JURNAL geografi

https://jurnal.unimed.ac.id/2012/index.php/geo/article/view/41767
https://doi.org/10.24114/jg.v15i2.41767 - (Vol 15, No 2 - 2023)
available at http://jurnal.unimed.ac.id/2012/index.php/geo
e-issn (2549-7057) & p-issn (2085-8167)

Tsunami Susceptibility Assessment Using Spatial Multi-Criteria Evaluation in Watukarung, Pacitan

Ikhwan Amri[1]*, Bella Sinta Hikmasari[1], Cornelius Antoni Nababan[1], Dessy Ayu Wijayanti[1], Dina Ruslanjari[1], Sri Rum Giyarsih[1,2]
[1]Masters Program in Disaster Management, Graduate School, Universitas Gadjah Mada, Yogyakarta, Indonesia
[2]Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia

ARTICLE INFO
Article History:
Received: December 28, 2022
Revision: August 13, 2023
Accepted: August 17, 2023

Keywords:
Tsunami
Susceptibility
Spatial Multi-Criteria Evaluation
Watukarung
Pacitan

Corresponding Author
E-mail:
ikhwan.amri@mail.ugm.ac.id

ABSTRACT

Tsunamis are natural hazards that have the potential to cause significant damage and losses to the South Coast of Java. As the initial foundation for local spatial planning and risk reduction, preparing a tsunami susceptibility mapping is imperative to minimize the disaster's impact. This study aims to identify the spatial distribution of tsunami susceptibility in Watukarung Village, Pacitan Regency, using the Spatial Multi-Criteria Evaluation (SMCE) method. The variables involved in the modeling include landform, elevation, slope, distance from the shoreline, and distance from the river. The value and weight of each factor were determined using the pairwise technique in the SMCE framework. The research results indicated that the tsunami susceptibility in Watukarung comprises four classes: safe (598.40 ha), low (9.68 ha), moderate (23.92 ha), and high (25.13 ha). The areas most prone to tsunamis are generally identified in the southern part of Watukarung, which is generally associated with beach or alluvial plain landforms, very close to shore, and low land elevation. Ironically, human settlements and coastal tourism are overgrowing in the tsunami-prone zone, highlighting that risk reduction measures must be implemented optimally to anticipate tsunami hazards. As a recommendation, further research must be carried out to comprehensively represent the tsunami risk in the Watukarung coastal region.

INTRODUCTION

Coastal tourism in Indonesia has become a development catalyst that affects various aspects of life with multi-dimensional characteristics. Coastal tourism development is often supported by optimizing planning, management directions, and resource utilization to improve people's welfare development. However, apart from presenting its natural beauty, the oceans hold hazards that could become catastrophic in an area at any time. Geologically, Indonesia is located between three major tectonic plates, namely the Pacific Plate, the Indo-Australian Plate, and the Eurasian Plate, which constantly move, creating subduction zones and active faults. Widiyantoro et al. (2020) recently found that the seismic gaps off Java's southern coast can generate large tectonic earthquakes on the seabed. These several things indicate the potential for a tsunami to endanger residents and tourists in coastal areas. Besides causing casualties, tsunami disasters often damage buildings and cause economic losses.

Tsunamis are sea waves with long periods caused by impulsive disturbances in the ocean (Nur, 2010). Tectonic earthquakes, underwater volcanic eruptions, and landslides in waters are the most common triggering factors for tsunamis. The characteristics of the tsunami in Indonesia are caused mainly by tectonic earthquakes originating in the sea with shallow depths and a magnitude of more than 6 Mw. The travel time from the tsunami source to the mainland is relatively short, less than one hour after the earthquake. Two major tsunamis off the south coast of Java have been recorded in the last three decades. A tectonic earthquake measuring 7.8 Mw caused a tsunami with a height of 6-9 meters in Banyuwangi, East Java (Harahap et al., 2019). Another tsunami with a maximum height of 20.9 meters devastated Pangandaran, West Java, in 2006, initiated by a tectonic earthquake of magnitude 7.7 Mw (Mutaqin et al., 2020).

