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Aging dams, political instability, poor human decisions and climate change: recipe for human disaster

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In Derna, Libya, a record-breaking storm and subsequent dam failures on September 10, 2023, caused over 11,000 deaths. Analyzing satellite data from 2016–2023, we found 1.8 mm/yr of differential settlement in dams contributed to their failure, and flooding damaged ~8570 buildings. We argue that the interplay of aging infrastructure, political instability, climate change, and human decisions drove this disaster, stressing the need for a holistic 'healthcare' management approach to prevent future catastrophes.

In the northeastern Libyan city of Derna, Storm Daniel[1], a mid-latitude cyclone that exhibited characteristics of tropical cyclones[2–4], caused a record-breaking precipitation event on September 10, 2023, with up to 400 millimeters of rain falling in just 24 h[5]. This extreme weather event caused a massive flood that washed away two embankment dams built to protect Derna against floods: the 75-meter-high Bu Mansour dam and the 40-meter-high Elbilad dam[1] (Fig. 1). The Bu Mansour dam was designed to withstand rare flood events and protect the city[6]. The collapse of these dams unleashed approximately 30 million cubic meters of water, destroying many buildings in Derna with a death toll of more than 11,000, and many more missing and homeless[5]. The United Nations highlighted that most casualties could have been avoided if proper early warning and emergency management systems had been operational[7]. Here, we leverage the entire archive of the synthetic aperture radar (SAR) data collected by Sentinel-1 satellites to detect slow but steady land settlement over the city of Derna and its infrastructures, including the dams. We further apply a Bayesian image classification to identify buildings damaged during the flood event. We discuss how the compounding effect of aging dams, political instability, climate change, and poor human decisions turned a hazard into a human disaster, where consecutive hazards with spatial and temporal overlapping impacts affect the dynamic vulnerability of a community, creating a disaster with devastating human consequences[8–10].

Subsidence: telltale sign of aging dams

Both failed dams in Libya were over 50 years old and had been reported to suffer from significant structural issues and inadequate maintenance[6,11]. Signs of defects and cracks in these aging dams were first reported in 1998. Among other defects, differential settlement in an aging dam often indicates an underlying issue within the body or foundation of the dam[12]. Differential settlement refers to unevenly settling a structure's foundation, where different parts sink at varying rates. This phenomenon can occur due to various factors such as soil conditions, load distribution, and structural integrity. If not adequately mitigated, excessive and uncontrolled differential settlement can significantly jeopardize the integrity of a structure[13,14], potentially leading to dam collapse. Here, we used satellite imagery to demonstrate that these dams have experienced substantial differential settlement over the past 8 years, suggesting that the disaster was likely decades in the making (Fig. 1A–E). To create a surface deformation map, we tracked the temporal change in the interferometric phase of each pixel on the ground. Assuming the principal deformation is vertical, we projected the line-of-sight measurements in the vertical direction to obtain vertical land motions (VLM). The VLM map indicates widespread subsidence (i.e., negative VLM) affected the city of Derna and its surroundings (Fig. 1A). The entire city subsides at an average rate of −0.7 mm/yr with a maximum subsidence rate of −5.8 ± 0.07 mm/yr affecting the city's flood protection infrastructure (Supplementary Fig. S5) due to the compaction of coastal sediments. Thus, the local sea level rise (i.e., the difference between land elevation and sea surface) rate that Derna experiences is nearly double the global average, amplifying extreme water levels due to storm surges. The farmlands to the city's southeast (marked in Fig. 1A) also experience maximum subsidence of −5.7 ± 0.05 mm/yr. In this semi-arid region, overexploitation of groundwater resources for irrigation has stressed aquifer systems[15], causing their compaction to manifest as land subsidence. Our dataset offers exceptional spatial resolution (~15 m), enabling us to investigate the settlement of individual buildings and infrastructure, such as the failed embankment dams, in the years leading up to the disaster. As observed, both dams have undergone differential subsidence with respect to the adjacent lands. The Bu Mansour dam, on average, subsided at a rate of −1.8 mm/yr with a maximum rate of −2.2 ± 0.05 mm/yr, while the Elbilad dam subsided at an average rate of −1.7 mm/yr and a maximum rate of −2.3 ± 0.05 mm/yr. These differential settlements from 2016 to 2023 resulted in an angular distortion up to 3.6×10^{-4} (0.021°) and 5.0×10^{-4} (0.029°), respectively. If accumulated over a decade or more, these distortions can compromise the infrastructure, posing a risk to the structural integrity of any dam. More broadly, they indicate poor maintenance and neglect of these structures, in addition to age and possible damage during past floods[11].

