

Compound Coastal Flood Risk and Infrastructure Loss Estimation in Bengkulu City, Indonesia, under Sea-Level Rise Using Google Earth Engine and OpenStreetMap

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Abstract. Bengkulu City, Indonesia, is facing increasing risks due to sea-level rise (SLR), yet risk assessments based on regulations are still absent for secondary coastal cities. This study models the compound flood hazard for three scenarios (+1.28 m, +2.13 m, +3.00 m) using Google Earth Engine, GIS and OpenStreetMap, to produce inundation zones of 12.64–77.76 ha. The five-class risk map generated by the Coastal Vulnerability Index weighted by AHP (CR = 0.016) covers 1,058.83 ha. Under Scenario B (2100, SSP5-8.5), the infrastructure exposure includes 22 buildings and 9.33 km of roads. Public facilities are excluded from the quantitative loss estimation because the buffer sensitivity analysis (200–1,000 m) shows 333–335 of 336 city amenities at all distances, indicating non-discriminating coverage. Confirmed direct replacement losses based on Kepmen PUPR No. 943/KPTS/M/2024, SE DJBK No. 68/2024 and Bengkulu IKK = 94.20, total IDR 47.1–102.0 billion across scenarios (Scenario B: IDR 86.1 billion). The loss due to annual maintenance is IDR 896 million/year (Pergub Bengkulu No. 25/2025). The regulation-compliant approach is transferable to other Indonesian secondary coastal cities as long as the site-specific VLM assessment is performed.

Keywords: compound coastal flood; sea-level rise; google earth engine; economic loss estimation; openstreetmap

1. Introduction

Combined with storm surges and other coastal hazards, the effects of rising global mean sea level due to thermal expansion and loss of land ice are exacerbated [1]. Compound coastal flood events are on the rise in frequency and severity with climate change, hence raising risks for infrastructure and urban systems [2], [3]. These concerns are of particular concern in low-lying coastal cities, where progressive flooding and catastrophic occurrences can combine to create losses higher than those from single hazards [4], [5].

Indonesia is one of the countries most vulnerable to coastal flooding and sea level rise, since numerous towns, roads and public institutions are located near the current sea level [4], [6]. Although much study has been devoted to large urban regions, second-tier coastal communities are still in need of spatially explicit and policy-compatible risk assessments that may inform adaptation planning and public funding [7]. One example is Bengkulu City, located on Sumatra island's west coast. The city is directly vulnerable to Indian Ocean waves and storm surges and about 2.89% of the municipal territory is below 2 m above existing sea level. Bengkulu serves as a regional service and transport hub, and damage to its coastal infrastructure could potentially effect broader province activity.

One major need in current studies is the integration of hazard and exposure mapping with official construction cost criteria. Currently, in Indonesia, the replacement-cost assessment can be based on a more transparent regulatory system, including Kepmen PUPR No. 943/KPTS/M/2024 for building costs, Surat Edaran Direktur Jenderal Bina Konstruksi No. 68 Tahun 2024 for road construction unit prices and the regional construction cost index (IKK) issued by BPS; however, this study only considers public facilities as exposure indicators and not as quantified replacement losses [8], [9], [10]. At the provincial level, Pergub Bengkulu No. Twenty-five Tahun 2025 provides maintenance-cost standards relevant to estimating recurrent losses rather than replacement costs [11]. However, such regulatory instruments have rarely been incorporated into local coastal flood loss assessment.

Conceptually, coastal risk arises from the interaction of hazard, exposure, and vulnerability [1]. The coastal vulnerability index (CVI) and AHP-based weighting are widely used to map vulnerability and support local planning [12], [13]. Meanwhile, GEE enables scalable and reproducible geospatial analysis using remote sensing archives and GEDs [14]. In this study, a seven-step GEE-based workflow was developed to assess compound coastal flood risk and infrastructure losses in Bengkulu City under multiple SLR scenarios. This study investigates how hazard extents change across scenarios, how exposed assets are distributed, and how direct and maintenance-related losses vary when Indonesian regulatory cost standards are explicitly applied.