Pacitan Regency is considered one of the tsunami-prone areas on the south coast of Java (Jamilah et al., 2021). Latifah (2022) simulated the height and arrival time of a tsunami due to an 8.7 Mw megathrust earthquake on the south coast of Java using ETOPO1 1 arc-minutes bathymetry data and a 90-meter resolution SRTM digital elevation model in the Community Model Interface for Tsunami (ComMIT) software. The results confirmed that Pacitan has a high level of tsunami hazard. Regional modeling scenarios, however, do not provide sufficient information for local planning purposes. More detailed studies must be carried out at the village level to understand the natural hazards better. In addition, research associated with the tsunami hazard has focused more on Pacitan Bay (Pratiwi, 2016; Hidayah et al., 2022). The study must also be carried out in areas with high population concentrations in other parts of the Pacitan Regency, which are neglected from scientific research. Watukarung, one of the villages in Pacitan Regency, should be prioritized for this purpose; this area also has popular coastal tourism attractions. Currently, Watukarung has been promoted as a surfing destination for foreign tourists, and there are many lodging places and food stalls around the beach.

Tsunami susceptibility mapping is crucial for supporting disaster risk reduction planning. Susceptibility is related to the spatial aspect of hazards without considering the timing or potential victims and economic losses (Domínguez-Cuesta, 2013). It is worth noting that susceptibility assessment differs from hazard assessment, where the latter addresses not only spatial aspects but also magnitude, frequency, and other characteristics (Nadim, 2013). Susceptibility assessment also differs from vulnerability assessment as vulnerability examines the potential for harm at the place as a function of the intersection between the built environment and infrastructure, social and economic systems, and physical systems (Cutter, 2013).

The National Disaster Management Agency (BNPB) has established particular standards for creating tsunami hazard maps in Indonesia. The distribution of the impacted area due to tsunami inundation is estimated through mathematical calculations formulated by (Berryman, 2006). These calculations consider the reduction in tsunami height for every 1-meter increase in inundation distance (water level), considering the distance values about slope and surface roughness (BNPB, 2018). However, the spatial information generated by the disaster management authority is typically designed for a regional scale. Meanwhile, if applied to smaller planning units, the results may be insufficient for further utilization in creating local plans. Thus, adjustments and alternative approaches are necessary to ensure planning effectiveness.

This research aims to estimate the tsunami susceptibility level in the Watukarung region using the Spatial Multi-Criteria Evaluation (SMCE) module. This method can produce a reliable tsunami susceptibility map at the village level (Waskita et al., 2020; Alwi & Mutaqin, 2022). The main advantage of SMCE is that qualitative data can be involved in the modeling in addition to quantitative data. Compared with the traditional overlay method, the subjectivity of experts in the weighting process can be controlled to reduce bias. The development of this research has the benefit of providing information about the hazard and increasing the preparedness of local communities regarding the tsunami disaster in Watukarung.

RESEARCH METHODS

Study Area

Watukarung is a village in Pringkuku Sub-district, Pacitan Regency, East Java Province (Figure 1). Dersono Village borders this area to the north and west, Jlubang Village to the east, the Indian Ocean to the south, and Sendang Village borders a small part of its territory to the west. The position of Watukarung Village is about 22 km from the capital of Pacitan Regency. The area of Watukarung is about 7.4 km^{2}, with a population of around 1,569 in 2021 (BPS Kabupaten Pacitan, 2022).

Watukarung region has a relatively heterogeneous topography because it is part of the Southern Mountains Zone, mainly composed of carbonate rocks (van Bemmelen, 1949). Karst hills are the most dominant landform found in the area. The maximum elevation in this village is about 164 meters above sea level. Meanwhile, the plains in this village are relatively narrow and are most dominantly found in coastal areas. Due to these terrain conditions, settlement areas are clustered in several locations, especially in the coastal areas (which are the most densely populated) and in the valleys between hills.

Watukarung coastal area offers an exotic view with its uniqueness in the presence of coastal cliffs, white sand beaches, and waves suitable for surfing activities (Figure 2). Not surprisingly, this area has become one of the leading tourism destinations in the Pacitan Regency. Many homestays and inns have been established to accommodate visitors who want to stay overnight. Nonetheless, coastal hazards must be considered and studied further to achieve sustainable tourism development.

