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TSUNAMI RISK IN PACITAN, INDONESIA: SPATIAL PATTERNS OF BUILDING VULNERABILITY IN AN EMERGING COASTAL TOURISM DESTINATION

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Abstract: Coastal tourism destinations along the southern coast of Java face significant exposure to tsunami hazards. This study models potential coastal inundation using the official deterministic worst-case scenario of an 11 m tsunami wave and evaluates tsunami-related building vulnerability in Watukarung, Indonesia, through the Papathoma Tsunami Vulnerability Assessment framework (PTVA-4). The analysis incorporates structural characteristics, water-related exposure, surrounding environmental conditions, and a composite Relative Vulnerability Index (RVI), based on field surveys of existing buildings within the inundation zone. The field survey identified a largely uniform stock of low-rise, non-engineered structures lacking substantial natural or engineered protection. Most buildings fell into moderate to high structural vulnerability (SV) categories, with concentrations of high and very high vulnerability along the Watukarung Beach corridor and near the fish landing site. Inundation modelling reveals that the greatest water depths occur along the immediate coastal strip and low-lying areas near the river mouth. Consequently, water inundation vulnerability (WV) was mostly high, with only a small proportion of buildings in the average and minor vulnerability classes. RVI results indicate that 33.34% of buildings are classified as high or very high vulnerability, while 24.36% are considered average, with higher vulnerability concentrated in coastal tourism zones. These patterns are closely linked to the prevalence of single-storey masonry buildings, shallow or non-engineered foundations, and limited natural barriers. The results demonstrate that tsunami risk in Watukarung is shaped not only by hazard intensity but also by the interaction of building characteristics and tourism land use. This spatial convergence of hazard, vulnerability, and tourism exposure emphasizes the requirement for risk-informed coastal planning and improved tourist safety management in tsunami-prone areas.

Keywords: coastal tourism, tsunami hazard, spatial analysis, building vulnerability, PTVA-4, Pacitan

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INTRODUCTION

The 2004 Indian Ocean Tsunami represented a pivotal moment in global coastal hazard assessment and disaster risk governance, particularly within Southeast Asia. This event revealed critical deficiencies in early warning systems, public preparedness, and coastal structural resilience. In response, significant policy and technological advancements were implemented, including the establishment of integrated tsunami early warning systems such as Indonesia's InaTEWS (Widiyantoro et al., 2020). Additionally, there was a broader transition in Disaster Risk Reduction (DRR) strategies toward hybrid probabilistic - deterministic assessments and enhanced risk communication (Goda & Risi, 2023; Zamora et al., 2021). Due to its complex tectonic environment, Indonesia remains one of the most tsunami-prone country worldwide. Recent geophysical and geological research has also underscored the considerable tsunami-generating potential of the Southern Java megathrust, where accumulated strain and identified seismic gaps may result in megathrust earthquakes up to Mw 8.7, with the potential to generate large tsunamis impacting densely populated coastlines (Fuad et al., 2025; PUSGEN, 2017). Despite probabilistic tsunami hazard models have been developed (Horspool et al., 2014), significant uncertainties remain regarding rupture complexity, cascading processes, and nearshore amplification (Harati & Van De Lindt, 2024). Consequently, Indonesian authorities have adopted official deterministic tsunami worst-case scenarios to inform preparedness planning and coastal land-use regulation.

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A central challenge in contemporary DRR practice is the translation of national-scale hazard scenarios into actionable, community-scale assessments. National tsunami hazard maps, despite their strategic value, often lack the resolution required to inform local zoning, infrastructure protection, and evacuation planning (Tika et al., 2025). As a result, studies increasingly advocate for integrating hazard, exposure, and vulnerability at fine spatial scales to identify high-risk hotspots and support targeted interventions (Fatchurohman et al., 2022; Zamora et al., 2021). Building-level physical vulnerability is critical in this context, as structural performance shapes both mortality risk and economic loss. Consequently, field-based vulnerability assessments remain essential for informing evidence-based DRR strategies tailored to local contexts (Aksha et al., 2020; Paulik et al., 2023).Beyond physical science and engineering considerations, recent literature highlights the need to understand tsunami risk within the broader socio-economic dynamics of coastal tourism. The tourism sector is highly vulnerable to catastrophic natural hazards such as earthquakes, tsunamis, volcanic eruptions, and wildfires, which damage tourism infrastructure and key attractions, leading to destination degradation and declines in tourism demand following major disaster events (Aliyev, 2025). Tourism infrastructure is typically located in the most exposed zones to maximize beachfront access and landscape aesthetics, resulting in the concentration of high-value economic assets and dense visitor populations in hazardous coastal strips. The transient nature of tourists strengthens this vulnerability: visitors generally lack knowledge of local geography, warning cues, or evacuation procedures, making them significantly more at risk during a tsunami than residents (Cisternas et al., 2024). At the same time, tourism-dependent communities face heightened long-term socio-economic consequences after disasters, as damage to accommodation, restaurants, recreational facilities, and coastal amenities can lead to prolonged livelihood disruption and destination collapse. Conversely, studies suggest that tourism can be leveraged to strengthen resilience when integrated into DRR planning through the use of multifunctional tsunami shelters, community-based tourism education, or tourism-governance partnerships (Filimonau & De Coteau, 2020). These findings underscore the importance of incorporating tourism-specific exposure, behavioral characteristics, and economic dependencies into local tsunami risk assessments, particularly in rapidly developing coastal settings.

This study addresses a critical research gap by focusing on the coastal community of Watukarung in Pacitan, an area where the urgency for risk assessment is amplified by its rapid emergence as a premier international tourism destination in Indonesia. The specific selection of Watukarung is driven by the unique "double exposure" created by its thriving tourism sector.

Firstly, the area has seen a proliferation of tourism infrastructure such as homestays and resorts constructed in close proximity to the shoreline to accommodate surfers and visitors, placing high-value economic assets directly in high-hazard zones. Secondly, the presence of a transient tourist population significantly alters the risk profile; unlike local residents, visitors often lack knowledge of local geography, evacuation routes, and hazard warning signs. Consequently, a tsunami event in Watukarung would not only threaten physical structures but could result in disproportionately high casualties among non-residents and catastrophic damage to the local tourism-dependent economy. Therefore, this research aims to: (1) model potential coastal inundation based on the official worst-case scenario of an 11-meter wave height established by Indonesian national authorities; (2) evaluate tsunami-related building vulnerability in a coastal tourism destination using the Papathoma Tsunami Vulnerability Assessment (PTVA-4) framework by integrating structural, water-related, and surrounding environmental factors, and examine its implications for tourist safety and spatial planning in tsunami-prone areas. This research contributes to strengthening long-term human security, safeguarding tourism-dependent livelihoods, and guiding policy transitions from hazard awareness toward integrated, tourism-informed coastal tsunami resilience planning

STUDY AREA

The research was conducted in the coastal area of Watukarung Village, Pringkuku District, Pacitan Regency, East Java, Indonesia. This region lies along the southern coast of Java and is directly exposed to the Indian Ocean, which makes it highly vulnerable to tsunamigenic hazards associated with the Java Trench subduction zone (Figure 1).