Existing studies on Indonesia's coastal flood risk have addressed compound hazard modeling, CVI-based vulnerability mapping, and infrastructure loss estimation as separate endeavors, often focusing on major cities such as Jakarta or Semarang using full hydrodynamic models. No published study has integrated these components within a single GEE-based workflow and grounded all loss estimates in Indonesia's current national construction cost regulations (Kepmen PUPR No. 943/KPTS/M/2024; SE DJBK No. 68/2024; regional IKK) for a secondary coastal city. This study fills that gap by providing an operational, regulation-aligned methodology that is directly applicable across the Indonesian archipelago.

2. Method

2.1. Research Design and Study area

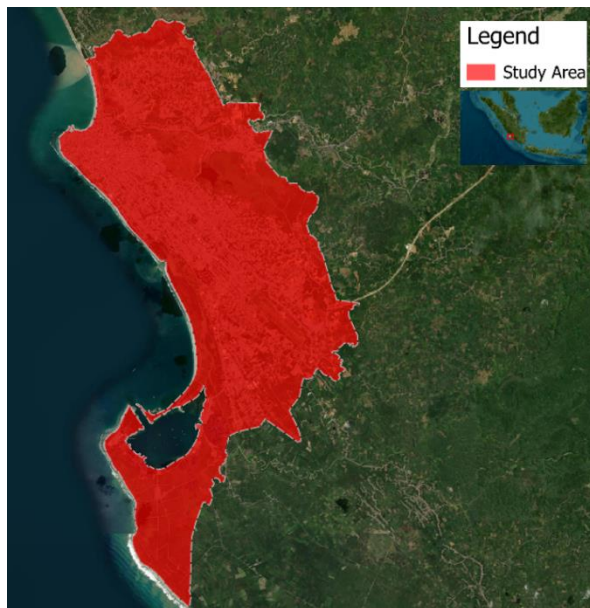


Figure 1. Study Area (Bengkulu City)

This research employs a quantitative spatial risk framework comprising seven stages: preprocessing and land masking, hazard modeling, exposure analysis, development of the CVI, risk overlay, assessment of economic loss, and validation. The study area is Bengkulu City, a low-lying secondary coastal city on Sumatra's west coast. Bengkulu City is situated on the southwestern coast of Sumatra, approximately between 3.72–3.90°S latitude and 102.22–102.42°E longitude. The area of interest encompasses roughly 15,101 hectares, with 436.59 hectares situated below 2 meters above sea level. Spatial analysis was performed in GEE and QGIS utilizing WGS84 and UTM Zone 48S for cloud processing and metric computations, respectively. Figure 1 illustrates the geographical position and administrative border of the research region, encompassing the low-lying coastal zone immediately subjected to Indian Ocean swells.

2.2. Data sources

Data sources Road networks and public facility points are supplied by Geofabrik OSM data (Sumatra extract) and building footprints by Google Open Buildings v3 (confidence ≥ 0.70) [15]. Often,

policy relevance and comparability are achieved by using replacement-cost methodologies based on national or regional unit-cost criteria for infrastructure damage assessment [4]. In Indonesia, the construction cost is regulated hierarchically by Kepmen PUPR No. 943/KPTS/M/2024 for Standar Harga Satuan Tertinggi (SHST) for government buildings and public facilities, and SE Direktur Jenderal Bina Konstruksi No. 68 Tahun 2024 for road construction unit price analyses (AHSP), both calibrated regionally using the Construction Cost Index (Indeks Kemahalan Konstruksi, IKK) published by Statistics Indonesia (BPS). Operationally, Peraturan Gubernur Bengkulu No. 25 Tahun 2025 sets binding provincial standards for the annual expenditure for maintenance of buildings rather than for the reconstruction costs. This distinction has direct methodological implications for quantifying damage and separating capital losses from recurrent operational losses. Data sources, specifications and their function in the analytical workflow are summarised in Table 1.

