 percent of the catchment area, covering roughly 380 km^2 and extends roughly 30 to 40 km from the western part of the basin at an altitude of up to 765 masl to Sirat Al-Washka at around 500 masl. While rainfall is highest in this part of the catchment, runoff is low due to the gentle slope, high permeability, and karst losses (Hidroprojekat 1972). The middle part of the basin covers approximately 80 km^2 and extends 20 to 30 km from Sirat Al-Washka to the Abu Mansour Dam, dropping to around 350 masl with an average width of about 4.5 km. It is considered the narrowest part of the basin and is characterized by significant karstic losses that typically collect almost all of the surface runoff. The lower reaches are characterized by lower permeable and covers an area of around 100 km^2 that extends from the Abu Mansur dam to the Derna Dam at the mouth of the valley, where surface runoff intensity is high, with the final reach continuing through the city of Derna to the sea (Map 3.1).

The geology of Wadi Derna has played a significant role in shaping the landscape and hydrology of the area. The area lies within the broader context of the Mediterranean region, where the African and Eurasian tectonic plates converge. This tectonic activity has resulted in the folding and faulting of rocks in the region over geological timescales. The wadi itself acts as a natural drainage system, channeling water during rainfall events and creating a unique ecosystem, with the geological formation part of the larger Cyrenaica Platform that is composed of sedimentary rocks that were deposited over millions of years. This platform extends along the coast over some 300 km and reaches heights up to 880 m above sea level, with a network of wadis permeating this mountainous platform functioning as drainage system. The region comprises various rock types, including limestone, sandstone, and shale. Limestone is the dominant rock type and forms extensive layers throughout the area. The limestone formations contain rich fossil deposits, dating back millions of years and are susceptible to erosion by water, resulting in the formation of steep-sided valleys, gorges, and caves. The soil is mainly composed of clay soil-sandy to clayey alluvial with low-salinity.

The climatic conditions of Wadi Derna are influenced by the Mediterranean Sea to the north and the Sahara Desert to the south, resulting in abrupt transitions of weather conditions across the basin. The Mediterranean coastal strip experiences dry summers and relatively wet winters, with annual precipitation from 1945/46 to 1969/70 estimated at 273 mm in the city of Derna and 578 mm in Shahat (Hidroprojekat 1972). These show strong seasonal signals (Figure 3.1), with temperatures in Derna averaging from a winter low of 12 degrees Celsius (average maximum 16 and minimum of 9 degrees Celsius) and summer highs averaging 27 degrees Celsius (average maximum 32 and minimum of 22 degrees Celsius) from 1991 to 2020. Over the same period precipitation has averaged 67 mm in December with less

MAP 3.1. Location of Derna on the east coast of Libya with the Wadi Derna catchment area.



Source: Original for this publication.

than 1 mm observed in June, July, and August. The Jabal Akhdal highlands experience a plateau climate, with higher rainfall and humidity and low winter temperatures. The long term annual mean surface air temperature averaged 21 degrees Celsius between 1901 and 2020 (average maximum 25 and minimum of 15 degrees Celsius) (Figure 3.2), with annual precipitation averaging 278 mm per year, ranging from a high of 448 mm in 2018 and low of 130 mm in 1955 (Figure 3.3).

One of the key challenges in assessing the hydro-meteorological conditions of Wadi Derna is the lack of a comprehensive network of weather and hydrological gauging stations. The Libya National Meteorological Center (LNMC) network consists of 25 automatic weather stations, five upper-air stations, and five climate stations (World Bank 2023).[6] The LNMC also has a mobile weather radar and a fixed weather radar that is located about 19 km from the closest seashore point at a latitude of 32° 31’ North and longitude of 20° 53’ East (LNMC 2009). This is an eight-meter-high tower, with a radius coverage of 200 km as long-range scanning (effective radius is 150 km as short-range scanning) that allows an estimation of the catchment rainfall (Map 3.2). However, the LNMC indicated that since 2011, a significant part of its network has been damaged by successive events and only a small number of weather, climate and hydrological stations located in the East were still operational prior to the floods, impairing weather monitoring and forecasting for localized flood early warning (Table 3.1). Only two synoptic stations (Derna and Shahat) and another rain gauge at the Ainmara station were operational for rainfall information (LNMC 2009).

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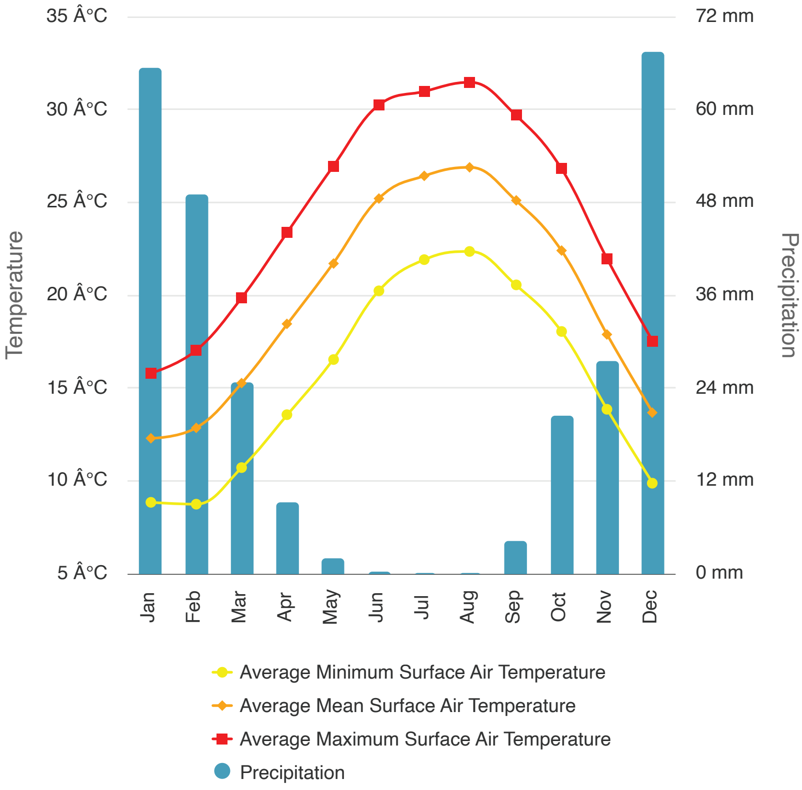
6 The LNMC was established in 1950 under the supervision of the Ministry of Transport and has over 845 personnel. Source: World Bank (2023).

TABLE 3.1. Operational weather, climate, and hydrological stations in affected areas prior to the flood.

AWSs	1 in Al-Marj, 1 in Benghazi (+ one planned in Al Abraq Airport)
Upper-air Stations	1 in Benghazi
Climate Stations	1 in Al Bayda
Hydrological Stations	Al Abraq, Al-Marj, Shahaat, Al Qayqab, Benghazi, Al Qubah, Al Abyar, Derna

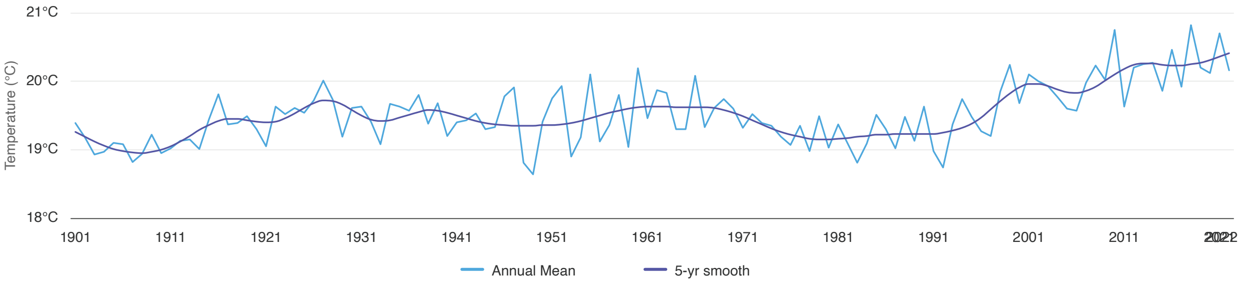
Source: World Bank 2023.

FIGURE 3.1. Monthly climatology of temperature and precipitation for Derna (1991-2020).



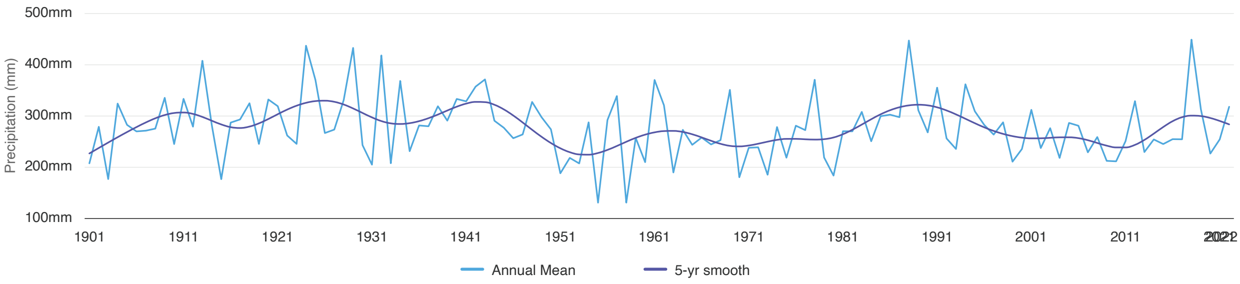
Source: World Bank Climate Knowledge Portal *https://climateknowledgeportal.worldbank.org/country/libya/climate-data-historical*. Retrieved July, 2024.

FIGURE 3.2. **Observed Annual average mean surface air temperature of Derna (1901-2022).**



Source: World Bank Climate Knowledge Portal *https://climateknowledgeportal.worldbank.org/country/libya/climate-data-historical*. Retrieved July, 2024.

FIGURE 3.3. **Observed annual average precipitation of Derna (1901-2022).**



Source: World Bank Climate Knowledge Portal *https://climateknowledgeportal.worldbank.org/country/libya/climate-data-historical*. Retrieved July, 2024.

The hydrology of Wadi Derna is determined by the catchment characteristics and the prevailing temperature and precipitation. These lead to a small run-off process and a time lag in flow between the upper and lower basin. Historically, hydrological monitoring was informed by 10 rain gauges, eight of which were located inside the watershed (Map 3.2). Hydrological monitoring was carried out prior to construction of the Derna and Abu Mansour dams at the Waskizi hydrological station from 1967 to 1971 (Map 3.2). The upper part of the catchment area is characterized by considerable karstic and skin-deep impervious layers which result in numerous springs with limited capacity, and rare surface flow which only manifests in the case of very heavy rainfall events. Similarly, the middle reach is a zone of abysses and karstic holes through which surface water from the upper part of the catchment disappears underground. The only time runoff is produced is when very high rainfall events are larger than the percolation capacity. The lower part of the catchment is the most impermeable and contributes the most in terms of runoff, supplemented by large karstic springs. This runoff is typically derived from local rainfall events and mostly derived from the Wadi Hilaz sub-catchment and not from the upper reaches of Wadi Derna. Surface water flows across the catchment only when high rainfall covers the entire catchment and the quantity and intensity are larger than the infiltration capacity. Total annual runoff with a probably return period of 1,000 years was estimated during the design phase at 10 MCM at Derna, 7.80 MCM at Abu Mansour and 2.20 MCM in Wadi Hilaz (Table 3.2).

The hydrological characteristics of the Wadi Derna are typical of seasonal, arid Mediterranean systems. These are characterized by short periods of intense and spatially variable precipitation. The coefficient of variation is very high (0.675) with significant temporal variation, and the high slopes and narrow valley result in torrential floods that are characterized by short duration, typically rising over several hours and lasting for one to two days, very high maximum discharge values, and proportionally smaller volume of the flood waves in relation to the maximum water discharge. Based on the flow rates recorded during the floods of 1959 and 1968, the basin's response to floods is estimated to be in the order of 3 hours when only the downstream basin is affected. When the entire basin is affected, the phase lag of contributions limits the maximum flow rates, with characteristic times of approximately 10 hours. The historical flood at the basin scale was around 1 m^3 per second per km^2 prior to 2023, which is not particularly strong. However, this event only affected the downstream part of the basin, which experienced an estimated flow rate of around 6 m^3 per second per km^2, a significant but not exceptional flow rate when compared to the flows of other Mediterranean wadis.

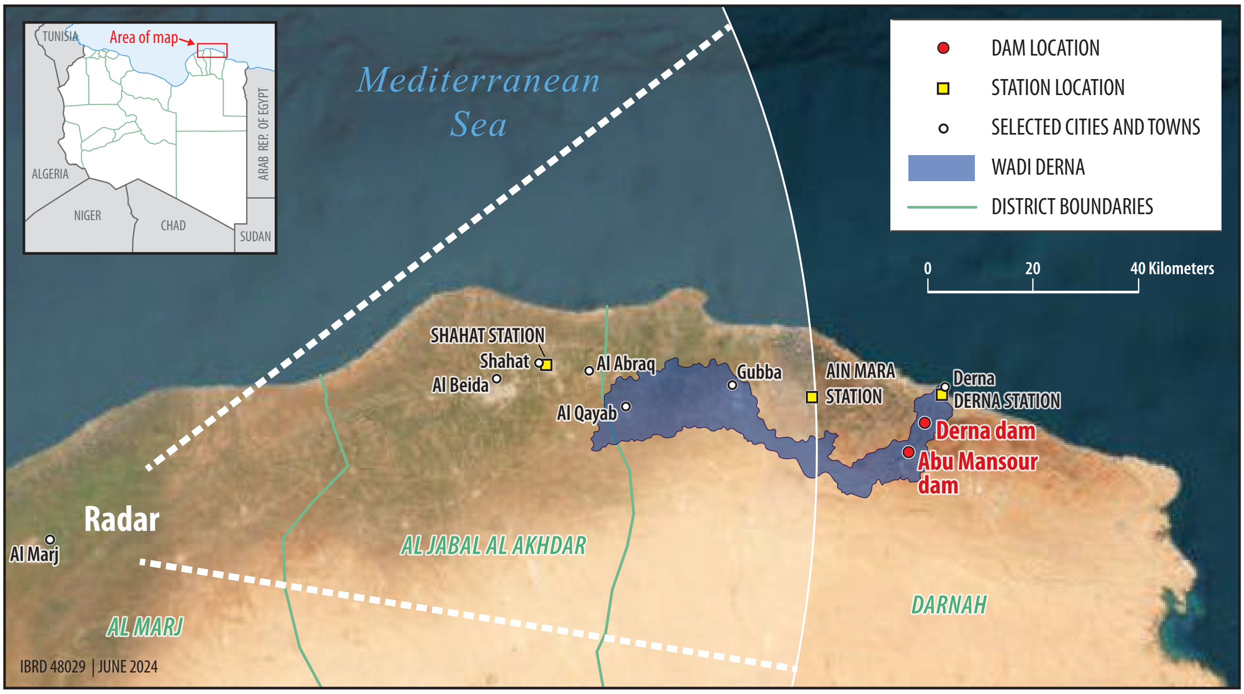
TABLE 3.2. Total annual water discharge and flood characteristics for probable return periods.

	Probable return period (years)								
	100			1000			10,000		
Section	Annual Discharge (MCM)	Flood Volume (MCM)	Maximum discharge (m^3/s)	Annual Discharge (MCM)	Flood Volume (MCM)	Maximum discharge (m^3/s)	Annual Discharge (MCM)	Flood Volume (MCM)	Maximum discharge (m^3/s)
Derna	8.00	10.0	610	10.00	18.0	1,100	12.00	29.0	1,780
Abu Mansour	6.30	0.0	490	7.80	14.0	855	9.40	22.5	1,380
Wadi Hilaz	1.69	1.72	105	2.20	2.82	172	2.60	4.25	258

Source: Hidroprojekat 1972

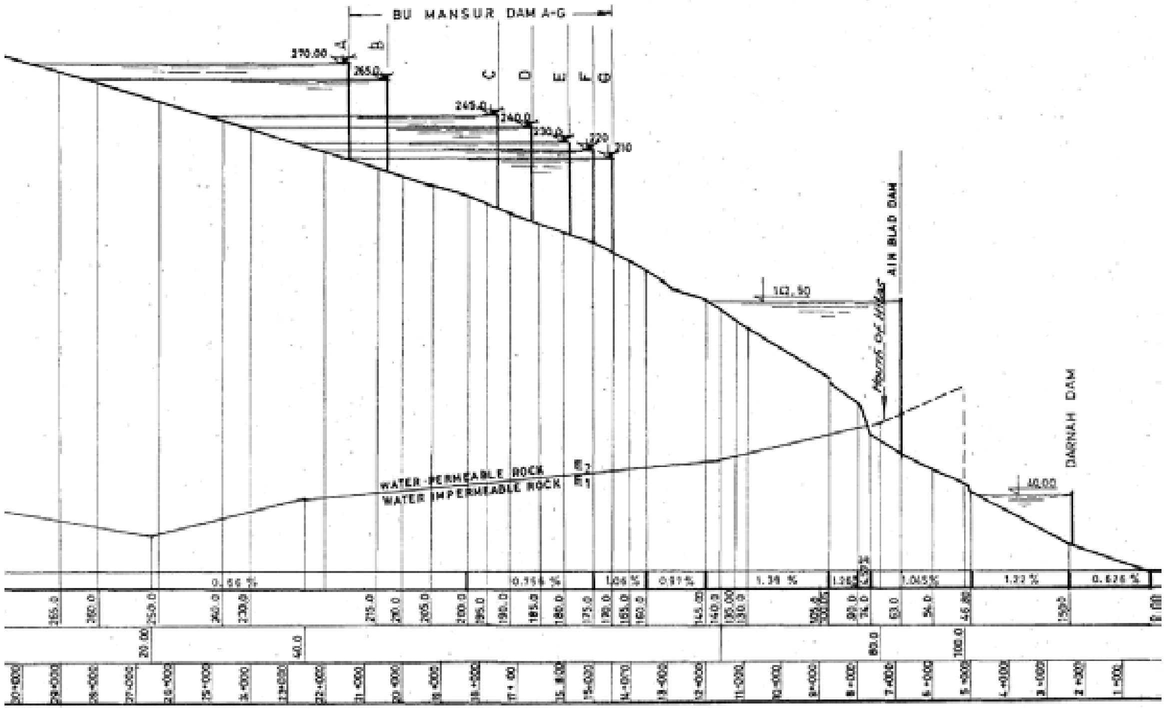
Hydraulic surveys were carried out at several wadi sections during the investigations to locate the dam sites in 1973. The cross sections and slope allow an assessment of the approximate relationship between water level and discharge for the wadi, as well as both dams (Figure 3.4). The river distance between the Abu Mansour Dam and the Derna Dam is roughly 10 km with a gradient of 1.1 percent, meaning that it will take a maximum of 1 hour for the water to flow from the Abu Mansour Dam to the Derna Dam. This period is smaller than the duration of a rain event. According to the longitudinal profile, the slope upstream of the Abu Mansur dam is 0.7 percent. Figure 3.5 shows water levels for different discharge values based on a simplified hydraulic calculation (Manning-Strickler formula). Downstream of Abu Mansur dam, and more specifically about 500 m downstream of the confluence with Wadi Hitaz, the longitudinal profile slope is about 1 percent. The width is smaller and the valley narrows between the hills (Figure 3.6 and Figure 3.7). An hydraulic simulation within Derna City undertaken as part of the 1973 study shows water levels in the city for discharges lower than 350 m^3 per second (Figure 3.8). Subsequently, two protection walls have been constructed to create a channel for Wadi Derna as it crosses the city (Photo 3.1). The available cross sections show that the left bank wall was 6 meters high, and the right bank wall was 4 meters high. Where bridge piers are present, head losses could result in overflow at flows less than 500 m^3 per second (Photo 3.4).

MAP 3.2. Radar coverage along with distribution and location of rain gauges in Derna and surrounding area.



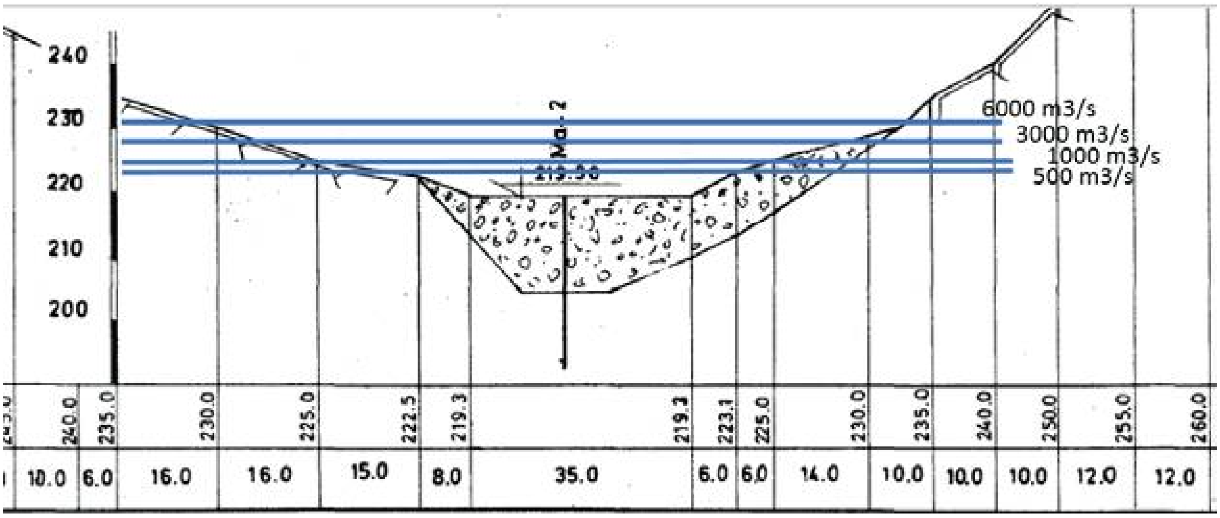
Source: Original for this publication.

FIGURE 3.4. Longitudinal profile of Wadi Derna showing the location of the Derna and Abu Mansour dams.



