https://jsras.rcc.edu.ly/
Vol.3 No.2 (2026), 68-78
Article history:
Received: 29 May. 2026
Accepted: 26 Jun. 2026
Published: 15 Jul. 2026

Journal of Sustainable Research in Applied Sciences

# Mapping The Environmental Footprint of Storm Daniel in Derna, Libya Using Satellite Imagery

Osama Rahil Shaltami[1,*], osama.rahil@yahoo.com, https://orcid.org/0009-0006-0890-9093,
Mustafa A. Ben Hkoma[2], m_hkoma2017@yahoo.com, https://orcid.org/0009-0006-6814-8468,
Firas Khamees Mohammed[3], firas.almabrook@omu.edu.ly, https://orcid.org/0009-0002-4951-3803,
Kamal Abraheem Almahdi[4], kamal.faraj@omu.edu.ly, https://orcid.org/0009-0009-2536-826X
[1]Department of Earth Sciences, Faculty of Science, University of Benghazi, Libya
[2]Sustainable Development Research Center, Ubari, Libya
[3,4]Department of Earth Sciences, Faculty of Science, Omar Al-Mukhtar University, Libya
DOI: https://doi.org/10.36602/jsras.2026.3.2.9
* Corresponding author osama.rahil@yahoo.com

***Index Terms***

Storm Daniel, Remote Sensing, Geographic Information Systems, Derna, Libya

***Abstract***

Storm Daniel triggered one of the deadliest and most destructive flood disasters in Libya's history, devastating the city of Derna after the failure of the Abu Mansour and Derna dams in September 2023. This study investigates the environmental impacts of the disaster using multi-temporal Sentinel-2 satellite imagery integrated with geographic information systems (GIS) and remote sensing techniques. A combination of land-cover classification, normalized difference vegetation index (NDVI) change detection, flood extent mapping, sediment transport analysis, coastal impact assessment, and digital elevation model (DEM) differencing was used to evaluate the environmental changes caused by the flood. The analysis revealed widespread flooding along Wadi Derna, extensive riverbank erosion, channel widening, large-scale sediment deposition, considerable vegetation loss, and severe damage to urban areas. Satellite imagery also showed a substantial sediment plume extending into the Mediterranean Sea, highlighting the close connection between upstream flood processes and coastal ecosystems. In addition, the findings suggest that the flood likely redistributed pollutants such as sediments, untreated sewage, petroleum products, and agricultural contaminants, which may have lasting consequences for soil, freshwater resources, coastal waters, and marine ecosystems. Overall, the study demonstrates that integrating satellite remote sensing with GIS provides a reliable and efficient approach for rapid post-disaster environmental assessment, offering valuable insights to support ecosystem restoration, disaster risk reduction, watershed management, and more sustainable urban planning in areas vulnerable to flooding.

# رسم خرائط البصمة البيئية للعاصفة دانيال في درنة، ليبيا، باستخدام صور الأقمار

أسامة رحيل الشلطامي[1]، مصطفى بن حكومة[2]، فراس خميس محمد[3]، كمال إبراهيم المهدي[4]
[1]جامعة بنغازي، كلية العلوم، قسم علوم الأرض، بنغازي، ليبيا، osama.rahil@yahoo.com، https://orcid.org/0009-0006-0890-9093
[2]مركز أبحاث التنمية المستدامة، أوباري، ليبيا، m_hkoma2017@yahoo.com، https://orcid.org/0009-0006-6814-8468
[3،4]جامعة عمر المختار، كلية العلوم، قسم علوم الأرض، ليبيا
[3]firas.almabrook@omu.edu.ly، https://orcid.org/0009-0002-4951-3803
[4]kamal.faraj@omu.edu.ly، https://orcid.org/0009-0009-2536-826X
DOI: https://doi.org/10.36602/jsras.2026.3.2.9
* المؤلف المراسل osama.rahil@yahoo.com

***الكلمات المفتاحية***

العاصفة دانيال، الاستشعار عن بُعد، نظم المعلومات الجغرافية، درنة، ليبيا

***الملخص***

تسببت العاصفة دانيال في واحدة من أكثر كوارث الفيضانات فتكاً وتدميراً في تاريخ ليبيا، حيث دمرت مدينة درنة عقب انهيار سدي أبو منصور ودرنة في سبتمبر 2023. وتتناول هذه الدراسة الآثار البيئية للكارثة باستخدام صور الأقمار الصناعية وكشف التحليل عن حدوث فيضانات واسعة النطاق على طول مجرى وادي درنة، وتآكلٍ كبيرٍ لضفاف النهر، واتساعٍ في المجرى المائي، وترسبٍ كثيفٍ للرواسب، وفقدانٍ ملموسٍ للغطاء النباتي، وأضرارٍ جسيمةٍ في المناطق الحضرية. كما أظهرت صور الأقمار الصناعية وجود سحابة كبيرة من الرواسب تمتد داخل مياه البحر الأبيض المتوسط، مما يبرز الارتباط الوثيق بين عمليات الفيضان في أعالي الوادي والنظم البيئية الساحلية.

## 1. INTRODUCTION

Over the past few decades, extreme weather events have become more frequent and intense across the globe, largely as a result of climate change and increasing global temperatures. The Mediterranean region is particularly vulnerable to a wide range of hydrometeorological hazards, including intense rainfall, flash floods, prolonged droughts, heatwaves, and Mediterranean tropical-like cyclones, commonly known as medicanes. Rising sea surface temperatures, combined with shifts in atmospheric circulation, are expected to increase the likelihood and severity of these high-impact storms, placing greater pressure on communities, infrastructure, natural ecosystems, and regional economies. Along the southern Mediterranean coast, countries such as Libya face heightened risks due to their semi-arid climate, rapid urban expansion, aging infrastructure, and limited capacity for disaster preparedness and emergency response.

