GEOSPATIAL ANALYTICS FOR DISASTER RISK REDUCTION

Flood Risk Vulnerability Mapping

Trincomalee & Galle Districts, Sri Lanka

NUS Masters in Data Science for Sustainability | AY 2025/26

SDG 11.5 Reduce Disaster Deaths	**SDG 11.b** DRR Planning	**SDG 9** Resilient Infrastructure	**SDG 13** Climate Action

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1. Introduction and Research Context

On 26 December 2004, the Indian Ocean tsunami killed over 35,000 people in Sri Lanka and forced displacement of over half a million[1,2,3]. Trincomalee in the northeast and Galle in the southwest were among the worst-hit areas. Although the Sri Lankan government introduced a 100-metre no-build zone[4] shortly after the disaster, the enforcement has remained uneven ever since[5]. Consequently, this study addresses the following **research question**: Has coastal infrastructure development in Trincomalee and Galle (as of 2025) resulted in different flood risk exposure patterns, reflecting lessons learned from the 2004 Indian Ocean tsunami?

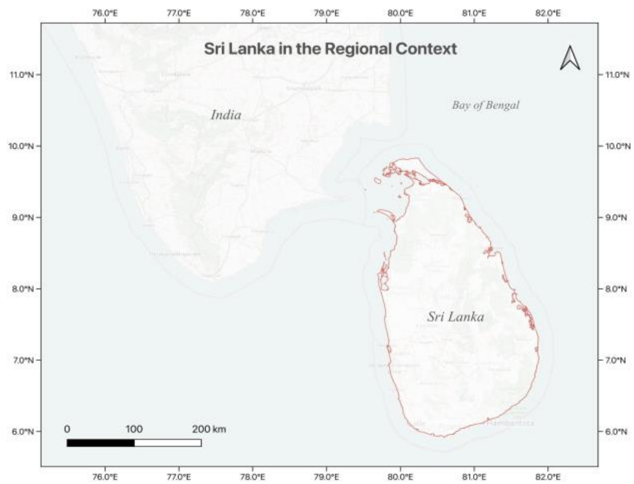

Figure 1. Regional context: Sri Lanka in the Indian Ocean.

These two districts form a natural comparative pair. Both are major port cities among the hardest hit in 2004, yet Trincomalee on the east coast faced the tsunami directly as the initial wave struck, while Galle on the southwest was struck by diffracted waves wrapping around the island, resulting in comparable destruction from fundamentally different exposure mechanisms. They also differ in coastal geometry and post-2004 development pressure, making them an analytically strong pair for examining how physical geography and governance interact to shape flood risk accumulation two decades after the disaster.

2. Study Area

Our study areas, Trincomalee and Galle[6], represent different physical characteristics as documented in Table 1. The analysis in this study is restricted to a 10 km coastal buffer, aligning with the documented 2004 run-up extent of 2-5 km inland[3].

Characteristic	Trincomalee	Galle
Province	Eastern	Southern
Coastline type	Sheltered bay (Trincomalee Bay)	Open Indian Ocean
Dominant monsoon	Northeast (Oct-Jan)	Southwest (May-Sep)
Elevation range	-35m to 255m	-14m to 831m
10 km coastal buffer area	1,266 km^2 (~47% of district)	647 km^2 (~40% of district)
Major Road segments	3,492	8,473
Hospitals	34	48

Table 1. Study area characteristics.