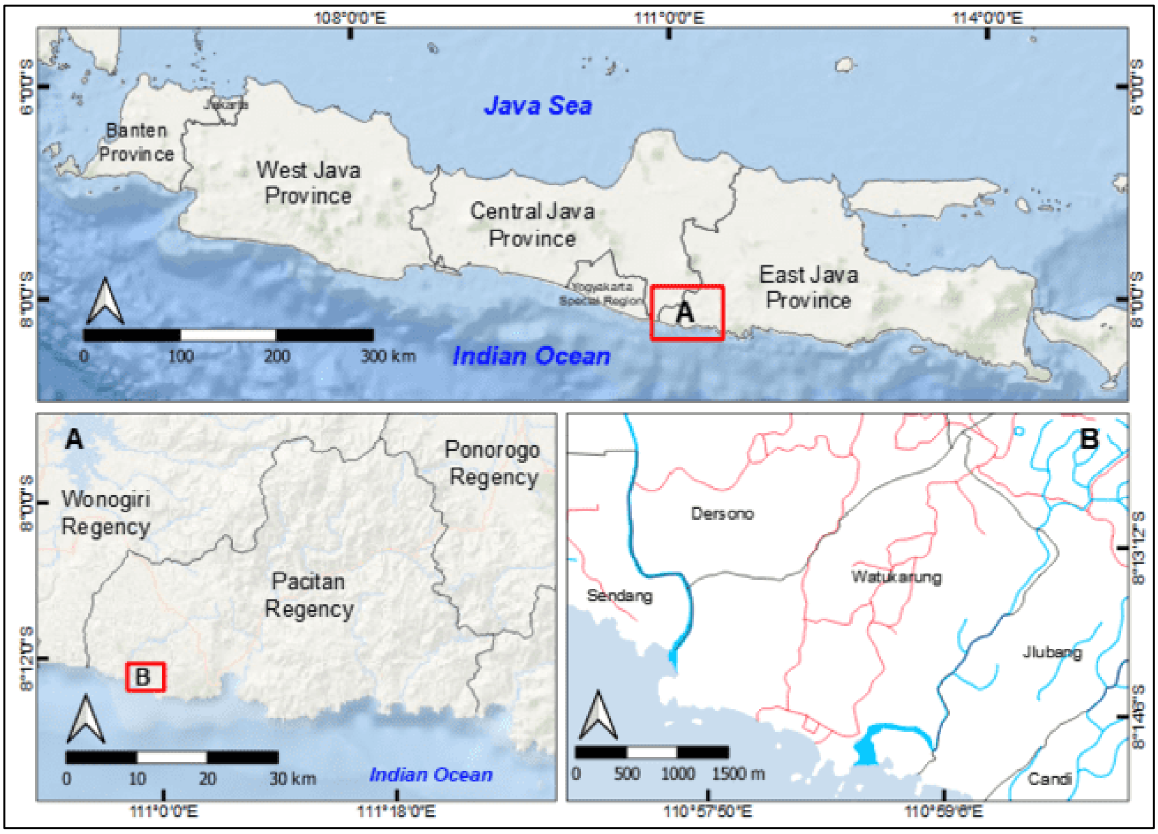

Figure 1. Study Area Map (Source: Data Analysis, 2023)

Figure 2. Coastal Landscapes in Watukarung (Source: Field Documentation, 2022)

Data Collection Technique

This study used five variables for the tsunami susceptibility analysis: landform, elevation, slope, distance from the shoreline, and river. These five variables were selected based on recent literature reviews (Oktaviana et al., 2020; Waskita et al., 2020; Alwi & Mutaqin, 2022). The spatial data used in this study were collected from various sources (Table 1). Field observations were carried out in October 2022 to collect the additional required data for validation.