The coastal morphology, defined by low-lying plains and a river mouth, further increases the potential for tsunami inundation. Watukarung contains a densely populated coastal settlement of more than 3,200 residents and includes essential public facilities (BPS, 2023). The local economy is primarily based on tourism and fisheries, with Watukarung Beach recognized as emerging international surfing destination (Figure 2).

Data from the Pacitan Statistics Agency (BPS) indicate that the area received over 116,000 domestic and international visitors in 2023(BPS, 2023). The combination of high tsunami exposure and concentrated residential and tourism assets highlights Watukarung as a critical location for comprehensive coastal risk assessment.



Figure 1. Map of the study area in Watukarung Village, Pacitan. (Source: Prepared by the authors using Google Street Map basemap (2025) and the East Java megathrust segment data from PUSGEN, 2017)



Figure 2. Surrounding condition of the study area (a) Watukarung Beach, a sandy coastal area intensively used for recreational tourism.(b) Fish landing site in the eastern part of the Watukarung coastal area, Pacitan, showing traditional fishing boats densely moored near the shoreline. (Source: Taken by the authors during the field survey on 18 May 2023)

MATERIALS AND METHODS

This study assessed the tsunami vulnerability of buildings in Watukarung coastal area using the revised PTVA-4 model (Dall'Osso et al., 2016). The methodological framework, illustrated in Figure 3, required the integration of the PTVA-4 model with a hazard-specific inundation map. This integration yielded a building Relative Vulnerability Index (RVI) map.

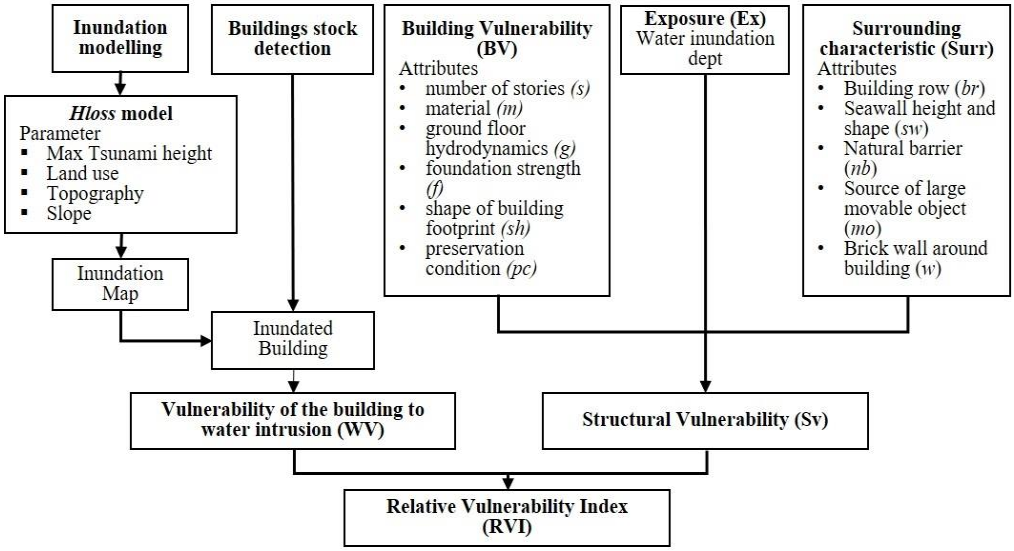


Figure 3. Methodological framework

Field Survey

A field survey was conducted in April- May 2023 to identify the characteristics of the building stock within the research location. This research using mixed-method strategy combining (1) a Rapid Visual Survey (RVS) conducted by the researcher to assess observable structural parameters (such as materials, storeys, and physical condition) and (2) structured interviews with household occupants (aged 25-65) to ascertain non-observable or historical data, most critically foundation type and construction process. The sampling strategy first required defining the target population (N). While Watukarung Village comprises approximately 298 structures, the population for this risk assessment was refined to only those buildings (N=285) situated within the potential tsunami inundation zone, as determined by hazard modelling. To establish a statistically representative sample size (n) from this at-risk population, Slovin's formula applied (Tejada & Punzalan, 2012). Based on this calculation, utilizing a population size (N) of 285, a sample size of 78 buildings was deemed sufficient. The selected sample size balances statistical representativeness and field survey feasibility, and is appropriate for spatially explicit vulnerability assessment aimed at supporting risk-informed tourism planning. The selection of these 78 units for the survey was then carried out using a simple random sampling technique.

Tsunami Hazard Modelling

The tsunami hazard component of this study was modelled using a deterministic, single-scenario approach. This approach was justified by the need to align the assessment with national-level disaster management policy, which utilizes a worst-case scenario for preparedness and spatial planning (Pranantyo et al., 2021). The specific scenario adopted was a tsunami generated by a submarine earthquake in the Java Trench, resulting in an 11-meter wave height at

the coastline, as officially established by the Indonesian National Disaster Management Agency (BNPB) by Regulation of the Head of the National Disaster Management Agency Number 4 of 2012.

To estimate the inland inundation extent and flow depth from this scenario, the semi-empirical *Hloss* model was employed (Berryman, 2006; Sambah et al., 2024). The application of simplified inundation models like *Hloss* is justified for first-order hazard assessments, particularly in contexts where detailed bathymetric data or computational resources for full hydrodynamic simulations are limited. These models offer a computationally efficient method for providing rapid, scenario-based inundation estimates that are crucial for initial risk mapping and prioritization (Gomez-Zapata et al., 2021). The *Hloss* model (Equation 1) calculates inundation based on key physical parameters derived from a Digital Elevation Model (DEM), primarily terrain slope and surface roughness (Berryman, 2006).

$$H_{loss} = \left(\frac{167.n^2}{H_0^{\frac{1}{3}}}\right) + 5 \sin S \qquad (1)$$

Legend:

H_{loss}: Head loss per 1 m of inundation distance; Ho: Tsunami wave height at the coastline (m);

n: Surface roughness coefficient; s: Slope gradient (rad)

DEM data was downloaded from the official Indonesia OneMap data server (https://tanahair.indonesia.go.id) which provides high-resolution elevation data with an approximate spatial resolution of 8.33 m and a vertical accuracy of 3.6 m. The DEM was employed to derive terrain characteristics, while surface roughness coefficients were assigned based on land-use and land-cover (LULC) classes (e.g., open fields, vegetated areas, built-up zones), affecting tsunami wave energy dissipation. LULC data were visually interpreted from high-resolution Google Maps imagery and subsequently validated through field surveys conducted in April–May 2023. Manning's surface roughness coefficients were adopted following the BNPB regulation (Amri et al., 2016). The tsunami hazard model generated a raster-based map representing both the spatial extent of inundation and the corresponding water depth across the study area.