In early September 2023, Storm Daniel formed over the Mediterranean Sea after leaving a trail of severe flooding across parts of southeastern Europe before tracking south toward Libya. Between 10 and 11 September, the storm brought exceptionally intense rainfall to northeastern Libya, with the heaviest precipitation recorded in the Al Jabal Al Akhdar region and the city of Derna. Rainfall totals far exceeded normal historical levels over a very short period, triggering devastating flash floods across the Wadi Derna watershed. The resulting surge of runoff quickly overwhelmed drainage networks and placed extraordinary stress on the dams located upstream of the city. Among the most catastrophic impacts of Storm Daniel was the successive failure of the Abu Mansour and Derna dams, both located upstream of the city. Their collapse unleashed millions of cubic meters of floodwater that rushed through Wadi Derna, sweeping away homes, bridges, roads, public buildings, and other essential infrastructure before emptying into the Mediterranean Sea. The disaster claimed thousands of lives, with many others reported missing, making it one of the deadliest flood events in the modern history of the Mediterranean region. In addition to the immense human tragedy, the floods left a profound environmental legacy. The powerful floodwaters caused extensive soil erosion, transported and deposited large volumes of sediment, reshaped river channels, and altered coastal landscapes. The disaster also resulted in widespread vegetation loss, contamination of surface water and groundwater, and severe damage to urban environments, creating long-term environmental challenges that will require sustained monitoring and restoration efforts.

Assessing the environmental impacts of catastrophic floods requires an integrated approach that combines hydrology, geomorphology, geochemistry, and geospatial technologies. Among these disciplines, geochemistry provides valuable insights into how flood events mobilize and redistribute sediments, nutrients, heavy metals, hydrocarbons, and other contaminants across the landscape. Floodwaters can transport both naturally occurring materials and pollutants released from urban areas, industrial sites, sewage networks, landfills, and damaged infrastructure. As a result, geochemical studies are essential for evaluating environmental contamination, changes in soil and water quality, sediment sources, ecosystem recovery, and the potential for long-term environmental impacts. This information is critical for designing effective remediation measures, protecting public health, and supporting sustainable reconstruction after major natural disasters. Satellite remote sensing has also become an indispensable tool for rapid post-disaster environmental assessment, offering timely, comprehensive, and repeatable observations over large areas. Multi-temporal imagery acquired by satellites such as Sentinel-2 and Landsat makes it possible to map flood extent, monitor land-cover changes, identify sediment deposition, assess vegetation damage, detect shoreline alterations, and evaluate damage to infrastructure with high spatial and temporal detail. When combined with geographic information systems (GIS), these datasets enable efficient change detection, spatial analysis, and long-term environmental monitoring. This integrated approach is particularly valuable in disaster-affected regions where on-the-ground surveys are difficult, hazardous, or impossible during the immediate aftermath of a flood.

This study uses multi-temporal satellite imagery together with remote sensing techniques to investigate the environmental impacts of Storm Daniel on the city of Derna in northeastern Libya. The main objectives are to quantify flood-related land-cover changes, identify areas affected by erosion and sediment deposition, evaluate damage to both urban infrastructure and natural ecosystems, and demonstrate the value of remote sensing for rapid post-disaster environmental assessment. By providing a comprehensive evaluation of the flood's environmental footprint, the study offers scientific evidence that can support ecosystem restoration, hazard mitigation, disaster preparedness, and more sustainable urban planning in Libya and other Mediterranean regions that are increasingly exposed to extreme hydrometeorological events. A growing body of research has examined the environmental impacts of Storm Daniel, offering important insights into how the disaster affected ecosystems, infrastructure, and the surrounding environment (e.g., WHO, 2023; Agfir and Sasi, 2024; Ben Miloud and Elmaremi, 2024; Fernandes et al., 2024; Nawaz et al., 2025; Normand and Heggy, 2024; Nemnem et al., 2025; Samir et al., 2025; Fawzy et al., 2026; Kushabaha et al., 2026; Lashhab, 2026).

The study area is the city of Derna, situated on Libya's northeastern Mediterranean coast between the Al Jabal Al Akhdar highlands and the Mediterranean Sea (Fig. 1). Located approximately 290 km east of Benghazi, Derna is one of the largest urban centers in eastern Libya. The city occupies a narrow coastal plain bisected by Wadi Derna, a seasonal river valley that drains a watershed extending from the elevated limestone plateau of Al Jabal Al Akhdar to the Mediterranean coast. Derna has a Mediterranean climate, with mild, rainy winters and hot,