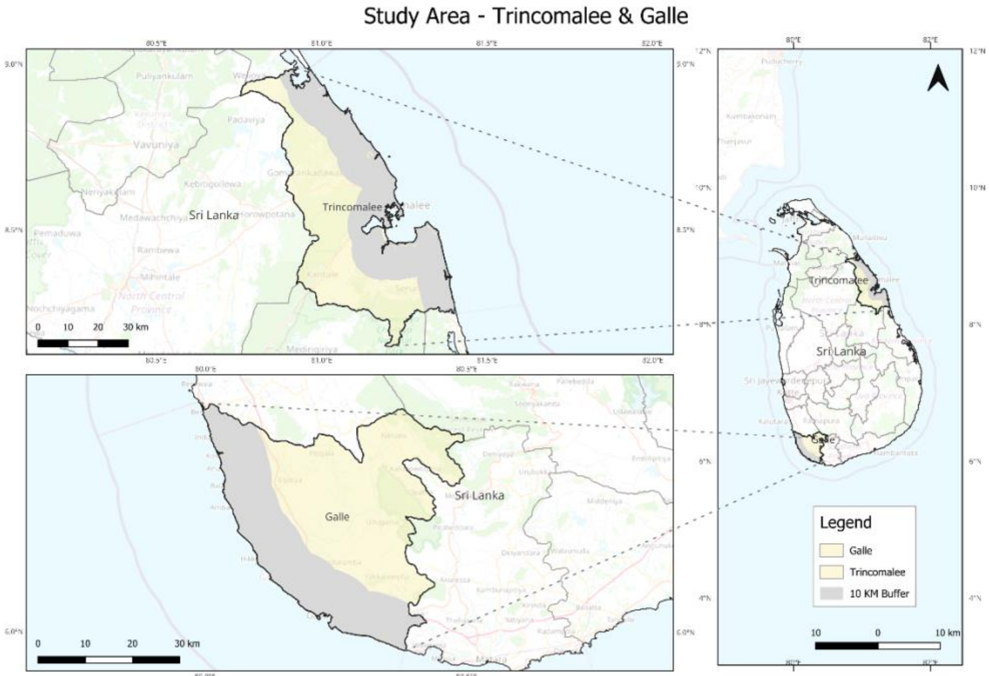

Figure 2. Study areas. Trincomalee sits on the northeast coast and Galle on the southwest, with contrasting coastline types and monsoon patterns.

3. Data and Methodology

3.1 Data Sources

All datasets used in this study are open-access, standardized to a 30m resolution and projected to EPSG:32644 (UTM Zone 44N). Table 2 lists all our data sources and the rationale behind including them.

Dataset	Source	Year	Resolution	Role
Landsat 5	USGS	2004–05	30m	Tsunami inundation proxy (NDWI)
SRTM DEM	USGS/NASA	2020	30m	Elevation; Derive coastal distance, slope, TWI
HydroSHEDS v1	WWF/USGS	2006 Based on SRTM	~500m	Derive TWI
JRC Global Surface Water	JRC	1984–2021	30m	Permanent water mask (>80% occurrence) for coastal proxy
ESA WorldCover	ESA	2021	10m	2025 built-up area; settlement type
WorldPop 2020	WorldPop, Univ. Southampton	2020	~100m	Population density
OpenStreetMap	OSM	2026 (Year accessed)	Vector	Derive road and hospital distance
LSIB	USDOS	2026 (Year accessed)	Vector	Sri Lanka coastline for 10 km buffer construction

Table 2. Data sources. All raster layers reprojected to EPSG:32644 (UTM 44N) at 30m[7-14].

3.2 Software Stack and Workflow

To ensure scalability and cartographic precision, this study employed a hybrid geospatial workflow. Primary data ingestion, image preprocessing, and heavy computation (including the calculation of NDWI, NDBI, and the Multi-Criteria Decision Analysis index)[15,16] were performed using the Google Earth Engine[17] (GEE) Python library within a Jupyter Notebook environment. This allowed for efficient handling of multi-temporal Landsat and SRTM datasets at a 30m resolution.

The resulting raster layers and risk classifications were exported via Google Drive for final processing and imported in QGIS 3.44. QGIS was utilized for zonal statistics, vectorization (polygonalizing) of risk zones, and the final cartographic layout generation, ensuring all maps adhere to professional standards for scale, orientation, and legibility.

3.3 Processing Pipeline

Figure 3 summarises the end-to-end processing workflow, from raw data inputs through pre-processing, indicator derivation, and two-stage classification to final outputs.