Table 1. Data Sources and Specifications

Data Type	Source	Specification
NASADEM DEM	NASA via GEE	30 m spatial resolution, float DEM
JRC Global Surface Water	Joint Research Centre via GEE	Occurrence and seasonality layers
Dynamic World v1	Google via GEE	10 m land-cover classification
Landsat 8/9 Collection 2	USGS/NASA via GEE	30 m imagery, 2015–2024
Google Open Buildings v3	Google via GEE	Building polygons, confidence ≥ 0.70
Roads and amenity points	OpenStreetMap / Geofabrik	2024 extract
Sea-level-rise projections	IPCC AR6	SSP2-4.5 and SSP5-8.5 scenarios
Storm-surge observations	BMKG Bengkulu	Tidal & surge records, 2000–2023
SHST for buildings	Kepmen PUPR	No. 943/KPTS/M/2024
AHSP Bina Marga	SE DJBK	No. 68/2024
IKK	BPS Provinsi Bengkulu	2024, IKK = 94.20
Building maintenance	Pergub Bengkulu No. 25/2025	Lampiran II Tabel 2.8

2.3. Hazard, exposure, and vulnerability analysis

The compound flood hazard was defined using the total water level (TWL) which is the sum of mean sea level, anticipated sea level rise, and storm surge[2], [16]. Three scenarios were modelled: Scenario A (+1.28 m, 2050 SSP2-4.5), Scenario B (+2.13 m, 2100 SSP5-8.5), and Scenario C (+3.00 m, severe case). The definition of inundation was performed by comparing TWL values with NASADEM elevation and masking permanent inland water by JRC surface-water occurrence data [17], [18].

Infrastructure exposure was estimated by connecting flooding zones with Google Open Buildings and OSM datasets. Exposure was quantified by the number of inundated units and the overall footprint area of the buildings. Road exposure was estimated by overlaying flooded areas with OSM road segments and converting flooded lengths to road-surface area using normal road widths from AHSP Bina Marga. Public facility exposure was assessed using a 500 m buffer around flooding zones, since no amenity points were directly crossed at the DEM resolution.

Criterion weights were determined using the Analytic Hierarchy Process (AHP) [19]. The pairwise comparison matrix (Table 2) was constructed by the authors as subject-matter experts, informed by the established primacy of topographic elevation in static inundation modelling [12], [13] and calibrated against weight distributions reported in comparable tropical CVI studies [12], [13]. Elevation is rated moderately more important than distance to shoreline ($a_{12} = 2$) and considerably more important than built-up density ($a_{13} = 4$), as high-elevation areas experience negligible inundation regardless of proximity or development intensity. Distance to shoreline is rated moderately more important than built-up density ($a_{23} = 3$), reflecting nearshore surge amplification independent of land use. The eigenvector weights (Table 3) are $w_1 = 0.557$ (elevation), $w_2 = 0.320$ (distance to shoreline), and $w_3 = 0.123$ (built-up density). Consistency was verified with $\lambda_{max} = 3.019$, $CI = 0.0095$, $RI = 0.58$, yielding $CR = 0.016$, well within the acceptable threshold of 0.10 [19].

Table 2. AHP Pairwise Comparison Matrix

Criterion	Elevation	Distance to Shoreline	Built-up Density
Elevation	1	2	4
Distance to Shoreline	1/2	1	3
Built-up Density	1/4	1/3	1

Table 3. Normalized Matrix and Eigenvector Weights

Criterion	C1	C2	C3	Weight
Elevation	0.571	0.6	0.5	0.557
Distance	0.286	0.3	0.375	0.32
Built-up	0.143	0.1	0.125	0.123
Sum	1	1	1	1

2.4. Economic loss estimation

Economic losses are calculated based on two regulation-based components: direct expenditures for replacement of infrastructure and annual maintenance losses from flood-induced degradation. The replacement cost of all components is adopted from Kepmen PUPR No. 943/KPTS/M/2024 and SE DJBK No. 68/2024 (AHSP Bina Marga) with adjustment to IKK Bengkulu 2024 ($\times 0.942$). The exposed structures are divided as residential (70%) and business (30%) based on OSM land-use trends. The unit cost of residential buildings is IDR 5,464,000/m² and IDR 8,195,000/m² for commercial buildings. The cost of road replacement assumes a complete reconstruction of every square metre of exposed surface area (length * standard Bina Marga width by functional class). Public facilities were assessed only as qualitative exposure and potential service-disruption risk, rather than being assigned direct replacement value. The buffer analysis produced near-universal coverage across 200–1,000 m, indicating insufficient spatial discrimination for reliable quantitative loss estimation. No facilities are directly inundated at the DEM resolution; the 28–57 facilities counted across scenarios lie within a 500-meter threat buffer, so reported figures represent potential asset exposure rather than realized physical damage.