dry summers. Most of the annual rainfall occurs between November and March. Although average precipitation is relatively low, short-duration, high-intensity storms can generate substantial surface runoff because of the steep terrain, increasing the risk of flash flooding. Wadi Derna is the main drainage system in the region and plays a central role in the area's hydrology and flood behavior. Rising in the Al Jabal Al Akhdar Mountains, the wadi flows through deeply incised valleys before passing through the center of Derna and eventually reaching the Mediterranean Sea. The watershed is characterized by steep slopes, fractured carbonate bedrock, sparse vegetation cover, and limited infiltration during intense rainfall, conditions that promote rapid runoff and high flood peaks. During Storm Daniel in September 2023, exceptionally heavy rainfall generated record flood discharges that overwhelmed the city's flood-control infrastructure. The resulting floods caused widespread geomorphological changes, including severe channel erosion, riverbank failure, extensive sediment transport, and large-scale sediment deposition across the floodplain and along the coastal zone. The Mediterranean coastline adjacent to Derna is both environmentally and economically important, supporting urban settlements, fisheries, tourism, and diverse marine ecosystems. During the flood, enormous volumes of water, sediment, debris, and contaminants were carried into the coastal waters, altering shoreline morphology, increasing water turbidity, and potentially degrading marine habitats. These impacts demonstrate the close linkage between watershed processes and the coastal environment, emphasizing how extreme flood events can rapidly transfer materials and pollutants from inland catchments to the Mediterranean Sea. To reduce the risk of flooding, two dams were built across Wadi Derna upstream of the city: the Abu Mansour Dam, also known as the Upper Derna Dam, and the Derna Dam, commonly referred to as the Lower Derna Dam. The Abu Mansour Dam, located about 13 km south of Derna, was designed to capture floodwaters from the upper catchment and reduce downstream flow. Approximately 1 km downstream, the Derna Dam provided a second level of protection by regulating floodwaters before they reached the urban area. During the night of 10–11 September 2023, both dams failed in succession under the extreme hydraulic forces generated by Storm Daniel. Their collapse released an immense volume of water that surged through Wadi Derna, inundating the city and causing catastrophic flooding. The resulting disaster led to extensive damage to infrastructure, widespread environmental degradation, and a tragic loss of human life. Derna's vulnerability to extreme flooding is largely a consequence of its unique physical and urban setting. The combination of a steep watershed, a narrow river valley, densely developed urban areas, and reliance on critical hydraulic infrastructure creates conditions that can amplify the impacts of intense rainfall events. For this reason, Derna provides a valuable case study for investigating flood-induced environmental change using satellite remote sensing and geospatial analysis. Mapping the spatial patterns of erosion, sediment deposition, land-cover change, and flood damage not only improves our understanding of the disaster's environmental consequences but also provides scientific information to support future environmental management, flood risk reduction, and resilient urban planning in northeastern Libya.




Figure 1. Location map of Derna and Wadi Derna.

## 2. METHODOLOGY

The maps were generated and finalized using GIS and remote sensing platforms such as ArcGIS Pro, QGIS, ESA SNAP, and Adobe Illustrator/PowerPoint for cartographic visualization.

## 3. RESULTS AND DISCUSSION

### *3.1 Flood Extent*

The flood inundation map (Fig. 2), together with the Sentinel-2 satellite imagery (Fig. 3), clearly demonstrates the scale and intensity of the flooding that struck Derna, northeastern Libya, on 10 September 2023 during Storm Daniel. The disaster was triggered by exceptionally heavy rainfall and was dramatically intensified by the successive failures of the Abu Mansour and Derna dams. Their collapse released a massive flood wave that surged through Wadi Derna before discharging into the Mediterranean Sea. The inundation map indicates that the flooding was primarily concentrated within the Wadi Derna catchment but spread rapidly across the city after the floodwaters entered the urban area. The greatest water depths, exceeding 5 m, were recorded within the main wadi channel and immediately downstream of the dam breaches, where flow velocities and erosive forces were at their highest. Flood depths gradually decreased with increasing distance from the channel, with large sections of the city experiencing inundation between 1 and 3 m, while shallower flooding of less than 0.5 m extended across the surrounding floodplain.

The flood extent map shows that the floodwaters traveled approximately 20 km, from the breached Abu Mansour Dam through the Derna Dam and ultimately to the Mediterranean coast. As the flood entered the city, the inundation corridor widened substantially, reflecting the

spread of water across the alluvial plain and densely populated urban areas. Although the overall flood pattern followed the course of Wadi Derna, floodwaters also spread laterally into residential neighborhoods where buildings, roads, and other infrastructure altered the natural flow paths. A comparison of Sentinel-2 imagery acquired before (August 2023) and after (September 2023) Storm Daniel highlights the profound changes to the landscape. Before the disaster, Wadi Derna appeared as a relatively narrow river channel, with the Abu Mansour and Derna reservoirs clearly visible upstream and the surrounding urban areas largely intact. In contrast, the post-flood imagery reveals the complete collapse of the Abu Mansour Dam and the failure of the Derna Dam, accompanied by extensive widening of the wadi channel as a result of severe erosion. Large volumes of sediment were deposited across the floodplain, while residential and commercial districts in central Derna experienced widespread destruction. The imagery also shows a prominent sediment plume extending into the Mediterranean Sea, providing clear evidence of the massive transfer of sediment from the watershed to the coastal environment.




Figure 2. Flood inundation map of Storm Daniel.




Figure 3. Sentinel-2 satellite imagery of Derna before (August 2023) and after (September 2023) Storm Daniel.

The inundation map further shows that the greatest concentration of building damage was located within the main flood corridor, especially where Wadi Derna flows through the urban area. Many bridges and transport links that crossed the wadi were swept away after being directly exposed to the powerful floodwaters. As the flood continued toward the Mediterranean Sea, it carried vast amounts of sediment, debris, and construction materials, demonstrating the enormous energy of the event and its capacity to transport material from the watershed to the coastal environment.

Generally, the mapped flood extent highlights the combined effects of extreme rainfall, the failure of the Abu Mansour and Derna dams, the steep terrain of the watershed, and rapid urban development downstream. The observed inundation pattern indicates that this was far more than a typical river flood. Instead, it was a catastrophic dam-break event marked by high-velocity flows, extreme water depths, and extensive geomorphological change. The flood extent maps provide valuable spatial information for assessing flood hazards, guiding infrastructure reconstruction, supporting resilient urban planning, and informing future flood risk management strategies in northeastern Libya.