Table 1. Variables and Data Sources

No	Variables	Data Sources
1.	Landform	DEMNAS and geological map
2.	Elevation	DEMNAS
3.	Slope	DEMNAS
4.	Distance from shoreline	Peta Rupa Bumi Indonesia (Scale 1:25.000)
5.	Distance from river	Peta Rupa Bumi Indonesia (Scale 1:25.000)

(Source: Data Analysis, 2023)

DEM Nasional (DEMNAS) is the finest free digital elevation model (DEM) in Indonesia provided by the Geospatial Information Agency (https://tanahair.indonesia.go.id/demnas). The spatial resolution of this DEM is 0.27-arcsecond. Aside from being a source of elevation data, DEMNAS acted as critical spatial data in delineating landforms and deriving slope information. For landform variables, the delineation process was assisted by the Topographic Position Index (TPI) Based Landform Classification, which was automated in SAGA GIS software. TPI is very suitable for delineating landforms in areas with heterogeneous topographical conditions, where it is based on the difference between the area's height at a certain point and the average height at a specific radius (De Reu et al., 2013). The classification results subsequently were reclassified in the QGIS software based on physiographic information and lithological characteristics of the constituents with the primary reference from geological maps (Surono et al., 1992). Meanwhile, the degree of slope was calculated directly in the ILWIS software with a specific formula.

The shoreline and river shapefiles were obtained from a topographic map (Peta Rupa Bumi Indonesia) digitized at a scale of 1:25,000. The vector data has been made available free of charge by the Geospatial Information Agency (https://tanahair.indonesia.go.id/portal-web/download/perregion). Proximity analysis for the two variables was done using the calculate distance tool in the ILWIS environment.

The five variables were grouped into several classes (Figure 3). Five landform types have been identified in Watukarung, namely karst hill, karst depression, alluvial plain, beach, and river. Landform types can be categorized as nominal data, where any quantitative value does not represent them. When dealing with continuous quantitative data (other than landforms), the categorization process employed the slicing technique within the ILWIS environment. The class domains were modified or referred directly to several references (Oktaviana et al., 2020; Waskita et al., 2020; Alwi & Mutaqin, 2022). Elevation (in meters above sea level/masl) consisted of five classes: ≤5.0 masl, 5.1-10.0 masl, 10.1-15.0 masl, 15.1-20.0 masl, and >20.0 masl. Slope consisted of six classes: flat (≤2.0°), gentle (2.1°-4.0°), more gentle (4.1°-8.0°), slightly steep (8.1°-16,0°), steep (16.1°-35.0°), and very steep (>35.0°). Distance from the shoreline was ≤300.0 meters, 300.1-700.0 meters, 700.1-1200.0 meters, and >1200.0 meters. Lastly, the distance from the river was divided into five classes: ≤100.0 meters, 100.1-200.0 meters, 200.1-300.0 meters, 300.1-500.0 meters, and >500.0 meters.