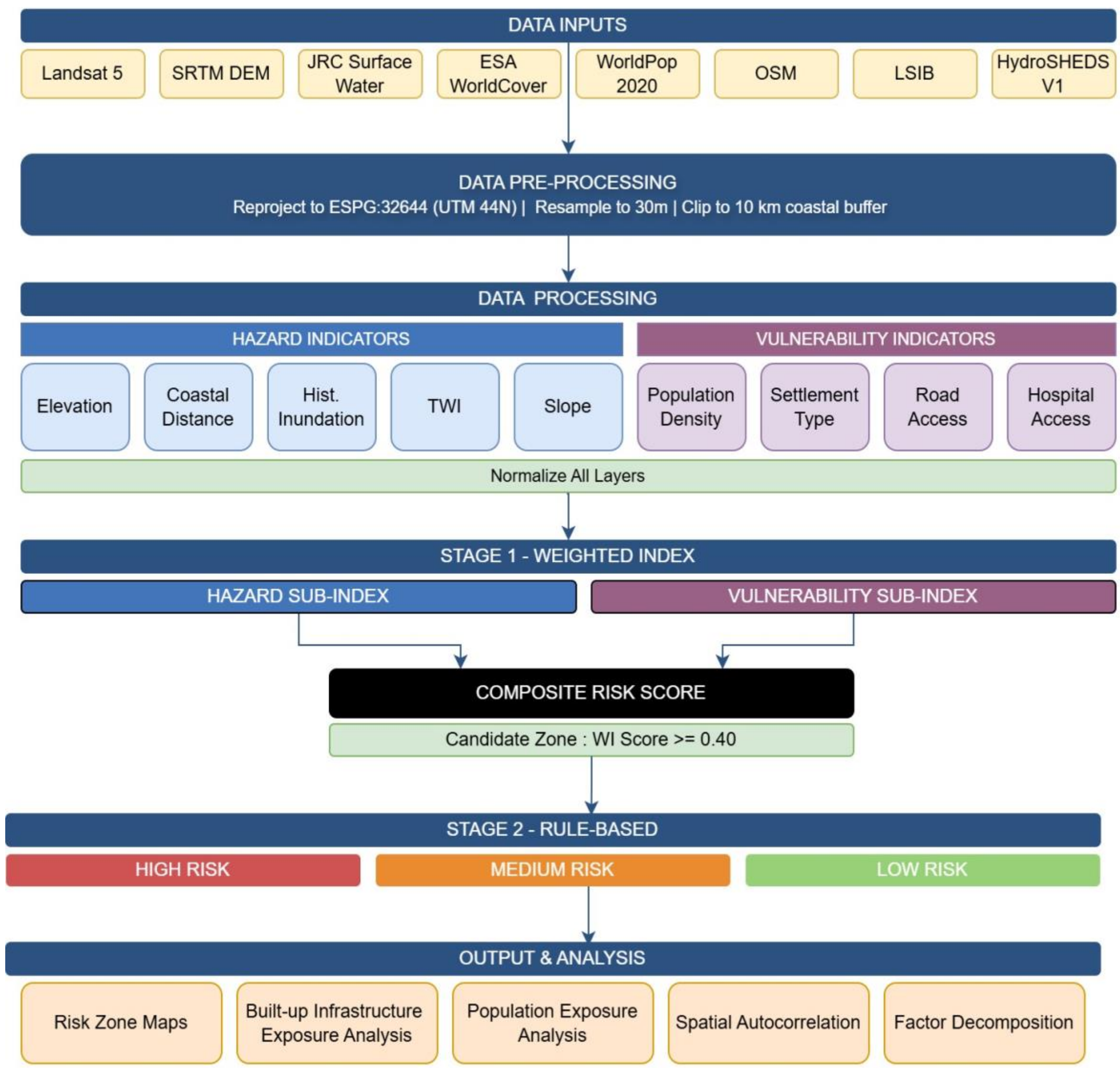

Figure 3. Processing Pipeline

3.4 Analytical Framework: Hierarchical Two-Stage Classification

As illustrated in Figure 4, we employ a hierarchical two-stage classification approach. In Stage 1, we apply a Weighted Index that integrates nine physical and social factors into a continuous [0-1] risk score. In Stage 2, we utilize a rule-based index that applies IPCC AR6-derived absolute physical thresholds[18] within the resulting candidate zone (Weighted Index >=0.40) to produce final Low/Medium/High classifications.