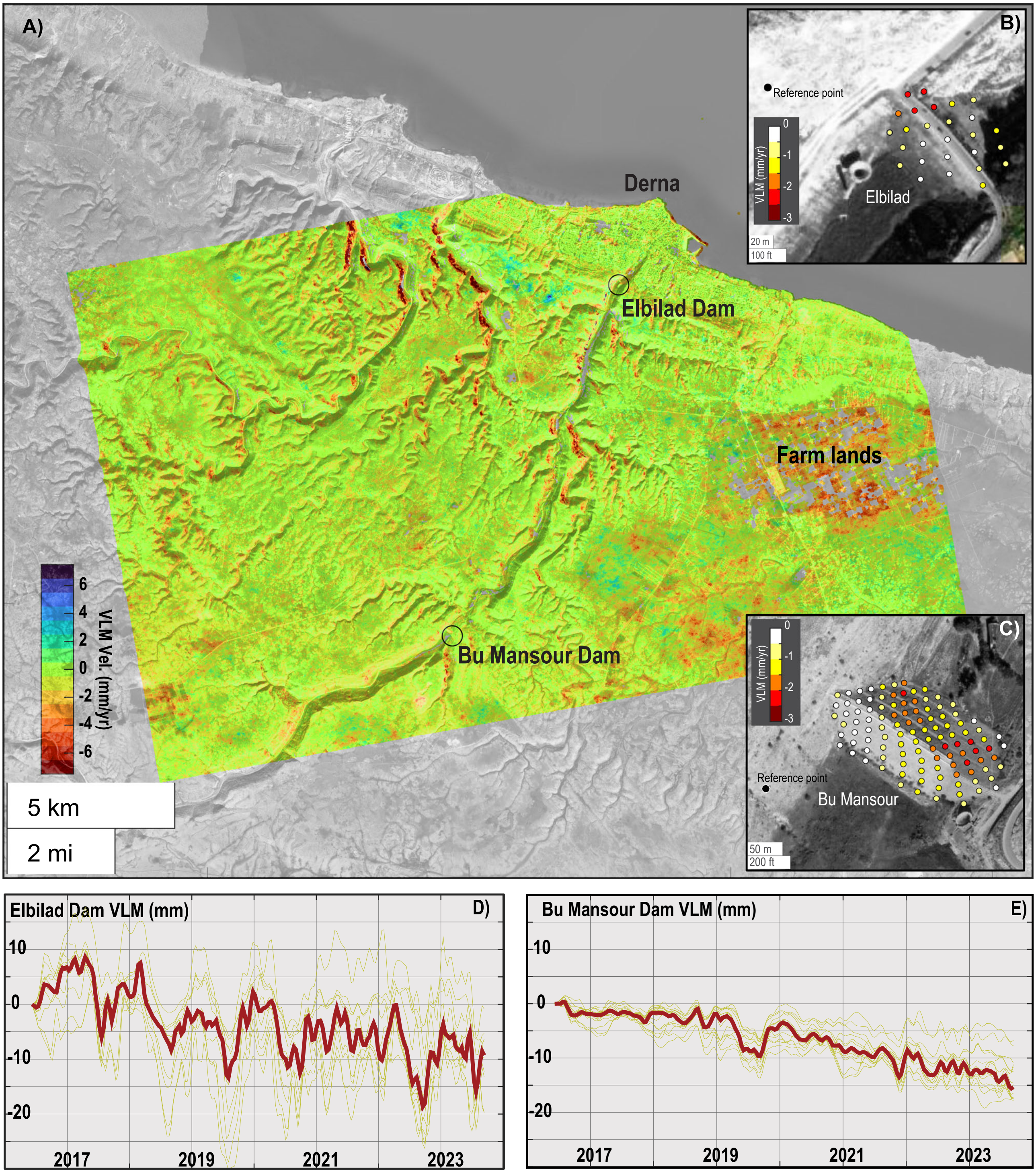

Fig. 1 | SAR interferometric land subsidence maps. **A** Vertical Land Motion (VLM) for the period 2016/06/08-2023/09/12 over the City of Derna, Libya, and its surroundings with respect to the IGS14 global reference frame. **B** and **C** show rate of VLM at the Bu Mansour Al-Bilad dams with respect to their surrounding stable lands marked by black circles as reference points. **D** and **E** Time series of VLM for pixels located on Elbilad and Bu Mansour dams are shown in yellow, and their average is highlighted in red. Background images in panels **A**–**C** are obtained from Google Earth.

Political instability fuels infrastructure neglect: leading to tragedy

Political instability poses significant challenges to infrastructure maintenance, which may have been a critical factor contributing to the catastrophic dam failure in Libya. Dams, like all infrastructure, require continuous monitoring and periodic retrofitting to ensure safe operation[16]. Proper maintenance and monitoring are essential as the dam ages, and its condition inevitably deteriorates. The Libya disaster is attributed to political instability leading to improper infrastructure maintenance[17], to the extent that some experts call for international investigation[18], highlighting the detrimental effects of governance issues on infrastructure upkeep. Regime changes and the lack of coordination between rival authorities have amplified the infrastructure crisis as essential services, including dam maintenance, suffered neglect[19]. Under such circumstances, it is not unusual to observe that funds meant for critical upkeep were diverted for other purposes, leaving the dams to wither under the relentless force of time and weather. Furthermore, the management and governance of critical infrastructure can become politicized, with decision-making processes influenced by political interests rather than purely technical or environmental considerations. For instance, despite the establishment of a $335 million fund by the Tripoli-based Government of National Unity in 2021 for the rehabilitation of Derna and Benghazi, these funds became entangled in political disputes, exacerbating challenges related to the cities' recovery, including the upkeep of the dams[19].

