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Original article

From Flood Hazard to Actionable Urban Resilience: Scenario-Aware Building, Road, and Evacuation Planning for Derna, Libya

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Abstract
The September 2023 Derna disaster has already generated high-quality flood reconstruction and remote-sensing damage studies. This paper shifts from retrospective damage detection to a scenario-aware decision-support framework for reconstruction and evacuation planning using official Copernicus EMSN177 5-, 100-, and 500-year flood products. We recompute scenario capture, marginal exposure density, mitigation effectiveness, and residual exposure from the technical-report statistics. The potentially exposed population is 6,945, 10,555, and 11,310 of 72,922, while exposed buildings are 4,236, 5,148, and 6,059. The 100-year envelope already captures 93.3% of the population and 85.0% of the buildings exposed under the 500-year case. Expanding from 5 to 100 years adds 3,610 people and 912 buildings (3.96 people per additional building), whereas 100 to 500 years adds only 755 people and 911 buildings (0.83 people per additional building). After the modelled mitigation package, exposed population falls to 4,939, 7,842, and 8,161, reductions of 28.9%, 25.7%, and 27.8%. These results support the 100-year envelope as a minimum risk-informed redevelopment buffer and the 500-year envelope for strategic siting of critical facilities and evacuation redundancy.
Keywords. Derna, Flood Resilience, Scenario Analysis, Mitigation, Geospatial Decision Support.

Introduction

The central research problem is no longer whether the 2023 flood damaged Derna; that has been established by satellite, hydraulic, and field-based studies [3–5]. The planning problem is how a recovering city should use multi-probability flood information to decide where development should be constrained, which road segments cannot be treated as reliable evacuation links, where safe shelters should be placed, and how to avoid protecting only the best-connected neighborhoods. We therefore shift the unit of contribution from event reconstruction to prospective urban decision support. The framework integrates official hazard depth, population and building exposure, infrastructure evidence, and transparent scenario metrics that can be reproduced directly from the EMSN177 technical report statistics.

Rather than reporting unexecuted route-time or shelter-location outputs, we quantify scenario capture, marginal exposure density, mitigation effectiveness, and residual exposure, then translate those quantities into explicit reconstruction, road-redundancy, and evacuation-siting rules. This decision-oriented framing is consistent with the broader risk-reduction emphasis of the Sendai Framework [14].

Shults et al. [3] used high-resolution GEOEYE-1 and Sentinel-2 imagery to estimate post-flood change and building damage. Armon et al. [4] combined atmospheric reanalysis, satellite data, and hydrologic modelling and found that dam failure amplified damage dramatically relative to a dam-free scenario. Nemnem et al. [5] reconstructed the cascade using hydrologic, hydraulic, geotechnical, satellite, machine-learning, and eyewitness evidence. Collectively, these studies make another image-classification paper difficult to justify.

Evacuation literature provides the missing decision layer. Location-allocation models can optimize emergency-center distribution, while network analysis can remove or penalize flooded links. Recent work also treats accessibility inequality as an explicit objective rather than an afterthought [6–12]. The unresolved gap for Derna is to connect these methods to the city-specific, official 5/100/500-year hazard products and their mitigation counterparts, then derive architecture and urban-planning rules from the resulting scenario stress tests.

Methods

Hazard and Exposure Data

The primary hazard source is the Copernicus EMS Risk and Recovery activation EMSN177 and its Technical Report [1]. The broader Copernicus Risk and Recovery Mapping flood-preparedness portfolio provides the operational programme context for this class of analysis [15]. A two-dimensional rain-on-grid model was run for 5-, 100-, and 500-year return periods. Copernicus provides flood-depth products, exposure assessments, reference vectors, mitigation measures, and remodelling after mitigation. Vector deliverables are available in geodatabase/GeoJSON formats and raster products in TIFF.

Buildings and Urban Morphology

Building footprints are obtained from the HDX Derna flood building-footprint dataset / Google Open Buildings source [2], for which an open conversion workflow to GeoJSON is documented. For each building, we calculate footprint area, compactness, nearest-channel distance, local building density, and scenario-specific maximum/mean flood depth. These variables support both exposure stratification and post-disaster redevelopment rules.

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Scenario-Based Road and Evacuation Interpretation

Copernicus P03 intersects the P01 flood-hazard outputs with the P02 reference information on buildings and infrastructure [1]. The EMSN177 technical report states that considerable road extents are exposed even in the high-probability (5-year) scenario to depths that may make driving infeasible or unsafe. It also advises that roads placed at riverbed level should not be relied upon where protection is not cost-effective [1]. Because the public report does not provide a segment-level routable travel-time matrix, this study does not invent route times or named shelter locations; road exposure is treated as a conservative planning constraint requiring protected and redundant evacuation access.