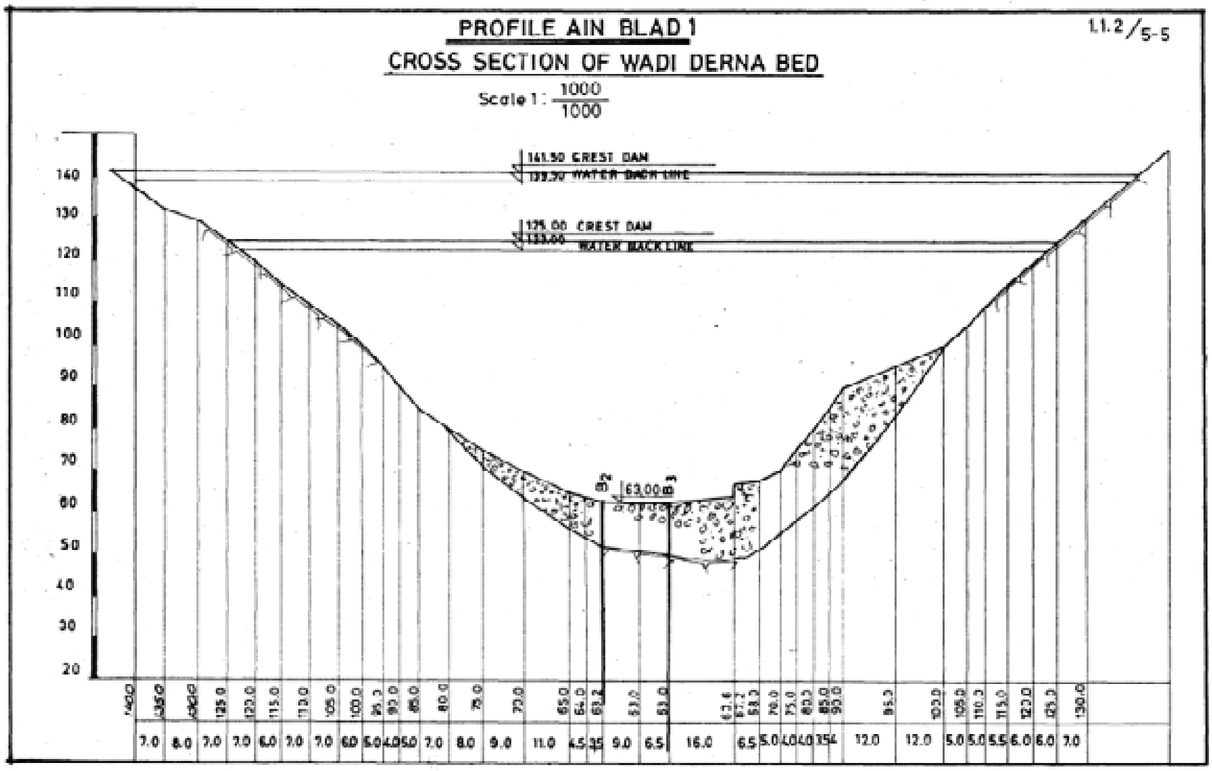
Source: Hidroprojekat (1972)

FIGURE 3.5. **Estimated water levels upstream of Abu Mansur dam prior to construction.**



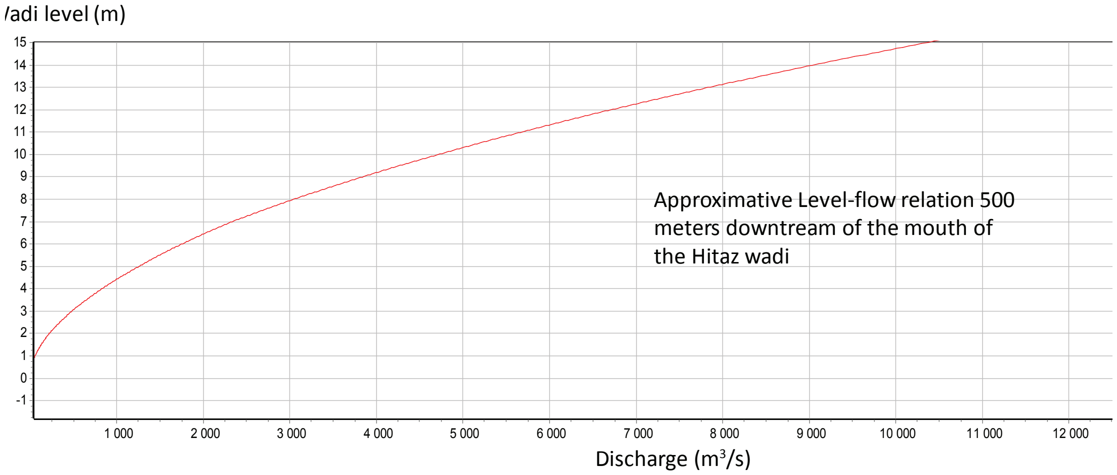
Source: Hidroprojekat (1972)

FIGURE 3.6. **Wadi Derna cross section at 500 meters downstream of the confluence with Wadi Hitaz.**



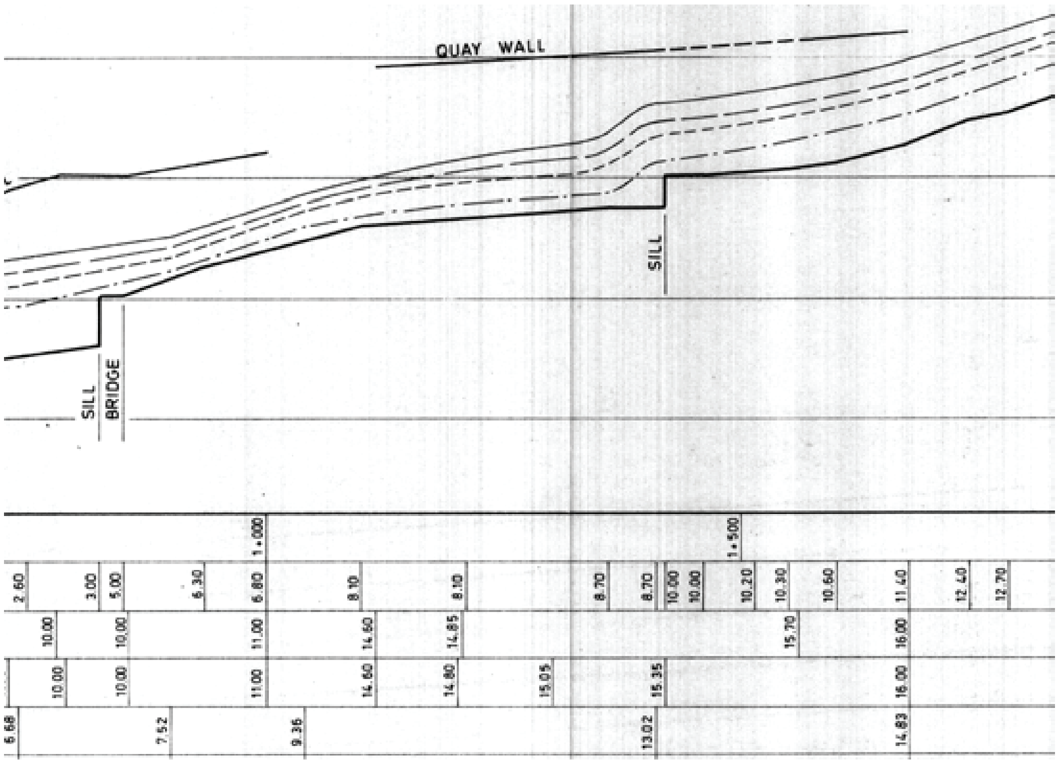
Source: Hidroprojekat (1972)

FIGURE 3.7. Relation between water level and discharge downstream of Wadi Hitaz confluence.



Source: Hidroprojekat (1972)

FIGURE 3.8. Wadi water levels within the Derna city for discharges lower than 350 m^3 per second.



Source: Hidroprojekat (1972)

PHOTO 3.1. The Wadi Derna watercourse before the 2023 flood event.

Source: United Nations Educational, Scientific and Cultural Organization.

3.2 THE CITY OF DERNA

Understanding the characteristics of the environment downstream of a dam is important to evaluate the potential consequences associated with any failure. In the case of the city of Derna, development can be traced back to ancient times when it served as an important trading hub in the region. The geographical location of this eastern port city made it an attractive destination for merchants and explorers, and Derna has witnessed the influence of various civilizations throughout history, including the Greeks, Romans, Byzantines, and Arabs, with each leaving their mark on the city's cultural heritage. The modern city was founded in the late 15th century on the site of an ancient Greek colony and was well-known as a center of intellectualism and independent thinking, cosmopolitanism, art, and culture.

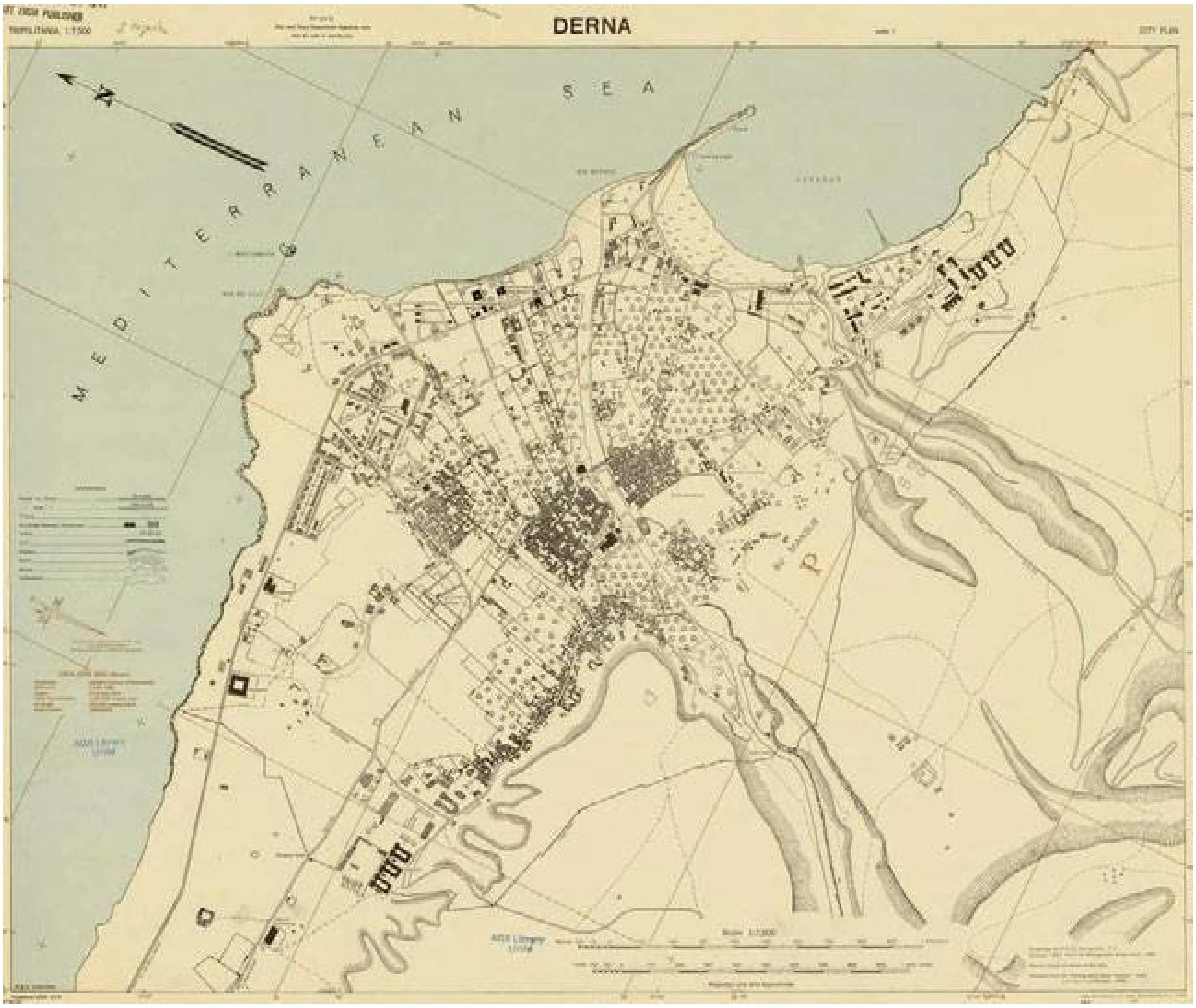
The city of Derna is home to around 120,000 people and split in two by the Wadi Derna, that is dry most of the year (Photo 3.2). Dotted with ancient churches and mosques, famous for its agriculture, and bordered by beaches, the city is built on an alluvial fan (delta). This is where land is formed at the bottom of mountains by sediment that is being washed down by rivers toward the sea. Long renowned for its attractive location on the Mediterranean coast, the city is flanked by some of arid Libya's only green forests. However, continued political conflict and instability has resulted in much of the public infrastructure being left to decay and the city's infrastructure has gradually eroded.

PHOTO 3.2. Scenery of the city of Derna before the disaster.

Source: Maherlink 2020 Wikimedia Commons *https://commons.wikimedia.org/wiki/File:□□□□□□□ □□□□ □□□□□ .jpg* CC BY-SA 4.0

Changes in population downstream of the dams reflect changes in the potential consequences associated with a dam failure. Derna has experienced fluctuations over the years, with the population consisting of around 85,000 people in 1964. This was around 108,000 people in 1972 and 157,000 people in 2012. Regarding population trends, it is important to note that accurate data are limited due to disruptions caused by conflicts. These variations can be attributed to factors such as internal migration, displacement, and the return of residents after periods of conflict. While no up to date data are available for immediately prior to the disaster, the population is commonly reported as just above 120,000 people. This relatively constant population is reflected in the spatial development of Derna over the past decades that can be illustrated using satellite images (Photo 3.3), which shows that the city has not expanded significantly over the past 30 years or more.

MAP 3.3. **The city of Derna in 1943.**



Source: Archives of American Geographic Society.

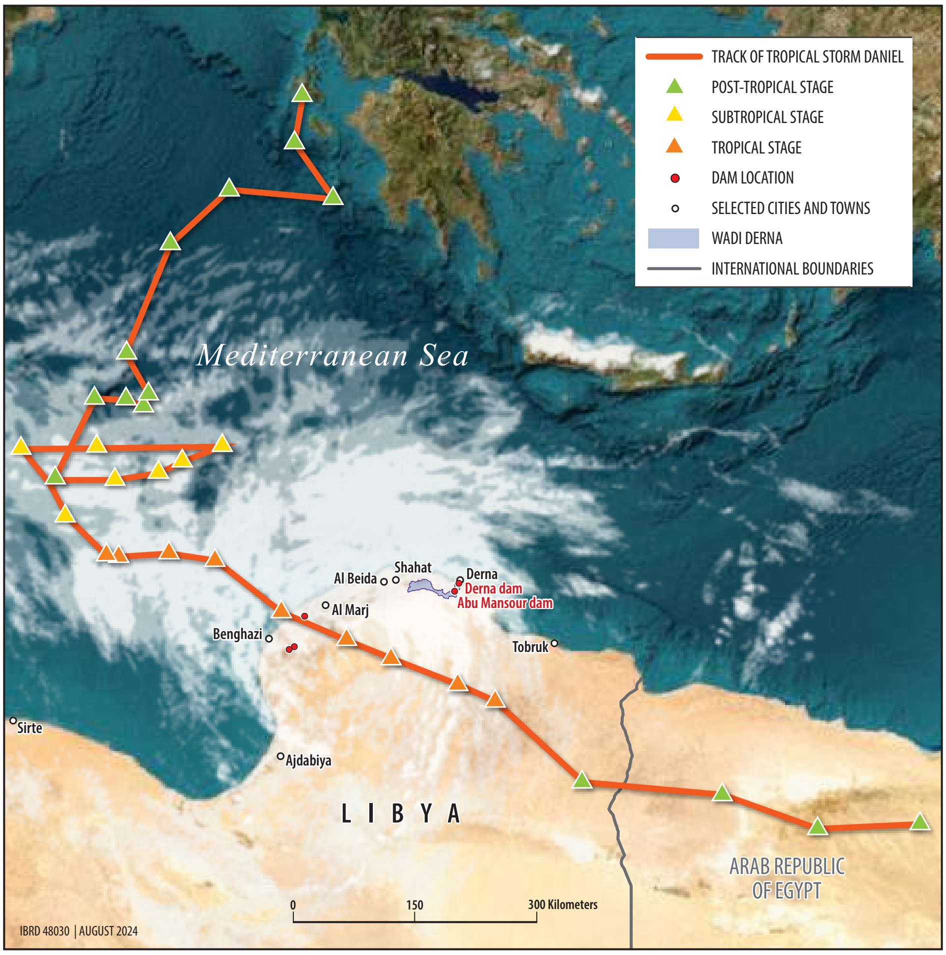
PHOTO 3.3. **Satellite imagery of the city of Derna through time: (A) 2022, (B) 2003, (C) 1987.**

Source: (A and B) Google Earth, Maxar, (C) NASA, Landsat 5.

3.3 THE CHARACTERISTICS OF STORM DANIEL

Storm Daniel, also known as Cyclone Daniel, formed as a low-pressure system over the Ionian Sea in the Mediterranean around September 4th, 2023. The storm developed in Greece as the result of an omega block; a high-pressure zone sandwiched between two zones of low pressure, and developed the characteristics of a Medicane - Mediterranean hurricane - as it moved towards Libya (Map 3.4). This hybrid phenomenon shows some characteristics of a tropical cyclone and others of a mid-latitude storm.[7] The storm affected Greece, Bulgaria, Türkiye, and Libya, with extensive flooding. The storm caused record-breaking rainfall in Greece on September 5th and 6th, with a reported 750 mm falling in 24 hours at a station in the village of Zagora; equivalent of about 18 months of rainfall, with many stations in central Greece receiving 400 to 600 mm of rainfall in 24 hours.

MAP 3.4. **Track map of Storm Daniel in September 2023.**



Source: Original for this publication based on NASA and WMO tracking data.

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[7] WMO 2023. *https://wmo.int/media/news/storm-daniel-leads-extreme-rain-and-floods-mediterranean-heavy-loss-of-life-libya*

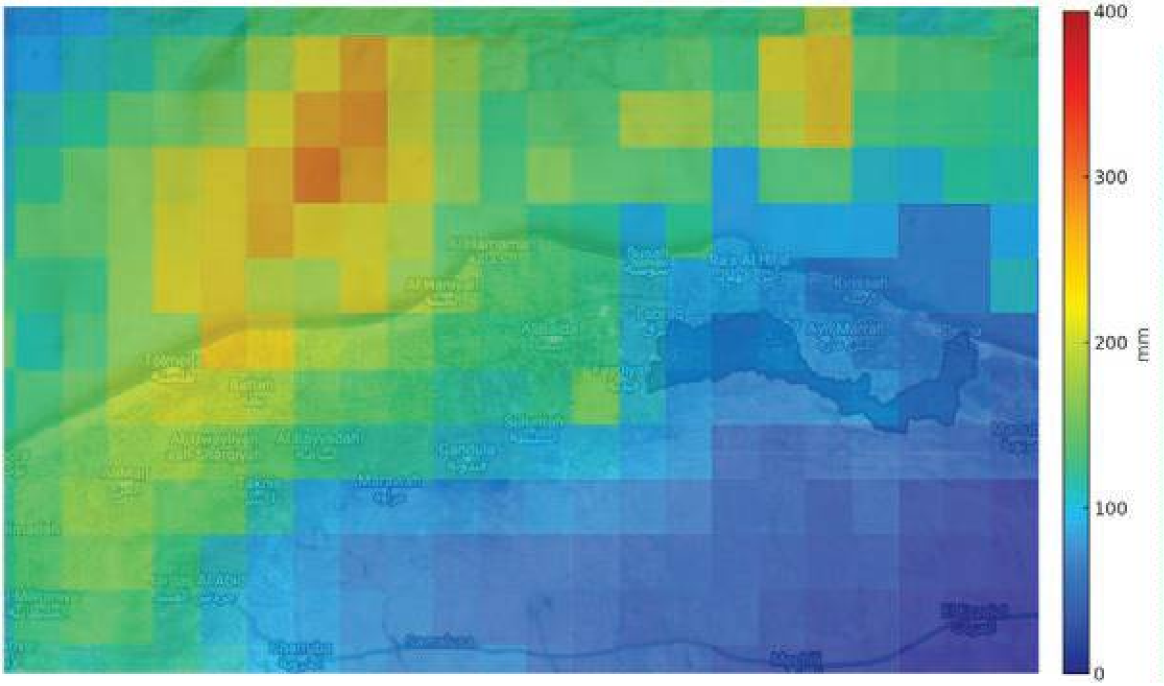
Storm Daniel made landfall in Libya around September 9th 2023 near the city of Benghazi (Map 3.4). The storm caused extreme rainfall, with Libya's National Meteorological Agency reporting rainfall of 414 mm at a monitoring station in Al-Bayda and more than 170 mm in the city of Labraq in 24 hours (100-150 km east of Derna, Map 3.5); well in excess of the long term average precipitation for September which is estimated at 1.46mm for Derna. Such rainfall would correspond to a return period of between 500 and 10,000 years. However, estimating average rainfall over the watershed is difficult and there is considerable uncertainty around the measurements with local stations providing various values. The measurements from Al-abraq are also likely biased, and under-estimated, with the area controller for the Eastern Meteorological Department reporting saturation of the rain gauge. It was also not possible to collect any radar observations of precipitation during the storm event. Even if such data were available, it would need to be calibrated against station data. Functional problems with data collection were reported during a meeting held in Tripoli on January 23rd, 2024, with rainfall estimates limited to data from Al Bayda and Al Abraq.

MAP 3.5. Rainfall estimates from rain gauges at Al-Bayda, Labraq, and Derna and an artificially derived gauge at a local minor dam N09.

Source: Original for this publication based on data from the Libya Meteorological Center.

Satellite-based precipitation measurements show a consistently lower rainfall intensity across the Wadi Derna catchment compared with the measurements of Libya's National Meteorological Agency. This is particularly true for the relatively large part of the Wadi Derna catchment draining to the Abu Mansour Dam. Measurements from NASA's GPM (IMERG) show a mean accumulated rainfall of 68 mm in the Wadi Derna catchment, while ERA5 estimates 83 mm (between 10-12 September). Both data sources show strong precipitation in the west of the Cyrenaica region, with a maximum near the city of Tolmeita (120-240 mm) (Figure 3.9). Then they show an eastwards (decaying) gradient, where rainfall intensities measured at Derna and the catchment draining into the Abu Mansour dam are considerably lower. These measurements are based on a multi-sensor approach, combining space-borne radar and IR measurements. These data sources are subject to different sources of uncertainties, and the spatial and temporal variability of the rainfall pattern might have resulted in strong bias in the rainfall estimates. Space-borne radar rainfall estimates often require local calibration with ground gauges, which still remain uncertain in this area and event.

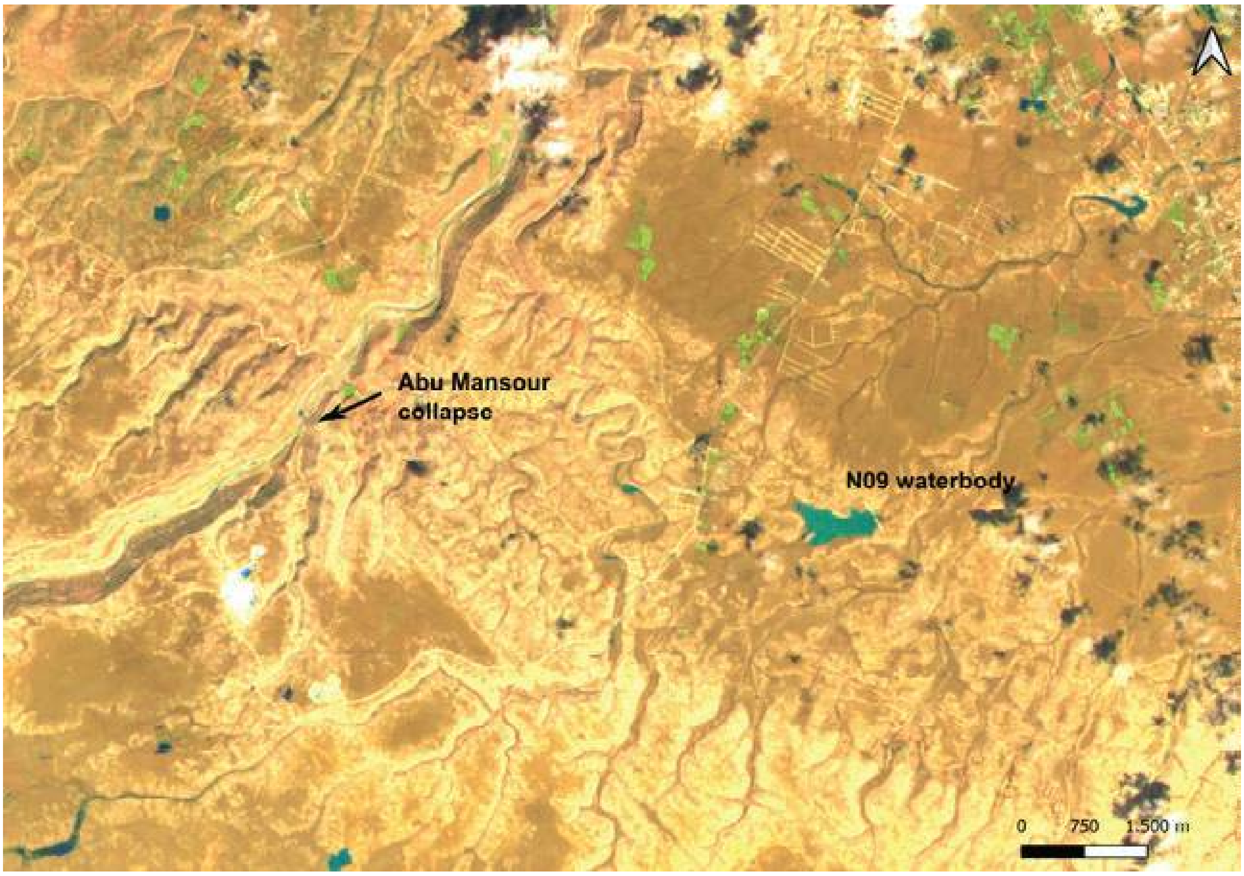
FIGURE 3.9. Accumulated precipitation over the region of Derna.



Source: NASA's GPM IMERG product.

Optical satellite imagery was also used to identify several waterbodies that filled during the storm event and identify. For instance, a small earth-filled dam was identified 7 km east of the Abu Mansour dam (named N09 in section 5.2). Satellite imagery shows the N09 reservoir was empty on September 9th and appeared almost full by September 12th (Figure 3.10). This was used to derive a synthetic rainfall gauge in the vicinity of the Abu Mansour Dam. To that effect, the wet area extent was derived for this reservoir one day after the event.[8] The Copernicus GLO30 DEM was used to estimate the hypsometric curve of the reservoir, and its associated drainage catchment area (8.9 km^2). Knowing that the catchment had dry antecedent conditions, the volume was estimated to be approximately 0.8 MCM by September 12th. Not accounting for infiltration or spills, this suggests a minimum average precipitation level of 103 mm in the N09 catchment. Given the antecedent dry conditions, a relatively high infiltration loss could be expected during the storm and the subsequent day before the image was captured, thus leaving a likely precipitation level between 120-200 mm, certainly larger than 100 mm. Further verification should be performed by improving the description of the infiltration level and runoff coefficient based on previous events and by improving the hypsometric curve estimate with higher resolution elevation data.