2.5. Annual maintenance losses

Annual maintenance losses due to permanent exposure of buildings to flooding are estimated based on Pergub Bengkulu No. 25 Tahun 2025, Lampiran II Tabel 2.8, which states IDR 191,000/m²/year for multi-storey and IDR 131,000/m²/year for single-storey buildings [11]. Scenario-specific annual maintenance costs for multi-storey and single-storey exposed buildings are derived based on an even split between the two building types and discounted over 25 years at 7% in line with the practice of coastal adaptation economics [5].

2.6. Validation and reliability

Three validation approaches are employed. First, the Scenario B inundation extent is compared to the JRC Global Surface Water maximum extent, yielding an observed spatial overlap of approximately 40.7% (290.89 of 714.19 ha), which is considered acceptable given that JRC represents historical water occurrence while Scenario B represents future higher TWL conditions [18]. Second, JRC seasonality was used to confirm hydrological connectivity, indicating that approximately 218.47 ha (30.6%) of the risk zone corresponds to seasonally inundated or seasonally wet areas [18]. Third, topographic checks show that the mean elevation of high-risk zones is approximately 0.23 m above present sea level with a standard deviation of 0.45 m, consistent with expectations under TWL thresholds of 1.28–3.00 m. [17]. Algorithmic reliability is further supported by careful processing of DEM data (use of float NASADEM rather than integer SRTM), cautious land masking so as not to lose too much low-lying coastal land, and use of AHP with a good consistency ratio for CVI weights [17]. Ethical concerns are limited since the study solely employs spatial datasets that are publicly available or officially released, and does not include individual-level human or sensitive socio-economic data.

3. Results and Discussion

3.1. Compound flood hazard extents

The flood danger exhibits considerable non-linearity across the three TWL scenarios, a trend that aligns with global assessments of low-slope coastal regions. Scenario A (TWL +1.28 m) submerges 12.64 hectares of land, representing 3.01% of the city's area below 3 meters and 0.08% of the total Area of Interest (AOI). Scenario B (TWL + 2.13 m) increases inundation to 35.58 hectares (8.60% of land area; 0.24% of AOI), whereas Scenario C (TWL + 3.00 m) extends inundation to 77.76 hectares (18.51% of land; 0.51% of AOI). The rise from Scenarios A to B (+23.49 ha; +186%) exceeds that from Scenarios B to C (+41.63 ha; +115%), indicating the concentration of low-lying land near the beach and a gradual decline in the slowly rising backshore terrain. Figure 2 depicts the geographical distribution of inundation zones throughout all three scenarios, emphasizing the incremental growth of hazard classifications along the western coastal strip and river mouths.