This model output was then used to identify buildings affected by inundation, providing the essential hazard input for subsequent physical vulnerability analysis based on the PTVA-4 framework.

Building Vulnerability Assessment

The physical vulnerability of the building stock was quantitatively evaluated using the Papathoma Tsunami Vulnerability Assessment (PTVA-4) model (Dall'Osso et al., 2016), an index-based framework selected for its comprehensive structure and demonstrated applicability. The PTVA-4 model originally developed by Papathoma (2003), is designed to evaluate the susceptibility of buildings to tsunami-induced damage. Detailed descriptions of the model can be found in Papathoma et al. (2003) and Papathoma & Dominey-Howes (2003). The model was initially established using post-tsunami field survey data, which were analysed to identify the parameters exerting the greatest influence on structural vulnerability. Weighting coefficients were then assigned according to the relative importance of these parameters, allowing for the computation of composite vulnerability indices. A revised version, known as PTVA-3, was later introduced by Dall'Osso et al. (2009), and its validity was confirmed through several studies, including those by Dall'Osso et al. (2010). The model has since been applied in multiple case studies across different coastal characteristics.

More recently, Dall'Osso et al. (2016) proposed an updated and enhanced version (PTVA-4) specifically adapted for urban coastal environments. This version refines the earlier PTVA-3 by incorporating 13 parameters, including six structural factors, five protection-level indicators, as well as inundation depth and water intrusion vulnerability. The core of the PTVA-4 model is the calculation of a final Relative Vulnerability Index (RVI) for each building.

Structural Vulnerability (SV)

The PTVA-4 framework defines structural vulnerability (SV) as the product of three key components. (Equation 2, Dall'Osso et al., 2016):

$$SV_{[1,125]} = BV_{[1,5]} \times Surr_{[1,5]} \times Ex_{[1,5]} \qquad (2)$$

BV represents the intrinsic building vulnerability derived from its engineering and structural characteristics; *Surr* accounts for the influence of the surroundings, encompassing both protective features and impact risks from large movable objects; and *Ex* quantifies the exposure, defined as a function of the tsunami water depth impacting the building. For more detailed formula for each component please refer to Dall'Osso et al. (2016).

Water Vulnerability (WV)

The Water Vulnerability (WV) component represents the proportion of building levels affected by tsunami inundation. It is calculated as the ratio between the number of inundated stories and the total number of stories in the structure (Equation 3, Dall'Osso et al., 2016).

$$WV_{[0,1]} = \frac{Height\ of\ inundation\ levels}{Total\ height\ of\ building} \qquad (3)$$

Relative Vulnerability Index (RVI)

The PTVA-4 model calculates the Relative Vulnerability Index (RVI) for each building using equation 4 (Dall'Osso et al., 2016). The RVI, SV, and WV scores are all measured on a vulnerability scale from +1.00 (minimum vulnerability) to +5.00 (maximum vulnerability). The RVI values were classified using the natural breaks (Jenks) and quantile classification

methods, which are commonly applied in thematic cartography to identify inherent data groupings and ensure balanced class distributions (Jenks, 1967; Slocum et al., 2022). The resulting vulnerability levels were grouped into five classes based on Jenks-defined intervals: minor (class 1), moderate (class 2), average (class 3), high (class 4), and very high (class 5). This classification provides a statistically consistent representation of spatial vulnerability patterns.

$$RVI_{[1,5]} = \frac{2}{3}SV_{[1,5]} + \frac{1}{3}WV_{[1,5]} \quad (4)$$

where : *SV*: structural vulnerability of the building; *WV* : vulnerability of the building to water intrusion

RESULTS AND DISCUSSION

Tsunami Hazard Characterisation: Inundation Extent and Depth

The initial phase of the analysis involved modelling the tsunami hazard based on the deterministic, 11-meter maximum wave height scenario prescribed by the Indonesian National Disaster Management Agency (BNPB).

The application of the semi-empirical *Hloss* model, using high-resolution topographic data and land-use-derived roughness coefficients, yielded a detailed spatial delineation of the potential tsunami inundation. The model results indicate a significant and widespread inland penetration of the tsunami. The total inundated area was calculated to be approximately 212 hectares. This extensive flooding is primarily attributed to the low-lying coastal topography and the presence of a river mouth, which acts as a natural channel for seawater to propagate inland.

A map of the modelled inundation, as presented in Figure 4, illustrates the spatial variability of the hazard. The inundation is not uniform; instead, it demonstrates a clear gradient of decreasing water depth with increasing inland distance and elevation. The maximum simulated water depths, reaching up to 11 meters, are concentrated in the immediate coastal strip and, most significantly, in the low-lying area in center of the bay and surrounding river mouth.

The concave geometry of the bay can focus tsunami energy toward the central area, resulting in locally amplified wave heights and increased inundation intensity (Fuad et al., 2025). Moreover, funnel-shaped river mouths can further focus tsunami wave energy into narrower corridors, thereby amplifying inundation depths and increasing flood risk in adjacent low-lying coastal areas (Lee et al., 2023). This area is projected to experience the most destructive hydrodynamic forces. As the inundation progresses inland, water depths gradually attenuate, though substantial areas of settlement are still projected to be inundated by water depths ranging from 5 to 10 meters.

This finding is critical, as it establishes the precise spatial "footprint" of the hazard, providing the essential Exposure *(Ex)* parameter for the subsequent vulnerability analysis.