### *3.2 Land Cover Change*

The land-cover change analysis reveals the significant environmental impacts of Storm Daniel on the Derna region and the Wadi Derna watershed between 23 August 2023 (pre-event) and 13 September 2023 (post-event). A comparison of the classified Sentinel-2 images shows extensive changes across the landscape, particularly along the Wadi Derna channel, the downstream floodplain, and the urban areas of Derna (Fig. 4). The post-event land-cover map indicates a substantial increase in areas of bare soil and newly deposited sediment, replacing land that had previously been covered by vegetation and agricultural fields. These changes are most pronounced along the Wadi Derna corridor, where the catastrophic flooding triggered by the collapse of the Abu Mansour and Derna dams transported massive quantities of sediment toward the Mediterranean Sea. The land-cover change map further supports this interpretation by identifying extensive zones of increased bare soil and sediment, reflecting widespread erosion in the upper watershed and large-scale sediment deposition downstream. The NDVI change analysis (Fig. 5) further reinforces these observations by showing a substantial decline in vegetation health across the watershed. Large areas of agricultural land and riparian vegetation exhibited strongly negative NDVI values (−0.6 to −1.0), indicating vegetation loss, burial by flood-deposited sediment, or severe stress resulting from prolonged inundation. The greatest reductions in vegetation were concentrated along the floodplain and cultivated areas bordering Wadi Derna, highlighting the vulnerability of agricultural landscapes to the flood. Urban areas also underwent significant land-cover changes.

The widening of the Wadi Derna channel through the center of the city coincides with extensive damage to built-up areas clearly visible in the post-event satellite imagery. Although urban land represents only a small portion of the watershed, the scale of its destruction had

major socioeconomic consequences. In addition, the extensive sediment deposits stretching from the city center to the Mediterranean coast illustrate the intensity of the flood, which redistributed vast quantities of material across the landscape and into the coastal environment. The magnitude of land-cover change generally declined with increasing distance from the main drainage network. Upland areas and densely vegetated hillsides remained largely unchanged, although localized vegetation loss was evident on steep slopes where intense runoff and slope instability accelerated erosion. Small areas showing apparent vegetation gains in the change detection map are more likely to reflect seasonal vegetation dynamics, increased soil moisture following the storm, or minor classification uncertainties than true ecological recovery. Combining supervised land-cover classification with NDVI change detection provides a more comprehensive assessment of the flood's environmental impacts. Land-cover classification identifies physical changes in surface cover, such as the conversion of vegetated areas to bare soil or sediment, whereas NDVI highlights changes in vegetation health, biomass, and overall condition. Together, these complementary techniques demonstrate that Storm Daniel caused not only extensive geomorphological changes but also widespread ecological disturbance throughout the watershed.




Figure 4. Land-cover change map of Derna and Wadi Derna before and after Storm Daniel.

In general, the results show that the disaster fundamentally reshaped the Derna watershed through large-scale vegetation loss, sediment redistribution, channel widening, and severe damage to urban areas. These environmental changes are likely to have long-term consequences for watershed stability, agricultural productivity, biodiversity, and future flood vulnerability. The study also demonstrates the effectiveness of Sentinel-2 multispectral imagery and remote sensing-based change detection as rapid and reliable tools for post-disaster assessment, providing essential information to support environmental monitoring, ecosystem restoration, recovery planning, and sustainable watershed management in flood-prone regions.




Figure 5. NDVI change detection map of Storm Daniel.

### *3.3 Sediment Transport*

The sediment transport pathways map (Fig. 6) reveals that Storm Daniel caused major changes to sediment movement within the Wadi Derna watershed. The combination of extreme rainfall, steep mountainous terrain, and the successive failure of the Abu Mansour and Derna dams produced a high-energy flood capable of mobilizing and transporting enormous quantities of sediment from the upper catchment to the Mediterranean Sea. The mapped pathways highlight the strong geomorphological connection between sediment source areas, transport routes, floodplain deposition zones, and coastal accumulation areas. The main sediment sources were located in the steep mountainous regions upstream of the Abu Mansour Dam.




Figure 6. Sediment transport pathways map of Storm Daniel.

During the storm, these slopes experienced severe surface erosion, gully formation, and channel incision due to intense runoff. The loss of surface soil, weathered rock material, and vegetation cover significantly increased sediment availability, supplying large amounts of both fine and coarse materials to the Wadi Derna drainage system. The extensive erosion features observed in the upper watershed indicate that hillslope processes were the dominant contributors of sediment to the flood system.

After entering the wadi network, the mobilized sediments were transported downstream through Wadi Derna as both suspended and bed loads. Fine-grained materials, including clay, silt, and fine sand, remained suspended in the turbulent floodwaters and were carried over long distances toward Derna and the Mediterranean coast. In contrast, larger particles such as gravel, cobbles, and boulders moved mainly along the channel bed during periods of peak flow. The successive collapse of the two dams greatly intensified these processes by increasing flow velocity and stream power, thereby enhancing the flood's ability to erode, transport, and redistribute unusually large sediment volumes across the watershed. As the floodwaters spread across the broader floodplain surrounding Derna, the decrease in flow velocity resulted in extensive sediment deposition. The mapped sediment pathways show evidence of widespread overbank flooding and shallow sheet flow across adjacent low-lying areas, leading to the accumulation of fine-grained sediments over residential neighborhoods, agricultural fields, roads, and open land. These deposits buried infrastructure, changed surface characteristics, and substantially altered the morphology of the floodplain. The distribution of deposited sediments reflects the process of hydraulic sorting. Coarser materials were mainly deposited within the wadi channel and along its immediate margins, where flow energy remained relatively high, whereas finer sediments were carried farther and spread across wider floodplain areas. At the mouth of Wadi Derna, floodwaters entered the Mediterranean Sea, where the abrupt reduction in flow energy caused large amounts of sediment to settle in the coastal zone. Satellite imagery reveals a prominent sediment plume extending offshore, indicating that suspended materials continued to travel beyond the river mouth before gradually depositing in the nearshore marine environment. Sediment accumulation near the coastline also contributed to the development and expansion of a temporary deltaic–alluvial feature, modifying shoreline morphology and influencing short-term coastal sediment dynamics. These coastal deposits provide clear evidence of the strong connection between terrestrial and marine systems, demonstrating the rapid transfer of sediment from the watershed to the Mediterranean Sea during an extreme flood event. The mapped sediment transport pathways further emphasize the environmental importance of post-flood sediment redistribution. Flood-deposited materials can act as carriers for nutrients, organic matter, heavy metals, hydrocarbons, and other contaminants derived from natural sources, urban areas, and damaged infrastructure. Therefore, locations identified as major sediment accumulation zones should be considered priority areas for post-disaster geochemical investigations, pollution assessment, and long-term ecological monitoring.