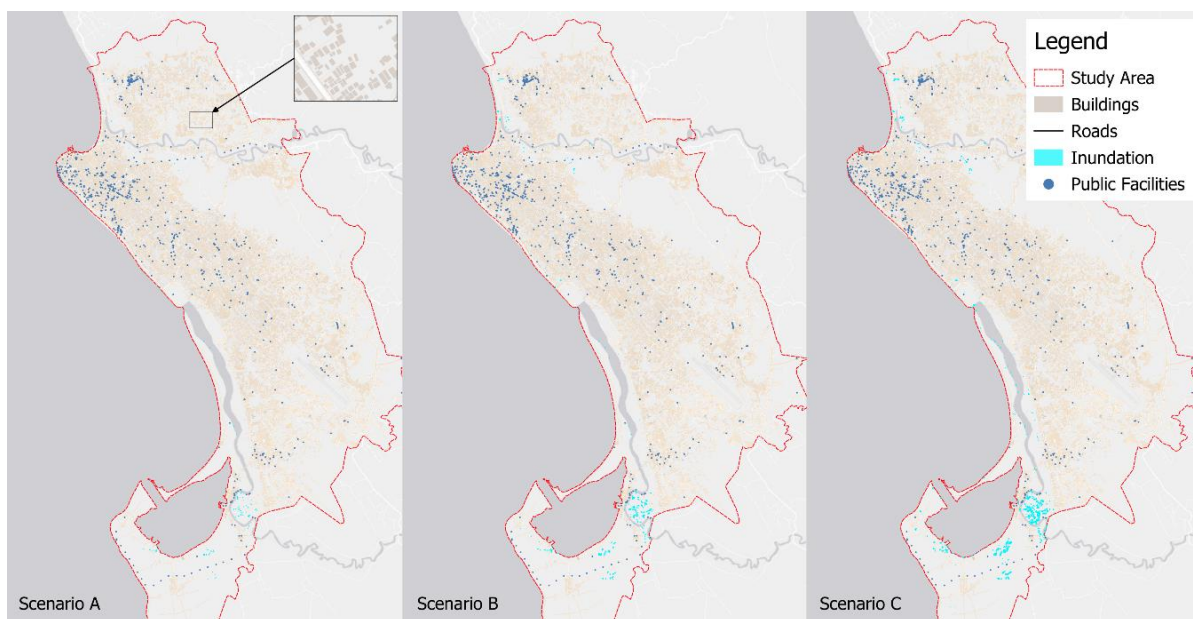


Figure 2. Compound Flood Hazard Maps for Scenarios A–C

Hazard classifications based on elevation ranges indicate that high hazard zones (0.50–1.28 m) include 11.60 hectares, whilst medium and low hazard zones span 23.51 hectares and 42.83 hectares, respectively. These zones aggregate throughout the western coastal strip, especially around river mouths and low-lying coastal plains, consistent with regional evidence indicating the interaction of fluvial and coastal processes in instances of compound flooding.[2], [3].

3.2. Infrastructure exposure

3.2.1 Buildings

Exposed buildings increase with TWL but with diminishing marginal footprint per additional depth, a pattern observed in other coastal cities where large facilities occupy very low elevations [4]. In Scenario A, eight buildings with a total footprint of 4,365 m² are inundated, implying an average footprint of 545.6 m² per unit. Scenario B exposes 22 buildings with 5,566 m² total footprint (average 253.0 m²/unit), and Scenario C exposes 36 buildings with 7,204 m² footprint (average 200.1 m²/unit). The decline in the mean footprint size suggests that larger complexes are concentrated in the very low zones, whereas smaller structures occupy progressively higher terrain.

The spatial distribution of exposed buildings indicates clustering near the coastal transport corridor and low-lying peri-urban neighborhoods, which is consistent with the patterns reported in global assessments showing that vulnerable housing and critical facilities often concentrate in near-shore floodplains [6]. Although the absolute number of inundated units is modest relative to the

total building stock, their functional importance and potential for cascading socio-economic impacts warrant targeted adaptation measures. Table 4 summarizes these trends alongside road and facility exposure.

3.2.2 Roads

In contrast to buildings, roads show a more pronounced proportional exposure, which aligns with global multi-hazard studies highlighting the vulnerability of transport networks [4]. Scenario A inundates eight road segments totalling 4.44 km (0.27% of the total 1,627.34 km network), Scenario B affects 15 segments with 9.33 km (0.57%), and Scenario C inundates 18 segments measuring 10.41 km (0.64%). As shown in Table 4, road exposure increases consistently across scenarios in both segment count and total length, with higher-class roads accounting for a disproportionate share of economic value despite representing a small fraction of the total network.

3.2.3 Public facilities

At 30 m DEM resolution, none of the public facilities were directly swamped in any scenario. Proximity buffer study at distances of 200, 500 and 1,000 m consistently identified 333–335 of the 336 total city amenities (99.1%–99.7%), suggesting that Bengkulu’s narrow coastal environment lacks discriminating power. Therefore, the quantitative economic evaluation ignores losses to public facilities. The 47 facilities inside the 500-m Scenario B inundation zones are qualitatively characterised as an indirect service interruption risk and not included in the monetary loss calculation.