Also, political instability exacerbates disaster impacts by affecting dynamic vulnerability and generating spatiotemporally variable susceptibility to hazards[9]. For instance, in politically unstable regions, neglect of healthcare facilities leaves communities more susceptible to disasters, limiting their ability to respond effectively when hazards occur. Political instability also intensifies vulnerabilities by restricting economic opportunities, increasing poverty rates, and causing displacement, all of which compound the risk when disasters strike. The cyclical nature of these vulnerabilities magnifies the impact of disasters, turning hazards into large-scale crises that are challenging to manage and recover from ref. 9.

Human decision to settle in floodplains: a prelude to tragedy

In recent decades, human settlements have continuously grown within floodplains and flood-prone zones globally[20]. This human decision, a prelude to the Libya tragedy, can set the stage for human disaster[21]. Derna, located on the northeastern shore of Libya, is a strategic city inhabited since the early days of human civilization[22]. The Derna's old city developed rapidly under Greek, Roman, and Ottoman rule within the Wadi Derna River valley, a floodplain, becoming a trade and culture center[22]. The appeal of fertile plains and proximity to water sources proved irresistible to developers and settlers[23–25]. Consequently, cities and towns emerged along riverbanks and low-lying areas, often unaware of the potential dangers. In the 20th century, following Italian occupation, the modern city emerged and proliferated after Libya's independence in 1943, albeit without proper city planning[22]. Following the Arab Spring in 2010, a large population immigrated to Derna, residing in the old city.