As a whole, the sediment transport pathway analysis reveals a complete sediment cascade triggered by extreme rainfall and intensified by the failure of the upstream dams. This process involved four main stages: (1) Erosion of hillslopes within the upper watershed; (2) Downstream movement of sediment through Wadi Derna as both suspended and bed loads; (3) Widespread deposition across the urban floodplain; and (4) Eventual transfer of sediment into the Mediterranean Sea. These results demonstrate the value of combining satellite remote sensing with GIS techniques to reconstruct post-flood sediment behavior and assess landscape changes. The findings provide important information for watershed rehabilitation, flood risk reduction, sediment management strategies, and the development of more resilient urban planning approaches in northeastern Libya.

### *3.4 Coastal Impact*

The Sentinel-2 image acquired on 12 September 2023 (Fig. 7) captures the immediate coastal impacts of Storm Daniel following the catastrophic flooding of the Wadi Derna watershed. The most prominent feature observed is the large sediment plume extending from the mouth of Wadi Derna into the Mediterranean Sea. The light-brown to greenish-turquoise coloration of the coastal waters reflects extremely high concentrations of suspended sediments transported by the floodwaters after the collapse of the Abu Mansour Dam and the subsequent failure of the Derna Dam. The extensive offshore plume indicates the enormous amount of eroded material generated during the event. Sediments originating from upstream slopes, riverbanks, agricultural areas, and damaged urban zones were carried through the Wadi Derna drainage system and deposited into the coastal environment. The curved dispersion pattern visible offshore reflects the combined influence of river discharge, wave activity, and coastal currents, which spread the suspended material across a wider area of the Mediterranean Sea. The large sediment influx significantly affected nearshore water conditions. Elevated suspended sediment concentrations increased turbidity, reducing water transparency and limiting the penetration of sunlight into the water column. These changes may have negatively influenced marine primary productivity by restricting photosynthetic activity in phytoplankton and submerged vegetation. In addition, the settling of fine sediments on seafloor habitats could disturb benthic communities and contribute to ecological stress within coastal ecosystems. The coastal impacts of Storm Daniel extend beyond sediment transport alone. Floodwaters likely carried substantial amounts of organic matter, nutrients, construction debris, and other materials released from damaged urban infrastructure and agricultural areas into the marine environment. The introduction of these materials may have increased nutrient levels, altered coastal water chemistry, and contributed to temporary changes in marine conditions.

Such disturbances can produce short- and long-term ecological effects, including reduced water quality, disruption of aquatic food chains, and degradation of sensitive coastal habitats. Satellite observations also indicate sediment accumulation along the shoreline and near the mouth of Wadi Derna, reflecting rapid geomorphological changes within the coastal zone. The deposition of flood-derived sediments can modify shoreline shape, alter beach characteristics, and influence

nearshore processes, including navigation conditions around coastal facilities. Furthermore, these newly deposited sediments may continue to be redistributed by waves and coastal currents for weeks or even months after the event, extending the environmental impacts beyond the initial flood period. When considered alongside the land-cover classification and NDVI change detection results, the coastal imagery provides evidence of a complete sediment transfer system initiated by Storm Daniel. Intense erosion across the watershed produced large sediment volumes, vegetation loss increased surface exposure and soil vulnerability, and the failure of the dams greatly enhanced downstream sediment transport. The sediment plume observed offshore represents the final stage of this interconnected process, demonstrating the direct link between inland landscape disturbance and marine environmental change.




Figure 7. Satellite image showing sediment plume entering the Mediterranean Sea.

Ultimately, the sediment plume observed after Storm Daniel demonstrates that the consequences of the disaster extended far beyond the flooded areas and urban districts of Derna. The flood significantly influenced the coastal environment by increasing water turbidity, redistributing sediments within the nearshore zone, and transferring large amounts of terrestrial material into the Mediterranean Sea. These observations emphasize the close connection between watershed processes and coastal ecosystems and highlight the effectiveness of Sentinel-2 satellite imagery for rapid assessment of both terrestrial and marine impacts following extreme flood events.