FIGURE 3.10. Sentinel 2 false color image of the N09 waterbody on September 12th, 2023.



Source: Original for this publication.

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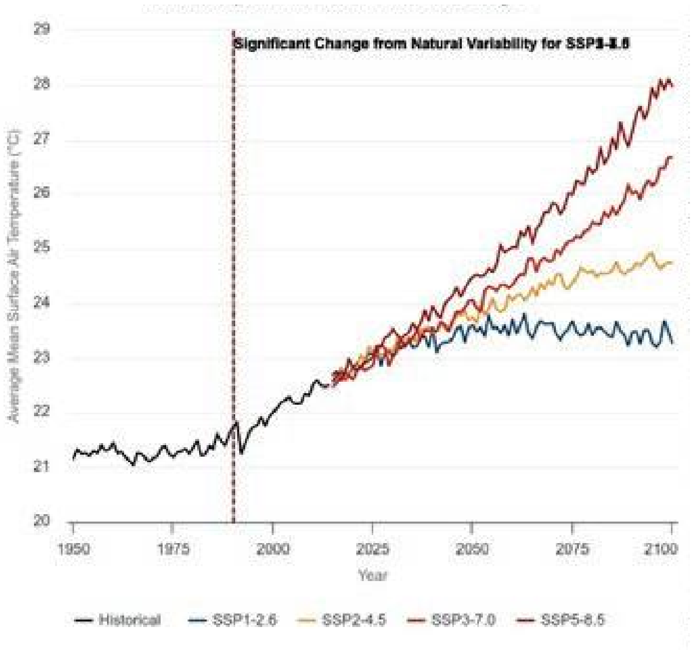
[8] from the available Sentinel 2 image (10 m resolution) using the reservoir volume computation routines established in the Global Water Watch (Deltares)

Despite the considerable uncertainty around the measurements relating to Storm Daniel, it can be safely concluded that the amount of precipitation was most probably in the order of 150-300 mm in the vicinity of Wadi Derna during Storm Daniel. While estimates vary significantly depending on the source, the aforementioned assessment estimates precipitation between 150-200 mm with a return period between 200 and 500 years based on the estimates provided by GPEX (Gründemann et. al., 2023). Alternative methods estimate precipitation between more than 170 to over 300 mm, corresponding to a return period between 500 and 10,000 years.

Both dams were designed in 1971 for 1/1,000 years return period flood events and verified for 1/10,000 years return period flood events, so should have been capable of dealing with the resulting flood. However, good practice requires the hydrology to be periodically revised after commissioning, and the capacity of the facility to handle the design flood must be verified. A possible 500 years return period of Storm Daniel in 2023 cannot be compared with the 1,000 years return period during design, as this was based on a different, shorter hydrological dataset. While further investigations are needed to definitively conclude the magnitude of the flood event, it means that a 500 years return period event today could be more extreme than what was anticipated for during the design of the dams.

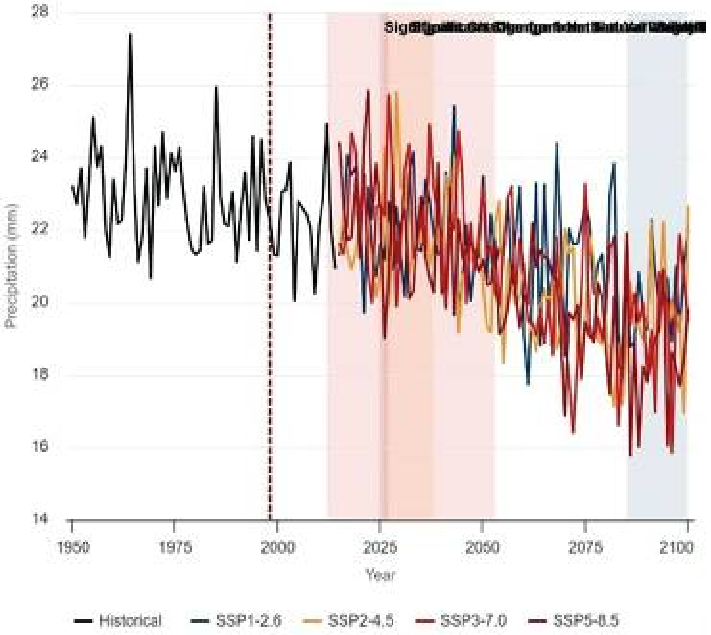
There has been significant speculation on the potential role of climate change on events such as Storm Daniel and Libya is particularly vulnerable to the impacts of climate change. Average temperatures have already risen above the global average of 1.1 degrees Celsius since 1900 with the southern Mediterranean region warming 20 percent faster than global averages. It is projected that this will increase by 2.2 degrees Celsius by 2040 and reach approximately 4 degrees Celsius by the end of the century (Figure 3.11). Rising temperatures are exposing Libya to more climate related hazards, including floods, droughts, wildfires, extreme heat, sandstorms, and desertification. Thermodynamic principles suggest that an increase of 1 degree Celsius could lead to an increase of 5-7 percent in precipitation, while the projected departure from natural variability suggests a decreasing trend in precipitation for Libya (Figure 3.12). However, the attribution of the 2023 flood event to the ongoing climate change due to human intervention remains uncertain, with the effects of warming-induced changes on extreme precipitation complicated and very difficult to quantify in river runoff, particularly in seasonal and ephemeral stream systems (Box 3.1).

FIGURE 3.11. **Projected departure from natural variability of average mean surface air temperature for Libya with trends.**



Source: World Bank Climate Knowledge Portal. *https://climateknowledgeportal.worldbank.org/country/libya*. Retrieved July, 2024.

FIGURE 3.12. **Projected departure from natural variability of precipitation for Libya with trends.**



Source: World Bank Climate Knowledge Portal. *https://climateknowledgeportal.worldbank.org/country/libya*. Retrieved July, 2024.

BOX 3.1. The Contribution of Climate Change.

The 6th Intergovernmental Panel on Climate Change (IPCC) assessment mentions that *"Available event attribution studies of observed strong Tropical Cyclones (TC) provide medium confidence for a human contribution to extreme TC rainfall. Peak TC rain rates increase with local warming at least at the rate of mean water vapor increase over oceans (about 7% per 1°C of warming) and in some cases exceeding this rate due to increased low-level moisture convergence caused by increases in TC wind intensity (medium confidence)."*

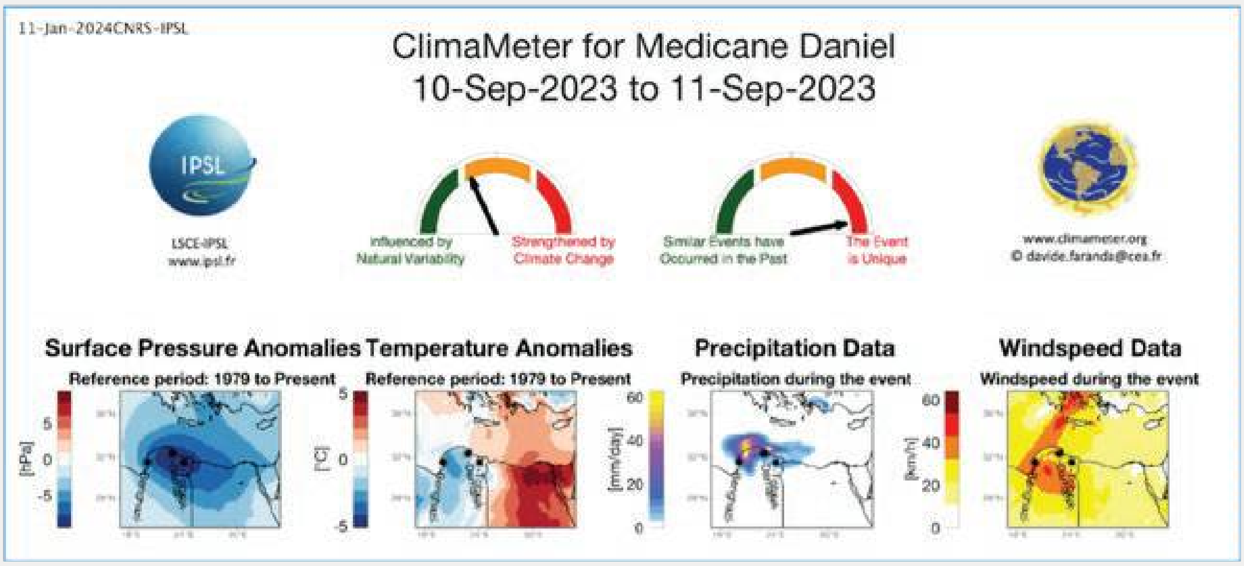
An assessment by World Weather Attribution (Zachariah, et al. 2023) concluded that human induced climate change made heavy rainfall in north-eastern Libya up to 50 times more likely to occur compared to a 1.2°C cooler climate. They also found the rainfall event was up to 50 percent more intense than it would have been in a pre-climate change world. This is supported by the ClimaMeter that concluded the landfall of Storm / Medicane Daniel was a largely unique event for which natural climate variability played a role and hypothesize that the changes observed in precipitation amounts compared to the past may be partially due to human driven climate change (Figure B3.1.1).

The role of climate change was evaluated by combining observation-based products and climate models to assess changes in the likelihood and intensity of a 1-in-600 year 1-day maximum rainfall event over Libya. The event magnitude for Libya is far outside that of previously recorded events, and the uncertainties for the return times are very high and depend on the exact region and dataset chosen. Individual locations can be very different from the ones reported and estimates encompass the possibility of no detectable change.

Notwithstanding these caveats, the authors are confident that climate change did make the event more likely: from theory it's know that an increase in rainfall intensity of around 10%, would be expected given current warming levels, so they could only report that there has been no change if there was a well-known dynamic process counteracting this effect, which there is not. Studies focusing on extreme rainfall with future warming also show an increase in heavy rainfall, rendering it probable that the observed increase in heavy rainfall is indeed a trend due to climate change. For these reasons, the authors do not give a central estimate of the influence of climate change, as in previous studies, instead giving an upper-bound of the effect.

The authors note that the volume of water and overnight timing of the dam failures meant that anyone in the path of the water was at increased risk, not just those who are typically highly vulnerable. The ongoing conflict and state fragility in Libya compounded the effects of the flooding and limited adaptation planning and coordination across a range of climate issues. The authors highlight the need to design and maintain infrastructure for not just the climate of the present or the past, but also the future. In Libya, this means taking into account the long-term decline in average rainfall, and at the same time, the increase in extreme rainfall like Storm Daniel. The report recommends a full after-action review to look at the design criteria of the dams in order to understand the extent to which different factors contributed to the disaster.

FIGURE B3.1.1. The result of the "climate meter" analysis of the impact of Storm / Medicane Daniel in Libya.



Source: *https://www.climameter.org/20230910-11-medicane-daniels-landfall.* Retrieved July, 2024.

3.4 THE CHARACTERISTICS OF THE 2023 FLOOD

Storm Daniel's west-east path represents the worst-case scenario for the accumulation of runoff in Wadi Derna. The magnitude of the resulting storm-driven flood volumes depends on the assumptions used in generating the rainfall estimates and, despite the uncertainty around rainfall estimates and the inability to provide a correct estimate of the rain depth, it is clear that the entire catchment was covered by high rainfall quantities and with an intensity that were much larger than the infiltration capacity.

Two methods were used to estimate the magnitude of the resulting storm-driven flood volumes. These used two states of basin saturation before the event and were subject to sensitivity analyses. The first approach included application of a hydrological model calibrated to the flood events of 1959, 1968, and 1986, with a sensitivity analysis testing a rainfall panel ranging from 150 to 330 mm. More information is given in Annex 1. The second approach relied on a model built using the Tygron platform[9] and a sensitivity analysis run with bandwidths applied for the input parameters to calculate whether the water exceeds the crest level of the Abu Mansour Dam. More information on the bandwidths is given in Annex 2 along with details about the software and the initial model set-up.

The first method estimated the runoff coefficient for the Wadi Derna catchment by using a known prior event. In 1986, a large storm with approximately 75 mm rainfall over the 476 km^2 Wadi Derna system resulted in a reported volume of 13 MCM at the dam. This would result in an approximated rainfall-runoff coefficient of 38 percent. Extrapolating this to the 2023 situation results in an estimated volume of [8.8, 17.6, 26.4, 35, 43] MCM for a rainfall event of an average accumulated precipitation of [50, 100, 150, 200, 250] mm respectively. This assumes the same coefficient for events of different return periods and so likely underestimates the peak flow and volumes for higher magnitude events which would result in ground saturation and most of the additional flow is runoff. This is reflected in the hydrological model estimates calibrated to the flood events of 1959, 1968, and 1986 that are generated using rainfall estimates ranging from 150 to 330 mm assuming the absence of any dams (Table 3.3).

TABLE 3.3. Estimated return period of discharge and precipitation (provided by GPEX) for Abu Mansour and Derna locations.

Return Period (years)	Daily rainfall (mm)	Peak flow (m^3/s)	Volume (MCM)
	Derna		
100	135	770	34
500	200	1,450	65
1,000	235	1,950	78
10,000	330	2,800	115

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[9] The Tygron Platform provides users with tools to simulate various future scenarios and test the potential impact of different development options in order to make informed decisions on complex spatial issues, such as flooding, housing, infrastructure, and nature. *https://www.tygron.com/*

Return Period (years)	Daily rainfall (mm)	Peak flow (m^3/s)	Volume (MCM)
Abu Mansour			
100	135	680	25
500	200	1,350	50
1,000	235	1,750	61
10,000	330	2,500	90

Source: Original for this publication.

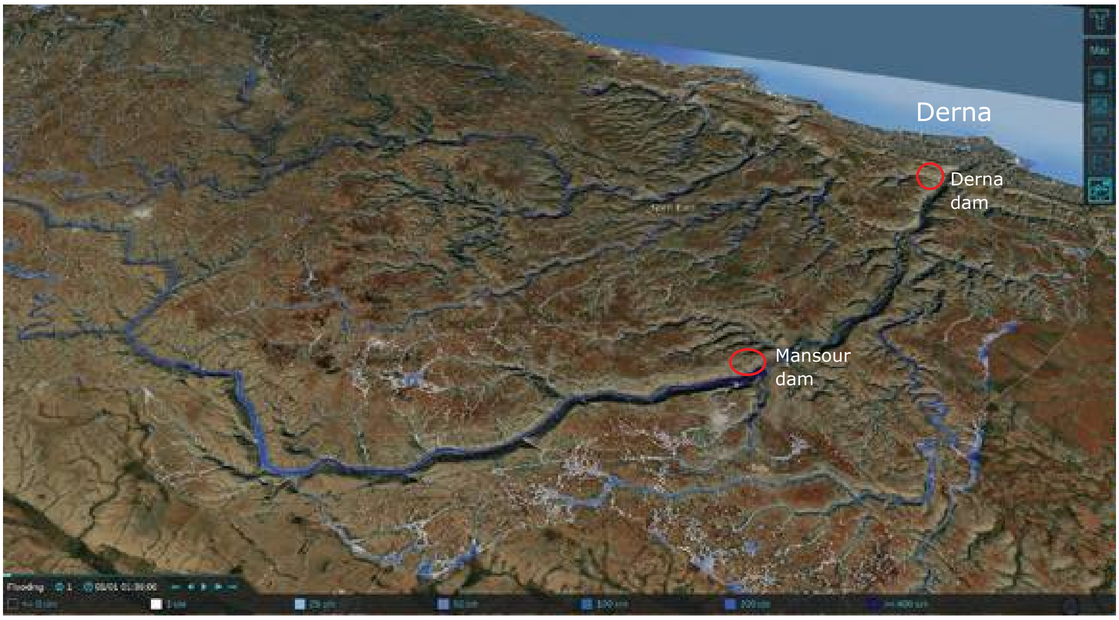
The model estimates of the return period associated with the peak flow and flood volume are considerably higher than the original design estimates. While both dams were originally designed to withstand a 1,000-year return period, the hydrological data available during design phase was limited, resulting in restricted statistical reliability. As a result, what was considered in the 1970s to be a 1 in 1,000-year event is estimated today to have a frequency of occurrence of once every 200 or 500 years. Given that the estimates were fitted on different datasets, the estimated return period of Storm Daniel may not be compared with the 1,000 years return period during the original design. Good practice requires the hydrology to be periodically revised after commissioning, and the capacity of the facility to handle the design flood must be verified. A comparison of the estimated peak flows and flood volumes for a 1 in 1,000-year return period determined as part of this assessment shows significant differences from those carried out during the original design (1972) as well as the "Stucky review 2003" (Table 3.4). This shows the danger of not periodically revising the hydrological design data after commissioning.

TABLE 3.4. Hydraulic design criteria related to flood protection for Derna and Abu Mansur Dams

Dam	Derna			Abu Mansur		
	Original design (1972)	Stucky Review (2003)	Model Estimates (2023)	Original design (1972)	Stucky Review (2003)	Model Estimates (2023)
Return period (year)	1,000	1,000	1,000	1,000	1,000	1,000
Peak flow (m^3/s)	~350	906	1,750	840	1,360	1,950
Flood volume (Mm^3)	4	35.4	61	14	47.6	78
Maximum released flow (m^3/s)	350	570		170	420	

The second approach using the Tygron platform was used to analyze the influence of different hydraulic factors on the peak flow and associated flood volume in the Wadi Derna system. This was done by performing a sensitivity analysis on a variety of model input parameters and for a situation that includes the presence of the dams. Studied hydraulic factors include uncertainty in actual rainfall amounts, how this rainfall was distributed in time and over the entire catchment, (soil) infiltration capacity, evaporation rates, and the water retaining height of the lowest part of the dam crest, among others. Given the uncertainty regarding rainfall, the sensitivity analyses provide a range of potential scenarios and were used to simulate the channel conditions (Figure 3.13). All simulations were then checked to determine if overtopping of Abu Mansour dam occurs or not, which means exceeding the reservoir capacity. Detailed results and implications for overtopping are presented in section 4.4.

FIGURE 3.13. **Example of the Wadi Derna filled with water in the model.**



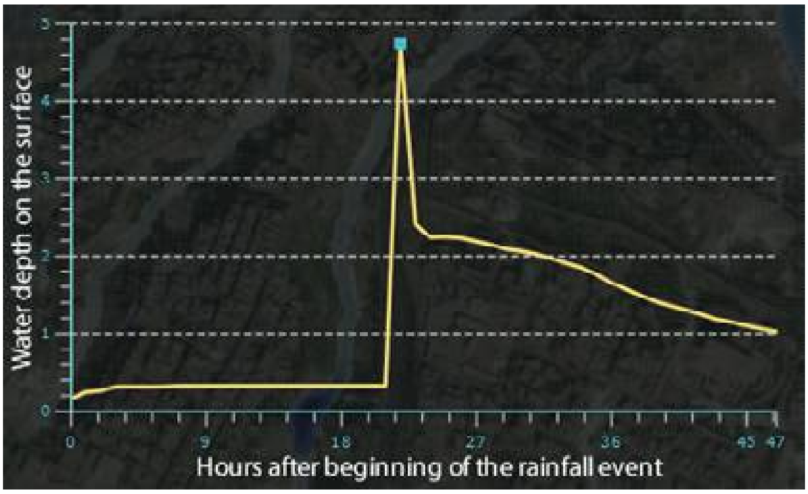
Source: Original for this publication based on hydrological modelling by Tygron (see Annex 2).

3.5 A WALL OF WATER: THE FLOOD WAVE RESULTING FROM THE FAILURE

There is considerable uncertainty around the hydrological estimates and the sequence of the dam failures. However, the failure of the Derna Dam is estimated to have generated a flood wave with a flow ranging between 1,500 m^3 per second. These estimates are based on observations during the disaster and illustrated by photos taken during the night (Photo 3.4). Such a water discharge can flood a significant part of Derna city. Simulations of the flood wave that was caused by the collapse of the Abu Mansour dam suggests the water level in the city of Derna rose between approximately 5 to 8 m within 30 minutes. These estimates depend on the assumptions used in the Tygron model that was used to simulate flood wave event that was caused by the collapse of the Abu Mansour dam (Figure 3.14). No such computer simulation was made for the collapse of the Derna Dam. The width of the main flow channel would have extended over 800 meters (indicated by white arrow in Figure 3.15) while the maximum water flow velocity is calculated at more than 8 m per second (color red; mainly inside the Wadi Derna, but also on the sides) (Figure 3.16).

Traces enable an estimation of discharge of around 7,000 m^3 per second following the subsequent failure of the Abu Mansour Dam, setting off a second 'wall of water' significantly exceeding the capacity of the city's drainage channel, which could handle a maximum of around 1000 m^3 per second. With high velocities (3-8 m per second), this water inundated even larger portions of the city than the first flood wave. Buildings along the river flood line were washed away in this disastrous hour, allowing water to increase in extent, causing more destruction and loss of human lives (see Box 3.2). When the water distributes over the city, the water level drops and sinks out at about 1 meter in approximately 24 hours. While such values correspond to the lower part of the estimations based on simplified hydraulic estimation, eyewitness reports largely confirm this chain of events, in line with the model results.

FIGURE 3.14. Water level rise downstream in Wadi Derna.

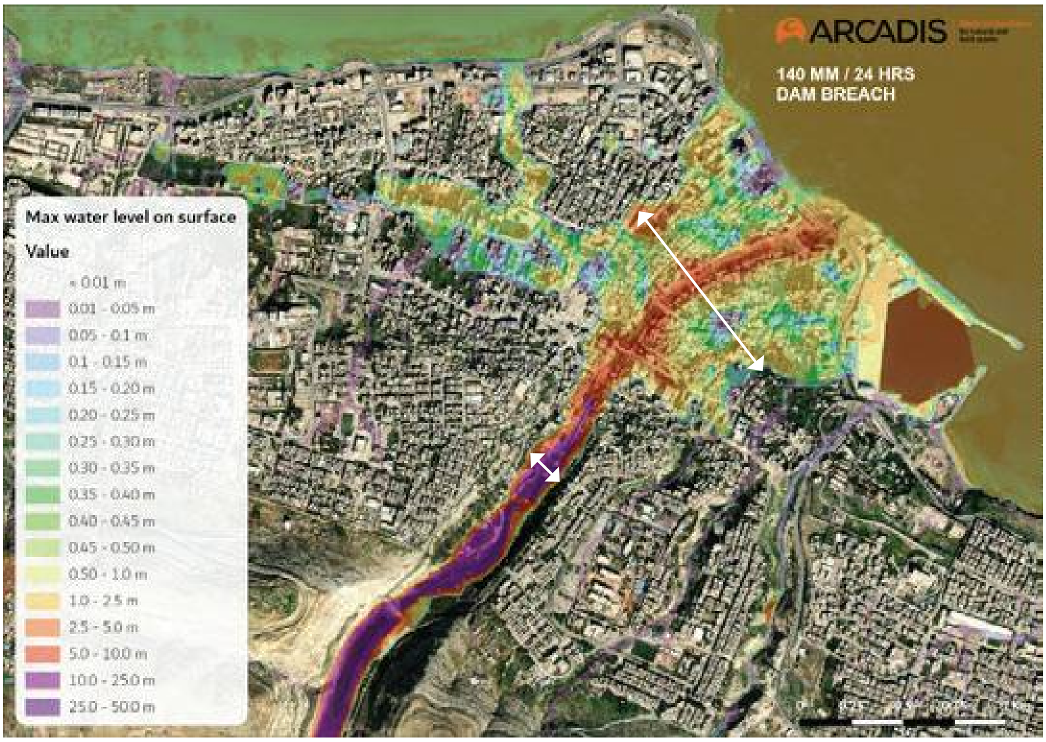


Source: Original for this publication based on hydrological modelling by Tygron (see Annex 2).

PHOTO 3.4. The water level in Derna during the 2023 flood event.