Scenario Metrics and Planning Classes

To complete the decision layer with auditable quantities available from the official products, we compute four metrics. Scenario capture is SC_s^P = P_s/P_500 for population and SC_s^B = B_s/B_500 for buildings. Marginal exposure density is MED_(a->b) = (P_b-P_a)/(B_b-B_a). Mitigation effectiveness is ME_s = (P_s-P_s^M)/P_s, and residual exposure is R_s = P_s^M/N, where N is the modelled population. The nested flood envelopes define four planning classes: Z1 inside the 5-year envelope; Z2 inside the 100-year but outside the 5-year envelope; Z3 inside the 500-year but outside the 100-year envelope; and Z4 outside the 500-year envelope. The 100-year envelope is evaluated as a minimum risk-informed redevelopment buffer, while Z4 is the preferred strategic reserve for critical facilities and major shelter functions.

Table 1. Completed Derna decision metrics and definitions

Metric	Definition	Decision role
Scenario capture	P_s/P_500; B_s/B_500	Fraction of extreme-scenario exposure captured by a lower planning threshold
Marginal exposure density	(P_b-P_a)/(B_b-B_a)	Added exposed residents per additional exposed building as the envelope expands
Mitigation effectiveness	(P_s-P_s^M)/P_s	Population-exposure reduction after the modelled mitigation package
Residual exposure	P_s^M/N	Share of the modelled population still exposed after mitigation
Planning class	Z1/Z2/Z3/Z4 nested scenario membership	Auditable land-use, critical-facility, and evacuation-siting rule

Results

Verified Official Flood-Depth Baseline

Copernicus reports maximum modelled depths of 8.60 m, 8.72 m, and 9.28 m for the 5-, 100-, and 500-year scenarios at steep tributaries upstream of Derna waterfall. Within the main river in the urban area, typical scenario depths are approximately 2 m, 3 m, and 4 m, respectively [1]. These values establish why road and evacuation decisions must be stress-tested across scenarios rather than optimized for one event.

Population Exposure: Verified Counts Plus Reproduced Calculations

From the official counts, population exposure increases by 51.98% from the 5-year to the 100-year scenario, by only 7.15% from 100-year to 500-year, and by 62.85% from 5-year to 500-year. The 100-year envelope already contains 93.3% of the population exposed under the 500-year case, identifying the medium-probability scenario as the dominant transition for population-oriented planning.

Table 2. Derna population exposure from EMSN177 P01/P03

Scenario	Modelled population	Exposed population	Exposure share
High probability / 5-year	72,922	6,945	9.50%
Medium probability / 100-year	72,922	10,555	14.50%
Low probability / 500-year	72,922	11,310	15.50%

Building/Infrastructure Exposure

Exposed buildings increase by 21.53% from 5 to 100 years and by 17.70% from 100 to 500 years, for a total increase of 43.04% from 5 to 500 years. In absolute terms, the two scenario expansions add almost the same number of buildings (912 and 911), but the associated population increases differ markedly. This distinction is quantified below using marginal exposure density.

Table 3. Exposed buildings from EMSN177 P03 and recomputed changes

Scenario	Exposed buildings	Relative increase vs previous scenario
High probability / 5-year	4,236	-
Medium probability / 100-year	5,148	+21.53%
Low probability / 500-year	6,059	+17.70%

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Verified Mitigation Baseline

After integrating the proposed mitigation measures into the P05 hydraulic model, Copernicus reports a 0.5-2 m reduction in flood depth along the main river and about a 3% reduction in flow discharge at the dam upstream of Derna waterfalls [1]. The P05 exposure reassessment gives 4,939, 7,842, and 8,161 potentially exposed residents in the 5-, 100-, and 500-year scenarios, respectively. Relative to P01/P03, these correspond to reductions of 28.9%, 25.7%, and 27.8%. The technical report also notes that small increases in exposed-building cells after mitigation are a hydraulic time-step artefact; therefore, this study uses population, not P05 building counts, for before-after mitigation claims [1].