Table 4. Exposed Buildings, Roads, and Facilities by Scenario

Infrastructure Component	Scenario A (+1.28 m)	Scenario B (+2.13 m)	Scenario C (+3.00 m)
Buildings (units)	8	22	36
Building footprint (m ²)	4,365	5,566	7,204
Road segments	8	15	18
Road length (km)	4.44	9.33	10.41
% of total road network	0.27%	0.57%	0.64%

3.3. Vulnerability and risk patterns

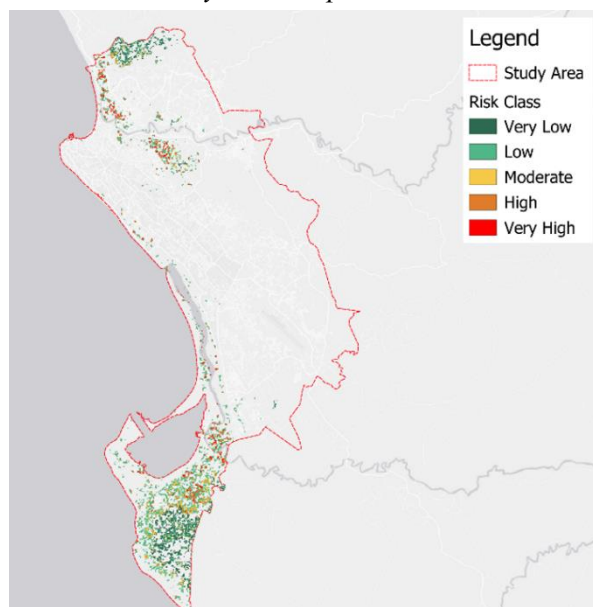


Figure 3. Coastal Vulnerability and Risk Maps

The CVI mapping shows that vulnerability is not confined to the local beachfront, but rather a band of high and very high susceptibility that extends inland along river corridors and the urban core is created by low elevation, short distance to the coast, and dense built-up patterns [12], [13]. Approximately 38.76% of the city’s land area falls under the high and very high vulnerability classes, indicating a high damage potential with an increase in danger.

Figure 3 displays the spatial distribution of CVI classes and the composite risk map. The composite risk map shows high and very-high risk zones concentrated in the low-lying neighbourhoods of the west, near estuaries and along vital traffic corridors. The risk mapping shows that 1,058.83 ha (7.01% of the AOI) are within non-negligible risk classes, of which the high and very high risk zones represent 137.92 ha (13.0% of the danger zone) and 51.49 ha (4.9%), respectively.

The high- and very-high-risk zones collectively account for 189.41 hectares, 17.9% of the

risk zone, and are mainly concentrated in low-lying neighbourhoods in the west, near estuaries and along key road sections. This distribution is comparable with global hotspot evaluations of compound coastal flood risk, which identify deltas and low-relief urban beaches as priority sites for adaptation [3], [5].

3.4. Economic loss estimates

To evaluate economic losses due to replacement losses and maintenance related losses, a two component framework was adopted. This revision refers to the Indonesian regulatory standards for capital cost estimates by using Kepmen PUPR No. 943/KPTS/M/2024 for buildings and public facilities, SE Direktur Jenderal Bina Konstruksi No. 68 Tahun 2024 for road reconstruction unit prices and regional calibration using 2024 Construction Cost Index (IKK 94.20) of Bengkulu. The present method enhances the source verifiability and consistency across infrastructure classes by replacing generic proxy values for public facilities with asset exposure estimates from SHST, compared with the prior version.

3.4.1 Direct replacement losses

Meanwhile, the direct replacement losses in the three scenarios also increase, from IDR 47.09 billion in Scenario A, to IDR 86.05 billion in Scenario B and IDR 101.99 billion in Scenario C. The estimates are based on unit costs of specific components adjusted by Bengkulu’s IKK factor of 0.942 (Indeks Kemahalan Konstruksi Provinsi Bengkulu 2024, BPS Provinsi Bengkulu, 2024). SHST prices are used to value buildings based on Kepmen PUPR No. 943/KPTS/M/2024, with 70% residential and 30% commercial types of exposed footprints, with losses of IDR 22.46, 28.62, and 37.03 billion, respectively. The roads cost is calculated based on the full reconstruction AHSP Bina Marga from SE DJBK No. 68 Years 2024 with the amount of IDR 24.63 billion, IDR 57.43 billion, and IDR 64.96 billion for Scenarios A, B, and C, respectively. In Scenario B, the composition of loss is 33% buildings and 67% roads. This suggests that the replacement-value exposure is dominated by road infrastructure in this version of the analysis.