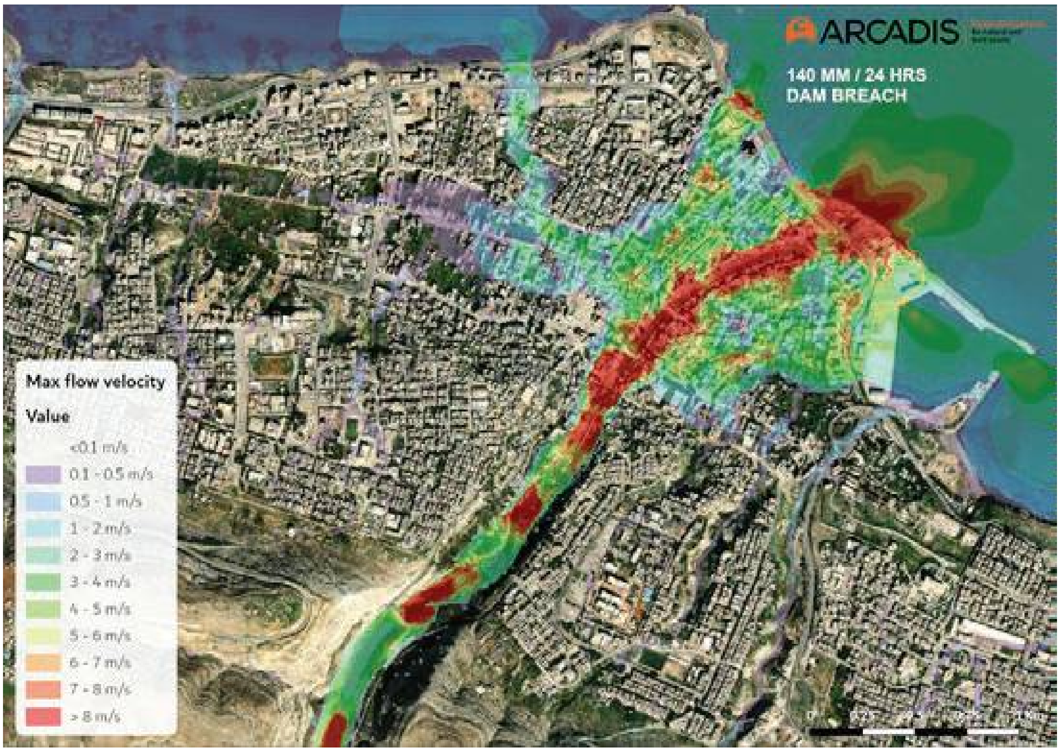
Source: United Nations Educational, Scientific and Cultural Organization.

FIGURE 3.15. Maximum water level after the dam breach at a rainfall event of 140 mm/24 h.



Source: Original for this publication.

FIGURE 3.16. Maximum flow speed after the dam breach at a rainfall event of 140 mm/24 h.



Source: Original for this publication.

BOX 3.2. The human perspective to the disaster: Insights into people's experiences during the flood in derna.

The following excerpts from a series of interviews conducted in December 2023 provide important insights into the individual experience of people during and after the flooding of the city of Derna.

- The disaster has been immense, causing thousands of deaths and destroying people's lives and livelihoods:

  "It was a nightmare. People who survived it even say it wasn't a day of reality. It felt like it was the end of the world."

- People were taken by surprise when the flood hit their houses in the middle of the night:

  "Nobody thought that it was going to be as bad. Only a few people left beforehand; most people stayed. They assumed that in the worst case, the first floor of their homes would be flooded and that's it. Nobody expected that it would be massive. [...] It was very quick. There was no time to panic. [...] In one second, you are living it. [...] It was about 3 o'clock in the morning when the dams broke, so people were sleeping and then suddenly you are living this nightmare."

- The impact has been tremendous and until now, no form of normality has returned:

  "[For the people in Derna,] it's like when something breaks your back. Your back has broken, it got hit and then it's never the same again. [...] The situation now [three months later] is that people are on their own, trying to survive, trying to clean up the city, rebuild it, and make a better place. [...] It's still survival mode. [...] It's not like you are in a comfortable home and you have to solve a problem and if you can't solve it, you still go to sleep in your nice bed and you are warm. Everything is destroyed and you need to fix everything."

- The disaster has also affected people's psychological well-being and their feeling of safety:

  "This definitely created some kind of trauma. You know, with any kind of rain, people immediately remember the disaster. [...] It's difficult having to go through this and survive. Sometimes, it is better to die than to survive because if you survive you have to cope with what happened and see how you can move forward. [...] Rain is definitely something that makes people now feel unsafe. And in general, there is not much feeling of safety since nothing really has been done yet by the officials."

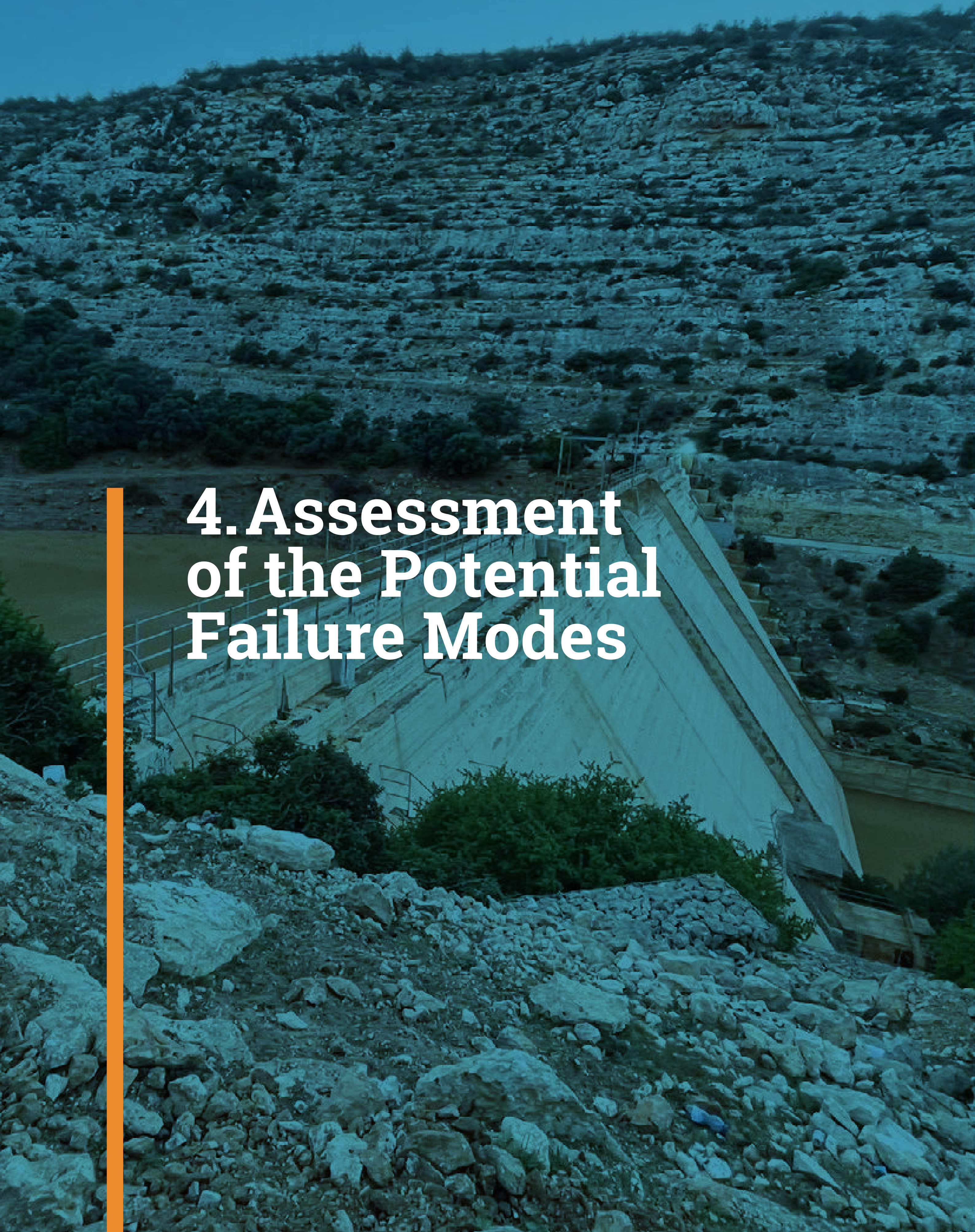
- People rely on themselves and their neighbors; external help seems limited:

  "It's all civilians helping civilians. You help your neighbor, and your neighbor helps you. [...] People really are the ones who stand for each other, you know."

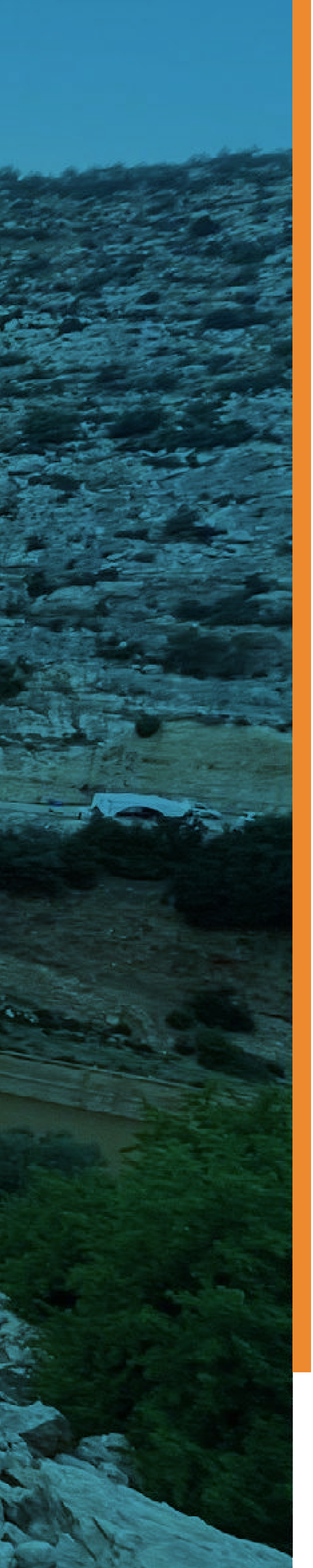
- People want to understand why this happened:

  "People in a way accept what happened from a natural point of view. Sometimes you go through trials, you go through such events, and they can be disasters and we accept the consequences whatever they may be, even if it's death, as long as what we can do as humans [to prevent it] has been done: If the right safety level has been ensured, if the right maintenance has been done, and then this happened, then it's ok. People will accept it. That's why it's important for people to know. [...] If they knew that this would have happened [...] [anyways] because the water was just too much, people would be more open to accept it. Then it's natural, it's from God. [...] Then we accept the consequences, and we can live with them. That's part of our faith."

Source: Original for this publication.



4. Assessment of the Potential Failure Modes



1 The major technical and reported potential failure modes were evaluated for the Abu Mansour and Derna dams.

2 Both dams likely failed due to overtopping as result of inflow exceeding capacity, leading to severe erosion with other failure mechanisms, such as piping and macro-instability, possibly contributing.

3 Both dams exhibited weaknesses in their original design, with limited hydrological data resulting in restricted statistical reliability, and severe settlement and seepage observed for both dams.

4 A flood wave at around 23:00 on September 10 due to the failure of Derna dam is estimated to have a discharge of 1500-5000 m^3/s, with the flood wave due to the failure of the Abu Mansour dam at around 02:40 on September 11 estimated to have a discharge exceeding 7,000 m^3/s.

5 While the magnitude and velocity of the two flood waves would have not allowed sufficient time for evacuation, a warning system linked to exceedance of critical water levels could have been developed based on the dams poor condition.

4.1 ENSURING THE SAFETY OF DAMS

Dams may fail due to one or a combination of factors. These can include overtopping caused by insufficient installed or available flow discharge capacity of the dam, mis-operation, or flawed operating strategies and plans; structural failure of materials used in dam construction; movement and/or failure of the foundation supporting the dam; settlement and cracking of concrete or embankment dams; internal erosion of soil in embankment dams; inadequate maintenance and upkeep; and, deliberate acts of sabotage. As such, it is critical to detect any abnormal behavior at an early stage through regular surveillance and monitoring, and to undertake timely corrective actions.

Ensuring the safety of dams is built around three key concepts. These include: (i) structural safety; (ii) surveillance and maintenance; and (iii) emergency concept (Figure 4.1). These dam safety measures are intended to secure the water and services for which the dam was developed, as well as to protect and ensure the resilience of downstream communities, assets, and infrastructure. In addition to these dimensions, the regulatory framework and institutional capacity will also have important implications for ensuring the safety of dams and downstream communities.

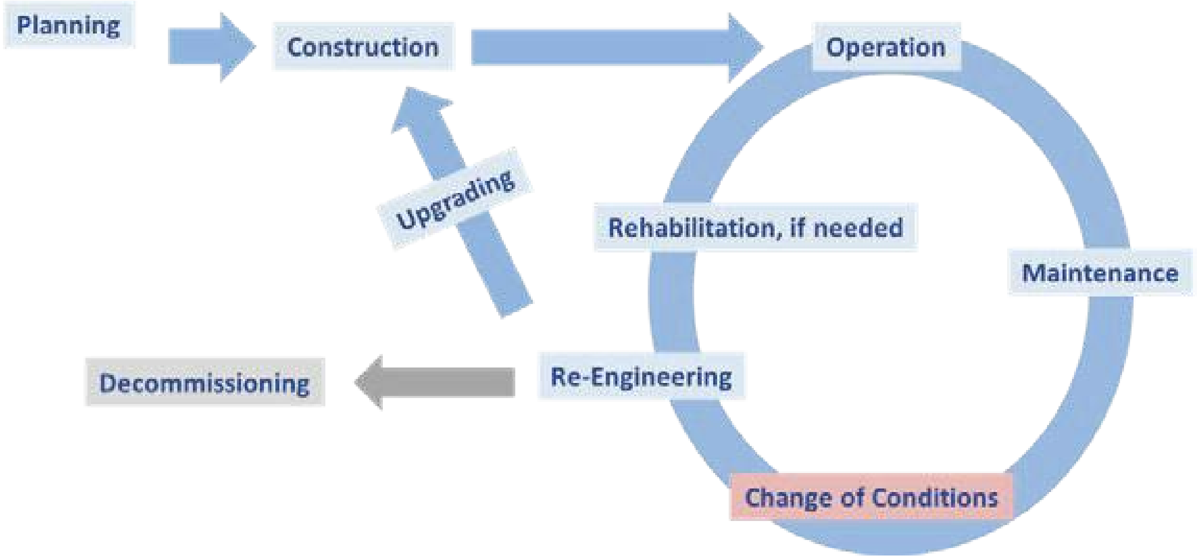
Structural safety depends primarily on the design and construction of the structure. Safety is also influenced by the methods and quality used in construction. As the project must adapt to the reality of the terrain as it is discovered during construction, the recording of any adaptations and modifications made during construction is very important. Structural safety also relates to hydraulic safety, which depends essentially on knowledge of hydrological conditions. Very often, the volume and quality of data available at the design stage are far from satisfactory. The designer is therefore required to base their design on assumptions based on good practice and available resources.

FIGURE 4.1. Key aspects of dam safety.

Source: Swiss Federal Office of Energy (2015).

Knowledge and practice evolve over time and structural safety needs to comply with contemporary good industry practices. While the data used to design the Derna and Abu Mansour dams in the 1970s may be presumed to corresponded to the practices of the time, these were very different from those used today for a new design or a safety review. The impacts associated with climate change also require new approaches to deal with increasing uncertainty. This implies the need for periodic reviews of safety, which consider improved knowledge of the hydrology and of the behaviour of the dam through its monitoring, along with changes in the environment around the structure, particularly as regards land use and urban development upstream and downstream of the dam, and the implementation of more effective means of analysis. This process should be repeated during the life of the structure (Figure 4.2).

FIGURE 4.2. Life cycle of dams.



Source: ICOLD General Report (Question 99, Mouvet, Stavanger 2015)

Surveillance and maintenance are important to characterize the behaviour of the structure in operation and to highlight any irregularities. Maintenance is important to keep the equipment in good working order. For embankment dams, such as the Derna and Abu Mansour dams, care must also be taken to maintain the crest and the upstream and downstream faces of the dam by preventing the growth of vegetation. The banks of the reservoir should also be inspected to identify any risk of landslide in the reservoir and in the vicinity of the dam, and any floating material that could interfere with the proper operation of the hydraulic devices. Surveillance is important to ensure continuous monitoring of the dam's behavior and is essentially based on three elements (ICOLD 2009, 2018):

1. Monitoring, using specific equipment installed on the dam and external monitoring resources, according to a predetermined monitoring plan. This monitoring mainly records the deformation of the structure, on a scale of centimeters for rockfill structures, pore pressures in the dam body and its foundation and seepage through the dam and its foundation.
2. Visual inspections by qualified personnel who report any visible changes in the structure, such as the appearance of cracks, local subsidence, traces of moisture or corrosion, etc. These inspections must be rigorously documented so that the different conditions can

be compared. Inspections also make it possible to identify defects even before they are detected by monitoring.
3. Testing of hydraulic safety equipment, such as spillway gates and bottom outlet gates.

The emergency concept aims to minimize the potential damage or consequences in case of an incident or dam failure. This is generally based on five components:

1. Identification of potential threats that could endanger the safety of the dam and thus require immediate action. If detected early enough, potential dam safety threats can be assessed, and preventive or remedial actions can be taken to avoid a dam failure or to mitigate the size and extent of the damages.
2. Characterization of the potential damage. A dam failure analysis and a flood routing mapping are used to indicate the areas affected in an emergency case. Careful planning and coordination with the authorities in charge of urbanization and land use is paramount.
3. Setting up a response plan, which includes preventive public information, alarm systems, and evacuation plans.
4. Definition of the role and responsibilities of each stakeholder and drafting a clear flow chart for communication and decision making.
5. Training of the communication chain and the emergency authorities.

4.2 POTENTIAL FAILURE MODES OF THE WADI DERNA DAMS

Understanding the key elements required for ensuring the safety of dams is important to contextualize the potential failure modes associated with the Derna and Abu Mansour dams. A series of potential failure modes were mentioned in the immediate aftermath of the collapse.[10] These potential failure modes are summarized and discussed in this section. The limited information on the behavior of the dams in the interim period between the intervention of Stucky (2002-2004) and Storm Daniel makes it impossible to assess the state of the two dams on the eve of the disaster. This is particularly important given the knowledge that both dams had already been subject to more than excessive settlement and piping by 2004, mainly in the foundation but also likely in the embankment. In the absence of these detailed reports and being able to carry out field visits to inspect the remaining infrastructure of the Abu Mansur Dam and the site of the Derna Dam (which was completely washed away), the assessment of probabilities associated with different potential failure modes was limited to the analysis of original design reports (Hidroprojekat 1972), studies conducted from 2002 to 2004 (Stucky 2003, 2004), videos, satellite images and photographs,[11] eyewitness reports, facts in the public domain, and expert elucidation. Given this context, it is important to note that this analysis may be revised following the availability of new elements provided even after the publication of this report. Should conditions allow, an inspection of the remains of Abu Mansur dam would help to confirm or review the probable scenario of its failure.

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[10] Relevant newspaper articles were for example found in Eos Buzz (13 Sept) The New York Times (16 Sept) and AP news (18 Sept).

[11] The team is particularly grateful to those provided by Dr. Claudia Gazzini (International Crisis Group) who visited Abu Mansur dam on September 17, 2023.

EYEWITNESS ACCOUNTS: THE FLOOD SEEMED TO COME OUT OF NOWHERE

Dr. Claudia Gazzini, a Senior Analyst with the International Crisis Group, travelled to gather first-hand information on the state of the disaster in Derna. On September 17th she accessed, together with several locals, to the site of the Mansour dam. She collected photos and videos of the location, the wadi Derna and the collapsed dam. She also interviewed several people in the ground, gathering several recounts of the event just a few days after the disaster. Key accounts from several witnesses reported the following:

- At sunset of the 10th, the Mansour reservoir was still dry.
- At around 8pm (EET) on the 10th, the dam started filling rapidly, and by 12am, the dam was half-full.
- Between 12am and 2am (11th) the water level started rising rapidly.
- By 2am, the dam overtopped, and water started overflowing the crest level.
- After overtopping, witnesses recall significant noise of rocks crashing as the water started creating a breach in the dam body at around the middle of the crest section.
- Sometime between 2:30-2:50 am witnesses saw the dam collapse, mentioning a lot of rock-friction noise:

Source: Gazzini 2023.

4.3 VISUAL ANALYSIS

Satellite images and photographs taken from site were selected to support the analysis made for the 2023 flood event. The satellite images show the dams before and after the flood event (Figure 4.3). Photo 4.1 shows the erosion occurred at the immediate downstream of the crest right abutment. In this zone, mainly topsoil was swept away, confirming the low head and the short duration of the overflowing. Photo 4.2 and Photo 4.3 suggest that the right abutment experienced significant flow striping, completely eroding the bedrock and leaving only fine material deposited at its foothill, likely at the end of the flood. In contrast, the left side of the embankment was spared, and the valley flank was preserved almost in its original appearance. A rockfill deposit formed at the base of this flank is attributed to the return currents which formed due to the concentration of the flow on the right bank side. Photo 4.4 shows that a shear surface developed on the remaining clay core, so smooth and continuous that it reflects the occurrence of a major landslide during flooding. The presence of the downstream crest parapet among the fallen upstream material supports the idea of upstream shoulder instability. Photo 4.5 shows the view downstream of Abu Mansur dam and the flood level, while Photo 4.6. shows evidence of flow concentration on the right hand side and wadi bed scouring due to the waterfall as the core remains high enough in the central part of the dam footprint.

FIGURE 4.3. **Abu Mansour Dam (left) and Derna Dam (right) before and after the floods.**

Source: World Bank / IPSOS 2023

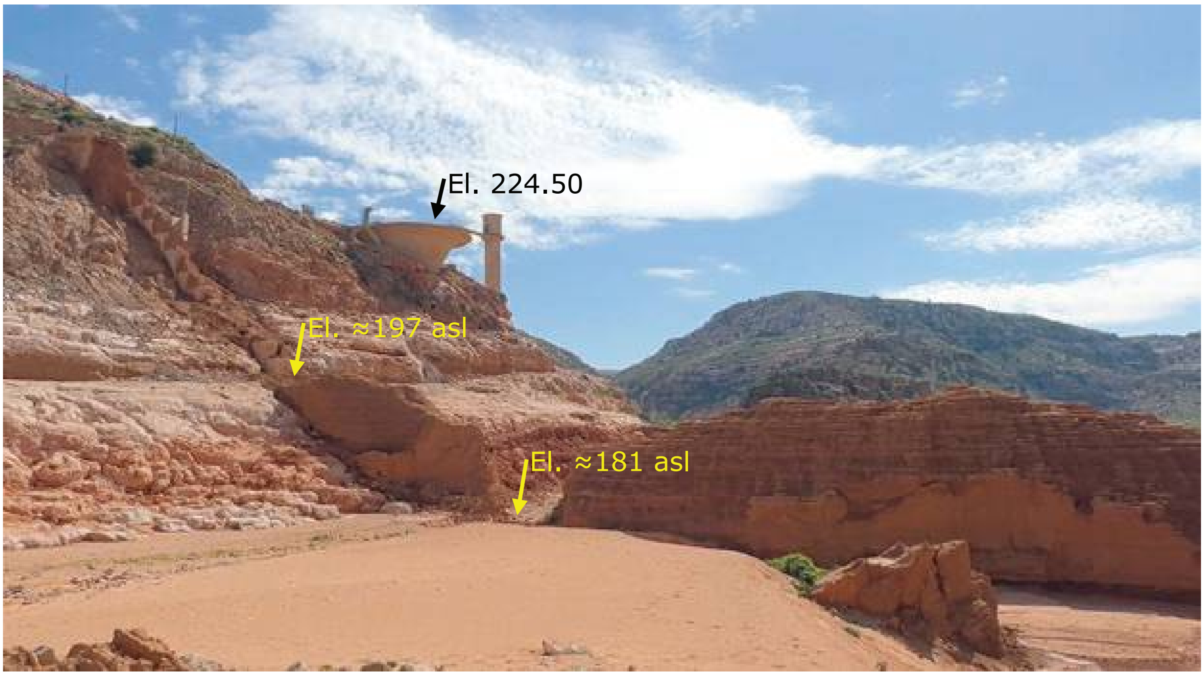
PHOTO 4.1. **Erosion due to the water overflowing the right abutment of the Abu Mansour Dam.**

Source: Photo from Claudia Gazzini / International Crisis Group, annotations by authors.

PHOTO 4.2. **View of the right abutment of the Abu Mansour Dam where the embankment was totally washed away. Concrete blocks correspond to the centerline of the core foundation and the grout curtain drilling.**

Source: Photo from Claudia Gazzini / International Crisis Group, annotations by authors.

PHOTO 4.3. **Downstream view of the right abutment of the Abu Mansour Dam.**



Source: Photo from Claudia Gazzini / International Crisis Group, annotations by authors.