Completed Scenario Decision Outputs

Completed computation scope: all numerical outputs below are reproduced from official EMSN177 P01/P03/P05 statistics or transparent arithmetic on those statistics. Segment-level travel times and named shelter locations are not inferred because the public technical report does not publish the routable travel-time matrix required for those claims. The paper therefore completes the decision stage with auditable scenario-capture, marginal-exposure, mitigation, and planning-class outputs rather than synthetic routing results.

Table 4. Completed scenario-capture and marginal-exposure outputs

Scenario	Exposed population	Exposed buildings	Population capture of 500-year	Building capture of 500-year	Marginal exposure density
5-year	6,945	4,236	61.4%	69.9%	-
100-year	10,555	5,148	93.3%	85.0%	3.96 (5->100)
500-year	11,310	6,059	100.0%	100.0%	0.83 (100->500)

The 100-year envelope captures 93.3% of the population and 85.0% of the buildings exposed under the 500-year scenario. Expansion from 5 to 100 years adds 3,610 exposed residents and 912 buildings, or 3.96 additional residents per additional building. Expansion from 100 to 500 years adds only 755 residents despite 911 additional buildings, reducing the marginal exposure density to 0.83. The mitigation package avoids potential exposure for 2,006-3,149 people across the scenarios, but residual exposure remains 6.8-11.2% of the modelled population.

Table 5. Mitigation effectiveness derived from EMSN177 P01/P03 and P05 population exposure

Scenario	Pre-mitigation population	Post-mitigation population	People avoided	Reduction	Residual share
5-year	6,945	4,939	2,006	28.9%	6.8%
100-year	10,555	7,842	2,713	25.7%	10.8%
500-year	11,310	8,161	3,149	27.8%	11.2%

Discussion

The completed scenario metrics identify the 100-year envelope as a defensible minimum risk-informed redevelopment buffer. It captures 93.3% of the population exposed in the 500-year scenario, compared with only 61.4% for the 5-year envelope. The marginal exposure density falls from 3.96 people per newly exposed building in the 5-to-100 year expansion to 0.83 in the 100-to-500 year expansion. Thus, the first expansion reaches substantially denser urban exposure, while the extreme fringe adds nearly the same number of buildings but far fewer residents. Mitigation materially reduces population exposure, but does not eliminate it.

The P05 package lowers potential exposure by 25.7-28.9%, while 4,939 to 8,161 residents remain exposed depending on the scenario. This supports a portfolio strategy: hydraulic works reduce hazard, while development control, protected road redundancy, and evacuation planning reduce consequences. Copernicus specifically warns that roads at riverbed level may be unsuitable for protective treatment and should be addressed through development planning [1]. The nested envelopes translate these quantitative findings into four auditable planning classes. Z1, inside the 5-year envelope, should avoid new permanent housing and critical facilities and prioritize flood-compatible open space. Z2, the 100-year minus 5-year band, is the core risk-informed redevelopment buffer and requires protected access and service redundancy. Z3, the 500-year minus 100-year fringe, permits only conditional development with extreme-event access safeguards. Z4, outside the 500-year envelope, is the preferred strategic reserve for hospitals, emergency coordination, major utilities, and facilities intended to serve as shelters.

Limitations and Reproducibility

The Copernicus products are model outputs rather than observations of a future event, and the fast-mode analysis inherits limitations in terrain, drainage, and hydraulic representation [1]. The public technical report supplies scenario exposure statistics but not a complete routable travel-time matrix or verified shelter capacities; therefore, this paper deliberately avoids fabricated route-time, accessibility-Gini, or named-shelter results. Operational deployment should ingest the downloadable CEMS GeoJSON/TIFF layers and a current road graph such as OpenStreetMap [13], then apply sensitivity

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tests for road passability, debris, mode, and user vulnerability. All scenario rules and formulas reported here are deterministic and can be recomputed from the cited source values.

Conclusion

This study reframes Derna flood research from retrospective damage detection to prospective urban decision support. Using the detailed EMSN177 scenario statistics, the 100-year envelope is shown to capture 93.3% of the population and 85.0% of the buildings exposed under the 500-year case. The marginal exposure density declines sharply from 3.96 people per additional building for the 5-to-100-year expansion to 0.83 for the 100-to-500-year expansion. The modelled mitigation package reduces population exposure by 25.7-28.9%, but residual exposure remains 6.8-11.2% of the modelled population. These results support the 100-year envelope as a minimum risk-informed redevelopment buffer, the 500-year envelope as a strategic siting constraint, and the area outside the 500-year envelope as the preferred reserve for critical and shelter functions. The framework remains computationally auditable while clearly separating verified scenario results from future graph-based routing extensions.

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Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

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