Figure 4. Analytical Framework: Two-stage hierarchical classification

Indicator weights reflect the relative importance of each factor in determining coastal flood risk. Hazard factors collectively receive 60% weight as physical exposure, principally nearshore elevation and proximity to the coast, is the primary determinant of inundation extent independent of human factors. Within hazard, elevation (30%) and coastal distance (25%) dominate since tsunami and storm surge run-up is governed primarily by nearshore topography, consistent with field observations from the 2004 event[13] in Sri Lanka. Historical inundation (20%) directly captures areas submerged during the 2004 tsunami, providing an empirical record of actual flood extent as a hazard indicator. TWI and slope (15% and 10%) capture compound fluvial flood susceptibility in low-lying areas. Vulnerability factors take the remaining 40%, with population density weighted highest (40% of vulnerability) as it is the strongest predictor of casualty magnitude in coastal flood events. Settlement type (25%) distinguishes formal from informal structures, while road and hospital access (20% and 15%) capture evacuation capacity and recovery potential respectively.

The Rule-Based thresholds in Stage 2 are derived from IPCC AR6 standards for coastal flooding[18] and sea-level rise. High risk is assigned to areas below 3m elevation anywhere in the buffer, areas below 5 m within 2 km of the coast, and areas directly inundated in 2004, as these represent absolute physical conditions under which tsunami and storm surge inundation is near-certain. Medium risk captures areas between 3 m and 5 m elevation, areas below 10 m within 5 km of the coast with slopes below 5 degrees, and remaining candidate zone pixels, reflecting elevated but conditional exposure. Everything else within the buffer is classified Low risk.

4. Results

4.1 District-Level Risk Zone

The hierarchical classification reveals that while Trincomalee has a predominantly Low risk buffer (66.5%), its high-risk zones are concentrated at the flat bay mouth. In contrast, Galle presents a more concerning picture despite its smaller buffer (646.9 km²). Only 30.5% is Low risk, while 58.7% is dominated by Medium (58.7%) and High (10.9%) risk zones due to its exposed open-ocean coastline[19].

Risk Zone	Trincomalee (km^2)	Trincomalee (%)	Galle (km^2)	Galle (%)
HIGH	107.4	8.5%	70.3	10.9%
MEDIUM	319.0	25.3%	377.8	58.7%
LOW	838.8	66.5%	196.8	30.5%
Total buffer	1,266	100%	647	100%