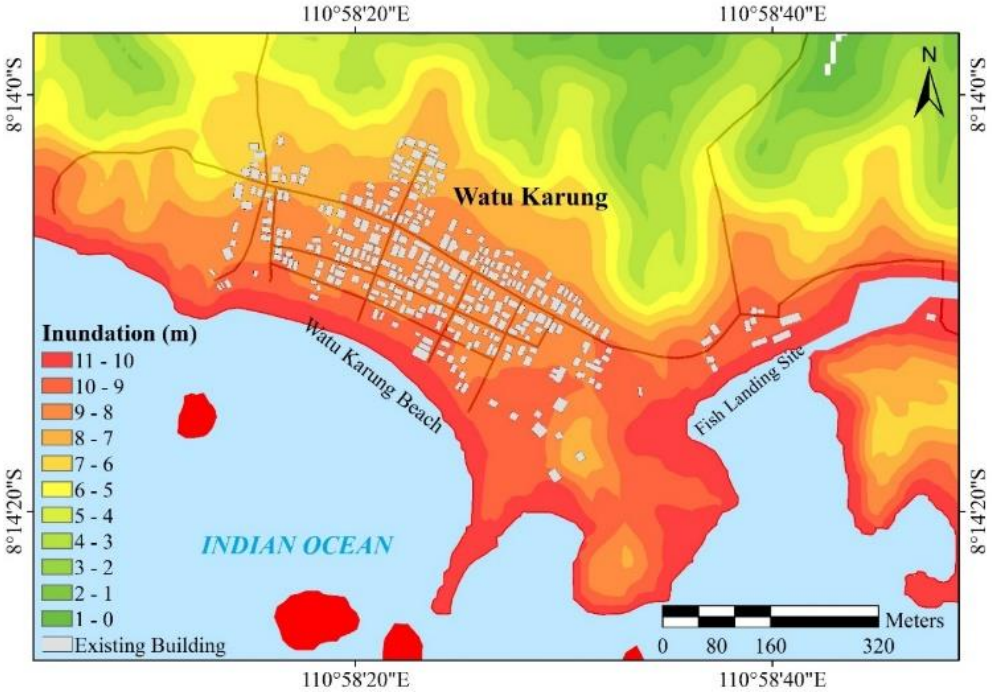


Figure 4. Tsunami Inundation Map for Watukarung (Source: Prepared by the authors based on field survey and GIS analysis, 2025)

Building Stock Characterisation and Vulnerability Parameters

The Building Vulnerability (*BV*) component of the PTVA-4 model was developed based on a field survey of 78 buildings, focusing on key structural attributes that influence tsunami-induced damage at the building level.

The complete *BV* parameters for the surveyed buildings is presented in Table 1. The findings reveal a largely uniform building stock, predominantly consisting of low-rise, non-engineered construction types.

This has significant implications for tsunami vulnerability and human safety, particularly in coastal tourist areas like Watukarung-Pacitan, where rapid tourism development has occurred along coastlines prone to tsunamis.

Table 1. Building Vulnerability [*BV*] Parameters for the Surveyed Buildings

Parameter Category	Attribute	Freq (n=78)	Percentage (%)
Number of Storeys [s]	Single-Storey	65	83.33%
	Multi-Storey (2+)	13	16.67%
Building Material [m]	Reinforced concrete or steel	11	14.10%
	Masonry	63	80.76%
	Timber, tin, clay or light materials	4	5.13%
Ground floor hydrodynamics [g]	Completely open plan	1	1.28%
	About 75 % open plan	14	17.95%
	About 50 % open plan	23	29.49%
	About 25 % open plan	40	51.28%
Foundation Type [f]	Deep pile foundation	3	3.85%
	Average depth foundation	43	55.13%
	Shallow non engineered foundation	32	41.03%
Shape of building footprint [sh]	Squared or almost squared	8	10.26%
	Rectangular	67	85.90%
	Complex (L, T or X shaped buildings, or other complex geometries)	3	3.85%
Preservation /Building Condition [pc]	Very good	67	85.90%
	Average	10	12.82%
	Very poor	1	1.28%

The surveyed buildings are predominantly single-storey structures (83.33%), encompassing residential houses (Figure 5a), lodging facilities (Figure 5b), and places of worship (mosques) (Figure 5c). In contrast, multi-storey buildings (two storeys or more) account for only 16.67% of the total building stock. This distribution indicates a built environment mainly characterized by low-rise structures across different functional categories, which has important implications for tsunami vulnerability and evacuation potential. This prevalence of low-rise buildings is associated with limited structural mass, reduced lateral resistance, and a lack of vertical evacuation options. Previous post-tsunami damage assessments consistently show that low-rise buildings sustain higher levels of damage compared to multi-storey structures, especially during near-field tsunami events (Dall'Osso et al., 2016; Fritis et al., 2018). Within the PTVA-4 framework, the number of storeys is a primary factor influencing *BV* variability. In tourism settings, this issue is worsened by the presence of non-local populations, particularly tourists who may not be familiar with tsunami hazards, warning systems, and evacuation routes, substantially increasing the risk of loss of life when vertical evacuation options are absent.



Figure 5. Representative single-storey building typologies in Watukarung Village, Pacitan, East Java, Indonesia: (a) residential house, (b) lodging facility, and (c) public facility (mosque) **(**Source: Taken by the authors during the field survey on 19 May 2023)

Regarding construction materials, masonry buildings dominate the study area, accounting for 80.76%of the building stock, whereas reinforced concrete or steel structures are rare, representing only 14.10%. Lightweight constructions account for the remaining 5.13%. This distribution of materials significantly impacts *Bv* outcomes, as masonry structures are known to be more susceptible to tsunami forces and debris impact than engineered reinforced concrete buildings (Fritis et al., 2018; Izquierdo et al., 2018). Residential buildings in the study area are predominantly of masonry construction without reinforced steel, particularly for long-established houses (Figure 6a).



Figure 6. Representative residential and lodging construction types in Watukarung Village, Pacitan, East Java, Indonesia: (a) unreinforced masonry house, (b) reinforced concrete residential building, (c) reinforced concrete tourist lodging, (d) lightweight wooden house. (Source: Taken by the authors during the field survey on 18 May 2023)

In contrast, newer residential buildings exhibit reinforced concrete structural elements, reflecting more recent construction practices (Figure 6b). For tourist lodging facilities, masonry construction remains common; however, a growing number of buildings are constructed using reinforced concrete frames, especially those developed within the last five years (Figure 6c). In addition, a small number of lightweight residential structures, primarily built from wood or similar materials, are still present in the area (Figure 6d) representing older or informal construction practices.

Unreinforced masonry buildings are common and pose a major risk because they have low ductility and do not resist hydrodynamic loads or debris impacts well (Zhang et al., 2024), which results in higher vulnerability scores in PTVA-based assessments. In comparison, reinforced concrete buildings are generally less vulnerable because they transfer loads more effectively and use stronger materials, though they are often not designed specifically for extreme tsunami forces. Having different types of buildings in the same coastal area creates a mixed environment, where vulnerability depends on factors like the age, function, and materials of each structure, as seen in other tsunami-prone areas like Santorini island, Greece (Batzakis et al., 2020), Pangandaran Indonesia (Nisaa & Nurmaya, 2022) and the cities of Coquimbo – La Serena, Chile (Fritis et al., 2018; Izquierdo et al., 2018). After tsunamis in Chile, damage reports show that tourism buildings such as small hotels, guesthouses, restaurants, and beachside businesses are often built with masonry and shallow foundations, focusing on function, looks, and cost rather than resistance to strong water forces (Izquierdo et al., 2018). These patterns align with the main building types identified in this study and highlight concerns about the strength of tourism infrastructure in Watukarung, Pacitan. Hydrodynamic forces at the ground-floor level make these buildings even more vulnerable. Most buildings have limited open space on the ground floor.