We investigated the extent of damage sustained by buildings during the Libya catastrophe, an indicator of human and economic loss. Our results reveal that more than 8570 buildings are damaged with >99% probabilities (Fig. 2). Areas with a high probability of damage are located within the Wadi Derna River valley, a floodplain comprising the old city, where post-event optical imageries[26] also show significant damage and thus poorly planned urbanization and rapid expansion have inevitably encroached[22,27]. Thus, the lack of foresight in floodplain development is pivotal in the unfolding disaster, although this is a widespread problem.

Discussion and conclusions

Our analysis indicates significant differential settlement at the dam sites, exacerbated by poor maintenance and political instability. The resulting structural weaknesses highlight a critical area where improved preparedness could make a difference. As discussed below, regular maintenance schedules, supported by political stability and adequate funding, are crucial for preventing such failures. Additionally, enhancing community resilience through education, early warning systems, and robust emergency response plans could mitigate the human toll of such disasters. These measures would empower communities to better cope with and recover from similar events in the future.

The aftermath of Libya's disaster offers valuable lessons for improving preparedness and community resilience to withstand, adapt to, and recover from disasters, which are critical components of disaster risk reduction[28–30]. These concepts involve the capacity of communities to anticipate, prepare for, respond to, and recover from adverse events. Understanding how these elements could have altered the outcome is essential in the context of the Libya disaster. As illustrated in Fig. 3, the tragic flood event in Libya is a poignant example of the confluence of multiple factors, including development in floodplains, political instability, inadequate infrastructure maintenance and management, and the specter of climate change, whose compounding effect can amplify the disaster. Libya's catastrophe serves as the most recent focal point in a larger landscape of neglect, as there are many other places, such as Afghanistan, Iraq, Syria, and Ukraine, where recent wars or political instabilities have diverted attention away from critical infrastructure, especially its maintenance. As Fig. 3 illustrates, several other major dams with extensive downstream development are located in regions where dam failure can rapidly lead to a human disaster.

Disaster outcomes are profoundly shaped by vulnerability, emphasizing that disasters are not simply "natural" occurrences but are often the result of underlying social, economic, and political factors. Disasters are disproportionately severe for communities with pre-existing vulnerabilities, such as poverty, weak infrastructure, and limited resource access, which hinder effective disaster response and recovery[31]. As such, disasters are human-made in terms of their impacts, as hazard risks escalate when communities lack the resources or resilience to withstand, adapt to, and recover from them[32,33]. Vulnerability turns hazards into disasters by exacerbating exposure and reducing the capacity to respond effectively[34]. This perspective underscores that addressing vulnerabilities, ensuring equitable access to resources, and strengthening community resilience is essential to mitigating disaster impacts and promoting more resilient societies.

The flooding disaster in Derna, Libya, exemplifies the devastating impact of multi-hazard risks and consecutive hazards, particularly when previous events like land subsidence, political instability, and infrastructure mismanagements have compromised vital structures. Overlapping and consecutive disasters pose compounded challenges, often exceeding the capacity of systems designed to withstand isolated events[8,10]. Derna's dams, initially constructed to shield the community from floods, were gradually weakened by ongoing subsidence and insufficient maintenance due to a lack of recovery investments to enhance their resilience. This failure to address structural vulnerabilities made the dams increasingly susceptible to subsequent hazards, such as heavy rainfall, ultimately leading to catastrophic flooding. Thus, the risk of exposure to future hazards is exacerbated without sustained recovery efforts that reinforce infrastructure against multiple threats.