Table 5. Direct Replacement Losses by Component and Scenario

Infrastructure Component	Scenario A (+1.28 m)	Scenario B (+2.13 m)	Scenario C (+3.00 m)
Buildings	22.46	28.62	37.03
Roads	24.63	57.43	64.96
Total direct loss	47.09	86.05	101.99

3.4.2 Maintenance-related losses

The long-term burden of flood-induced deterioration of buildings was estimated by recurrent maintenance losses. This component refers to Peraturan Gubernur Bengkulu No. 25 Tahun 2025, Lampiran II Tabel 2.8, which states the maintenance standards per year of IDR 191,000/m² for multi-storey buildings and IDR 131,000/m² for single-storey buildings (Gubernur Bengkulu, 2025). These values are not SHST and AHSP, but rather a measure of operational upkeep and not reconstruction.

Assuming that multi-storey and single-storey buildings are equal, the annual maintenance losses are IDR 726 million for Scenario A, IDR 896 million for Scenario B and IDR 1.161 billion for Scenario C. Discounted at 7% over 25 years, these correspond to NPVs of approximately IDR 7.93 billion, IDR 9.78 billion and IDR 12.67 billion respectively. Scenario B is particularly interesting because it highlights the long-term cost of recurring maintenance, in addition to the direct replacement losses.

Together with the direct replacement costs, the total economic exposure under Scenario B is around IDR 172.9 billion. This shows the need to include both capital and recurrent costs in coastal adaptation planning, municipal budgeting and flood-risk financing. Table 6 shows the annual maintenance losses and the corresponding 25-year NPV for the three scenarios.

Table 6. Annual and NPV Maintenance Losses

Scenario	Annual maintenance loss (IDR million/year)	NPV 25 year @ 7% (IDR billion)
Scenario A (+1.28 m)	726	~7.93
Scenario B (+2.13 m)	896	~9.78
Scenario C (+3.00 m)	1,161	~12.67

3.5. Model Plausibility Assessment and Validation

Validation was based on the spatial plausibility as no direct measurements of inundation depth from previous flood events were available for calibration purposes. The historical records of tidal flood events in Bengkulu Province [20] are presented for 12 tidal flood events in 2022-2024 with the maximum impact of 12,860 affected houses on August 30, 2022. The sub-districts of Ratu Agung, Teluk Segara, Sungai Serut, and Kampung Melayu, which experience recurrent flooding, align closely with the high-hazard zones of Scenario B depicted in Figure 2, therefore validating the model's geographic accuracy. Furthermore, the JRC seasonality study revealed that 57.1% of the high- and very-high-risk zones (20.09 of 35.21 ha) coincided with frequently inundated regions, signifying substantial hydrological plausibility.

The second validation check was the comparison of the modelled inundation with the JRC Global Surface Water maximum extent, which had an overlap of 40.7%. This level of agreement is appropriate, considering JRC data indicate historical water occurrence and the model represents expected future conditions under raised total water level. The mean elevation of the high-risk zones is about 0.23 m above the present-day sea level, agreeing with the modelled hazard thresholds and further supporting the topographic plausibility of the results. Whilst the 30 m DEM reduces local precision, the procedure is still appropriate for city-scale screening, prioritisation and planning.

In practice, the results show that transport and public-service infrastructure in Bengkulu needs specific adaption measures. Structural protection or elevation of exposed trunk and principal roadways would limit network disruption and public facilities within the 500 m threat buffer must be prepared for continuity planning. More comprehensive costing based on SHST, AHSP and IKK makes the conclusions more applicable to policy for local APBD planning and financing of disaster risk.

3.6. DEM Vertical Accuracy and Vertical Land Motion Uncertainty

NASADEM 30 m has a documented vertical RMSE of $\pm 2-9$ m in tropical coastal regions, which may surpass the sea-level rise signal projected in Scenarios A (+1.28 m) and B (+2.13 m) [6], [17]. A DEM sensitivity analysis with ± 2 m RMSE offsets to TWL thresholds produces significantly asymmetric limits: In Scenario B, the upper-bound flooding attains 131.75 hectares (3.7 times the base estimate of 35.58 hectares), but the lower bound diminishes to 0 hectares (Table 7).