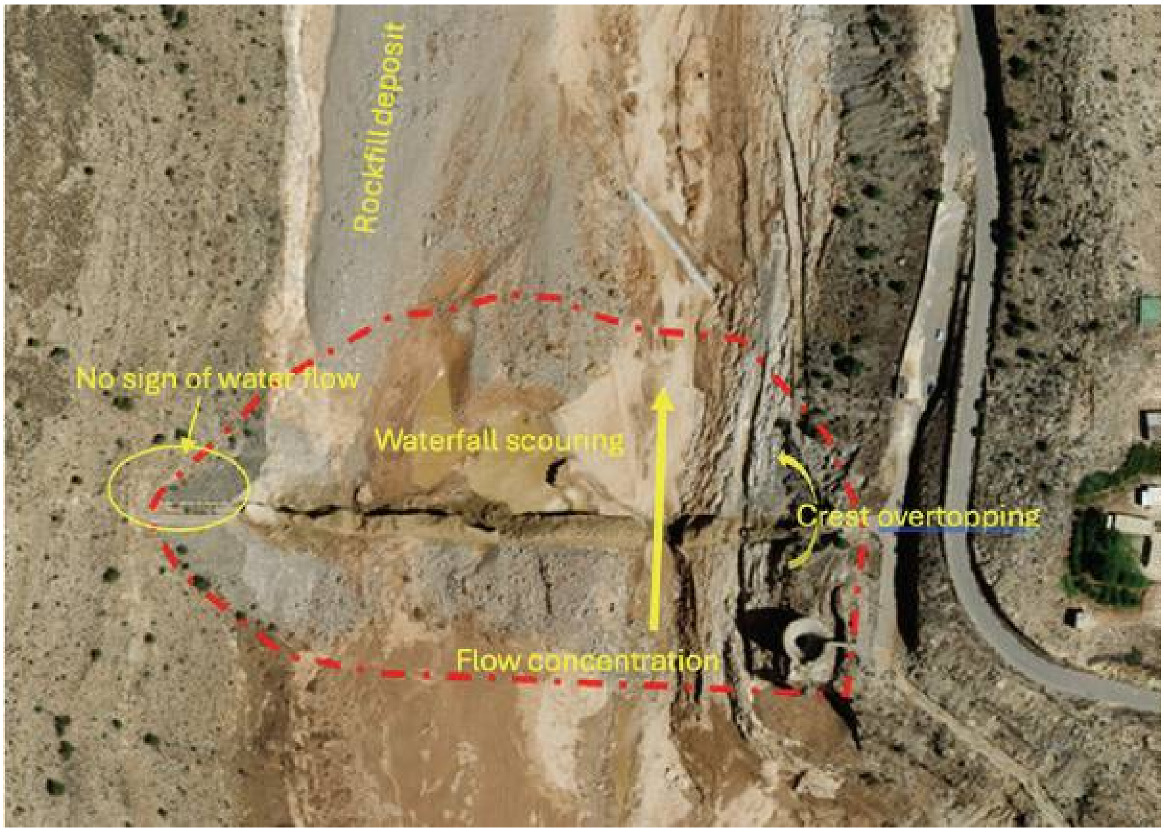
PHOTO 4.4. View of the remains of the dam's left abutment of the Abu Mansour Dam.

Source: Photo from Claudia Gazzini / International Crisis Group, annotations by authors.

PHOTO 4.5. The view of the downstream of Abu Mansur dam.

Source: Photo from Claudia Gazzini / International Crisis Group, annotations by authors.

PHOTO 4.6. **Satellite view of Abu Mansur dam (13 September 2023).**



Source: World Bank / IPSOS, annotations by authors

4.4 OVERTOPPING

Overtopping occurs when the water level behind a dam rises over the top of the dam and the embankment, which supports the dam, is gradually eroded until part or the entire structure fails and the water flows freely. There were three potential contributing factors that may have increased the probability of overtopping of the Derna and Abu Mansour dams. The first of these relates to the relatively limited capacity of the morning glory shaft spillway (about 350 m^3 per second in the case of Derna dam and 170 m^3 per second in the case of the Abu Mansour Dam) which are limited to the original design flood, meaning that precipitation higher than design conditions leads to quick saturation, when compared to a surface spillway, and overtopping.[12] The second of these factors relates to severe settlement of the dam crest for both dams, lowering the level of the dam resulting in a 'V-shape' of the dam in which the crest was lower than the dam sides, thus reducing the volume needed for overtopping. The third factor is the probable weakness of the embankment, particularly at the right abutment, as consequence of the steepness of the valley flank and the reported piping during the 1986 flood, where the reservoir reached el. 216.65 masl, that is around 8 m below the full supply level (Stucky 2002-2004; Ministry of Water Resources, personal communications 2024).

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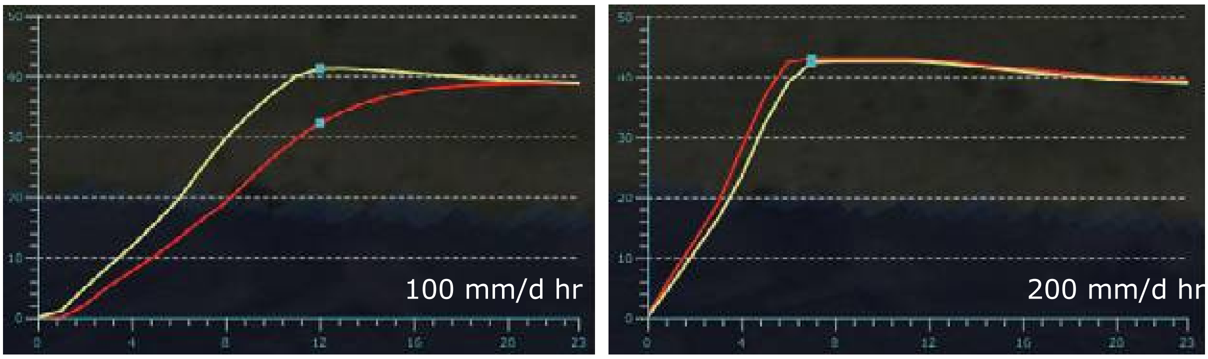
[12] This is in line with the observation of no erosion of the hill slopes next to Abu Mansour Dam (post failure). Such erosion would have been expected in case of overtopping a dam with a normal longitudinal profile (higher in the middle of the crest and decaying towards the banks).

FIGURE 4.4. **Water levels in Abu Mansour reservoir.**

Y-axis: water depth in meters. X-axis: timeframes (1 timeframe = 2 hours). Yellow and red represents the simulations with 50 mm/d and 25 mm/d infiltration, respectively.



Source: Original for this publication based on hydrological modelling by Tygron (see Annex 2).

The different measurement sources available suggest that the event was very likely capable of inducing an overtopping at both the Derna and Abu Mansour dams. With an estimated maximum capacity of between 23.7 and 28.5 MCM, the Abu Mansour Dam would probably have exceeded its capacity with an accumulated average precipitation of 150-200 mm in the catchment. In theory, the water level within Abu Mansur's reservoir remains below the crest at this rainfall quantity, but the crest level is predicted to be lower than 227 masl due to settlement. This becomes clear when 150 mm is multiplied with the surface area of the entire catchment area giving a possible storm volume of nearly 70 MCM (not accounting for infiltration). Similarly, the water level in the Derna reservoir overtops the dam's crest with rainfall more than 150mm. More than 200mm of rainfall leads to the submersion of both dams.

However, there are a number of complicating hydraulic factors. These include uncertainty in actual rainfall amounts, how this rainfall was distributed in time and over the entire catchment, infiltration capacity, evaporation rates, and the actual height of the dam crest, among others. From satellite imagery, it is clear that the initial state of the reservoir was empty and that the antecedent situation was dry. Given the uncertainty regarding rainfall, the sensitivity analyses provide a range of potential scenarios. The Tygron model results show that significant overtopping does not occur for low rainfall intensity of 68 mm in 12 hours (Table 4.1), whatever the setting of the other hydraulic factors. When infiltration and crest height are set to a 'worst case' scenario, meaning that overtopping is expected sooner, there is a possibility of overtopping by 10 cm, but this is considered insignificant. For events of 100 mm per 24 hours, overtopping occurs if the infiltration is set 'worst case', while overtopping occurs for events of 200 mm per day, no matter the other variables. The model results further show that rainfall across the entire watershed with an intensity of 140 mm in 24 hours gives a discharge of approximately 520 m^3 per second, filling the reservoir of the Abu Mansour Dam and causing overtopping after 20 hours (140 mm/24 h, infiltration of 50 mm/d and a crest height of +226 m above mean sea level). As part of the sensitivity analysis, similar graphs are generated for rainfall events of 100 mm and 200 mm in 24 hours, with different infiltration rates (Figure 4.4). Figure 4.5 shows the overtopping as simulated with the computer model for a 100 mm per day (left) and a 200 mm per day event. These figures show that – as expected – the rise of the water level in front of Abu Mansour dam goes faster with the higher precipitation intensity (24 hours versus 15 hours to reach the critical level). If these amounts were received in less than the assumed 24 hours, they would result in even greater intensity. Comparing the yellow (25 mm/d infiltration rate) with the red line (50 mm/d), shows that water level rises faster with lower infiltration rates. This is because more water is available to raise the water level in the reservoir. This effect is smaller for the higher rainfall intensity (right versus left figure).

TABLE 4.1. Simulation results of water levels and possible overtopping with various input parameters.

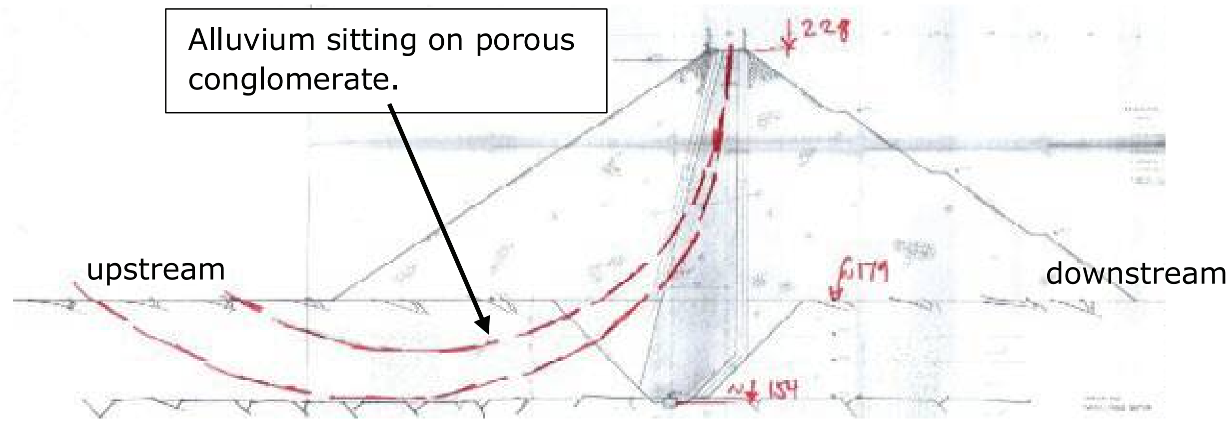
Rainfall [mm/d]	Infiltration [mm/d]	Minimal crest height (in the center) [+ masl]	Overtopping	Max water level over crest [m]	Max water level in the basin [+ masl]	Remarks
68	50	227	No	-	222	GPM Nasa *[in 12 hours]*
100	50	227	No	-	225	Sensitivity
200	50	227	Yes	1.25	228.25	GPEX
68	25	227	No	-	226	GPM Nasa *[in 12 hours]*
100	25	227	Yes	0.5	227.5	Sensitivity
200	25	227	Yes	1.5	228.5	GPEX
68	25	226	No	0.13	226.3	GPM Nasa *[in 12 hours]*
100	25	226	Yes	1.0	227	Sensitivity
200	25	226	Yes	2.5	228.5	GPEX
68	50	226	Yes	-	222	GPM Nasa *[in 12 hours]*
100	50	226	No	-	225	Sensitivity
200	50	226	Yes	2	228.25	GPEX

FIGURE 4.5. Screendumps of Tygron results before (left) and after the overtopping of the Abu Mansour Dam.

Source: Original for this publication based on hydrological modelling by Tygron (see Annex 2).

Shortly after the overtopping of the Abu Mansour Dam, the embankment began to wash away. This occurred on the right bank due to its steeper slope and in the central part because of the lowest crest levels. The erosion was more pronounced on the right bank, as evidenced by the deep scouring of the rock. The deposition of eroded material at the foot of the left bank is also an indicator of the concentration of the flow along the opposite bank. The shear surface shown in Photo 4.4 is likely the result of sliding that developed during the flood (Figure 4.6), indicating that a structural weakness was present and possibly initiated long before September 2023. While not a trigger for the failure, this sliding could have been reactivated during the heavy rainfall observed at the dam site before the arrival of the flood, or at the beginning of the overflowing, leading to a relatively rapid decrease in the upstream level. The breaching process slowed down when the thickness of the core became sufficient to resist the flow. The erosion of the remaining downstream shoulder continues, followed by the upstream shoulder through the breaches in the core. These eroded channels correspond approximately to the location of the vertical settlement tubes where compaction could not be properly achieved.

FIGURE 4.6. Types of possible sliding surfaces.



There are a number of other contributing factors to the vulnerability of overtopping in the case of the Abu Mansour Dam. First the seepage, observed downstream mainly through the foundation and likely at the interface of the core with the foundation due to the geometry of the concrete blocks particularly on the right abutment. Another factor is the thin filter, the effective thickness of which is considerably reduced by the internal deformation of the embankment, either during construction or because of excessive settlement. In Figure 4.6, the elevation 0, should correspond to almost 3 m above the original wadi bed as the height of the embankment is 48 m above the wadi bed. The height of the overflow was relatively small on the right abutment. However, in the central part of the embankment, where the settlement has lowered the crest by more than 1.20m (measured in 2004 and confirmed by the icesat2 lidar measurements), the water overflow should exceed 1.50 m, which will have a significant erosive effect.

BOX 4.1. Adapting dam operations to climate uncertainties

Dam safety has traditionally focused on the structural and hydraulic performance of dams in order to protect them against overtopping caused by extreme hydrological events. The primary concept is that of the Probable Maximum Precipitation (PMP), being the theoretical upper limit of precipitation over a dam's watershed. There are multiple methodologies that can be implemented to calculate the PMP and the available data typically dictate which methodology is used in a given context. Ultimately, the process should calculate the maximum possible moisture-inflow into the catchment area. The PMP also determines the related Probable Maximum Flood (PMF), which is the maximum flood discharge resulting from a PMP event. The PMF is obtained by converting the estimated PMP into the PMF through rainfall-runoff modeling. The PMF determines the functioning and safety of a dam under the most extreme conditions and is often used as the safety check flood. The PMP, and by extension the PMF, are highly variable within changing and uncertain climatic conditions. It is thus necessary to tie these calculations to projected climate changes.

Climate change is leading to shifts in the amount of rainfall, as well as it's spatial and temporal distribution. More rainfall leads to higher water discharges in rivers and higher loads on dams. Climate change also induces changes in the catchment, making the land drier, harder, and increasingly devoid of vegetation, meaning that it is less able to absorb the water before it pools up dangerously behind the dams. This is the conclusion of Ashoor (2022), who considered climate change and desertification in Libya has influenced runoff and storage of water in Wadi Derna.

The inherent sensitivity of the water sector to changes in precipitation, river basin runoff and increasingly extreme river flows makes long-term planning more challenging for dam related projects. Historical observed data are no longer adequate by itself for medium- to long-term planning within the context of climate change. While this will affect many types of infrastructure, severe risks are associated with potential dam failures due to intensified floods under future climate change conditions. High-risk dams subjected to highly intensified rainfall and a sharp increase in flood discharge, as well as high consequences in case of dam failure, require more advanced assessment methods of assessment that consider a combination of four dimensions: data, downscaling, incorporating uncertainty and rainfall-runoff modeling.

Resilient design principles and adaptative management are also increasingly needed to deal with increasing uncertainty. These include six principles that can help build the resilience of water systems and be implemented in complementary ways:

- Conducting network and criticality analysis to identify where to invest in strengthening or redundancy.
- Improving maintenance, to reduce vulnerability.
- Managing demand, to mitigate the impact of interruptions.
- Working with nature and better integrating the WSS system with the management of the water sources.
- Focusing on planning and institutions.
- Testing new technologies and innovations, where available and sensible.

Source: World Bank (forthcoming); Ashoor (2022) and Stip et al. (2019)

4.5 SPILLWAY DESIGN

Ensuring sufficient capacity to safely allow water to pass from the reservoir to the downstream area of the dam is critical for ensuring safety. Spillways are designed to handle excess water inflows, especially during periods of heavy rainfall, to prevent the reservoir from overtopping and potential failure of the dam. If the spillway capacity is too small to allow the water to drain safely, this can result in higher water levels behind the dam and an increased risk of failure. Design drawings make it possible to calculate the maximum capacities of the spillways: 350 m^3 per second for the Derna Dam and 170 m^3 per second for the Abu Mansour Dam (Figure 3.9). The spillway capacity of the Derna Dam was higher than of the capacity of the Abu Mansour Dam, because the flow from the intermediate catchment area between the two dams (ca. 100 km^2) doesn't benefit from the retention effect of the large Abu Mansour reservoir. Notably, there was only one spillway device at each dam based on a morning glory design with limited capacity. The result was that an exceedance of the reservoir volume combined with a water input higher than the limited spillway capacity leads to dangerous overtopping and contemporary dam design practices would recommend a significantly larger capacity or alternative type of spillway to ensure safe passage of the floodwaters.

PHOTO 4.7. Morning glory spillway at the Abu Mansour Dam.

Source: Claudia Gazzini/International Crisis Group.

4.6 PIPING, CRACKS AND FISSURES DUE TO SETTLEMENT

Settlement is frequently observed on embankment dams in the first years after construction because of its own weight and the long-term consolidation of the material constitutive of the clay core. Importantly, settlement of the dam can be a sign of damage in the impervious clay core. The damage can open water paths across the core, permitting fine clay particles to migrate downstream and open cracks in the impervious component of the dam. This phenomenon can lead to internal erosion, creating a pipe-like channel through the dam or its foundation, known as “piping”, as well as changes in the pore water pressure in the dam body, that undermine the structural integrity of the dam. However, a sound design makes these cracks self-reparable. The purpose of the monitoring of the dam is to control and to confirm that the behavior of the dam is correct and that the dam is secure and in good operational condition.

The crest of the Abu Mansour Dam showed substantial and asymmetrical settlement since its first impounding, according to elevation data and to earlier reports (Hidroprojekat 1985b; Stucky 2004). The settlement of the central part of the dam reached 60 cm during the first years of operation. It increased significantly when a strong storm hit the region in 1986. In 1999, a total settlement of 1.20 m was measured in the highest part of the dam. A horizontal deformation was also observed. While reinforcement and mitigation measures proposed in the 2000s these were not implemented. Surveys in 2002 revealed the settlements had resulted in horizontal fissures in the core of a certain part of the Abu Mansour Dam. These were assessed as extremely detrimental for the safety of the dam (Stucky 2003), with a sudden loading of the dam by even a modest flood having the potential to cause internal erosion of the core and the destruction of the dam by mitigation of the materials in the core downstream.

During the 1986 flood, a probable wash out of water was observed at the downstream toe of the Abu Mansour Dam. The color was different to that of the river water and the downstream zone of the dam was saturated (Stucky 2003). The whitish waters seeping through both dams during previous high-water events suggests that piping was probably already underway in both the foundation and the embankment. While it is not possible to confirm that any such piping occurred simultaneously to the overtopping, the two failure mechanisms have the same causes, including a rapid rising of the reservoir due to the 2023 storm event, a non-resilient or inappropriate design, inadequate reviews of the dam safety and a lack of mitigation measures during operation.

The design drawings show some possible karstic features in the limestone bedrock in the dam foundation. The cracks were filled during construction by grouting. However, there is no known information on the grouting procedure (number, depth group material, grouting volume and pressure, permeability tests performed, etc.). The probable differential settlement of the embankment would have also caused severe cracking, particularly near the right abutment where the slope is very steep, promoting deeper drying of the core. This could have contributed to erosion and subsequent collapse of the clay core contributing to failure by overtopping. While there were no signs of seepage or cracks reported in the Derna Dam, this does not mean they had not developed.

4.7 DAM AGEING / DESICCATION

If dams are well designed, monitored and maintained, ageing is not a cause for reduction of safety. However, continued seepage over time can lead to changes in the pore pressure in the dam body. The sensitivity to such effects depends on the type of clay. The investigations in 2003 and 2004 show a low plasticity of the clay (Stucky 2004), so the sensitivity was low. The probability of failure because of seepage through the clay core is therefore assumed to be low given the low plasticity of the clay.

The Derna and Abu Mansour reservoirs only ever filled with water during short periods following floods, which are not annual occurrence. This can result in desiccation of the clay core near the crest if it is dry for an extended period. As a result, the clay may shrink, leading to cracks in the core. Significant dam deformations might result in disturbance of the relatively thin clay core in the dam and a higher permeability.

The clay core is visible on design drawings and on pictures of the failed dams. While significant settlement of the crest has been observed, there is no information about the causes of these deformations and if the clay core has suffered. As the reservoir is empty most of the time, there is no, or limited, seepage and thus no other evidence of ageing, desiccation, or disturbance of the clay core.

PHOTO 4.8. Remains of clay core in collapsed dams: the Abu Mansour Dam (left) and the Derna Dam (right).

Source: Claudia Gazzini/International Crisis Group.

4.8 DAM OPERATIONAL MANAGEMENT

Several reports mentioned that the engineer responsible for the dam should have made sure that water did not exceed the dam's upper carrying capacity by releasing water to keep its level lower than the critical limit when observing the considerable volume of water entering the reservoir. However, the free-flow morning glory spillway does not allow any action from an operator and the only mechanical device that can be opened and closed is the bottom outlet. According to the design drawings, the steel pipes of the bottom outlets have a diameter of 1 or 1.5 m and are used to control the reservoir level for maintenance purposes, which is not within the magnitude of the estimated flood discharge. Furthermore, there is no indication of obstruction of the spillways by debris or other floating material, with satellite images showing that the reservoirs were emptied within one week after filling in previous years. The assumption of improper dam management was based on videos of the flood in Derna that show low river discharge just before the dam collapsed. However, the maximum river discharge of an open spillway at the Derna Dam was only 350 m^3 per second and would not give a remarkably high river discharge. This suggest that improper dam operation and management during the events of September 10 and 11 cannot have been the cause of the dam failures.

4.9 MAINTENANCE AND SURVEILLANCE

There were several reports that both dams suffered damage and were not maintained according to international standards (Section 2.4) with urgent rehabilitation works recommended for both dams in 2004 (Stucky 2004). Measures were particularly needed for the Abu Mansour Dam based on the observed behavior, including raising of the dam to ensure an adequate freeboard, grouting to consolidate the core, and enlarging the spillway capacity. A conclusion of Ashoor (2022) is that the dams in the Wadi Derna basin needed periodic maintenance to decrease the high potential of flood risk, and that damage had been incurred on the hydraulic devices caused by the floods in 1986.

In the case of the Derna and Abu Mansour dams, lack of maintenance could have had several negative effects. There is no evidence of an update of the design after periodic safety evaluations. The original dam design in the 1970s shows a number of deficiencies according to contemporary design criteria. The design conditions were based on a theoretical precipitation-discharge transfer function and an extrapolation of available hydrologic data of a short period (about 20 years data) to determinate low-frequency flood events. Over the years, more hydrological data has been made available. The state-of-the art of dam construction knowledge has developed since then and the dams were not fitted to the contemporary design conditions. Any new dams should be adapted to modern practice, and to current hydrological estimates, which seem to be much larger than computed during the dam design.

Given the prevailing conditions, there was likely a lack of, or limited, surveillance that would preclude proper monitoring and checking of the dam's behavior to determine if it was performing according to the design purpose. There was also likely limited visual inspections, combined with repair activities and emergency plans. A dam often suffers damage by gradual degradation, extreme weather conditions or by unwanted human activities. Damage of the dam construction may affect safety but will only occur after extreme loads or too many unwanted human activities (like removing stones). Given the lack of available data and information it is difficult to ascertain the amount of degradation or damage. Gradual degradation of hydromechanics parts is normal. As the safety devices of Derna and Abu Mansour dams are free-flow, morning glory spillways, not controlled by hydromechanical equipment, the dam safety is not directly affected degradation of the hydromechanics parts. The lack of monitoring, visual inspection, regular dam safety reviews and repair activities, are likely to have negatively impacted the reliability of the dams. However, it is likely that the rehabilitation work recommended in 2003 aimed at improving the safety of the dams would not have prevented the failure of both dams, as it did not address properly the excessive subsidence of the dams, or the internal erosion evidenced since 1986.