While political instability can cause infrastructure mismanagement, some stable countries, such as the United States, face substantial infrastructure challenges, too. The American Society of Civil Engineers' 2021

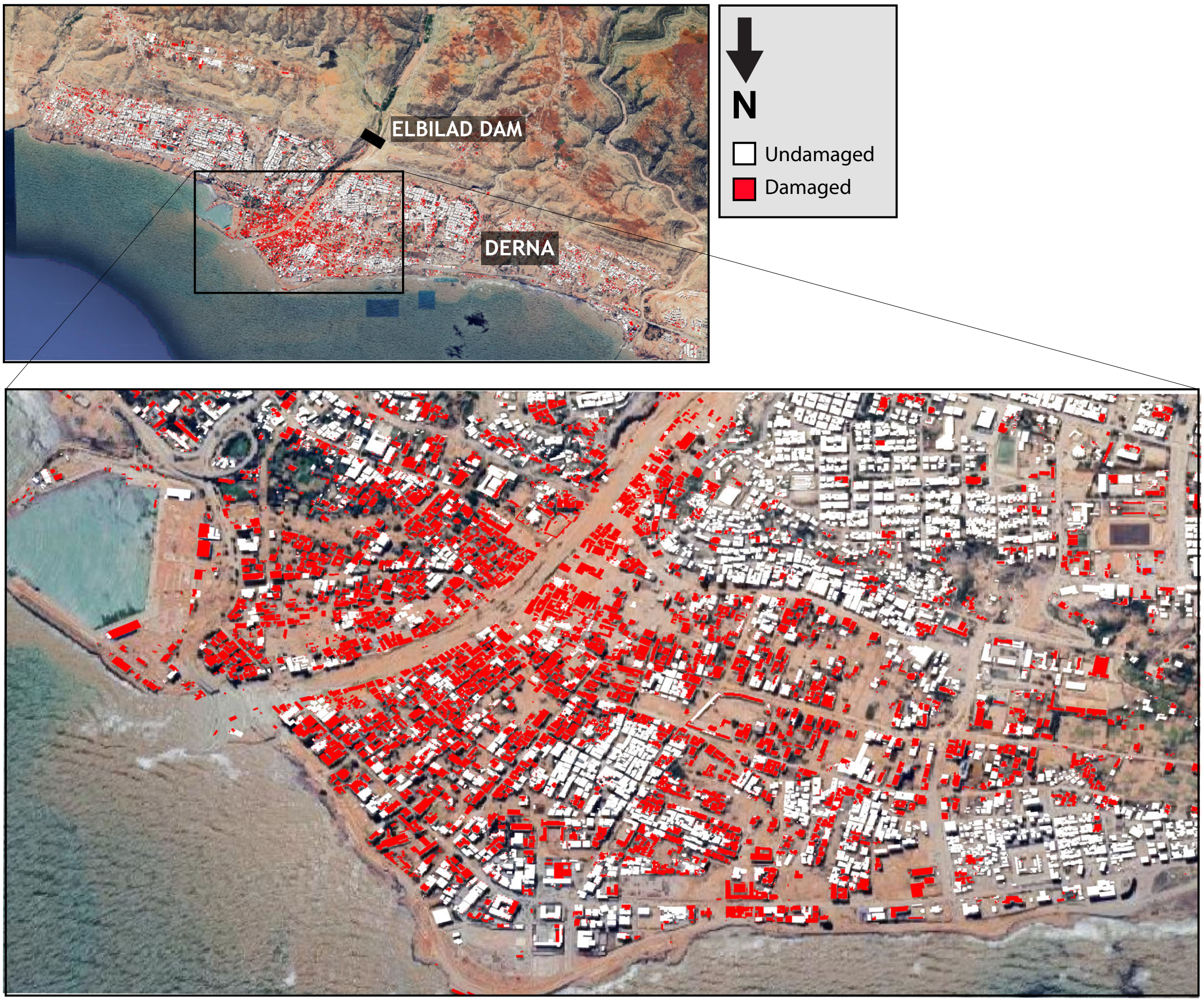

Fig. 2 | Building damage map. We assigned a damage probability to each building by applying a Bayesian framework to the coherence map of a SAR interferogram spanning the flood event (Supplementary Fig. S7). Here, buildings with a damage probability greater than 99% are color-coded red. We estimate that ~8570 buildings are damaged with >99% probability. Background image is obtained from Google Earth.