### *3.5 Geomorphological Changes*

The digital elevation model (DEM) differencing analysis (Fig. 8) provides a detailed evaluation of the geomorphological transformations produced by Storm Daniel in the Wadi Derna watershed after the catastrophic dam failures and extreme flooding. By comparing elevation data collected before and after the event, the analysis reveals widespread zones of erosion and deposition that significantly altered the landscape from the upstream reservoir area to the Mediterranean coastline. The most pronounced geomorphological changes occurred along the main Wadi Derna channel, where intense erosion, channel incision, and bank instability reshaped the river system. The DEM change map shows extensive areas of elevation loss (red to dark red) extending from the Abu Mansour Dam, through the Derna Dam, and into the urban area of Derna. These patterns indicate that the exceptional flood discharge generated enough erosive force to remove large quantities of sediment, deepen the channel, and modify adjacent floodplain surfaces. In some sections of the main channel, erosion depths reached approximately 8–10 m, highlighting the extraordinary energy associated with the sudden release of reservoir water following the dam failures. In contrast, areas of elevation increase (light to dark blue) are widespread downstream of the main erosion corridor, particularly across the floodplain, urban areas, and near the wadi outlet. These positive elevation changes represent zones of sediment accumulation where material eroded from upstream areas was deposited. As the floodwaters moved into flatter terrain and the coastal plain, the reduction in flow velocity promoted rapid sediment settling and widespread surface aggradation. This shift from erosion in the upper watershed to deposition downstream reflects the natural behavior of high-magnitude floods and demonstrates the strong connectivity between different parts of the Wadi Derna system. The longitudinal profiles further support these observations. The upstream section (A–A′) shows a marked decrease in channel elevation compared with pre-event conditions, confirming severe incision and sediment removal. Further downstream, the profile changes to areas of positive elevation gain, indicating the accumulation of transported sediments. Similarly, the cross-section across Derna city (B–B′) reveals both channel deepening and surrounding sediment buildup, demonstrating that erosion and deposition occurred simultaneously within the urban flood corridor. The observed elevation changes closely correspond with the results of land-cover classification and NDVI analysis. Areas affected by intense erosion coincide with major vegetation loss and the expansion of exposed bare surfaces, whereas depositional areas correspond with increased sediment cover identified in the land-cover change analysis. The sediments transported through the watershed were eventually discharged into the Mediterranean Sea, forming the large coastal sediment plume observed in satellite imagery. This confirms that erosion, sediment transport, floodplain deposition, and coastal sediment accumulation were interconnected stages of a single watershed-scale process. The geomorphological patterns identified are consistent with the effects of catastrophic dam-break floods, which commonly generate high-energy, sediment-rich flows capable of rapidly modifying river channels and surrounding landscapes. The collapse of the Abu Mansour and Derna dams greatly increased flood discharge, stream power, and sediment transport capacity, accelerating channel widening, bank erosion, and floodplain degradation. Further downstream, the gradual reduction in flow energy resulted in extensive sediment deposition, covering agricultural areas, infrastructure, and

parts of the urban landscape with newly deposited alluvial material.

The DEM statistics show that erosion and deposition influenced almost comparable portions of the study area, emphasizing that the event was characterized by large-scale sediment redistribution rather than simple sediment removal. Although the watershed experienced an overall decrease in elevation, much of the eroded material was transported and deposited in downstream areas instead of being completely lost from the system. This redistribution significantly modified channel morphology, floodplain elevation patterns, and coastal sediment processes, creating new surface features that may affect future drainage behavior and flood vulnerability.




Figure 8. Digital elevation model (DEM) showing erosion and deposition caused by Storm Daniel.

In summary, the DEM differencing analysis confirms that Storm Daniel caused a major geomorphological transformation within the Derna watershed. The flood dramatically reshaped the river channel through intense incision, transported and redistributed substantial sediment volumes across the floodplain, and altered coastal landscapes through downstream sediment accumulation. These results highlight the importance of combining DEM analysis with land-cover mapping, NDVI change detection, and satellite-based observations to achieve a more complete understanding of landscape responses and recovery processes following extreme hydrological events.

### *3.6 Environmental Implications*

The integrated satellite imagery (Fig. 9) and conceptual pollutant transport model (Fig. 10) show that the environmental consequences of Storm Daniel extended well beyond the areas directly affected by flooding. The combination of extreme flood flows, dam failures, severe erosion, sediment redistribution, and widespread urban destruction triggered a series of interconnected environmental processes that influenced terrestrial ecosystems, water resources, coastal environments, and potentially human health across the Derna watershed and adjacent Mediterranean coastal zone.

A major consequence of the disaster was the extensive mobilization and redistribution of sediment throughout the watershed. Satellite observations reveal widespread sediment accumulation along the Wadi Derna floodplain and the formation of a large sediment plume extending into the Mediterranean Sea. These features indicate that substantial amounts of material eroded from hillslopes, riverbanks, agricultural areas, and urban surfaces were transported downstream by the floodwaters. The resulting increase in suspended sediment concentrations affected water quality by increasing turbidity, reducing light availability within the water column, and altering the physical conditions of both freshwater and nearshore marine environments. The flood also caused severe disturbance to terrestrial ecosystems. Land-cover classification and NDVI analysis indicate widespread vegetation loss, particularly within riparian corridors and agricultural lands bordering Wadi Derna. The removal of vegetation increased soil exposure, weakened surface stability, and enhanced the potential for future erosion and sediment production. Damage to agricultural areas reduced productive capacity and may contribute to long-term soil degradation through the loss of fertile topsoil and the burial of farmland beneath newly deposited sediments. The failure of the Abu Mansour and Derna dams greatly intensified the movement of sediments and contaminants throughout the watershed. The high-energy floodwaters transported large quantities of debris, organic material, sewage, petroleum-related substances, household waste, construction debris, and other pollutants released from damaged infrastructure. The conceptual pollutant transport model illustrates the pathway by which these materials were incorporated into flood flows and carried downstream with suspended sediments, expanding the spatial extent of environmental contamination. The destruction of urban areas introduced multiple pollution sources into the aquatic system. Flood damage to residential districts likely released untreated sewage, domestic waste, plastics, chemicals, and other hazardous materials into the floodwaters. In addition, impacts on fuel storage facilities, industrial sites, and transportation networks may have contributed hydrocarbons, heavy metals, and other chemical contaminants to the drainage system. Agricultural areas provided an additional source of pollutants through the transport of fertilizers, pesticides, and nutrient-rich sediments into Wadi Derna. Together, these sources created a complex mixture of contaminants that was ultimately transferred from the watershed into the Mediterranean coastal environment. The conceptual model further emphasizes that contaminants were transported through several interconnected pathways. Although surface runoff and river flow represented the dominant mechanisms of contaminant movement, infiltration into the ground may have contributed to localized groundwater contamination. Substances such as nitrates, hydrocarbons, heavy metals, and pathogenic microorganisms can migrate through soils and potentially reach shallow aquifers and wells, posing risks to water supplies even after surface flooding has subsided. This highlights that the environmental impacts of Storm Daniel are not restricted to the immediate aftermath of the