4.10 CONCLUSIONS

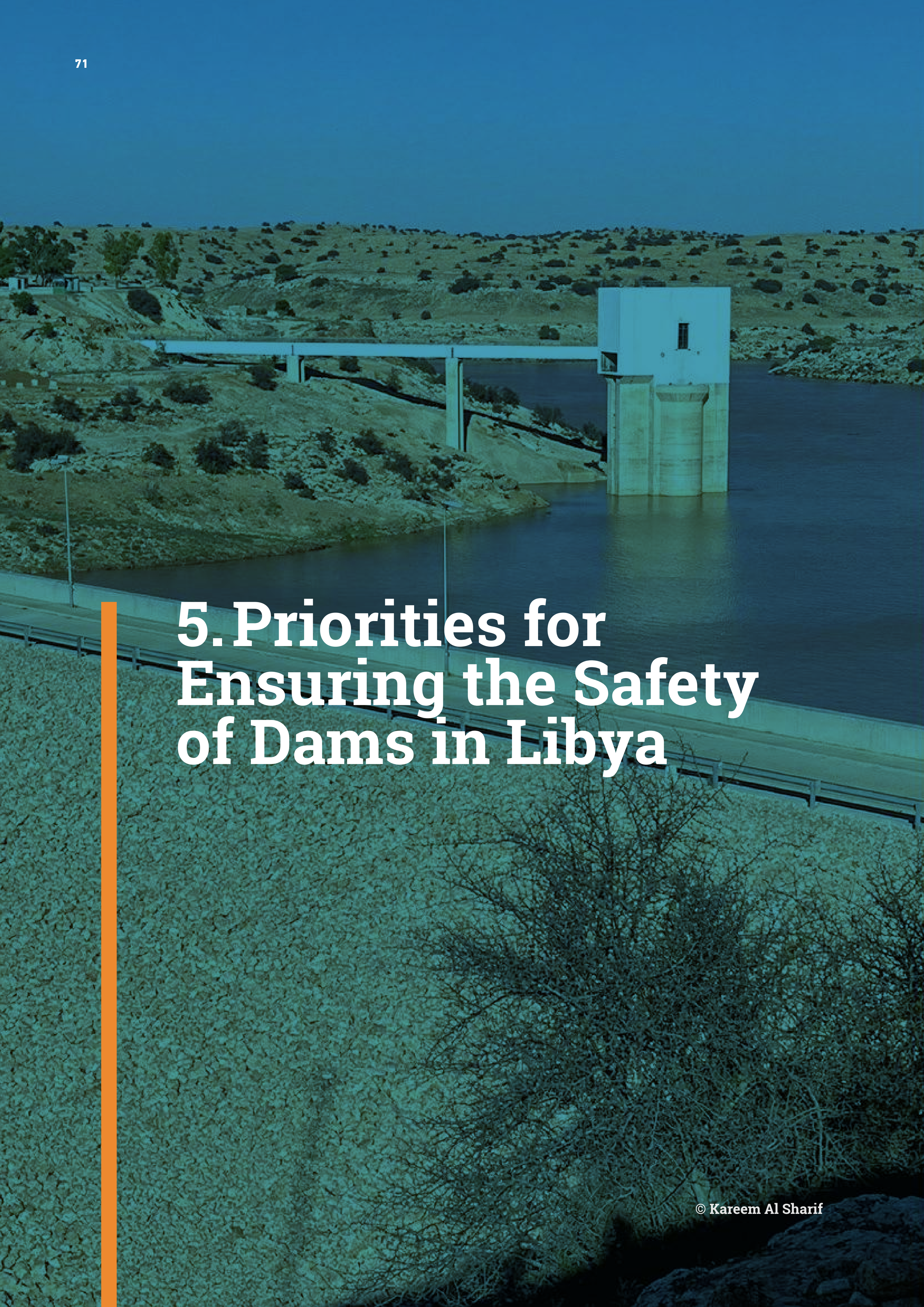
The tragic failure of the dams in Wadi Derna is the culmination of a range of factors stemming from the original design, exacerbated by the extreme precipitation during Storm Daniel. Precipitation across the catchment resulted in runoff higher than the flood volume in the reservoir resulting in overtopping that was aggravated by the limited spillway capacity. The safety threshold of each dam was too low because of an outdated and inadequate design that was not adapted to modern standards and updated design conditions, as well as the severe and probably differential settlement, particularly at the Abu Mansour Dam due to the very steep right abutment. Both dams were only designed to withstand a 1,000 year return period and did not have an emergency spillway, so were not designed for overload conditions. After a flood event, the reservoirs were only drawn down by the leakage through the foundation, which could have led to the development of more piping. While regular dam inspections were carried out, these were not sufficient to identify behavioral anomalies and prevent possible damage to the dams. Inadequate dam operation management in the days prior to and during the event does not seem to have contributed to the failures.

The assessment concludes that there were likely two independent failure events. Both dams received runoff volumes higher than their capacities and the exact sequence remains uncertain and subject to further verification. However, while the specific sequence remains unclear, eyewitness accounts suggest that the Derna Dam failed at around 11:00pm on the evening of September 10, 2023. Given that the precipitation was estimated to be over 150mm in 24 hours, water levels most likely reached the full supply in five hours, overtopping the crest of the dam. Overtopping likely resulted in damage to the surface of the dam and probably led to erosion at crest level, allowing even more water to flow over the dam. The breach could have been accentuated by instability or internal erosion. Once the dam overtopped, breaching would have continued and most likely the core, which was already in a poor state, ultimately collapsed, leading to the sudden and complete collapse of the entire structure. This resulted in a flood wave with a flow estimated to have been in the order of between 1,500 and 5,000 m^3 per second. This flood wave would have reached the city of Derna within a few minutes, and been more than sufficient to flood a significant part of the city.

The Abu Mansour Dam is thought to have failed at around 02:40am on the morning of September 11, 2023, due to overtopping, which was accentuated by piping, geotechnical instability, and issues with the original design. This would have resulted in a second flood wave with a flow estimated to have been in the order of 7,000 m^3 per second, inundating and overwhelming a significant part of the city. There were likely a number of contributing factors and concerns had been identified following the initial construction, including severe settlement of the crest, seepage through the foundation particularly on the right abutment, as well as likely at the interface of the core with the foundation. Another contributing factor likely included the thin filter, the effective thickness of which was considerably reduced by the internal deformation of the embankment, either during construction or because of excessive settlement. As a result, piping or internal stability was probably underway in both the foundation and the embankment prior to the storm event and would have likely led to an eventual failure in the absence of remedial measures. There are likely other contributing factors, such as differential settlement of the embankment that would have caused severe cracking, particularly near the right abutment where the slope is very steep, promoting deeper drying of the core, and desiccation of the clay core near the crest due to dry weather and the upper 10 meters of the embankment having remained dry since the dam was built. Although this is likely to be correct, no flood routing considering the remedial works has been performed to my knowledge. Considering the uncertainty in the hydrology (reinforced by recommendations in Section 6.2) this feels quite speculative and could be criticized. Wasn't one of the dams due to be raised? Having said that the large leakage observed during the 1986 flood, if piping was a contributory factor to the overtopping failure if not addressed by remedial works would have been problematic. It may be worth considering rewording this section. The erosion of the embankment shortly after the overflow would have initially occurred, and was more pronounced, on the right bank due to its steeper slope and in the central part because of the higher water level. The erosion of the remaining downstream shoulder would have continued, followed by the upstream shoulder through the breaches in the core. These eroded channels correspond approximately to the location of the vertical settlement tubes where compaction could not be properly achieved.

The consequences associated with the failure of the Derna Dam and the Abu Mansour Dam were catastrophic and would have been the same irrespective of the failure mode. Furthermore, given the magnitude of the flood event, it is unlikely that the rehabilitation work recommended in 2003 would have prevented the failure of both dams. The safety reviews carried out during operation, particularly those in 2003-2004, were not sufficiently conclusive and did not result in the implementation of adequate mitigation measures. While the measures were aimed at improving the safety of the dams, the recommendations did not properly address the excessive subsidence of the dams or the piping evident since 1986. Contemporary dam design practices would also recommend a significantly larger capacity or alternative type of spillway to ensure safe passage of the floodwaters. In addition, no measures were put in place to improve the flood protection of the city and the absence of any Emergency Preparedness Plans and effective early warning systems likely exacerbated the consequences associated with the failure of both dams.

It is important to note that several questions remain unanswered, and this analysis may be revised following the availability of new data or information. These include: (i) the maximum water level at the time of the breach, the functionality of the spillway, and the flood passing over the crest of the dam; (ii) the occurrence of the dam's embankment and instability before the reservoir was high enough, given the weakening of the foundation and embankment due to erosion, on the one hand, and the heavy rains to which the dam was subjected, on the other; (iii) the traces left by the flood wave along the watercourse from upstream of the Abu Mansur dam to the entrance to the city of Derna downstream; and, (iv) the occurrence of any sliding of the river flanks between the two dams, which could have caused breaking waves that would have aggravated the situation.



5. Priorities for Ensuring the Safety of Dams in Libya

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1 A remote sensing assessment identified 14 dams not included in the original register, none of which are estimated to above 15m high but some of which potentially impound more than 3 MCM.

2 A preliminary estimate of the population and infrastructure exposed downstream of all 28 dams was carried out to provide a rapid, high level assessment of the potential consequences of another dam failure.

3 Several dams rank as presenting a very high risk and should be subject to an immediate evaluation to review the design criteria and outlet/spillway characteristics, along with the early warning systems and emergency preparedness plans in place.

5.1 AN UPDATED INVENTORY OF DAMS IN LIBYA

The tragic failure of the dams in Wadi Derna highlights the need to assess the safety of other dams in Libya. Central to any such assessment is having a comprehensive inventory of all existing dams that includes information on the size or dam geometry (height, crest length, reservoir capacity, and so forth) as well as the type of dam and downstream hazard potential. This can help to inform a preliminary hazard classification and determine those dams that should be subject to more detailed assessments and specific technical regulatory provisions.

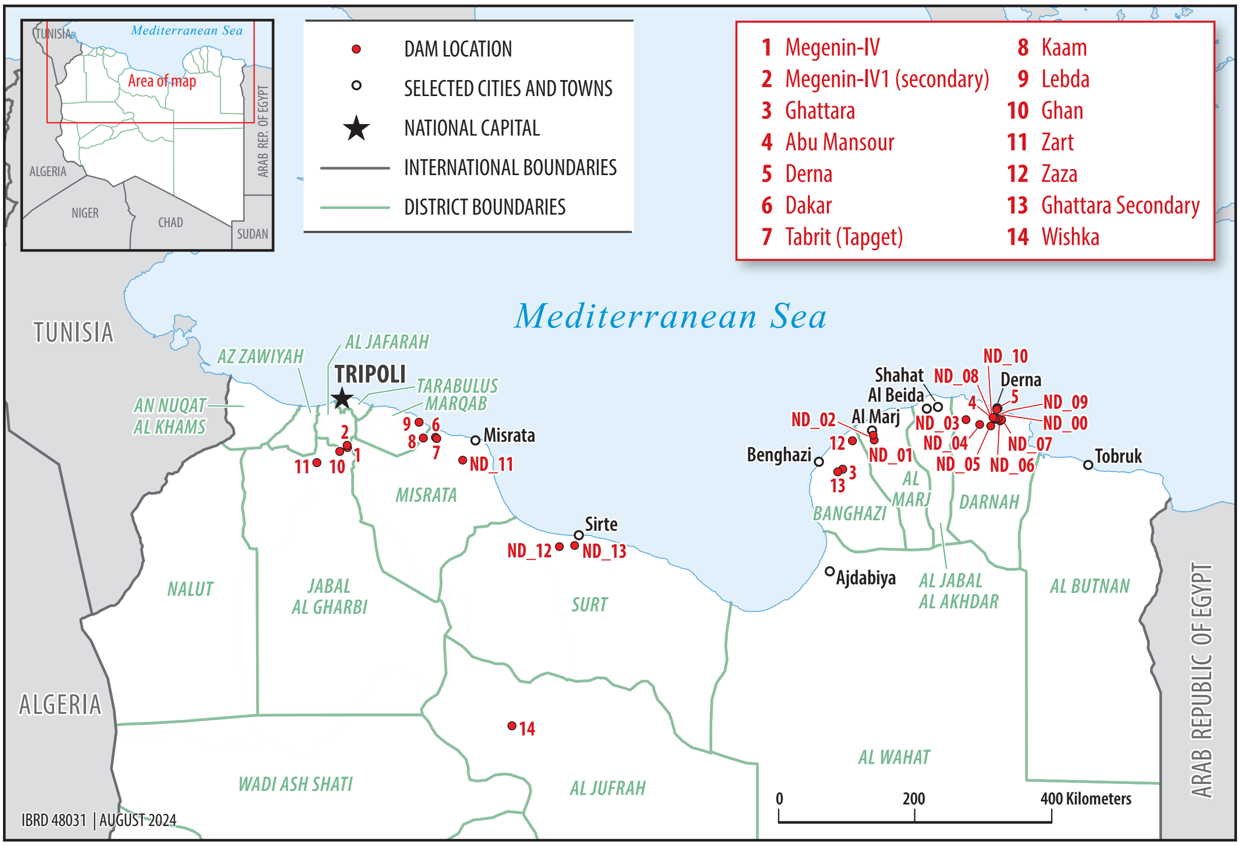
While the development of national inventories has proven cumbersome in the past, improvements in remote sensing technologies and the development of pattern recognition algorithms specific to dams and reservoirs are helping to simplify the initial inventory and capture small dams. Such remote sensing approaches can also be useful in facilitating rapid, high-level assessments of potential consequences that can inform a preliminary risk classification. Based on this initial assessment, more detailed dam-break modeling, flood mapping, and loss-of-life assessments can be conducted and used to develop emergency preparedness plans for higher risk dams.

The existing inventory of large dams in Libya includes 14 dams according to the World Register of Dams (WRD). This is a global database of large dams curated by the International Commission on Large Dams (ICOLD) that includes more than 62,000 records from over 166 countries. The attributes include characteristics specific to the dams (year of commissioning, height, length, type, etc.), the associated reservoirs (volume of the reservoir, area of the reservoir, purposes, etc.), stakeholders (owners, design offices, contractors, etc.) and elements relating to geography (country, river concerned, locality). Most of the large dams registered in the WRD are dedicated to flood-protection or irrigation purposes. The 14 records for Libya have been curated by updating and verifying the coordinates and their contributing catchment area. These are displayed along with some of the attributes reported by the WRD (such as height, crest length, storage, and spillway capacities) (Table 5.1). Most of these dams were designed and built during the 1970s to the 1980s (Photo 5.1).

An updated inventory was prepared using a semi-automated routine based on remote sensing data to identify dams not reported in public records. First, a national water occurrence map was derived from multispectral imagery of Landsat and Sentinel 2. This identified the presence of surface water (NDWI thresholding) in any satellite image, thus identifying potential water bodies. Due to the ephemeral nature of the waterways in Libya and the minimal water retention in dams along the wadi systems, an additional topographic analysis was conducted. This consisted of identifying presence of sink-regions in a digital elevation model (Copernicus GLO-30 DEM) which could lead to dam-like structures. Both methods created a list of potential locations of dams, which were first run through an automated classification algorithm, and manually reviewed and curated. Several relatively small (2-12 m) height earth-filled dams were identified, with those that were categorized as dams of significance and showed signs of previous water retention retained in the inventory (Table 5.2). The height of the dam body and length of the crest were extracted, and the dams further classified according to construction type. Many of these structures are dedicated to erosion and flood mitigation in the predominantly dry wadi systems that are only active during significant rainfall events, as well as irrigation activities (Photo 5.2).

While none of the dams identified through remote sensing are reported to be over 15m, several are above 5m and may impound more than 3 MCM and could thus be considered large dams.[13] It should also be noted that the dam heights were derived from a DEM (Copernicus Glo-30) that could potentially have an error of between 2 to 5 m in high-slope areas. Thus, the actual height values remain with a certain degree of uncertainty and should be verified through physical inspections. This notwithstanding, good industry practice would ensure dam safety provisions are applied to any dam that could cause safety risks, regardless of size or retention capacity. Such provisions apply to all World Bank financed investment projects and are outlined in the Environmental and Social Framework, Environmental and Social Standard 4 (ESS4) Annex 1.[14] A number of dams identified exhibit downstream populations (for instance ND_02 and ND_09 have a sparsely populated area 2 and 5 km downstream respectively). Several of these structures were identified in the proximity of the Wadi Derna, with ND_08 and ND_10 damming a small lateral tributary to Derna, after the Abu Mansour Dam, with others draining to wadi systems to the south and east of Derna.

MAP 5.1. Location of major dams in Libya.



Source: Original for this publication.

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[13] ICOLD and the World Bank define large dams as those having a height of 15 meters or greater from the lowest foundation to crest; or between 5 and 15 meters, impounding more than 3 million cubic meters.

[14] Safety risks such as an unusually large flood-handling requirement; location in a zone of high seismicity; foundations that are complex and difficult to prepare; retention of toxic materials; or potential for significant downstream impacts.

TABLE 5.1. Inventory of Libyan large dams based on the ICOLD World Register of Dams and updated through remote sensing data.

Name	Year	Nearest Town	Dam Type	Height (m)	Reservoir Capacity (MCM)	Catchment area (km^2)	Spillway Capacity (m^3/s)	Crest Length (m)	Latitude	Longitude	Code in Photo 5.1
Megenin-IV	1972	Tripoli	Earthfill	42	58	576	50	881	32.294026	13.247623	I)
Megenin-IV1 (secondary)	1972	Tripoli	Earthfill	30	58	576	50	871	32.305089	13.251100	J)
Ghattara	1973	Benghazi	Earthfill	55	122	1240	92	335	32.027034	20.405291	E)
Abu Mansour	1978	Derna	Earthfill	73	23.7	463	170	280	32.753066	22.631407	A)
Derna	1978	Derna	Earthfill	40	1.15	400	350	100	32.659484	22.577248	C)
Dakar	1978	Zletin	Earthfill	19	1.6	2300	-	358	32.417111	14.519696	B)
Tabrit (Tapget)	1978	Zletin	Earthfill	24	2	12	-	200	32.402929	14.537017	K)
Kaam	1979	Khoms	Earthfill	50	111	2500	500	650	32.409220	14.341901	G)
Lebda	1982	Khoms	Earthfill	33	5.2	300	416	515	32.600870	14.281787	H)
Ghan	1982	Gharian	Earthfill	80	30	650	1640	316	32.244338	13.136161	D)
Zart	1982	Gharian	Earthfill	32	8.6	640	1050	2700	32.108046	12.804462	M)
Zaza	1984	Benghazi	Gravity Concrete	38	1.75	170	60	135	32.375671	20.544973	N)
Ghattara Secondary	2005	Benghazi	Earthfill	34	5.3	61	240	235	31.995419	20.334579	F)
Wishka	2006	Hun/ Waddan	Earthfill	25	3.65	417	315	235	28.832113	15.623938	L)

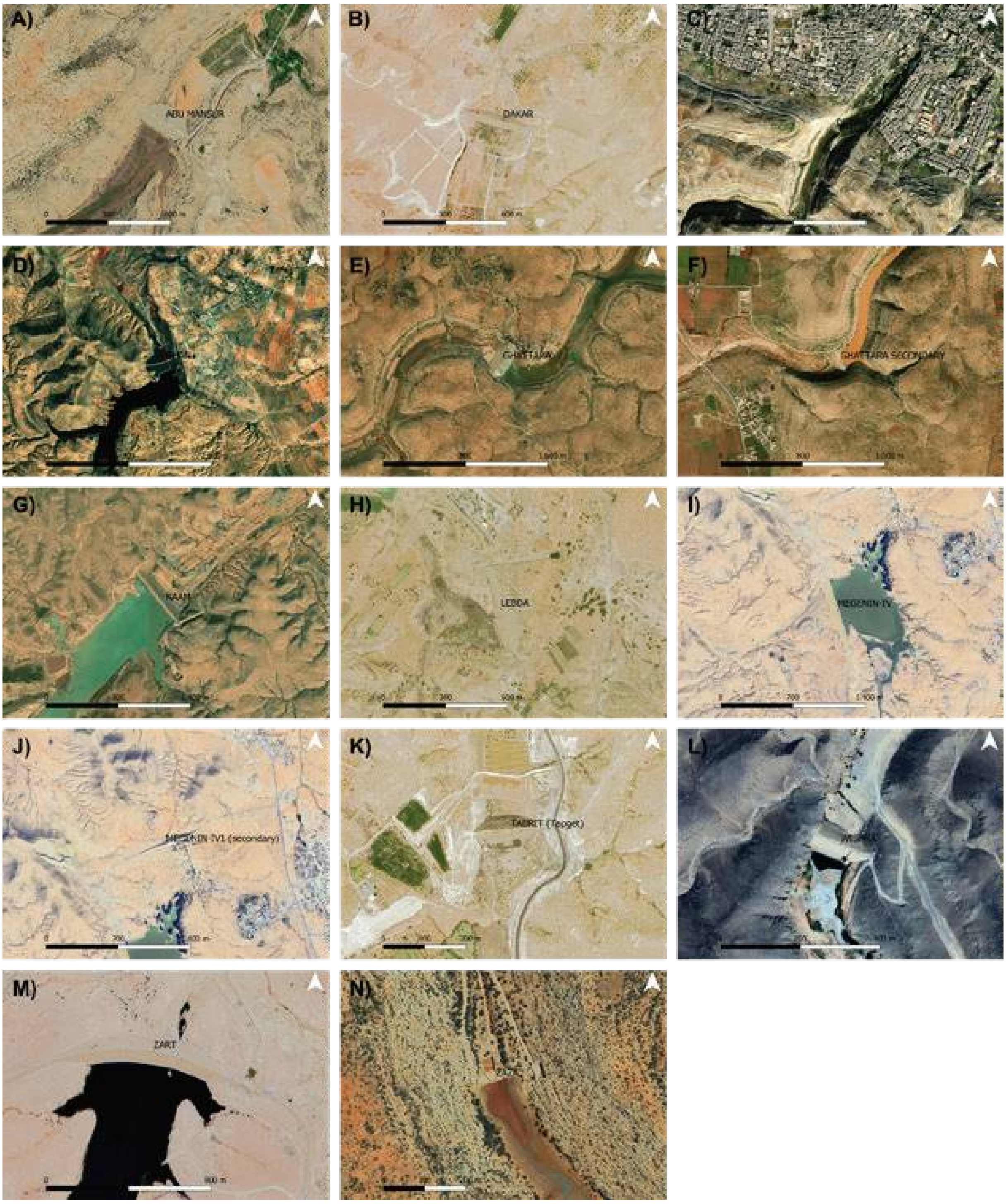
TABLE 5.2. Inventory of Libyan dams based on remote sensing data.

Name	Year	Nearest Town	Dam Type	Height (m)	Reservoir Capacity (MCM)	Catchment Area (km^2)*	Spillway capacity (m^3/s)	Crest Length (m)	Latitude	Longitude	Code in Photo 5.2
ND_00			Earthfill	10		7.2		90	32.63712	22.65215	A)
ND_01			Earthfill	1.5		4.44		104	32.38232	20.86216	B)
ND_02	<1984		Earthfill	11		156		490	32.44282	20.84662	C)
ND_03			Earthfill	12		75		400	32.63033	22.19046	D)
ND_04			Earthfill	5		139		440	32.57156	22.38716	E)
ND_05			Earthfill	12		576		320	32.55325	22.54808	F)
ND_06			Earthfill	5		144		103	32.61362	22.68276	G)
ND_07			Earthfill	7		126		320	32.62892	22.70456	H)
ND_08			Earthfill	2		15		160	32.63358	22.61557	I)
ND_09	1994		Earthfill	10		8.9**		440	32.6452	22.64932	J)
ND_10			Earthfill	4		16.8		360	32.64305	22.61446	K)
ND_11			Earthfill	3		2140		2400	32.13593	14.91522	L)
ND_12			Earthfill	7		96.7		700	31.07096	16.31345	M)
ND_13	<1984		Earthfill	7		832		540	31.08719	16.53383	N)

* Estimating using Hydromerit upstream area
**Refined from a drainage analysis using TandemX COPGLO30 DEM.