report card rated U.S. infrastructure—covering airports, schools, roads, bridges, dams, and levees—as mostly in "mediocre" or "poor" condition, with only railways achieving a "good" rating[35]. This was followed by a 2022 report that noted that "public investment in U.S. infrastructure as a share of GDP has fallen by more than 40 percent since the 1960s," leading to deteriorating roads, bridges, and public transit systems[36]. In contrast to the U.S., Singapore, a developed country, consistently ranks highly in global infrastructure quality, mainly due to its strategic planning, sustained investment, and a strong focus on maintenance. The government employs a forward-thinking approach with long-term infrastructure planning initiatives, such as the Land Transport Authority's "Land Transport Master Plan," which maps out developments decades in advance. Furthermore, Singapore allocates significant funding to ensure infrastructure upkeep and uses advanced technologies to monitor and manage infrastructure in real time[37]. These examples illustrate that while political instability directly undermines infrastructure maintenance, political stability alone does not guarantee well-maintained infrastructure. Effective governance, consistent investment, and prioritization are crucial to ensure the longevity and safety of infrastructure systems.

As the world grapples with the consequences of a changing climate, Libya, too, felt the impacts of erratic and unexpected weather extremes[4]. The unusually intense precipitation event due to Storm Daniel[4] may be attributed, in part, to a warming atmosphere with a higher capacity to hold moisture, as suggested for other events worldwide[38,39]. A recent site-specific study clergy showed that the devastating storm that caused the flooding in Libya was made significantly more likely and intense due to human-caused climate change[40]. Their findings suggest that the storm was up to 50 times more likely to occur and 50% more intense because of the current levels of global warming. Ground-based observations and future projections indicate that the frequency and severity of such extreme precipitation events have increased and are expected to rise further[41,42]. This heightened frequency and intensity of extreme precipitation[43] events are a stark reminder of the urgent

Fig. 3 | Catastrophic nexus of human decisions, aging infrastructure, political instability, and climate change has driven the human disaster in Libya and can trigger similar disasters in other parts of the world, such as Iran (Karkhe Dam), Iraq (Mosul Dam), the USA (Whittier Narrows Dam), and India (Mullaperiyar Dam), where large settlements in flood-prone areas are threatened by poor infrastructure and political inactions in climate change era. Background images are obtained from Google Earth.

need for adaptive measures in the face of this rapidly changing climate worldwide.

Urban planning must address the rising risks of development in flood-prone areas by prioritizing flood adaptation and mitigation strategies. This involves investing in resilient infrastructure that can withstand and quickly recover from disasters. Additionally, promoting public awareness and education on flood risks and the importance of individual and community preparedness is essential. Derna's old city, encompassing mainly 1–2 story buildings, is located within the Wadi Derna River valley and is home to large immigrant communities that moved to Derna following the revolution. Due to a lack of funding and generally poor population and despite its cultural and historical importance, the old city lacked essential flood protection and adaptation plans[22] and thus was extensively damaged during the flood event[27] with major loss of life.

The current holistic approaches for critical infrastructure protection[44–46] focus mainly on preparation for, protection against, and response to infrastructure disruption. To avert such catastrophes in the future, we believe more efforts should focus on infrastructure 'health' monitoring, considering pre-existing conditions and future climate to prevent infrastructure failure from becoming a human disaster. This requires continuous screening and several diagnostic and treatment stages, ranging from minor repairs to major infrastructure retrofits. In some cases, managed removal of critical infrastructure due to flawed design[6] or a design incompatible with the operational requirements under expected future climate scenarios may be necessary. Additionally, investment in research and development to better understand potential threats to infrastructure and develop innovative solutions to emerging, complex, and interconnected challenges is a crucial component of such a holistic preventative approach.