Table 3. Hierarchical risk zone areas within the 10 km coastal buffer

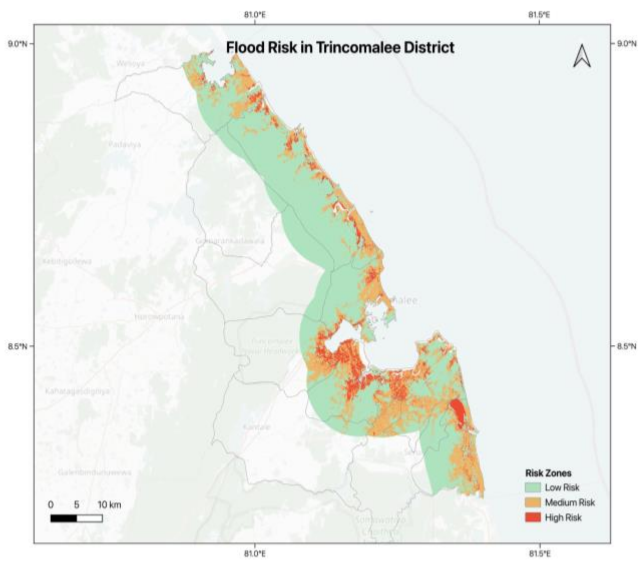

Figure 5. Flood Risk - Trincomalee

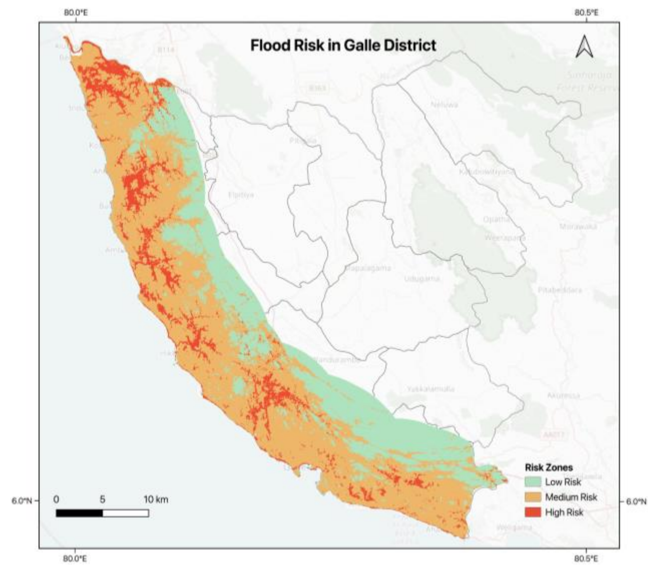

Figure 6. Flood Risk - Galle

Figures 5-6. Hierarchical risk zone classification within 10 km coastal buffers. Green = Low, orange = Medium, red = High. Galle's coastal zone is dominated by Medium/High risk.

4.2 Built-up Infrastructure Exposure

To quantify the exposure of the 2025 built-up area, we overlaid the 2025 built-up area (ESA WorldCover[11] class 50) onto the risk zones within each district's coastal buffer.

Trincomalee has a higher share of infrastructure in High risk zones (7.8%) compared to Galle (2.3%). However, both districts exhibit a Medium-risk trap: 84.9% of all coastal built-up in Trincomalee and 96.0% in Galle sit within Medium risk zones, indicating that almost no coastal infrastructure in either district occupies genuinely safe ground (Table 4).

Risk Zone	Trincomalee (km^2 / %)	Galle (km^2 / %)
HIGH	1.44 km^2 (7.8%)	0.42 km^2 (2.3%)
MEDIUM	15.72 km^2 (84.9%)	17.66 km^2 (96.0%)
LOW	1.36 km^2 (7.4%)	0.30 km^2 (1.7%)
Total built-up	18.52 km^2	18.39 km^2

Table 4. Built-up infrastructure exposure by hierarchical risk zone (primary output). Source: ESA WorldCover, class 50 overlaid on Stage 2 risk zones, within 10 km coastal buffer.

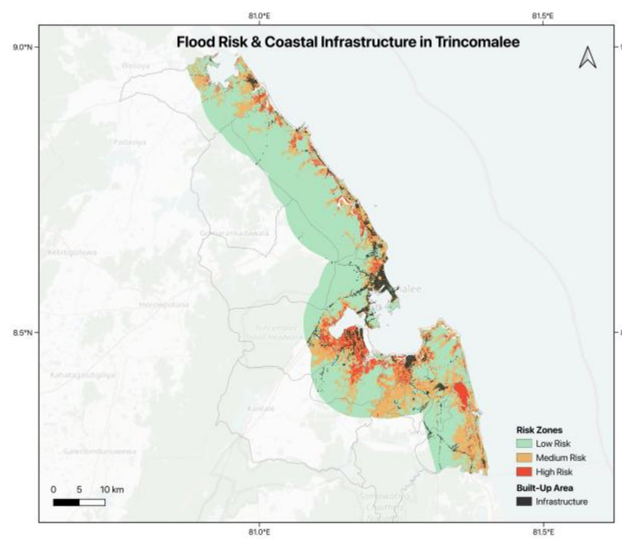

Figure 7. Infrastructure Exposure - Trincomalee

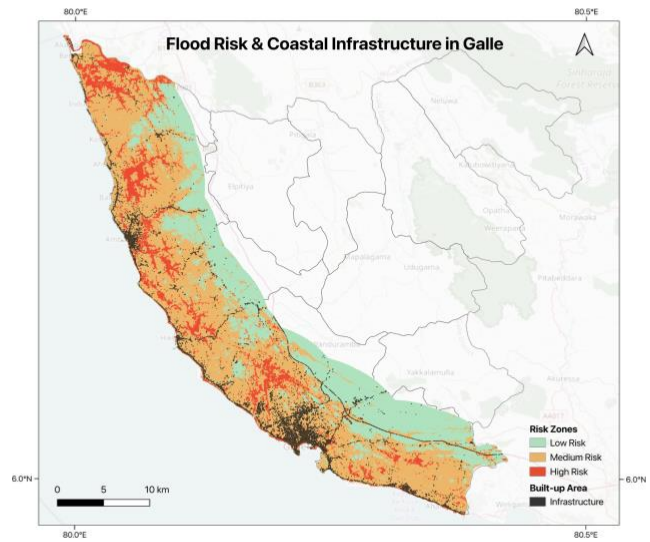

Figure 8. Infrastructure Exposure - Galle

Figures 7-8. Risk zones overlaid with 2025 built-up area (black dots = infrastructure). In Galle, built-up pixels cluster densely within High and Medium risk zones along the entire coastal strip.