flood but may continue through delayed contamination of groundwater resources. The coastal zone was among the most affected environments due to the direct discharge of floodwaters into the Mediterranean Sea. The extensive sediment plume detected in Sentinel-2 imagery indicates the transport of large quantities of suspended sediments, nutrients, organic matter, and human-derived pollutants into coastal waters. Increased turbidity can reduce light penetration, limiting photosynthetic activity in phytoplankton and submerged aquatic vegetation, while excessive sediment accumulation may disturb benthic habitats. In addition, elevated nutrient inputs may promote algal growth and modify coastal biogeochemical processes, with potential consequences for marine biodiversity and ecosystem stability. These environmental disturbances have important implications for ecosystem health and the services provided by natural systems. Sediment burial and vegetation loss can reduce the quality and availability of terrestrial habitats, while deteriorating water conditions may negatively affect freshwater and marine organisms. Furthermore, contaminants such as heavy metals and persistent organic pollutants may accumulate within aquatic food webs, increasing ecological risks for fish and other marine species. Over time, such contamination could affect fisheries productivity and food security through the transfer of pollutants to higher trophic levels. The consequences of Storm Daniel also extend to public health and the long-term resilience of the watershed. Contamination of surface water and groundwater increases the risk of exposure to waterborne pathogens and chemical pollutants, particularly in areas where water supply infrastructure has been damaged. Flood-deposited sediments containing sewage, hydrocarbons, and industrial contaminants may continue to present health concerns during cleanup and reconstruction activities. Moreover, severe erosion, vegetation loss, and changes to river channel morphology have altered the hydrological behavior of the watershed, potentially increasing vulnerability to future flood events. Thus, Storm Daniel has not only reshaped the physical landscape of the Derna catchment but has also created lasting challenges for environmental recovery and watershed management.




Figure 9. Environmental impacts of Storm Daniel.

On the whole, the combination of satellite observations and the conceptual pollutant transport model demonstrates that Storm Daniel triggered a large-scale environmental disturbance involving closely linked physical, chemical, and biological processes. The event reshaped the landscape through intense erosion and sediment redistribution, caused widespread impacts on terrestrial and aquatic ecosystems, mobilized contaminants from various sources, and transferred these materials from the watershed into the Mediterranean Sea. These findings highlight the importance of integrated post-disaster environmental monitoring approaches that combine remote sensing, water quality investigations, sediment geochemistry, and ecological assessments. Such approaches are essential for guiding ecosystem restoration, managing pollution risks, and supporting long-term sustainable recovery of flood-affected watersheds.




Figure 10: Conceptual model of pollutant transport of Storm Daniel.

## 4. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates that satellite remote sensing combined with GIS provides an effective approach for evaluating the environmental impacts of Storm Daniel in Derna, northeastern Libya. Using multi-temporal Sentinel-2 imagery, the analysis clearly identified the extent of flooding and revealed major changes in land cover, vegetation, sediment distribution, coastal conditions, and landscape morphology following the catastrophic collapse of the Abu Mansour and Derna dams. The results show that Storm Daniel dramatically reshaped the Derna watershed. Severe channel erosion, extensive sediment deposition, widespread vegetation loss, and significant destruction of urban infrastructure transformed both the natural environment and the built landscape. Large volumes of sediment were transported from the upper catchment to the Mediterranean Sea, highlighting the close connection between upland watersheds and coastal ecosystems during extreme flood events. Beyond these physical changes, the disaster has important environmental consequences. Increased sediment and pollutant transport may compromise water quality, accelerate ecosystem degradation, reduce soil stability, and create long-term risks for biodiversity and

public health. The integration of land-cover classification, NDVI analysis, DEM differencing, and sediment transport mapping provided a comprehensive understanding of the environmental processes triggered by the flood and their spatial distribution. The study also demonstrates that satellite-based methods offer a rapid, cost-effective, and reliable means of assessing disaster impacts, particularly in areas where field surveys are difficult or unsafe. These techniques can support emergency response, environmental monitoring, and hazard assessment by providing timely information for decision-makers. All things considered, the findings contribute valuable scientific evidence for strengthening watershed management, guiding post-disaster recovery, and promoting sustainable planning in Libya and other Mediterranean regions increasingly exposed to climate-related extreme weather events.

Based on the findings of this study, the following recommendations are proposed:

(1) Establish a long-term environmental monitoring program that integrates Sentinel-2, Landsat, and other Earth observation satellites to track land-cover change, vegetation recovery, erosion, and sediment movement over time.

(2) Carry out detailed field investigations supported by geochemical analyses of soils, sediments, surface water, and groundwater to determine the extent of contamination from heavy metals, hydrocarbons, sewage, and other pollutants mobilized during the flood.

(3) Strengthen flood risk management by improving hydrological models, enhancing early warning systems, and implementing routine inspections of dam infrastructure and watershed conditions to reduce future disaster risks.

(4) Restore damaged ecosystems through riverbank stabilization, rehabilitation of riparian vegetation, and the adoption of soil conservation practices that minimize erosion and limit sediment transport.