Enclosed or partly enclosed ground floors can increase drag and internal pressure during a tsunami, thereby accelerating structural failure. These problems have been seen in damage surveys after the 2015 Chile tsunamis (Fritis et al., 2018; Izquierdo et al., 2018). In tourism buildings, ground floors are often used for shops, dining, and social events, so many people are present at the most vulnerable level. This overlap of high occupancy and weak structure greatly raises the risk of casualties. Foundation characteristics significantly influence building vulnerability (*Bv*).

Based on rapid observations and interviews with building occupants (Figure 7a), the majority of buildings are supported by shallow non-engineered foundations (41.03%) (Figure 7b), or average-depth foundations (55.13%) (Figure 7c), while deep pile foundations are uncommon, representing only 3.85%. Shallow and moderately deep foundations are especially susceptible to scour and instability during tsunami events. According to the PTVA-4 framework, this foundation configuration results in higher *BV* values, particularly when combined with low-rise masonry construction. The geometry of building footprints exhibits limited variability, with 85.90% of surveyed buildings displaying rectangular shapes. Square and complex geometries are relatively rare. This homogeneity, combined with the lower relative influence of footprint shape in the PTVA-4 model, results in this attribute playing a minor role in differentiating *BV* across the study area. Nevertheless, building footprint geometry and orientation significantly affect tsunami-induced vulnerability. Rectangular buildings typically correspond to average vulnerability scores, while more compact footprints, such as square or near-circular shapes, tend to demonstrate lower vulnerability due to reduced exposure to hydrodynamic forces (Hou et al., 2025). Although these structural vulnerabilities are present, the majority of buildings are classified as being in very good preservation condition (85.90%).

Nevertheless, previous validations of the PTVA-4 model indicate that preservation condition exerts a relatively minor influence on overall vulnerability when unfavorable structural typologies are common (Izquierdo et al., 2018).



Figure 7. Foundation characteristics of surveyed buildings in Watukarung Village, Pacitan, East Java, Indonesia : (a) identification of foundation depth based on interviews with building occupants, (b) residentials buildings supported by shallow, non-engineered foundations, and (c) guest house with average-depth foundations. **(**Source: Taken by the authors during the field survey on 21 May 2023)

Building Surroundings Characteristics

Analysis of surveyed buildings demonstrates that these structures are located in a coastal environment with minimal natural and engineered protection, resulting in a high degree of exposure to tsunami impacts (Table 2). The spatial distribution reveals that a substantial proportion of buildings are positioned within the first six rows from the shoreline. The largest concentration is found in the 4th to 6th rows (35.90%), followed by the 2nd to 3rd rows (21.79%) and the 1st row (19.23%). Few buildings are situated beyond the 7th row. This configuration indicates that many buildings are subject to relatively direct tsunami flow, with limited attenuation from upstream structures. Previous post-tsunami assessments have shown that, in the absence of practical barriers, buildings in intermediate rows may experience damage levels comparable to those located closer to the shore (Fritis et al., 2018). The analysis identifies a complete absence of natural barriers and seawalls, with all surveyed buildings lacking both natural protection and seawall support. This

absence is significant because natural and engineered barriers are recognized as effective in reducing tsunami energy, limiting inundation depth, and minimizing structural damage (Oetjen et al., 2022).

Without these barriers, tsunami flow energy is maintained mainly as it moves inland, increasing the vulnerability of the built environment regardless of proximity to the coast. Regarding brick walls, most buildings (88.46%) are surrounded by walls that are only 0-20% of the expected water depth, while 11.54% have walls that reach 20-40% of that depth.

These low wall heights provide limited hydrodynamic shielding and are unlikely to reduce flow velocity or debris impact significantly. Empirical evidence from post-tsunami damage surveys indicates that low boundary walls frequently fail under tsunami loads and may even increase debris hazards rather than provide protection (Fritis et al., 2018). Assessment of large movable objects shows that most buildings face low debris risk (64.10%), but a notable proportion is exposed to average (28.21%) or very high (7.69%) debris risks. Although these debris sources are spatially localized, they are critical because debris impact is a significant contributor to tsunami-induced structural damage, particularly in areas without seawalls or natural buffers (Kaida et al., 2024). Even limited debris sources can significantly increase local vulnerability.

Table 2. Building surrounding characteristics (*Surr*)

Parameter Category	Attribute	Freq (n=78)	Percentage (%)
Building row [br]	>10th	3	3.85%
	7–8–9–10th	15	19.23%
	4–5–6th	28	35.90%
	2nd–3rd	17	21.79%
	1st	15	19.23%
Natural barriers [nb]	No Protection	78	100.00%
Seawall [s]	No Seawal	78	100.00%
Brick wall around building [w]	Height of the wall is from 20–40 % of the water depth	9	11.54%
	Height of the wall is from 0–20 % of the water depth	69	88.46%
Sources of large movable objects [mo]	Very low risk from movable objects	50	64.10%
	Average risk from movable objects	22	28.21%
	Very high risk from movable objects	6	7.69%

Structural Vulnerability (Sv)

The structural vulnerability analysis results show that 15 building categorized as minor vulnerability, 21 have moderate, 17 have average, 21 have high, and four have very high ratings. The high and very high vulnerability classes are predominantly located along the Watukarung Beach corridor and near the fish landing site. At the same time, the minor and moderate class are mainly distributed further inland (Figure 8). This spatial pattern indicates a vulnerability gradient influenced by building characteristics and proximity to the coastline, which is typical in index-based vulnerability mapping for coastal areas. The predominance of high and moderate vulnerability classes is largely due to the prevalence of low-rise buildings constructed with masonry or simple reinforced concrete, as well as limited ground-floor openness. These features significantly increase vulnerability scores within the PTVA-4 framework.

Similar spatial and typological patterns have been observed in coastal tourism regions of the Mediterranean (Batzakis et al., 2020) and South America (Vera San Martín et al., 2018), where rapid tourism development has outpaced the adoption of tsunami-resilient construction practices. Studies conducted post-event in Chile further confirm that buildings in the higher PTVA-4 classes generally experience severe structural damage (Izquierdo et al., 2018). Moreover, post-tsunami surveys following the 2006 Pangandaran tsunami in Indonesia consistently show that damage levels were largely controlled by building construction type (Reese et al., 2007). However, it is important to note that the model provides relative vulnerability assessments rather than absolute predictions of damage (Izquierdo et al., 2018). Therefore, the findings for Watukarung should inform the prioritization of structural risk management.