4.3 Population Exposure

We built Population exposure maps (Figures 9-10) using WorldPop 2020 data[12] to illustrate the distinct settlement patterns in the two districts.

In Trincomalee, the dense populations are tightly clustered at the High-risk bay-mouth. In Galle, population density is distributed relatively more uniformly across the coastal strip. Unlike Trincomalee, there is no single concentrated high-risk population centre - instead, dense settlement pervades the coastal zone at broadly similar intensity across both Medium and High risk areas. This is consistent with Galle's higher mean vulnerability index (0.242 vs Trincomalee's 0.119), driven primarily by its population density contribution of 0.164 - five times higher than Trincomalee's 0.032 (Table 6).

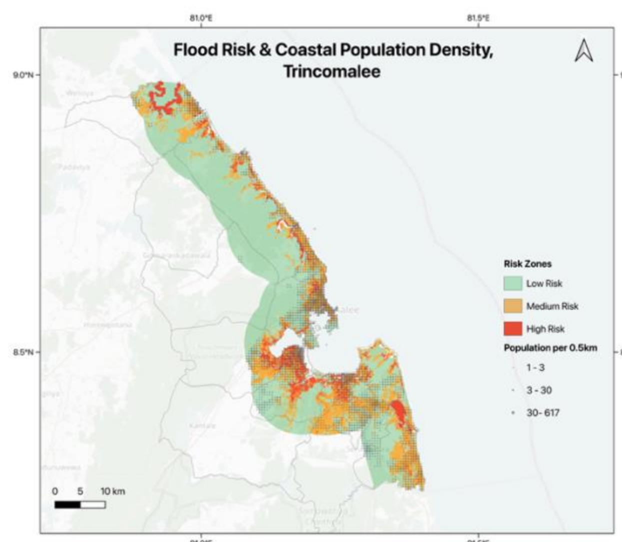

Figure 9. Population Density - Trincomalee

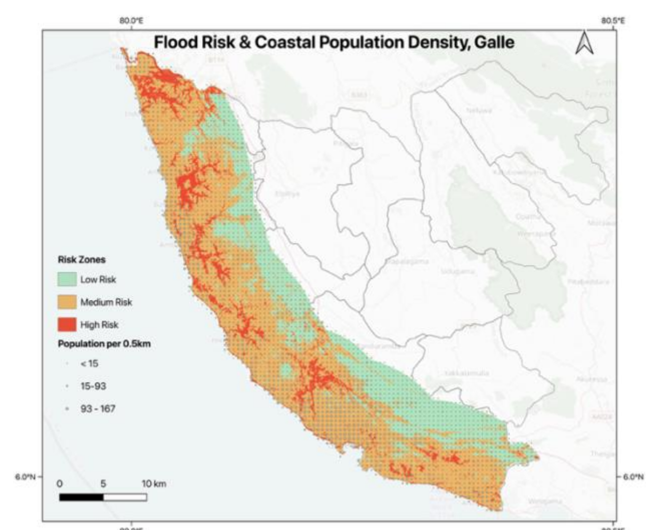

Figure 10. Population Density - Galle

Figures 9-10. Flood risk zones overlaid with WorldPop 2020 population density (dots scaled by population per 0.5 km grid cell). Galle shows high population density concentrated uniformly across Medium/High risk zones.

4.4 Spatial Clustering: Are Risk and Infrastructure in the Same Places?

As illustrated in Table 5, spatial autocorrelation confirms that risk is not randomly distributed. The spatial clustering of risk scores in both districts is confirmed through Global Moran's I[20] (statistically significant at 0.001). Bivariate Moran's I confirms significant co-location of infrastructure in the high-risk clusters (Trincomalee BVI = 0.185, Galle BVI = 0.154; statistically significant at p = 0.002), proving that coastal development has continued to concentrate in flood-prone zones post-2004.