Although Bu Mansour Dam was intended to withstand rare hydrological events[6], its design did not consider the unprecedented rainfall of Storm Daniel. Derna's disaster is the culmination of years of governance instability and political discourse[23]. Many countries do not have the resources, political stability, or human capacity to address such challenges. For this reason, there is a need for an international service similar to the World Meteorological Organization (WMO) or World Climate Research Programme (WCRP) that continuously monitors infrastructure health and generates early warnings for at-risk communities. Climate extremes will likely increase, with developing countries bearing the worst impacts.

Concerted international efforts can assist these countries in becoming more resilient in the face of climate change, and design guidelines and risk assessment methods should be updated to account for the expected changing risks.

This study underscores the importance of integrating preparedness and community resilience into disaster risk management strategies. The findings highlight how various factors contributed to the Libya disaster and suggest that a holistic approach, encompassing regular infrastructure maintenance, political stability, and community engagement, is vital for mitigating future risks. Future research should continue to explore these connections, providing a more comprehensive understanding of how to enhance resilience and preparedness in vulnerable regions. Community engagement is a crucial component of effective disaster risk management, as it empowers local populations to take an active role in preparedness and response efforts. Involving communities in risk assessment, early warning dissemination, and response planning increases awareness and fosters a sense of shared responsibility for resilience. Previous studies[47,48] have shown that communities engaged in preparedness and decision-making are better equipped to respond to and recover from disasters. Incorporating community perspectives, resources, and knowledge into resilience strategies can strengthen overall preparedness and foster adaptive, sustainable practices that align with local needs and conditions."

Methods

SAR interferometric deformation analysis. To generate high-resolution maps of surface deformation over the city of Derna, Libya, we applied Wavelet-based InSAR (WabInSAR) algorithm, an advanced multi-temporal interferometric synthetic aperture radar (InSAR) processing framework to 214 SAR images acquired in ascending orbit of Sentinel-1 A/B satellites, during 2016/06/08-2023/09/12. We first generated a large set of high-quality Interferograms using GAMMA software[49]. We applied a multi-looking factor of 6 by 1 in the range and azimuth direction to improve the signal-to-noise ratio and obtain an average ground resolution of ~15 m × ~15 m. We discarded distributed scatterers with coherence less than 0.65 and permanent scatterers with amplitude dispersion of more than 0.3, following the approach detailed in ref. 50. Next, we employed a minimum cost flow phase unwrapping algorithm modified to be applied to a sparse set of less noisy pixels to estimate absolute phase changes in each interferogram. We corrected all unwrapped interferograms for the effect of orbital error[51] and reduced the effects of topographically correlated atmospheric phase delay and spatially uncorrelated DEM error[52,53]. To estimate each pixel's line-of-sight (LOS) time series and velocity, we applied a reweighted least-squares optimization[53]. Assuming that the principal deformation is vertical, we used the satellite unit vectors[54] and projected the LOS in the vertical direction. To transform the InSAR-based vertical land motion (VLM) to the IGS14 global reference frame, we utilized the global VLM model generated by Hammond et al.[55], which mainly includes long-wavelength deformation signals due to glacial isostatic adjustment, tectonics, and total water storage changes in a global reference frame, and applied an affine transformation following[13,56]. Supplementary Fig. 1 shows the LOS velocity map with respect to a local reference point (Lon: 22.5206°, Lat: 32.6708°), and associated standard deviation and local incidence angles are shown in Supplementary Figs. 2 and 3. Supplementary Fig. 4 shows the spatial distribution of VLM in a local reference frame as a result of dividing the LOS velocity of each pixel by the cosine of the associated incidence angle. Figure 1 shows the VLM map in the IGS14 reference frame. Supplementary Fig. 5 is a closeup map showing the subsidence at some coastal infrastructure, particularly the Derna's seawalls, where a subsidence rate of up to −5.8 mm/yr is observed.