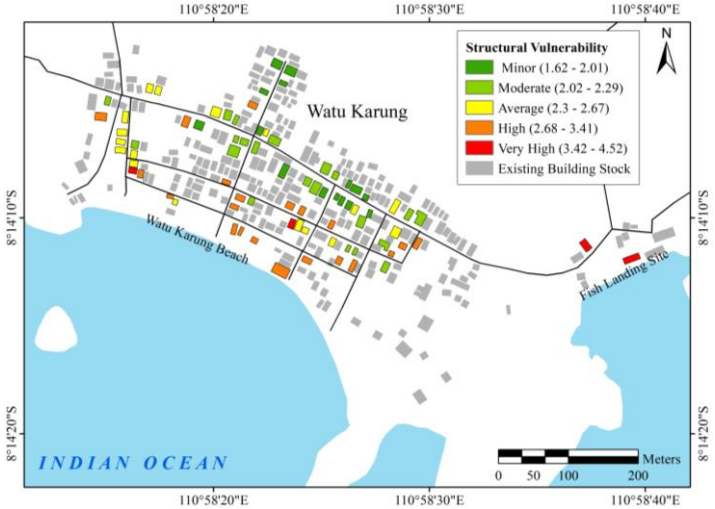


Figure 8. Spatial distribution of Building Structural Vulnerability (SV) (Source: The authors based on field survey and GIS analysis, 2025)

Vulnerability of Building to Water Inundation (WV)

The water vulnerability assessment indicates that 3 residential buildings fall into the minor water vulnerability class, 19 buildings into the average class, and 56 buildings into the high class. The spatial distribution reveals a pronounced dominance of high water vulnerability along the Watukarung Beach corridor and extending toward the fish landing site, whereas average and minor classes are sparsely distributed further inland (Figure 9).

This pattern reflects the strong control exerted by tsunami inundation depth and flow intensity on water-related vulnerability, particularly in low-lying coastal tourism areas. Most residential buildings fall into the high vulnerability category, meaning they are likely to face deep flooding and strong water forces during a tsunami. In the PTVA framework, water vulnerability is a key factor in predicting structural damage, making buildings more at risk no matter how well they are built. Similar patterns have been observed after tsunamis in Chile (Fritis et al., 2018) and Sicily (Lo Re et al., 2022), where buildings exposed to deeper water suffered greater damage and functional loss. The small number of buildings in the minor class shows there are few natural or artificial barriers in Watukarung to reduce tsunami energy, which is common for open, sandy beaches with gentle slopes (Batzakis et al., 2020; Izquierdo et al., 2018).

Having many residential buildings with high water vulnerability directly affects human safety, especially in tourist areas with many visitors. These buildings are unlikely to serve as temporary shelters during a tsunami, so it is important to plan for quick evacuation and to identify strong vertical evacuation options. Research shows that water depth is a main factor in both building failure and casualty rates, especially when there is little time to evacuate (Cels et al., 2023; Fritis et al., 2018). The pattern of water vulnerability in Watukarung underscores the importance of including building vulnerability mapping in evacuation plans and tsunami risk management for both residents and tourists.

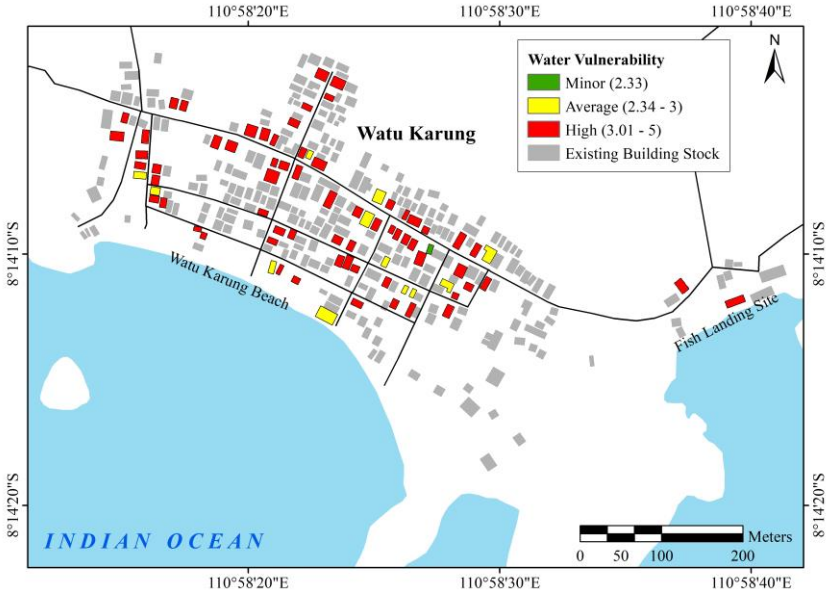


Figure 9. Spatial distribution of Building Vulnerability to Water Inundation (WV) (Source: The authors based on field survey and GIS analysis, 2025)

Building Relative Vulnerability Index [RVI]

The application of the full PTVA-4 model, integrating the 13 parameters and their respective weights, yielded a final Relative Vulnerability Index (RVI) for each of the 78 buildings. The classification results indicate that the building stock is predominantly characterized by moderate and high vulnerability levels, with 16 (20.51%) buildings are classified as minor vulnerability, 17 (21.79%) buildings as moderate, 19 (24.36%) buildings as average, 22 (28.21%) buildings as high, and 4 (5.13%) buildings as very high. This distribution, with one-third of all surveyed buildings falling into the high and very high vulnerability category and a clear majority being average vulnerable and above, underscores the systemic fragility of the built environment in Watukarung. The spatial distribution of RVI shows that buildings within the high and very high RVI classes (33.34% combined) are predominantly concentrated along the immediate coastal zone of Watukarung Beach and around the fish landing site, whereas buildings with minor and moderate RVI are more frequently located further inland along secondary road corridors (Figure 10). This pattern highlights the strong spatial control exerted by proximity to the coastline and surrounding environmental conditions on composite building vulnerability. The dominance of average to high RVI classes (52.57%) indicates that more than half of the building stock is affected by multiple interacting vulnerability drivers, including construction materials, building typology, foundation characteristics, surrounding conditions, and water-related exposure. Similar distributions have been reported in other coastal tourism destinations, where integrated vulnerability indices reveal higher relative risk in areas combining low-rise masonry buildings and high inundation potential (Batzakis et al., 2020). Post-tsunami validation studies further demonstrate that zones characterised by elevated composite vulnerability indices tend to experience disproportionate structural damage and functional disruption, even when individual vulnerability components appear moderate when considered separately (Fritis et al., 2018; Izquierdo et al., 2018). From a tourism safety perspective, the presence of 33.34% of buildings within the high and very high RVI classes represents a critical concern

for Watukarung as an active coastal tourism destination. Buildings in these classes are fail to function as safe temporary shelters during tsunami inundation and may exacerbate evacuation difficulties through structural failure or debris generation. In tourism areas with fluctuating visitor numbers and limited hazard awareness, such spatially concentrated vulnerability significantly increases potential casualty risk. Previous research emphasizes that incorporating relative vulnerability mapping into tourism planning and coastal risk management is essential for identifying safe zones, optimising evacuation routes, and supporting risk-informed tourism development (Cels et al., 2023; Re et al., 2022).