Metric	Trincomalee	Galle
Global Moran's I (Weighted Index score)	0.675 (p = 0.001)	0.651 (p = 0.001)
Bivariate Moran's I (risk x built-up)	0.185 (p = 0.002)	0.154 (p = 0.002)
HH hotspot pixels (LISA)	19.8%	19.4%
Sample size (coastal points)	2,968	2,992

Table 5. Spatial autocorrelation results.

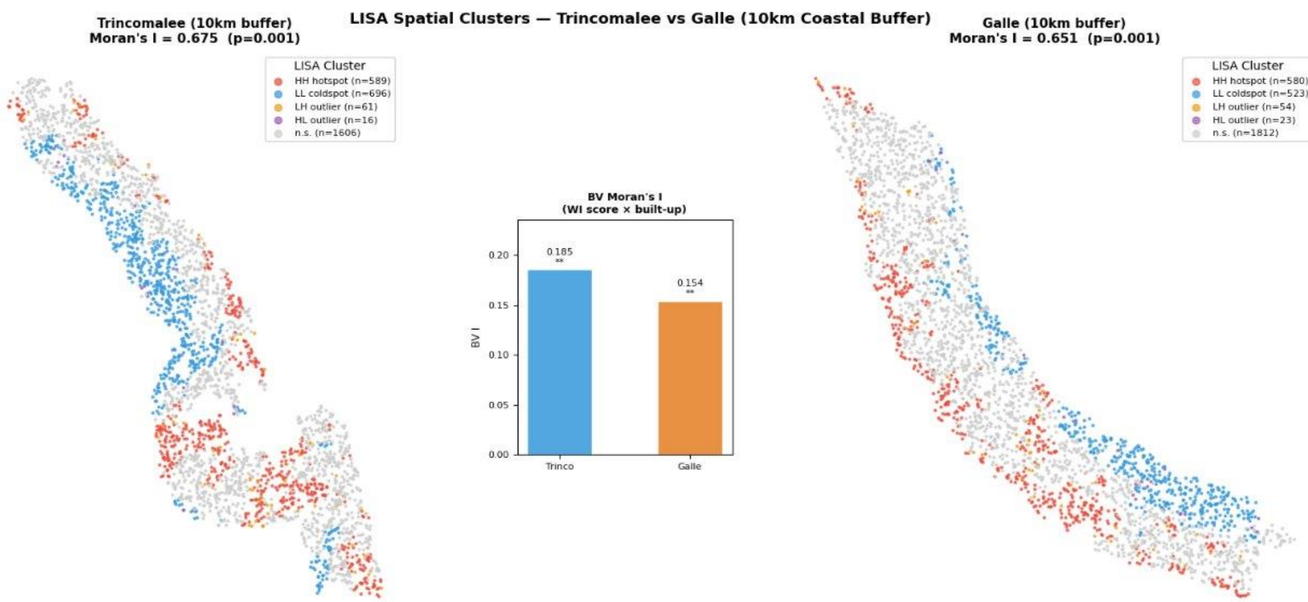

Figure 11. Spatial Clustering – Trincomalee and Galle

5. Discussion and Limitations

Trincomalee's higher built-up exposure in High-risk zones (7.8% vs Galle's 2.3%) presents a paradox: while Galle's mean hazard index is marginally higher (0.548 vs. 0.540; factor decomposition, Table 6), Trincomalee's flat bay mouth geometry, which houses its city centre and fishing infrastructure, makes its built up more vulnerable to floods than Galle's.

The Factor Decomposition (Table 6) reveals Galle's vulnerability (0.242) is driven by its five-fold higher population density (0.164 vs. Trincomalee's 0.032), while that of Trincomalee (0.119) is marked by its fragile, dispersed settlement patterns (0.062).

Metric	Trincomalee	Galle
Mean WI composite score	0.372	0.426
Mean Hazard Index	0.540	0.548
Elevation contribution	0.229	0.252
Coast distance contribution	0.175	0.172
Hist inundation contribution	0.000	0.000
TWI contribution	0.043	0.038
Slope contribution	0.094	0.087
Mean Vulnerability Index	0.119	0.242
Population density contribution	0.032	0.164
Settlement type contribution	0.062	0.034
Road access contribution	0.024	0.011
Hospital access contribution	0.001	0.033

Table 6. Factor Decomposition analysis.