The location of Bengkulu atop the Sunda Megathrust contributes to increased ambiguity regarding Vertical Land Motion (VLM). The SuGAR GPS data reveal an interseismic sinking of -2 to -5 mm/yr, interspersed with coseismic uplift episodes [21], [22]. Conservative vertical land motion constraints of ± 2 mm/year over 76 years (2024-2100) adjust Scenario B flooding to 31.2-43.0 hectares ($\pm 20\%$ relative to baseline), far less than digital elevation model uncertainty.

The sources provide a direct loss range of IDR 0-395.4 billion (base: IDR 163.1 billion) for Scenario B, taken as a measure of methodological transparency rather than a probability interval. The implementation of this approach in additional Indonesian secondary coastal towns necessitates a site-specific evaluation of vertical land motion, particularly when tectonic subsidence or groundwater extraction is substantial.

Table 7. Scenario B Inundation Uncertainty: DEM Error and VLM

Source	Lower	Base	Upper
DEM RMSE ± 2 m	0 ha	35.58 ha	131.75 ha
VLM subsidence -2 mm/yr	31.2 ha	35.58 ha	-

Source	Lower	Base	Upper
VLM uplift +2mm/yr	-	35.58 ha	43.0 ha
Combined worst-case	0 ha	35.58 ha	131.75 ha

3.7. Comparison with previous studies and implications

The results are consistent with those of prior studies showing that even a modest rise in sea level can sharply increase coastal exposure, especially in low-slope areas with high asset density [5], [6]. The dominance of roads in the loss composition also matches global evidence that transport infrastructure absorbs a large share of flood-related damage [4].

This study further confirms the value of compound-event approaches for local risk assessment, as sea-level rise and storm surge interact nonlinearly and can amplify coastal impacts beyond single-hazard estimates [2]. Finally, integrating SHST, AHSP, and IKK into the loss model improves policy relevance and supports budgeting and adaptation planning [8], [9], [10].

4. Conclusion

This study developed a compact and reproducible framework for assessing compound coastal flood risk and infrastructure losses in Bengkulu City using GEE, GIS, and OSM. Inundation expands nonlinearly from 12.64 ha to 77.76 ha across the modeled SLR scenarios, with 189.41 ha covering high-to-very-high-risk zones covering 189.41 ha. Under Scenario B (+2.13 m, 2100 SSP5-8.5), confirmed direct replacement losses reach IDR 86.05 billion, comprising roads (66.7%) and buildings (33.3%); public facilities are excluded from quantitative estimation as buffer sensitivity analysis (200–1,000 m) identified 333–335 of 336 city amenities across all distances, indicating non-discriminating coverage in Bengkulu's compact coastal geography. Annual maintenance losses add IDR 896 million per year, equivalent to a 25-year NPV of IDR 9.78 billion.

The study makes three contributions. Initially, it consolidates hazard, exposure, vulnerability, and economic loss into a unified GEE-based framework tailored for secondary coastal communities. Secondly, it anchors all cost components in prevailing Indonesian legislation, namely Kepmen PUPR No. 943/KPTS/M/2024, SE DJBK No. 68/2024, and Pergub Bengkulu No. 25/2025, hence enhancing transparency and policy pertinence. Third, sensitivity analysis is necessary for exposure measurements of buffer-based facilities. Fixed buffers may achieve nearly complete city coverage in dense metropolitan areas but lack the ability to accurately quantify losses.

Significant constraints comprise a 30 m DEM resolution, with sensitivity analysis indicating that Scenario B inundation varies from 0 to 131.75 ha within ± 2 m RMSE boundaries, and intricate vertical land motion from the Sunda Megathrust subduction zone, where ± 2 mm per year VLM alters inundation by $\pm 20\%$. The amalgamation of DEM and VLM uncertainty results in a loss range of IDR 0 to 395.4 billion for Scenario B. Future investigations ought to include higher-resolution elevation data (DEMNAS or LiDAR), dynamic hydraulic modeling, site-specific vertical land motion correction utilizing SuGAr GPS data, and explicit socioeconomic vulnerability indicators.

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