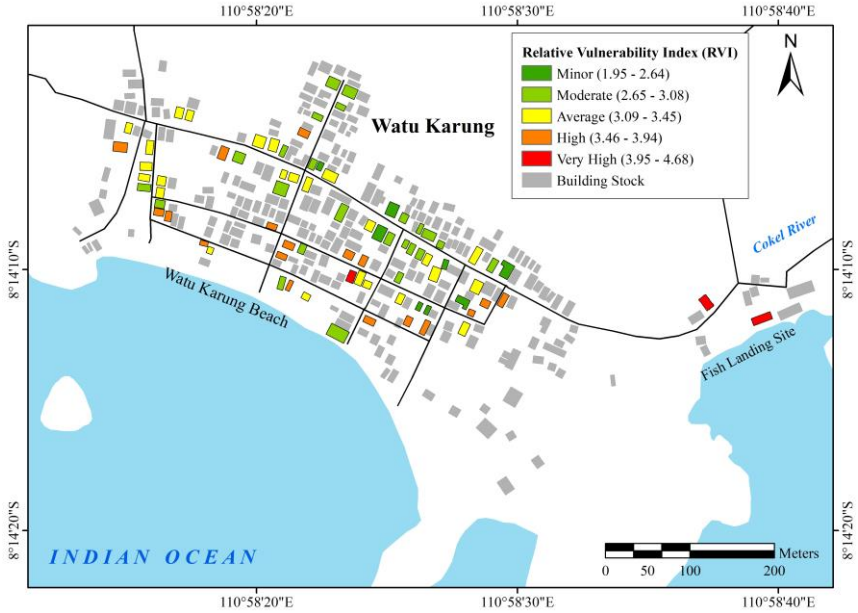


Figure 10. Spatial distribution and classification of Relative Building Vulnerability (RVI)
(Source: Prepared by the authors based on field survey and GIS analysis, 2025)

Dominance of Fragile Building Typologies: Implications for Human Safety

The elevated vulnerability scores in Watukarung are primarily attributable to the characteristics of the local building stock, as detailed in Table 1. The predominance of single-storey (83.33%) unreinforced masonry (80.76%) structures constructed on shallow foundations (41.03%) is the principal factor contributing to the area's intrinsic fragility. This observation is consistent with a substantial body of post-tsunami research conducted in Southeast Asia and other regions.

Extensive research demonstrates that unreinforced masonry buildings are among the most vulnerable to severe damage or collapse when subjected to the hydrodynamic and debris impact loads generated by tsunamis (Oddo & Cavaleri, 2025; Waenpracha et al., 2023). This vulnerability is well documented in the broader literature on masonry structures, which are particularly prone to collapse under the high hydrodynamic forces associated with deep, fast-moving water (Belliazzi et al., 2023; Oddo et al., 2025) . The structural systems prevalent in the study area lack the ductility and robustness of engineered reinforced concrete and the flexibility of well-anchored wood-frame structures, both of which have been shown to possess lower vulnerability indices (Chock et al., 2013; Suppasri et al., 2012). This contrasts sharply with reinforced concrete or well-anchored wood-frame structures, which generally exhibit lower vulnerability indices (Waenpracha et al., 2023; Zapata et al., 2023). The widespread presence of this fragile building typology is a principal factor contributing to the elevated Building Vulnerability *(BV)* scores observed in the area. The low vulnerability classification assigned to the limited number of multi-storey, reinforced concrete buildings in the surveyed building further substantiates this conclusion.

These structures benefit from superior material strength and the potential for vertical evacuation, which significantly reduces their vulnerability, as documented in studies examining the impact of building height (Oddo et al., 2025). The building stock in Watukarung exemplifies a concentration of high-risk typologies. Such patterns are not unique to this locality but are characteristic of many rural coastal communities in Indonesia, where traditional construction practices have not been widely adapted to address tsunami-specific hazards. This underscores a systemic issue that extends beyond Watukarung and highlights the regional necessity for enhanced construction guidance and the enforcement of appropriate building standards.

These structural deficiencies have significant implications that extend beyond material damage and directly impact life safety. The findings reveal a dual crisis: the immediate failure of safety mechanisms during a tsunami event and the subsequent, long-term erosion of community resilience. The predominance of single-storey, non-engineered masonry buildings, as quantified in Table 1, effectively eliminates vertical evacuation as a viable life-safety strategy for most residents. These structures are highly prone to immediate collapse and cannot serve as safe evacuation points, posing a direct threat to occupants (Amini et al., 2023). The absence of engineered resilience in over 80% of the building stock renders reliance on higher floors or rooftops infeasible. As a result, the community is critically dependent on rapid, unobstructed horizontal evacuation to reach designated safe areas (Mirzaei-Zohan et al., 2023; Sun et al., 2022). This dependency is exacerbated by the likelihood that collapsed masonry buildings will generate debris, obstructing escape routes and severely impeding the necessary horizontal evacuation (Amini et al., 2023; Xiao et al., 2023).

In a community such as Watukarung, which relies on tourism for its economy, these vulnerable buildings serve as both residences and sources of livelihood, including guesthouses, shops, and restaurants. Their destruction would result in the collapse of the local economy and a systemic loss of income for residents (Cocola-Gant, 2023). The resulting mass displacement and economic disruption lead to chronic shelter insecurity, perpetuating a cycle of vulnerability and social fragmentation that significantly hinders long-term recovery (Junias et al., 2025). Consequently, the findings of this study should be viewed not merely as an assessment of structural risk but as a clear indication of an impending crisis affecting both the immediate human safety and long-term economic security of the Watukarung community.

Implications for Tourism Planning and Local Disaster Management

The results of the PTVA-4 assessment in Watukarung have significant and actionable implications for disaster risk reduction and the future direction of tourism development in this rapidly emerging coastal destination. By mapping the spatial distribution of structural fragility, surrounding conditions, and inundation potential, PTVA-4 delivers evidence critical to both tourism planning and local disaster governance. The clustering of highly vulnerable tourism structures, including homestays, cafés, and rental accommodations along the shoreline, highlights the necessity for risk-sensitive development strategies that integrate land-use planning, building regulations, and evacuation planning.