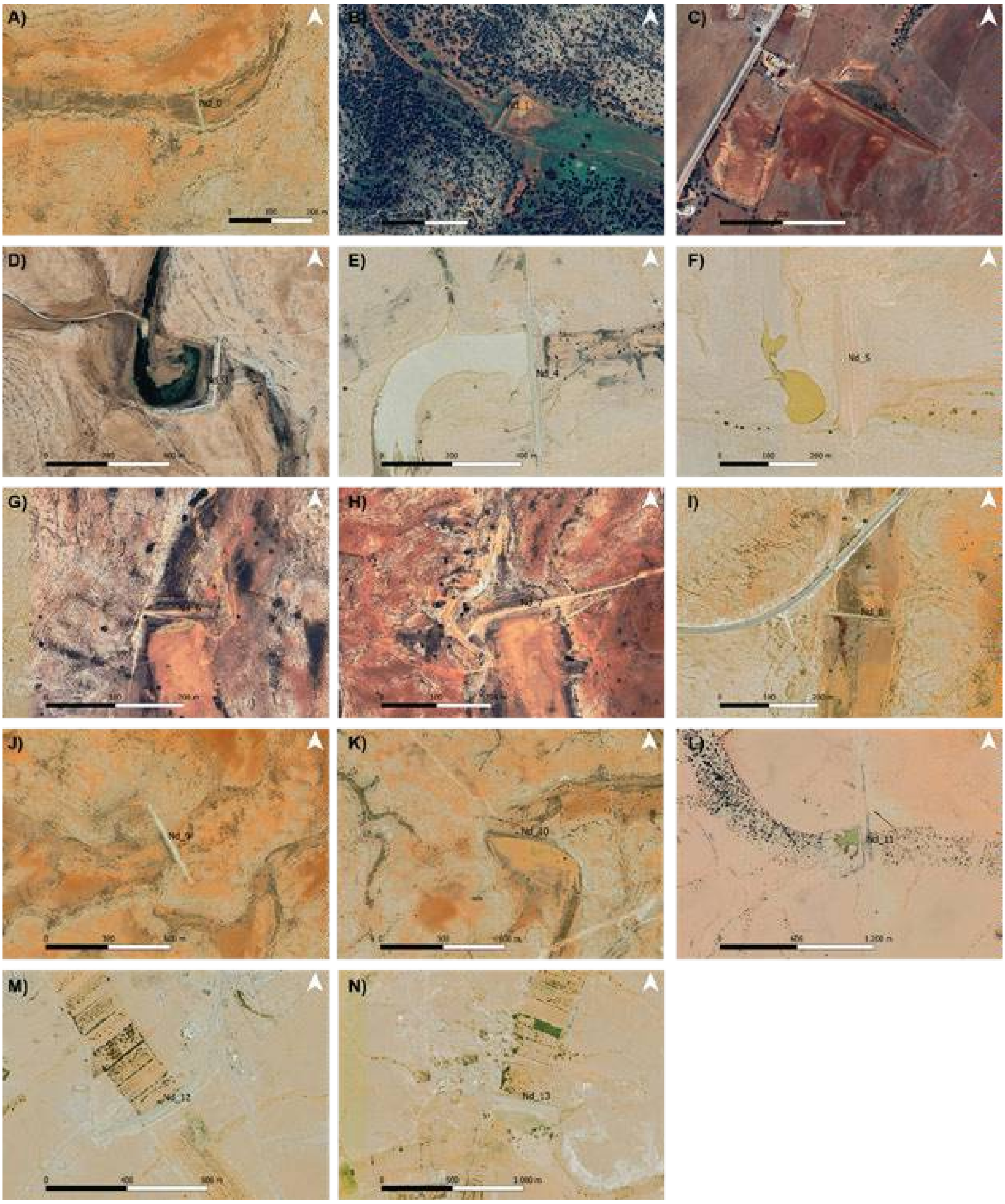
Note: heights here refer from lowest to highest point of the dam body structure (without accounting for foundation), also the height estimates might remain uncertain (errors on the order of 2-5 m are expected).

PHOTO 5.1. **Detail images from the georeferenced ICOLD's World Register of Dams for Libya.**



Source: Original for this publication based on manual georeferencing (images: Google earth, Maxar/Airbus).

PHOTO 5.2. **Detail images from the georeferenced newly detected dams.**



Source: Original for this publication based on manual georeferencing (images: Google earth, Maxar/Airbus).

5.2 SPATIAL ANALYSIS OF POTENTIAL CONSEQUENCES

The potential impact of another dam failure in Libya was evaluated using remote sensing. This was achieved by evaluating each dam main characteristics, such as spillway works, constructive type, volume, associated catchment area, and volume/area ratio. Additionally, a preliminary assessment of the population and infrastructure exposed downstream these structures were carried out following the approach outlined in ICOLD (1989). A data-driven estimate of the flood-area extent was performed using the following criteria:

- The first 45 km downstream of the dam are evaluated. Based on the wave propagation celerity (8-45 km per hour) of historic dam-break disasters this would be representative of the first 1-5 hours after breach depending on the downstream hydraulic characteristics.

- A catastrophic and sudden dam break occurs. The flood-wave propagates downstream following the main drainage pathway (as computed by available digital elevation models), and the flood wave can reach up to a maximum of 4/9th of the maximum dam height (following Ritter's idealized sudden dam break at breach water level) above the drainage level, additionally the extension of the flood wave is limited to a maximum of 2 km lateral from the main routing direction.

- The population downstream affected by each potential failure was computed by overlaying the flood area with the JRC GHS-Population maps for 2020 (Schiavina et. al 2023).

This method intends to provide a preliminary assessment of the order of magnitude of downstream population and infrastructure potentially affected. However, this methodology neglects several aspects, like the limited volume discharged by the dam, the actual flood-wave generated by the dam breach and the local hydraulic characteristics. The results should be improved and verified with dedicated dam failure studies that consider physically based flow routing schemes and realistic dam failure mode scenarios.

5.3 PRELIMINARY RISK ASSESSMENT AND PRIORITIZATION

A level of risk was attributed to each dam based on the analysis and evaluating the downstream topography, contributing catchment and characteristics for each dam. These range from low, medium, medium-heigh, high and very high. Table 5.3 presents the prioritization, along with comments on each specific structure and recommendations for immediate action. The population at risk was used as the prime indicator of the potential consequences of dam failure. Beyond any specific action, all the identified dams in Table 5.3 should proceed urgently to a dam safety assessment as described by the World Bank (2020, Appendix 6, Tier I). Furthermore, for the dams where downstream population is directly exposed (risk medium-high to very high) should prepare and implement an Emergency Preparedness Plan.

Several structures rank as presenting a very high risk. This is due to large direct downstream population, a low volume to catchment area ratio, and the characteristics of their spillway and location. This includes the failed dams of Derna and Abu Mansour. The Ghattara and Ghattara secondary dams present very similar conditions; earth filled embankment dams situated in a large area wadi system, with a relative low volume to area ratio and morning-glory type spillways. Both dams drain to a narrow wadi canyon that flows towards a wide, populated floodplain (the south of the city of Benghazi). It is recommended that these dams are subject to an immediate evaluation to review the design criteria, and outlet/spillway characteristics, and early warning systems and emergency preparedness plans in place. It is reported that the Municipality of Benghazi has initiated an assessment of the risk posed in Al-Ghattara valley, and some actions are being taken to ensure the safety of the people and assets by ensuring an open watercourse in case of flood events.

TABLE 5.3. Potential impact and preliminary prioritization of large dams in Libya.

Name	Height (m)	Catchment (km^2)	Volume (MCM)	V/A ratio * 1000 (mm)	Population at Risk	Risk	Comments	Recommendation
Derna	45	129	1.5	12	15,350	very high	Confined wadi draining to populated floodplain. Failed	NA
Abu Mansour	75	460	22.0	48	15,350	very high	Confined wadi draining to populated floodplain. Failed	NA
Ghattara	55	1298	122.0	94	27,000	very high	Confined wadi draining to populated floodplain, large population downstream (Benghazi). Large contributing catchment	Inspect and re-evaluate immediately.
Ghattara Secondary	34	52	5.3	102	27,000	very high	Downstream of Ghattara. Same conditions	Inspect and re-evaluate immediately.
Kaam	50	2285	111.0	49	5,540	high	Very large contributing catchment. Upstream of Khoms. Narrow valley that leads to medium-density inhabited floodplain.	Inspection of outlet works and evaluation of design criteria. Reevaluation of climate forcing.
Lebda	33	179	5.2	29	2,500	high	Very large contributing catchment for its volume. Population directly downstream. Free flowing lateral spillway.	Inspection of outlet works and evaluation of design criteria. Reevaluation of climate forcing.

Name	Height (m)	Catchment (km²)	Volume (MCM)	V/A ratio * 1000 (mm)	Population at Risk	Risk	Comments	Recommendation
Ghan	80	646	30.0	46	4,300	high	Sparsely populated, impact to farming and mining infrastructure.	Inspect, medium priority
Megenin-IV	42	570	58.0	102	6,300	high	Direct flood plain with relative minor settlements downstream. Free-flowing spillway. Mining infrastructure downstream.	Medium-priority, check infiltration.
Megenin-IV1 (secondary)	30	570	58.0	102	6,900	high	Direct flood plain with relative minor settlements downstream. Free-flowing spillway. Mining infrastructure downstream. Normal water level does not seem to reach the dam.	Medium-priority, check core status after long-dry periods.
Dakar	19	12	1.6	133	29,500	medium-high	Large population downstream (floodplain), however very small contributing catchment, mostly empty.	Inspect, medium priority.
Tabrit (Tapget)	24	7	2.0	286	30,700	medium-high	Large population downstream (floodplain), however very small contributing catchment, mostly empty. Absence of outlet works.	Inspect, medium priority
Zaza	38	535	1.8	3	367	medium	Narrow wadi canyon leading to sparsely populated floodplain. Concrete gravity dam with free-flowing spillway, thus low-risk of overtopping catastrophic failure.	Reevaluate stability. Estimated very frequent spills due to very low capacity for its catchment.

Name	Height (m)	Catchment (km²)	Volume (MCM)	V/A ratio * 1000 (mm)	Population at Risk	Risk	Comments	Recommendation
Wishka	25	412	3.7	9	1,230	low-medium	Low populated area, large floodplain downstream, mining activities directly downstream. Potential impact to productive infrastructure	Low-priority
Zart	32	171	8.6	50	1,350	low	Relatively unpopulated, floodplain with small farming infrastructure. To verify with a more accurate flow model the potential impact to the town of Al-Manasir.	Study flow path and evaluate population at risk.

6. Recommendations

1. The failure of the Abu Mansour and Derna dams provide important lessons for the reconstruction of Derna, assuring the safety of dams and downstream communities in Libya and the international dam safety community.

2. The recommendations acknowledge the uncertainties in the absence of having access to the sites and provide for additional or updated assessments in the event of new information.

3. The recommendations highlight opportunities to inform the reconstruction efforts and approaches allowing Room for the River as an opportunity to leverage the tragedy and build back better.

4. The recommendations outline measures for strengthening the national systems for ensuring the safety of dams and downstream communities and advocate for the development and implementation of a national dam safety program.

The tragic failure of the dams in Wadi Derna provides a number of important lessons and highlights the need to identify a set of priorities for safeguarding the rest of the national portfolio. Lessons learned from the failure of dams in Libya and other countries underscore the critical importance of proper design, construction, maintenance, surveillance and preparedness to anticipate and prevent undesirable behavior, as well as mitigate the potential impacts of dam failures on infrastructure, public health, and the environment. These insights can inform future efforts to enhance dam safety and resilience in Libya and beyond.

The continued instability in Libya has created a number of challenges for ensuring the regular operation and maintenance of critical infrastructure and provision of basic services. Libya has dealt with opposing governments located in the east and west of the country respectively since 2011. This has resulted in overlapping, and sometimes competing, mandates, affecting the funding, planning, execution, and maintenance of infrastructure projects, while also diluting accountability. The impact of Storm Daniel and the failure of the Derna and Abu Mansour dams underscores the importance of close collaboration and coordination among stakeholders across the country around key technical issues and the need for a uniform approach to ensure the safety of the dams and downstream communities.

A series of national priorities and eight specific recommendations are made for immediate implementation. The assessment and recommendations contained herein are intended to inform recovery and reconstruction efforts that are inclusive, coordinated and help to build a more resilient future for the people of Libya. By providing an objective, independent assessment of the potential failure modes it is hoped that this report will provide lessons for the reconstruction of Derna and help Libyan stakeholders move towards conceiving, planning, and implementing an efficient and effective recovery program through a coordinated national platform, while providing insights to enhance the safety of dams and downstream communities in Libya, and contributing to efforts by the international dam safety community to improve the management of risks associated with dam failures. Through this, Libya can come out of this disaster, stronger and more resilient, by converting adversity into an opportunity for building back better and contributing towards a resilient, inclusive, and sustainable recovery for people in Libya.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6.1 NATIONAL AND SUB-NATIONAL PRIORITIES

The experience of the Abu Mansour and Derna dams underscores the need to identify national priorities for safeguarding the rest of the national portfolio and mitigating the potential impacts of further dam failures on infrastructure, public health, and the environment. In order to identify these priorities a series of national and sub-national consultations were carried out, including meetings in Tripoli on January 23rd, 2024, and in Benghazi on January 24th, 2024. The information gathered during these consultations were combined with the findings of the expert assessment, a comprehensive review of the existing literature and good international industry practices pertaining to measures that can improve the safety of dams and downstream communities.

Based on this, eight specific actions are proposed. The priorities and needs identified call for immediate actions and set the foundations for the medium and long-term interventions required to improve climate resilient disaster risk management and assure the safety of dams in Libya (Table 6.1.). One of the key recommendations emerging from the consultations was recognition of the need to establish a National Coordinating Mechanism (NCM) for Libyan dams. The proposed NCM would bring together all of the various agencies and a range of stakeholders responsible for the planning, management, assessment, monitoring, inspection and regulation of dams in Libya under clear terms of reference.

To help inform this process a preliminary stakeholder map was undertaken (Table 6.2). Stakeholder mapping is essential for making better decisions by considering the characteristics, perspectives, preferences, and expectations, as well as potential influence and impacts of different actors. This should include anyone who can affect or be affected by decisions, actions, or results. The process helps to identify key actors and determine how best to communicate and engage with them effectively by developing and implementing a stakeholder engagement plan that is tailored to the needs of each stakeholder group in order to enhance communication and collaboration. By aligning with stakeholder needs and expectations, it can also increase support for decision making and help manage and mitigate risks, while monitoring and evaluating stakeholder feedback and performance. This leads to more informed, strategic, and effective decisions that take into account the complex stakeholder landscape.

TABLE 6.1. **Priorities identified during the assessment period (September 2023 - February, 2024).**

	Actions / Medium Impacts	Actions / High Impacts
High Priority	**Immediate** • Assessment of Wadi Derna dams pre- and post-disaster and plans for the inspection and monitoring of all dams in Libya. • Characterize the parameters that led to the inundation and failure of dams in Wadi Derna. • Establish a National Coordination Mechanism to address the post-disaster interventions and actions on Wadi Derna dams. • Assess the safety and update hydrological assessments for all dams in Libya, starting with the Ghattara and Ghattara secondary dams. • Assess land use practices and characterize the geology of the Derna catchment. • Update the inventory of springs and review hydrology of the Derna catchment. • Map hydrometeorological hazards, including floods and droughts, and link to dams. • Define the preferred level of flood protection for Derna city. • Evaluate the regulatory framework for assuring the safety of dams and downstream communities.	**Short-term** • Perform a national vulnerability assessment of dams in Libya to changing climate. • Establish flood and drought monitoring platform for Libya. • Revisit the land use and management policies and plans, based on mapping of hydro-meteorological risks. • Assess the perception of risks of hydro-meteorological hazards by society and decision-makers to manage risks. • Develop regulatory measures and / or guidelines for assuring the safety of dams in Libya, including emergency preparedness measures for any future flood events. • Organize trainings on hydro-meteorological hazards with remote sensing and forecasting agencies. • Undertake a cost/benefit analysis for existing dams and any proposed new dams. • Identify and implementation priority interventions to improve safety of Derna city, including emergency preparedness. • Rehabilitation and revival of Wadi Derna.
Medium Priority	**Medium term** • Strengthening institutional and systemic capacities on Early Warning Systems (EWS). • Provide trainings for young researchers and professionals on EWS equipment, data analysis, modelling, and synthesis to ensure evidence-based decisions on prevention and reduction of hydrometeorological hazards. • Organize a high-level workshop on climate risks and the emerging impacts of a rapidly changing climate. • Capitalize on the services and data of remote sensing institutions and improving their institutional and individual capacities. • Build comprehensive meteorological database serving multisectoral decision-making on hydro-meteorological risks. • Implement national dam safety program. • Implement priority interventions to improve flood protection of Derna city. • Adopt regulatory framework for assuring the safety of dams & downstream communities.	**Long term** • Strengthen the preparedness of Libya to address hydrometeorological hazards, including floods and drought. • Strengthening the human capital of civil protection and provision of modern equipment for the measurement of weather conditions and ensuring the availability of hydrometeorological time series records. • Develop an emergency preparedness plan and network to include all sectors in cases of hydrometeorological events and other natural hazards. • Establish a strong community of practices on water management and hydrometeorological hazards. • Increase use of Nature based Solutions (NbS) to improve catchment conditions and the urban environment in Derna city. • Regular review of the safety of dams and regulatory framework and adapt to changing conditions.

TABLE 6.2. National and subnational stakeholders' map, their influence and capacity in dams monitoring, inspection, and management.

Tertiary Actors • Local community groups • Youth groups • Universities	**Primary Actors** • National Research Centers • Order of Libyan Engineers • Sub-national Meteorological Stations
Secondary Actors • Ministry of Agriculture, Livestock and Marine Resources • Ministry of Local Governance • Universities / Faculty of Engineering • National Centre for Meteorology and Remote Sensing • Libyan Center for Remote Sensing and Space Sciences	**Critical Actors** • Ministry of Water Resources • Ministry of Environment • Ministry of Planning • Libyan Center for Research in Crises Changes, • Ministry of Foreign Affairs • National Centre for Natural Risks and Crises • Libyan Center for Remote Sensing and Space Sciences

■ **Critical Actors:**
manage closely, strategic development, lead agency.

■ **Primary Actors:**
mainstream, build capacity, awareness, planning, control on site.

■ **Secondary Actors:**
collaboration for better monitoring and planning, exchanges, and support (financial, technical, managerial).

■ **Tertiary Actors:**
keep informed of activities and issues, help in the control on ground.

Source: Original for this publication based on consultations in Tripoli and Benghazi January 2024.

6.2 CARRY OUT A MORE DETAILED ASSESSMENT OF THE 2023 FLOOD EVENT.

There is a relatively high level of uncertainty regarding the spatial and temporal distribution of Storm Daniel's rainfall through the Wadi Derna catchment area and the present assessment has demonstrated the difficulty of accurately characterizing the return period of the flood event. As a result, further in-depth analysis is required based on a more comprehensive set of data, information and investigations. This will be important to provide design conditions for any reconstruction measures aimed at building back better and would need to include the following activities:

a. Survey of typical cross-sections: This should be based three cross-sections along the wadi, each at least 300 m long, located (i) upstream of Abu Mansur; (ii) between Abu Mansur and Derna dams; and, (iii) in the city of Derna. The survey would enable a more accurate estimation of the volume of the flow that would have passed in 2023, based on the flood traces.

b. Rainfall and climatic conditions: More detailed data and information is needed for 2023. The data needed is related to the reason of the malfunctioning of the Derna rain gauge; the method for estimating pixelated rainfall proposed by the Libyan Meteorological Centre; the final product proposed by the Integrated Multi-satellitE Retrievals for GPM (IMERG) after calibration; analysis of the corrections made to the raw IMERG data proposed by Jasim et al (2024); any local information likely to improve rainfall estimation; and wind conditions and dew point temperature during the event.

c. Information on the 2011 flood event. This would be used to support calibration of the Soil Conservation Service (SCS) Unit hydrograph hydrological model; daily rainfall data from stations; and accurate high-water marks, time-stamped photographs, and flood timing.

It is recommended that a hydraulic model be developed, surveys be carried out of at least three cross sections along Wadi Derna and efforts be made to source more detailed data and information on the rainfall and climatic conditions related to the 2023 storm event. This will help better understand the flood characteristics, inform flood management and mitigation measures for ensuring the protection of the city of Derna, as well as provide support to the reconstruction and recovery efforts.

6.3 CARRY OUT A MORE DETAILED ASSESSMENT OF THE DAM FAILURES.

The present assessment has provided a number of insights into the potential failure modes and their probabilities. However, the assessment is based on eyewitness reports, original design reports and feasibility studies, rehabilitation studies conducted from 2002 to 2004, as well as observations based on photographs, satellite images and expert elucidation. While the Derna Dam was completely washed away, no physical inspections or investigations were possible at the Abu Mansour Dam site due to challenges around access. As such, this analysis may be revised following the availability of new elements provided even after the publication of this report. Should conditions allow, an inspection of the remains of Abu Mansur dam would help to reconstruct the probable scenario of its failure. An inspection of the site of the Derna Dam would also be useful to understand the local conditions post-disaster.

Further in depth analysis is required whereby a set of information and investigations are needed to answer the following questions: (i) the maximum water level at the time of the breach, the functionality of the spillway, and the flood passing over the crest of the dam; (ii) the occurrence of the dam's embankment and instability before the reservoir was high enough, given the weakening of the foundation and embankment due to erosion and the heavy rains to which the dam was subjected; (iii) the traces left by the flood wave along the watercourse from upstream of Abu Mansur to the entrance to the city of Derna downstream; and, (iv) the occurrence of any sliding of the river flanks between the two dams, which could have caused breaking waves that would have aggravated the situation. Additional analyses could be performed based on the existing data to evaluate overtopping erosion (e.g. EMBREA model), internal erosion (Excel, evaluation with HETs), micro-instability (Excel) and macro-instability (e.g. Plaxis, DStability) and provide more insights into the most probable failure mode.

It is recommended that the assessment be updated as new information, studies and investigations become available. Efforts should be made to facilitate visits to allow for physical investigations of the Derna and Abu Mansour dam sites by an expert team, including national and international experts in dam engineering, geology, and hydrology, among others. Soil samples should be taken of the clay core and the alluvial soil for geotechnical investigations in the laboratory (such as soil identification, index tests, unit weight, erosion tests, sieve curves) and additional analyses performed to increase the confidence around the most probable failure mode.

BOX 6.1. World Declaration on Dam Safety

The International Commission on Large Dams issued the Declaration on Dam Safety in 2019. Recognizing the contribution that dams have made to development, the declaration acknowledges that dams create new hazards involving potential risks to downstream communities, including potential adverse impacts on life, property and the environment. It also acknowledges that the science, technology and human roles in dam safety are in constant evolution with many changing conditions. Reflecting these changing conditions, the goal of the declaration is to promote an awareness of dam safety, by restating the fundamentals principles that have been learned over time and reminding all entities involved to ensure, through the fulfillment of their responsibilities, that these fundamentals are respected in order to minimize risks associated with dams and reservoirs. The pillars on which these fundamental principles are based include the following:

1. Structural integrity of dams is the keystone to dam safety.
2. A routine surveillance and maintenance programme is necessary for early detection.
3. An instrumentation and monitoring programme is essential throughout the life of a dam.
4. Design-Intrinsic risks need to be adequately addressed.
5. Natural hazard risks change with time, thus should be regularly reviewed and updated.
6. Emergency planning is of utmost importance for all dams.
7. Adequate training of operators is part of a comprehensive dam safety programme.
8. Sharing lessons learned benefits the entire industry, making all dams safer.
9. A comprehensive dam safety approach will allow minimization of risks.
10. A dam owner has the ultimate responsibility for its dam.
11. The role of regulatory authorities is paramount for safety.
12. An international perspective to dam safety can be enlightening.

Source: International Commission on Large Dams (2019)

6.4 IMPROVE FLOOD FORECASTING, EARLY WARNING SYSTEMS AND EMERGENCY PREPAREDNESS.

The risk of flooding remains high for Derna, particularly in the absence of any flood protection measures. As one of six districts in Libya with an extreme risk of flooding, there is need for investments in strengthening hydro-meteorological services, forecasting and early warning systems, emergency preparedness and disaster response mechanisms. This should include repairing and upgrading equipment for hydro-meteorological observation, real-time monitoring and forecasting; developing detailed flood risk maps and risk-informed development plans, developing preparedness and emergency response plans; upgrading equipment and facilities for emergency response and strengthening capacities for response and recovery; and, organizing community level awareness campaigns. These should be supplemented by measures to reinforce the institutional and regulatory framework for disaster and climate risk management.

The forecast system should be based on various elements, including: (i) real-time rainfall data transmission at Derna and Shahat stations; (ii) automatic stations installed in the upstream basin; (iii) real-time data transmission of water levels along the wadi; hydrometeorological stations and flood gauges at the former sites of the Derna and Abu Mansour dams, along with one in the city center; and, real-time rainfall forecasts from the meteorological center; and an abacus linking daily rainfall, sea level, water level at hydrometeorological stations and risk. The forecast must be able to establish risk levels that trigger specific actions linked to the emergency preparedness plan and disaster response mechanisms. This should include an incremental approach based on phased warnings linked to vigilance, pre-alert, and alert levels. In addition, a set of tasks need to be predefined, including organization of emergency services, on-call duty, closure of vulnerable access points, targeted communication depending on the level of risk. These systems work best if people stay aware of the dangers associated with floods, and if they are informed and trained about what to do in case of emergencies. Under such circumstances, early warning systems can be effective, in addition to preventive measures, in preparing people for situations that can become dangerous.

The magnitude and velocity of the flood wave resulting from the dam failures make it unclear if an early warning system would have been effective in this context. According to design criteria (1/1000) the dams would be considered safe if the 1/500 year event of Storm Daniel was predicted, and once the dams collapsed, there would have been very little time to issue a warning and make sure people could move to safer grounds. However, given what was known about the inadequate design and the lack of implementation of earlier recommendations for strengthening the safety of the dams, combined with the extreme rainfall event, an effective warning system could have been put in place to predict the consequences associated with critical water levels being exceeded, increasing the risk of failure and allowing for improved preparedness.