Building damage probability. To generate a probabilistic map of building damage for the city of Dena, we use interferometric phase coherence of two interferograms spanning the pre-flood period 2023/08/07–2023/08/19 and the co-flood period 2023/08/19–2023/09/12 and apply a Bayesian image segmentation framework[57,58]. We also used the building footprint provided by Google Research. Supplementary Fig. 6A, C show buildings color-coded to their pre- and co-flood coherence. To this end, we identified the nearest pixel to the center of each building and assigned its coherence value to it. Given the interferometric phase coherence (ρ^o) of each building, the conditional probability of being damaged, $p(D/\rho^o)$, is estimated as following:

$$p(D/\rho^o) = \frac{p(\rho^o/D)p(D)}{p(\rho^o)} \tag{1}$$

$$p(\rho^0) = p(\rho^0/D)p(D) + p(\rho^0/\bar{D})p(\bar{D}) \tag{2}$$

where $p\left(\rho^o/D\right)$ is the probability of recording a given coherence value ρ^o for damaged building (D), $p(\rho^0/\bar{D})$ is the probability of recording a given coherence value ρ^o for a non-damaged building ($\bar{D}$). Supplementary Fig. 6B, D show the histogram of the coherence of the buildings before and after damage used to estimate $p\left(\rho^o/D\right)$ and $p(\rho^0/\bar{D})$. Also, $p(\rho^0)$ is the marginal probability of recording a given coherence value ρ^o for any building. The terms $p(D)$ and $p(\bar{D})$ are the prior probabilities of a building being damaged and non-damaged. In a Bayesian framework, $p(D)$ represents the prior probability of damaged building, prior to the coherence being measured, and $p(\bar{D}) = 1 - p(D)$. We choose a noninformative prior as $p(D) = p(\bar{D}) =$ 0.5, namely, the initial chance of a building being damaged is the same as not being damaged. We tested different values and found that the posterior probability distribution of damaged buildings depends weakly on the choice of prior values. Supplementary Fig. 7 shows buildings color-coded according to their probability of being damaged.

Distortion angle. In geotechnical engineering, the angular change in relative elevation of two adjacent points, so-called angular distortion, is widely used to indicate infrastructure damage due to differential settlement[13,59,60]. Given two observation points apart by horizontal distance l and settlements of δ_1 and δ_2, the angular distortion, β is given by Eq. ((3)):

$$\beta = \frac{\delta_2 - \delta_1}{l} \tag{3}$$

Depending on the type of materials, a range of β is suggested as an indicator for negligible to severe infrastructure damage due to differential subsidence. For instance, Wood et al.[61] reported cracks and damage to brick walls and encased steel frames for a β of 1/1000 to 1/100. Also, β greater than 6.6/1000 is associated with structural damage in beams and columns, and β larger than 3.3/1000 can cause cracking in structures with steel or reinforced concrete frames[14].

Data availability

No datasets were generated or analyzed during the current study.

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Author contributions
M.S. designed the study, performed the analysis, and wrote the first draft of the manuscript. F.V. contributed to the discussions and revised the manuscript. N.S. contributed to the discussions and revised the manuscript, L.O. contributed to the discussions and revised the manuscript, O.D. contributed to the discussions and revised the manuscript, A.T. contributed to the discussions and revised the manuscript, S.W. contributed to the discussions and revised the manuscript, M.A. contributed to the discussions and revised the manuscript, Y.Z. contributed to the discussions and revised the manuscript, R.N. contributed to the discussions and revised the manuscript, and A.A. contributed to the discussions and revised the manuscript. All authors have read and approved the manuscript.

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