First, high-hazard areas along the coastline and river mouth should be formally designated as no-build or restricted-development zones, in accordance with best practices that direct urban growth away from the most hazardous locations (Arifah et al., 2021; Marfai et al., 2021). For tourism planning, this requires limiting new beachfront accommodation development and prioritizing future investments in medium and low vulnerability zones. It is recommended that Watukarung actively plan and implement the relocation of essential public facilities and tourism-supporting infrastructure to lower-risk areas. This practical, long-term strategy can guide the destination toward a more sustainable, disaster-resilient tourism model. However, such risk management measures must be implemented and communicated carefully to avoid generating negative perceptions of tourism destinations. Large-scale relocation or restrictive interventions undertaken without effective communication and community engagement may adversely affect tourists' willingness to visit, as they can reinforce perceptions of the destination as unsafe. Perceived exposure to natural hazards often leads tourists to form negative evaluations of destinations, which can influence their travel decisions and risk avoidance behaviour (Praprom & Laipaporn, 2025). Second, the vulnerability analysis indicates an urgent need for strengthened building codes and retrofitting programs, especially in areas with a prevalence of unreinforced masonry and non-engineered structures. These structural weaknesses greatly increase the possibility of collapse during tsunami events. Regulatory frameworks requiring tsunami-resilient design, such as reinforced concrete frames, elevated floors, and deep foundations, should be enforced for all new developments within the inundation zone (Chock et al., 2013; Raby et al., 2024). For existing structures, the identification of 26 high-vulnerability buildings establishes a clear priority list for targeted retrofitting, a strategy shown to improve building resilience in tsunami-prone regions (Mostafizi et al., 2017). In the tourism sector, these measures directly enhance visitor safety and reduce the risk of mass casualty incidents during peak tourist seasons. Third, the study provides essential insights for evacuation planning and the safety management of both residents and tourists. The widespread presence of single-storey, structurally vulnerable buildings highlights the urgent need to enhance tsunami evacuation capacity in Watukarung. In the absence of dedicated vertical evacuation shelters, it is essential to prioritize clearly marked tsunami evacuation routes, signage directing residents and tourists to higher ground, and accessible evacuation information. Where horizontal evacuation is constrained by travel time or challenging topography, the construction of reinforced multi-storey buildings or dedicated evacuation towers should be considered, as many existing public buildings in coastal areas may lack the structural integrity required for safe vertical evacuation (Idris et al., 2021; Soviana et al., 2024).

PTVA-4 outputs can inform the optimal placement of these facilities to ensure accessibility for populations in high-risk clusters. Integrating these facilities with participatory mapping processes can enhance route design, community acceptance, and practical usability (Koswara et al., 2021). Furthermore, future coastal development should promote the construction of stronger and more resilient buildings. However, adopting concrete or multi-storey buildings should not be viewed as a standalone solution, as their effectiveness depends on proper structural design, adherence to hazard-resistant standards, and integration with comprehensive tsunami evacuation planning. Advanced tsunami simulations can further improve evacuation timing and support the development of targeted preparedness training for both residents and tourists (Choi et al., 2024). These findings demonstrate that PTVA-4 provides a robust evidence base for aligning tourism development with disaster resilience, supporting Watukarung's transition toward a safer, more sustainable coastal tourism future.

CONCLUSION

This study presents a spatial assessment of tsunami-related building vulnerability in the coastal tourism area of Watukarung, Indonesia, by integrating structural characteristics, water-related exposure, surrounding environmental conditions, and a composite Relative Vulnerability Index (RVI). Under the official deterministic worst-case scenario of an 11-meter tsunami wave height, the greatest simulated inundation depths are concentrated along the immediate coastal strip and near the eastern river mouth, coinciding with densely populated and tourism-intensive zones. The Papathoma Tsunami Vulnerability Assessment (PTVA-4) framework was applied to 78 buildings within the inundation zone. The survey found a predominantly uniform building stock characterized by low-rise, non-engineered construction. These structures are situated in a coastal environment with minimal natural or engineered protection, resulting in elevated exposure to tsunami impacts. Most buildings are located within the first six rows from the shoreline, with the highest concentration in the 4th to 6th rows (35.90%), followed by the 2nd to 3rd rows (21.79%) and the 1st row (19.23%). This spatial arrangement indicates that many

buildings are directly exposed to tsunami flow, with limited mitigation from seaward structures. Structural vulnerability was categorized as minor (15 buildings), moderate (21), average (17), high (21), and very high (4), with the high and very high categories concentrated along the Watukarung Beach corridor and near the fish landing site. The water inundation vulnerability (WV) assessment indicated that most buildings were classified as high (56), followed by average (19) and minor (3) categories. The RVI results indicate that 33.34% of buildings are classified as having high or very high vulnerability, while 24.36% are classified as average. These higher-vulnerability classes are primarily located along the coast and in tourism zones and are dominated by single-storey masonry buildings with shallow or non-engineered foundations. The findings reveal that tsunami risk in Watukarung arises from the spatial convergence of severe inundation potential, vulnerable building stock, and intensive tourism land use. The PTVA-4 approach is an effective tool for identifying vulnerability hotspots and informing risk-based coastal zoning, evacuation planning, and tourism management strategies in tsunami-prone coastal destinations.

Limitations and Avenues for Future Research

While this study offers a geographically grounded assessment of tsunami-related building vulnerability in a coastal tourism destination, several limitations highlight important directions for future, policy-relevant research. The analysis is based on a deterministic, single-scenario hazard assumption and a PTVA-based Relative Vulnerability Index (RVI), which provides relative rather than absolute estimates of risk. Consequently, the results should not be interpreted as direct predictions of damage or casualties, but rather as an evidence base to support spatial prioritisation in tourism and coastal management policies. Another limitation concerns data availability for certain building attributes, particularly foundation characteristics, which were inferred from occupant interviews rather than direct geotechnical investigations. Although appropriate for rapid assessments, this approach introduces uncertainty that may affect policy decisions if not transparently acknowledged. Future research should therefore aim to strengthen the policy relevance of vulnerability assessments by integrating probabilistic tsunami hazard analysis (PTHA) with building vulnerability mapping to support risk-informed zoning, development control, and investment prioritisation in coastal tourism destinations. The incorporation of tourism-specific exposure indicators such as seasonal visitor density, evacuation capacity, and accessibility of safe areas would further enhance decision-making for destination managers and local authorities. Such advances would enable vulnerability assessments to move beyond diagnosis toward actionable guidance for safer and more resilient tourism development in tsunami-prone coastal regions.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Use of Generative AI: During the preparation of this manuscript, the authors used ChatGPT® and Grammarly® for language editing and improvement of readability, grammar, spelling, and sentence structure. These tools were used only to improve the presentation of the manuscript and were not used for generation images and graphics, data analysis, interpretation, or the development of scientific conclusions. All outputs were critically reviewed and edited by the authors, who take full responsibility for the final content of the manuscript.

List of abbreviations: BNPB: Indonesian National Disaster Management Agency; BPS: Indonesian Statistical Agency; BV: Building Vulnerability; DEM: Digital Elevation Model (DEM); DRR: Disaster Risk Reduction; LULC: Land-Use and Land-Cover; PTHA: Probabilistic Tsunami Hazard Analysis; PTVA-4: Papathoma Tsunami Vulnerability Assessment framework; RVS: Rapid Visual Survey; RVI: Relative Vulnerability Index; SV: Structural Vulnerability; WV: Water Vulnerability.

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