Key Limitations:

- **Historical Proxy:** The 2004 Landsat-derived inundation layer substantially under detects the actual tsunami extent (0.27 km² and 0.13 km² detected), contributing near-zero to Weighted Index scores despite its 20% weight.
- **Built-up Data:** ESA WorldCover (2021)[11] is used as a 2025 built-up proxy and likely undercounts informal coastal structures, such as fishing stalls and settlements within agricultural fields; the infrastructure exposure figures should be treated as conservative lower bounds.
- **Calibration:** Shared indicator weights across both districts may overlook regional drivers, future work requires district-specific calibration using historical damage.

6. Conclusions and SDG Relevance

Two decades after the 2004 tsunami[1], this study confirms that coastal development in Trincomalee and Galle has not transitioned to safer ground. While the districts face different challenges, Trincomalee faces a physical geometry problem and Galle faces a governance & density problem, the result is a Medium-risk issue. The overwhelming concentration of infrastructure in Medium/High risk zones proves that post-2004 development patterns have largely failed to reflect on the lessons from the disaster.

The most poignant evidence of this stagnation is the Colombo-Matara railway corridor. As shown in Figure 12, the railway line, to this date, remains entirely within Medium/High-risk zones, passing through the exact site of the 2004 disaster in Peraliya[21]. This lack of managed retreat for critical infrastructure highlights the urgent need for statutory changes outlined in Table 7.

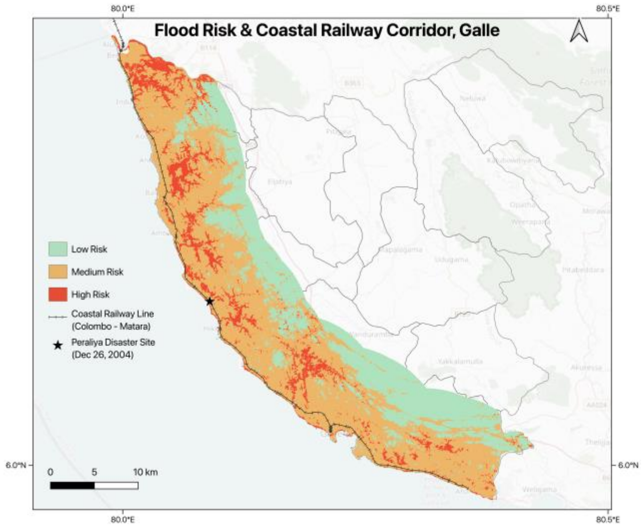

Figure 12. Flood risk and coastal railway corridor, Galle. The Colombo-Matara railway line (black dashes) runs entirely within Medium/High risk zones. The ★ marks the site where the Peraliya disaster occurred on Dec 26, 2004

6.1 Policy Recommendations

District	Priority Action	SDG Target	Evidence
Trincomalee	Enforce strict 2 km no-build boundary at bay-mouth; prioritise road network expansion in coastal communities to improve evacuation capacity	SDG 11.5, 11.b	7.8% built-up in HIGH; road vulnerability score 0.024 weighted
Galle	Enforce statutory coastal setback beyond Heritage Zone; regulate tourism-driven coastal densification; mandate AR6-aligned flood risk assessment before any coastal development approval	SDG 11.b, 13	BV I = 0.154 (p = 0.002); 96% built-up in Medium/High risk
Both	Integrate HIGH zone consensus areas into district land-use plans as no-development or managed-retreat zones; update tsunami inundation mapping with SAR or dedicated field survey	SDG 9, 11.5, 13	Both BV I significant; historical inundation proxy severely underestimates actual 2004 extent

Table 7. Policy recommendations derived directly from analysis results.

6.2 SDG Relevance

SDG 11.5 (primary): The percentage of built-up land in High-risk zones is a clear, measurable indicator of how exposed coastal infrastructure is to disaster. Our results give district planners a replicable baseline to track progress.

SDG 11.b: Because high-risk zones are spatially clustered, targeted coastal setback enforcement covering a defined strip of land would address most of the exposure in both districts without sweeping restrictions across the whole area.

SDG 9 and 13: By using IPCC AR6-aligned thresholds[18], these risk maps serve as an evidence base for building climate-resilient infrastructure and planning evacuation routes that meet modern safety standards.

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