It is recommended that a comprehensive flood management and disaster preparedness strategy be developed and implemented. This should be based on a detailed topographic survey of vulnerable areas; risk mapping based on rainfall and sea level, including flow speed and water height, considering affected areas and access routes; and mapping of refuge areas for the affected population. Investments in hydro-meteorological stations, as well as forecasting and early warning systems should be urgently made, and annual evaluations carried out pre- and post-flood season to evaluate the effectiveness of the intervention procedures and determine the need for any adjustments.

6.5 DETERMINE THE LEVEL OF PROTECTION FOR DERNA CITY.

Flood risk management is built on the fundamental principles of protection, prevention, and preparedness. These should combine to provide an acceptable level of safety that considers the hazards (probability of occurrence) and the consequences (casualties and economic losses). The notion of acceptability depends on the local context and is informed by efforts to minimize the potential loss of life and considerations of possible economic losses.

Determining the appropriate level of safety protection is important for the detailing of any option, particularly given the increasing uncertainty due to the impacts of climate change. This requires adaptative planning and management that can also accommodate changes in socio-economic conditions. However, higher safety levels generally cost more and require more intense management and governance, and so any determination should be informed by a stakeholder led process to debate and build consensus on what is considered acceptable within the financial, technical, and human capacity constraints of the particular context.

Protection can be afforded through structural and non-structural measures. Structural measures are physical interventions aimed at reducing flood hazards, including grey infrastructure such as dams and reservoirs for flood control, floodwalls, embankments, and river training works, as well as green infrastructure that focuses on restoring or enhancing natural features, such as wetlands, floodplains, vegetated buffer strips, and retention ponds. These all aim to regulate water levels, redirect flow paths, and by doing so protect vulnerable areas. These require regular maintenance and periodic assessments to ensure their functionality and adaptability to changing flood patterns. Non-structural measures complement structural interventions and focus on reducing the vulnerability and exposure of communities to flood hazards through measures including floodplain zoning, land-use planning, and building codes that require flood-resistant designs, education, and awareness campaigns to inform individuals and communities about flood risks, preparedness, and response strategies.

It is recommended that a discussion paper be prepared to facilitate a process that can build consensus around an acceptable level of protection for the city of Derna. This would help inform the reconstruction efforts by identifying a range of potential appropriate interventions that can help Derna build back better.

6.6 DETERMINE APPROPRIATE INTERVENTIONS FOR BUILDING BACK BETTER.

Assuring an acceptable level of flood protection for the city of Derna will require significant investments. The massive flood wave washed away buildings, bridges, and other structures in Derna, creating a relatively open flood plain in the city with an average width around 80 to 120m. This provides opportunities out of the tragedy to revision a new urban redevelopment plan to build back better using climate resilient, inclusive principles. Building back better would allow for city redevelopment that provides an open space to accommodate future peak discharges and allows ‘Room for the River’ type solutions. Creating a channel with several levels ensuring the transit of water through the area to be protected with wetlands, elevated boardwalks, as well as measure to widen and harden the riverbed and bank in specific areas to limit the amount of space needed. It is, however, unlikely that a Room for the River solution alone can avoid serious urban flooding and appropriate interventions will need to include a combination of structural and non-structural measures. These require a systems approach that evaluates all possible options and combines non-structural measures working with nature with grey infrastructure, such as upstream dams and or diversion tunnels, that can dampen the flood peaks, help regulate flows through the city and limit the required room for the river inside the city.

Reconstruction of a dam, or dams, upstream of Derna would allow for flood waters to be stored and to reduce flood peaks. However, the specific technology, as well as the type and shape of the spillway should be determined through a detailed feasibility study that is based on the specificities of the site, an updated hydrological assessment, due consideration of the geological and topographical conditions, as well as the cost and availability of construction material. A concrete dam equipped with a wide free-flow spillway, discharging on an open-air chute with free surface flow, such as labyrinth spillways or a PK-Weir, should be considered within the context of the prevailing geological and topographical conditions. The retention effect could be improved by integrating an orifice outlet to discharge the inflow from the beginning of the flood event. Any such proposal would need to be part of an integrated solution to protect urban flooding in Derna city and validated through a detailed assessment of all possible alternative options.

Diverting the flood waters through a tunnel or open-air channel could also help to reduce flood peaks and improve flood protection. This could be done by reshaping or creating another channel through the city with several levels calibrated for flow rates with different return periods to ensure the transit of water through the area to be protected. However, preliminary analysis suggests this option does not necessarily lead to a reduction in the urban flood risk. Another option could be to divert part of the water from Wadi Derna to the adjacent wadi system to the west over a distance of roughly 8-10 km with a slope around 1 percent. This is only slightly more effective than a second city channel and likely significantly more expensive, without some of the potential co-benefits associated with urban redevelopment opportunities. Any such proposal would need to be part of an integrated solution to protect urban flooding in Derna city and validated through a hydraulic study with a cost-benefit analysis of alternatives.

It is recommended that a scoping paper be prepared with identification of potential options and that these be subject to a pre-feasibility study before committing to reconstruction of the dams upstream. A combination of room for the river and lowering the design peak discharge requires an interactive design process that balances the advantages and disadvantages of both types of interventions (Table 6.3). It is important to follow an integrated, inclusive approach in such a design process to ensure that all – often conflicting – spatial demands are considered in a holistic manner and that all stakeholders are not only involved and informed but that they also have influence on the process. These options should be assessed to inform an optimal set of investments that provide an acceptable level of protection. These should be complemented by a series of non-structural measures to improve forecasting, early warnings, and emergency preparedness, particularly in the interim period while comprehensive measures are put in place to manage and mitigate the flood risks associated with Wadi Derna.

TABLE 6.3. Potential interventions to manage and mitigate flood risks associated with Wadi Derna.

	With new dam(s)	Without new dam(s)
With diversion (second channel or tunnel)	Can work – lower dam, less impact to city redevelopment options	Difficult because of a lack of open space in the city for primary and second channel.
Without diversion	Can work – higher dam, more impact on city redevelopment options	Only if a low safety level is accepted by the stakeholders.

Source: Original for this publication.

6.7 DEVELOP A REGULATORY FRAMEWORK FOR DAM SAFETY ASSURANCE.

The foundation for effective dam safety assurance is an appropriate and well-designed regulatory framework that captures the legal, institutional, technical, and financial elements in the reality of a particular jurisdiction (Wishart et al. 2020; ICOLD 2021; Box 6.1.). Establishing and maintaining a regulatory framework that is fit for purpose is, therefore, necessary for ensuring the quality of dam design, construction, and operation and maintenance. The regulatory framework for assuring the safety of dams and downstream communities also ensures that safety measures are reflective of the risks inherent in managing these structures and the context in which they are developed. Such frameworks need to be developed as part of a holistic strategy for water management that is integrated in basin and regional planning processes, and supported by institutions that can monitor and enforce such measures.

The regulatory framework for ensuring the safety of dams and downstream communities in Libya lacks clarity. The political transition has resulted in a complex process that has led to an evolving legal and constitutional framework, with a number of challenges in establishing a stable and uniform legal system across the country. While legislation in 1977 established the Ministry of Dams and Water Resources with a specific department responsible for dams, detailing the responsibilities for studies and research on dams and reservoirs, as well as their technical supervision, operation, and maintenance, there is a need to review the existing institutional and regulatory framework for the safety of dams and downstream communities. This should include a review of organizational roles and responsibilities, along with the legal and regulatory elements governing the planning, design, development, implementation, operation, and maintenance of dams in Libya. This can be used to benchmark specific performance indicators against regional and international good practices, identify opportunities and provide recommendations for improving the safety of dams and downstream communities.

It is recommended that a national platform be established to build consensus on required measures and prepare draft regulatory provisions in anticipation of an enabling environment at the national level conducive to their promulgation. In the interim, a series of technical standards and guidelines should be prepared to guide a uniform approach to assuring the safety of dams and downstream communities across Libya. This should be accompanied by an institutional assessment to identify capacity building requirements.

6.8 LAUNCH A NATIONAL DAM SAFETY PROGRAM

The failure of the dams in Wadi Derna highlights the need to develop and implement a national dam safety program to ensure that the technical and financial capacity are in place to ensure that dams in Libya are structurally sound and well-maintained, and that communities living downstream are protected. A national dam safety program would help to safeguard these assets, ensuring their continued operation and the benefits they provide to society. The updated inventory and initial high-level assessment have identified a number of dams not captured under the national inventory, with the spatial analysis indicating several potentially medium-, high- and very high-risk dams that require further investigation. The Ghattara and Ghattara secondary dams are earth filled embankment dams situated in a large area wadi system, with a relative low volume to area ratio and specific type spillways that drain into a narrow wadi canyon that flows towards a wide, populated floodplain (the south of the city of Benghazi) and should thus be considered a priority.

The national dam safety program should review, update and build consensus on the national inventory of dams. This is an essential foundation for assessing risks across the national portfolio of dams in Libya and prioritizing interventions. This will provide the basis for development of national database and further spatial analytics, including a more comprehensive assessment of the downstream population at risk, economic activity using night light activity, and exposure to various hazards, such as potential seismic risks. Policy recommendations should be provided for improving the safety of dams and downstream communities, and a program implemented to enhance the capacity of technical specialists and officials, including targeted knowledge exchanges with countries implementing similar dam safety programs. Priority investments should be identified using a risk informed decision-making framework that can move those with the highest priority through the required due diligence, procurement and implementation in a transparent and timely manner. The national program should also enhance capacity by identifying training requirements and facilitating knowledge exchanges. The knowledge exchange should be focused applied training and sharing knowledge between national, regional, and international experts.

It is recommended that a national dam safety program be developed and implemented. This should build on the initial screening and include inspections for all dams that were indicated as medium- to high-risk, with priority given to the Ghattara and Ghattara secondary dams in Wadi Al-Ghattara that drains towards Benghazi. Emergency preparedness plans and early warning systems should be developed and sensitized for all high-risk dams and a capacity enhancement program implemented to strengthen the national capacity for ensuring the safety of dams and downstream communities.

6.9 IMPLEMENT A STAKEHOLDER ENGAGEMENT AND COMMUNICATIONS PLAN

It is important that the results of this assessment are disseminated to all those who were affected by the disaster, as well as national stakeholders and the international community. A well-designed communication campaign can be a strategic tool to educate and inform people on the probable cause of the dam failures, as well as empower local people affected by the flood to take practical steps to inform recovery efforts and minimize the impact of future disasters. Communicating the findings to national stakeholders can help to identify potential risks and prioritize actions around other dams at risk, while also allaying the fears of downstream communities. Disseminating the findings of the assessment among the international community will also help to inform improvements in the design, operation and management of dams, as well as knowledge on the risks from dam failures.

It is recommended that a stakeholder engagement and communications plan be developed and implemented to: (i) sensitize those in the city of Derna directly affected by the failure of the Derna and Abu Mansour dams to the probable cause, reconstruction options and the importance of dam safety and flood protection; (ii) engage those responsible for the safety of dams across Libya and the general population around the safety of dams in Libya and the importance of flood protection; (iii) inform the international community around the probable failure modes of the Derna and Abu Mansour dams from which lessons can be derived and general dam safety improved. This should begin with preparation and dissemination of: (i) a short policy note to convey recommendations to policy makers; (ii) a PowerPoint presentation to ensure consistent messaging; (iii) a series of infographics to convey key messages; and, (iv) a short video to be shared on social media and used to raise awareness on the importance of dam safety and flood protection.

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8. Annexes

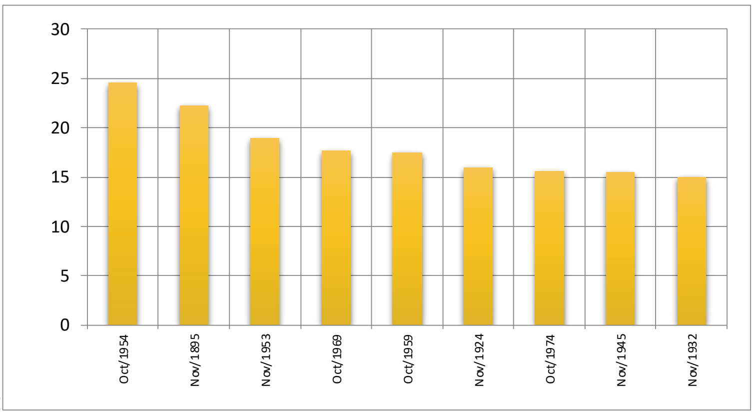
ANNEX 1: PAST FLOOD EVENTS: OVERVIEW AND ANALYSIS

The study of 1973 identified the main hydrological events in Derna (Table A1.1), with the biggest one taking place in October 1959 with a record of 6.48 Mm^3 volume and of 400-600 m^3 per second peak discharge. Among the 13 reported floods 1961-1971, the 2023 flood event is the biggest, followed by flood event that took place in October 1967. Other reported hydro-meteorological events between 1891 and 2019 show that the 1959 volume is larger (Figure A1.1).

TABLE A1.1. List of events with corresponding water volume and discharge in Derna.

Date	Volume (Mm^3)	Peak discharge (m^3/s)
1-2 October 1959	6.48	400-600
26 October 1961	2.47	
17-18 January 1962	1.03	
7-8 December 1962	1.53	
21Octoer 1965	2.4	
20-21 October 1967	2.85	
12-13 January 1968	2.556	147.1
18-19 October 1969	1.094	43.7
25-26 October 1969	1.209	77.6
27 October 1969	0.216	31.4
24 November 1970	0.080	7.6
8 January 1971	0.140	12.1
21 January 1971	0.180	6.1
11 April 1971	0.537	37.8

FIGURE A1.1: **Surface runoff amount (Mm³) for main floods of Wadi Derna (1891-2019).**



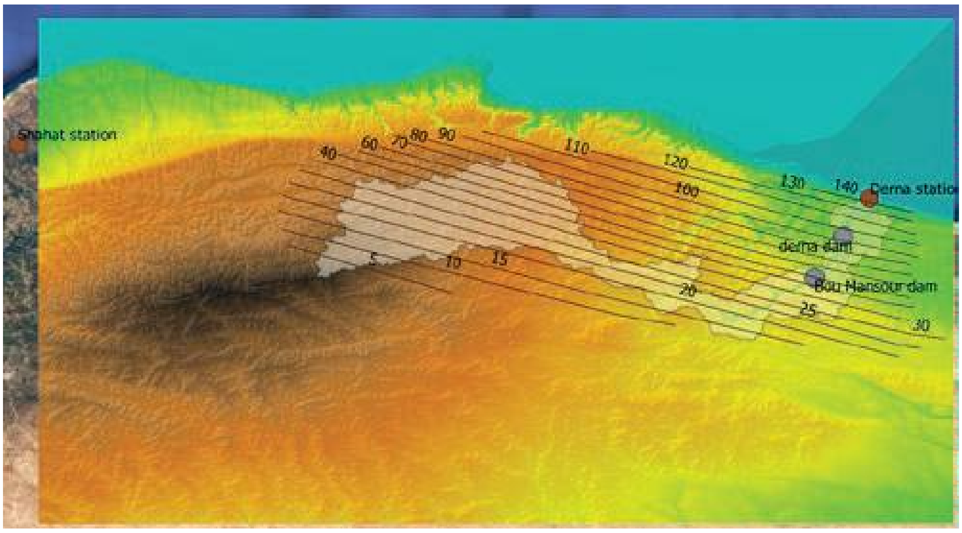
*Source:*Dr. Elfadli, *personal communication*, Tripoli, 2024

Flood event 1959

The flood event of 1959 was felt by the population. Preliminary studies carried out in 1971 revealed the following: "*there are no available data about the flood occurrences in the past; therefore, it is not known how frequent and strong the floods were. However, the local population still vividly remember the flood from 1959, when, according to some estimates, the discharge amounted to 600 m³/s and the flood caused both human and materials losses. It is probably the 1959 flood that initiated the idea of a radical protection of the town*".

The study carried out in 1971 drew the 1959 event isohyets as results are shown in figure A1.2. A high rainfall variability is observed between the upper basin and the lower basin, with record of around 40 mm upstream and 80 mm downstream. As shown in the hydrograph, the flood rises in around 3 hours which can be explained by the permeability of the upper basin. The runoff is observed only in the lower basin.

FIGURE A1.2.: **The isohyets of the flood event in 1959.**



Source: Original for this publication based on data from Hidroprojekat (1971).

Flood event 1986

The flood event in1986 is characterized by a small variability in rainfall. The maximum water level and rainfall of the flood of 1986 are known. Five rain gauges allowed a good assessment of the daily watershed rainfall. Both dams were fully filled in 1986 (Figure 20).

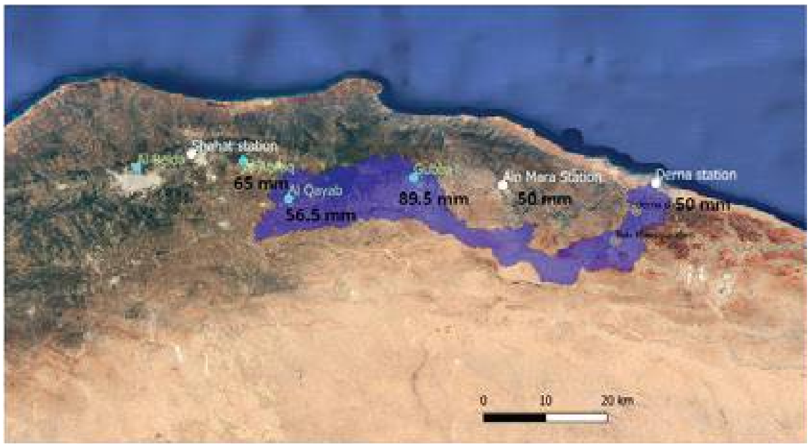
FIGURE A1.3.: The filling state of the dams during the flood event of 1986.

Derna Dam **Abu Mansur dam**

Source: Personal communication with Dr Abdelwanees A.R Ashoor

The floods records of 1986 event provided by the dams Administration (Figure A1.4) shows that the maximum water level reached by the reservoir is limited to 216.65 masl, which is 7.85m below the spillway elevation. Additionally, during the first 24 hours, between 28 and 29 November, the reservoir lost about 1.3 Mm^3. The bottom outlet, located around 100m downstream of the dam, appears to be closed according to the photo in Figure A1.3. Therefore, the average seepage losses are estimated at 15 m^3 per second for a reservoir el. 216 masl. when considering no inflow, distributed between the reservoir and the dam foundation, which is enormous. The part passing through the dam foundation is unknown but still important.

FIGURE A1.4.: The daily precipitation recorded in 1986.



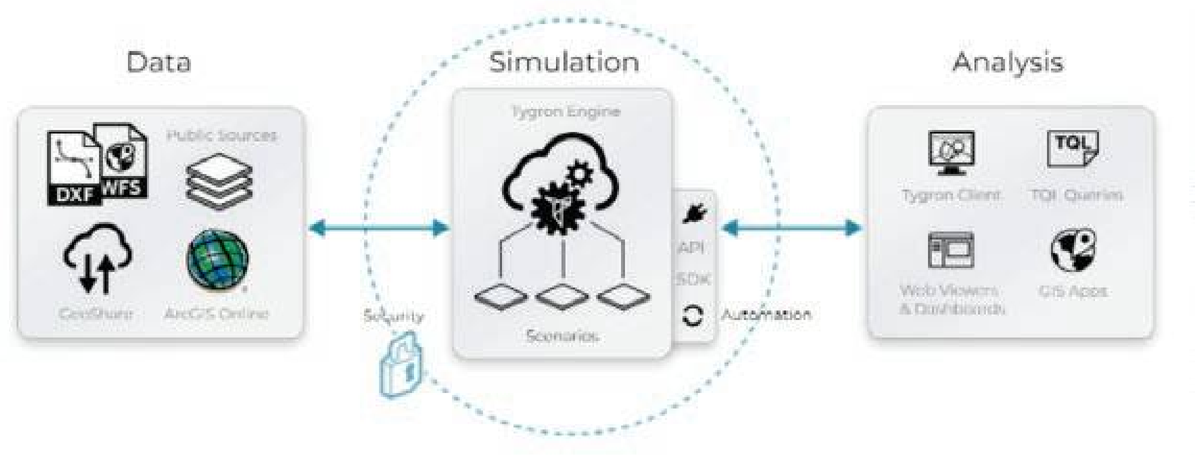
Source: Based on data from Ashoor 2022

ANNEX 2: TYGRON MODEL SET-UP

The flood risk modelling is performed with Tygron Platform. This is software specifically designed for sustainable urban planning, with features such as environmental and climate impact assessments to help stakeholders evaluate the potential impact of development projects on the local environment and infrastructure. In this case, the rainfall overlay is used to simulate the extreme rainfall events in the catchment area of the Wadi Derna. The rainfall overlay specializes in displaying the hazard and impact of (extreme) rainfall over the specified area. Based on the elevation model and terrain roughness several result types can be generated by the accompanying Water Module.

The software makes use of public data on Buildings, Infrastructure, Water and Neighborhoods. For Libya these are all sourced by Open Street Map (OSM). For the terrain elevation, the most important data for the purpose of this assessment, it uses the Digital Elevation Model (DEM) by ESRI Airbus. The tiles are 24 by 24 meters with a vertical uncertainty of approximately 4 meters.

FIGURE A2.1. The schematization of a model process within Tygron.



Parameters

Dam crest height

This DEM initially showed a dam crest height of +220 masl, which is 35-40 m higher than the reservoir base. Due to the rough resolution of the DEM, the crest height of the dam may be smoothed (Tygron interpolates the surrounding tiles), possibly resulting in an unreliable crest height.

The design height of the Mansour Dam crest is 228 masl. The settlement of the crest is 1.5 to 2 m according to dam monitoring data from the period between 1976 and 1990 and recent elevation measurement (Icesat2, a NASA operated LIDAR altimeter). That is why the crest height just before dam collapse was about 226-227.5 m masl. The settlements resulted in a ‘V-shape’ of the dam in which the crest was lower than the ‘shoulders’ of the dam (more information in section 4.4). The simulations were made with the dam crest height on +226 and +227 masl, as part of the bandwidth for dam crest height. See figure figure A2.2 below for the schematization of the Mansour Dam in the model.

FIGURE A2.2.

Source: Original for this publication

Infiltration capacity

Given the extensive information provided in the document ‘Hydrology of Wadi systems’, estimating the specific amount or percentage of infiltration from a rainfall event over 24 hours in a wadi system requires a nuanced approach. The text highlights the unique hydrological processes in arid and semi-arid areas, emphasizing the significant variability in both spatial and temporal rainfall, as well as the importance of understanding the infiltration processes, which include both direct rainfall infiltration and transmission losses from ephemeral wadi flows.

Factors that influence infiltration in a wadi system include:

1. **Soil and Bed Characteristics**: The infiltration capacity is highly dependent on the soil and bed properties of the wadi. Sandy soils or alluvial deposits typically have higher infiltration rates compared to clayey or compacted soils.

2. **Rainfall Intensity and Distribution**: The variability in rainfall intensity and its distribution over the wadi catchment area plays a crucial role. Intense rainfall over a short period may lead to higher runoff and lower infiltration, whereas lighter, more prolonged rainfall might enhance infiltration.

3. **Antecedent Moisture Content**: The existing moisture content in the soil before the rainfall event affects the infiltration rate. Dry soils can absorb more water compared to soils that are already near saturation.

4. **Vegetation and Land Use**: Vegetation can enhance infiltration by improving soil structure and reducing surface runoff. In contrast, urbanized or barren areas in wadis may have lower infiltration rates.

Given these factors, a specific estimation without detailed data on soil types, wadi bed composition, existing moisture levels, and vegetation cover would be challenging. However, in general terms, wadis in arid regions can have a significant portion of rainfall infiltrating, especially if the underlying soils are permeable and the area has not been subjected to extensive urbanization or soil compaction.

For a rough estimate, assuming favorable conditions for infiltration (such as sandy or alluvial soils), it might not be unreasonable to expect that a significant portion, potentially ranging from 25-50 mm could infiltrate in a day. This estimate, however, is highly speculative and should be used with caution. Accurate assessment would require field measurements and specific studies in the wadi of interest.

In the model a bandwidth for infiltration is taken, simulations with maximal (50 mm) and minimal (25 mm) infiltration.

Rainfall

Due to uncertainty in literature and satellite data on the actual precipitation on the day of the event, a bandwidth is considered for rainfall. From the minimum mean rainfall of satellite data by GPM NASA of 68 mm in 12 hours to the maximum rainfall of 200 mm in 24 hours, an arbitrary number based on Libyan's National Meteorological agency reports and the assumed return period stated in the document *'Mediterranean Region Flood Assessment 2023'* (when correlated with the GPEX dataset, Gründemann et. al 2023, this would even indicate a mean of 270 mm / 24 hrs).

Besides the min and max in the bandwidth, a rainfall intensity of 100 mm / 24 hrs is considered as part of a sensitivity analysis.