(5) Integrate remote sensing and GIS technologies into national disaster management strategies to enable rapid damage assessment, continuous environmental monitoring, and more effective emergency response.

(6) Improve urban planning by limiting development in flood-prone areas and promoting resilient infrastructure designed to withstand increasingly frequent and intense flood events.

(7) Establish long-term monitoring of coastal and marine environments to evaluate the effects of sediment deposition, increased turbidity, nutrient enrichment, and pollutant transport into the Mediterranean Sea, and to guide ecosystem restoration efforts where necessary.

(8) Encourage closer collaboration among geologists, hydrologists, ecologists, environmental chemists, engineers, planners, and policymakers to develop integrated and science-based watershed management strategies.

(9) Increase investment in climate adaptation, disaster preparedness, and community resilience programs to reduce the vulnerability of populations exposed to future extreme weather events.

(10) Expand future research by combining high-resolution satellite imagery with unmanned aerial vehicles (UAVs), LiDAR, and machine learning techniques to improve the accuracy of flood mapping, environmental monitoring, change detection, and post-disaster impact assessments.

## REFERENCES

Agfir, N.F. and Sasi, E.A. (2024): Storm of Daniel and the catastrophic damage to the dam in Derna and the urban area (Recommendations and proposals after the disaster). International Science and Technology Journal (ISTJ); 33(2): 1-27 (In Arabic).

Ben Miloud, H.M. and Elmaremi, R. (2024): A diagnostic study of Storm Daniel's meteorological and environmental characteristics in Derna, eastern Libya, 2023. Sebha University Journal of Pure and Applied Sciences; 23(2): 40-43.

Fawzy, M., Heggy, E., Szabo, G. and Barsi, A. (2026): Storm Daniel flooding aftermath in Libya: Drivers, implications, and the need for a rapid assessment system. npj Urban Sustainability; 53p.

Fernandes, R.C., Wanderley, H.S., Carvalho, A.L. and Frigo, E. (2024): Influence of galactic cosmic ray flux on extreme rainfall events in Greece and Libya. Journal of Atmospheric and Solar-Terrestrial Physics; 263: 106327.

Kushabaha, A., Scardino, G., Miglietta, M.M., Bonaldo, D., Monforte, P., Mastronuzzi, G., González-Alemán, J.J. and Scicchitano, G. (2026): Assessing future coastal hazards due to Mediterranean hurricanes under sea-level rise and storm intensification. International Journal of Disaster Risk Reduction; 142: 106247.

Lashhab, S.R.H. (2026): The impact of Mediterranean Storm Daniel on the natural environment and infrastructure of the Wadi Derna Basin. The Journal of Comprehensive Sciences; 10(40): 35-62 (In Arabic).

Nawaz, A., Alfio, M.R., Babakos, K., Chatzi, A., Fiorese, G.D., Panagopoulos, A., Pisinaras, V. and Balacco, G. (2025): Response of Pinios hydrologic observatory (Agia basin-Thessaly, Greece) to storm Daniel. Groundwater for Sustainable Development; 31: 101528.

Nemnem, A.M., Tanim, A.H., Nahian, A., Khan, S., Goharian, E. and Imran, J. (2025): How extreme rainfall and failing dams unleashed the Derna flood disaster. Nature Communications; 16: 4191.

Normand, J.C.L. and Heggy, E. (2024): Assessing flash flood erosion following storm Daniel in Libya. Nature Communications; 15: 6493.

Samir, A.S., Saad, S. and Elmoustafa, A.M. (2025): Sensitivity analysis of hydrodynamic models to storm, DEM, and dam configurations: the Bu Mansour Dam Basin in Derna, Libya. Ain Shams Engineering Journal; 16: 103802.

WHO (World Health Organization, 2023): Libya: “A disaster of epic proportions” (available at https://www.emro.who.int/libya-floods/index.html).

## BIOGRAPHIES



**Osama Rahil Shaltami** is a professor in the field of geochemistry and a senior researcher. His most important works are publications related to geochemistry of sedimentary rocks, industrial geology, economic geology, petroleum geochemistry, gas geochemistry, hydrogeochemistry, nuclear geochemistry, environmental geochemistry, and sustainable development.



**Prof. Dr. Mustafa Ahmed Ben** Hkoma holds a Ph.D. in Project Management and is an academic researcher and international consultant specializing in sustainable development, project management, environmental management, and GIS. He is Director of the Libyan Center for Sustainable Development Research (Zliten Branch), Founder and President of the Libyan Association for Carbon Footprint and Sustainable Transformation, and President of the Distinguished Researcher Academy (UK). He has published nearly 90 peer-reviewed scientific papers in Scopus-indexed and other scholarly journals, authored several academic books, and serves as an international reviewer for scientific journals and conferences. He is the founder of the Researcher Fingerprint (Basmat Bahith) Project, which provides professional training in scientific writing through the program "Writing Research Papers: From Idea to Publication." His research interests include sustainable development, digital transformation, environmental sustainability, and scientific research methodology.



**Firas Khamees Mohammed** is a faculty member in the Department of Geology at Omar Al-Mukhtar University, specializing in geochemistry. His research focuses on the chemical composition of Earth's materials and their applications in environmental management and natural resource exploration. I am passionate about advancing geoscientific knowledge and collaborating on interdisciplinary research projects.



**Kamal Abraheem Almahdi** is a faculty member in the Department of Geology at Omar Al-Mukhtar University, with a specialization in geochemistry. His research interests focus on the geochemical characterization of Earth materials and their applications in environmental management, sustainable resource exploration, and natural resource assessment. He is committed to advancing geoscientific knowledge through interdisciplinary research and academic collaboration.