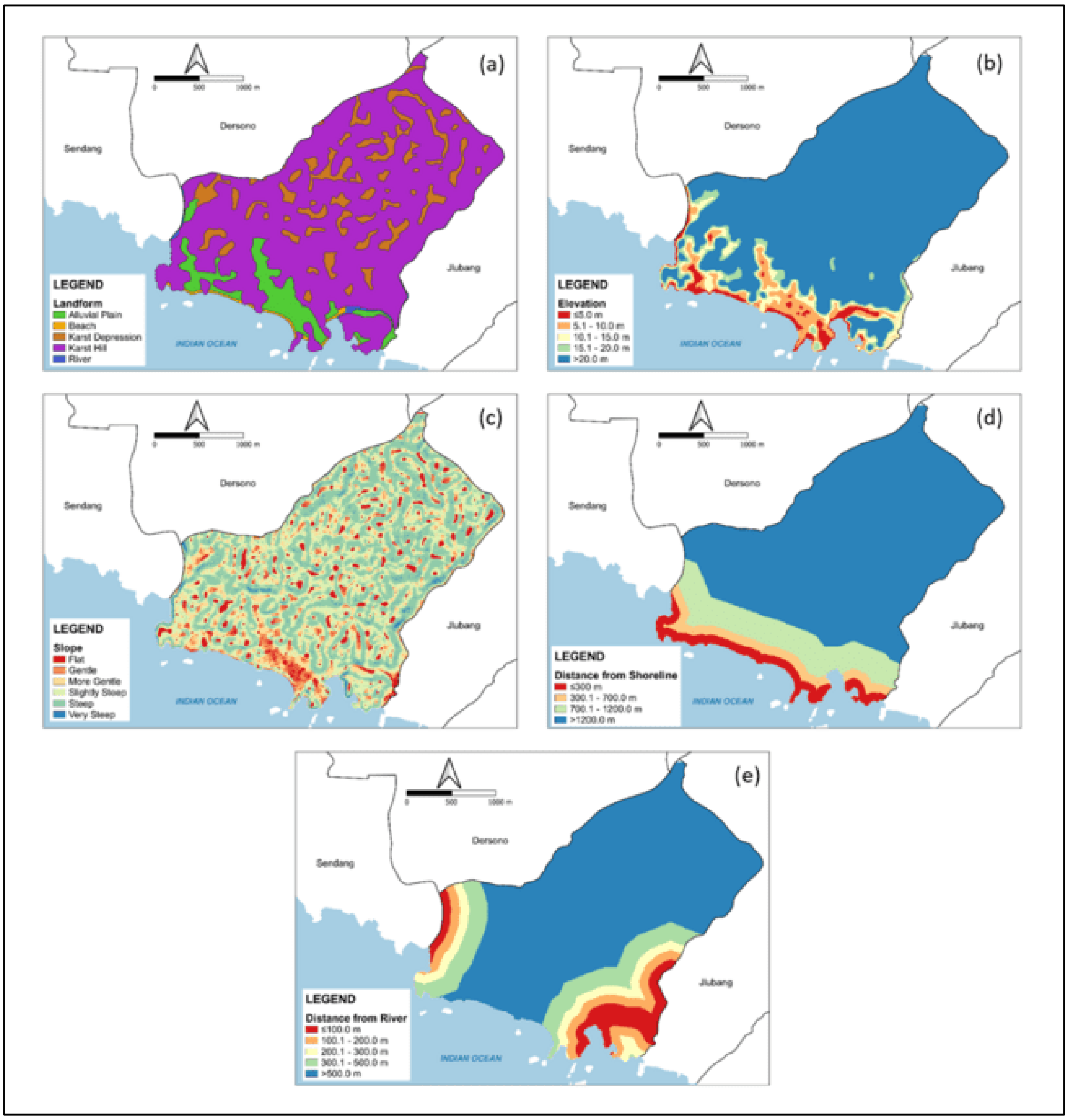

Figure 3. Tsunami Susceptibility Variable Maps: (a) Landform, (b) Elevation, (c) Slope, (d) Distance from the Shoreline, and (e) Distance from the River (Source: Data Analysis, 2023)

Spatial Multi-Criteria Evaluation Model

SMCE is a semi-quantitative approach used in the decision-making process where the analysis considers several criteria in spatial data. A set of variable maps is grouped, standardized, and weighted in a criteria tree (Biswas & Sil, 2023). This model was evaluated using ILWIS software. The variables and each of their classes used in this study were given a rating based on their relative contribution to tsunami susceptibility. The pairwise technique has been implemented in rating determination. For each variable, the higher a class's normalized priorities values (NPV), the higher the influence on tsunami susceptibility is assumed. The weights for the five variables were also determined based on the pairwise comparison. Inconsistency ratio tests accompanied all these rating procedures to reduce subjectivity. Pairwise results were considered feasible if the inconsistency ratio was less than 0.1. Finally, a tsunami susceptibility map was generated and classified into four classes: safe, low, moderate, and high.

RESULTS AND DISCUSSION

NPV and Weight of Physical Factors

Table 2 shows the scoring results for each class of physical factor of tsunami susceptibility in Watukarung. The score has a range of 0 to 1. The higher the NPV, the higher the assumed level of susceptibility. The inconsistency ratio of the pairwise technique on all variables is less than 0.1, proving that the degree of (in)consistency is acceptable and feasible to generate the expected output.

Three landforms are considered the most susceptible to tsunamis: rivers, beaches, and alluvial plains. As a type of water body, the river often acts as a free passage for tsunami waves to reach inland farther. This situation is strongly supported by the relatively small level of surface roughness (BNPB, 2018). As it is directly adjacent to the shoreline, the beach is one of the landforms most likely to be exposed to tsunami waves for the first time, especially those with low-lying flat areas (Waskita et al., 2020). The alluvial plain on the backshore also has a relatively high NPV due to morphological conditions that increase tsunami susceptibility. The dominating geomorphological process in this plain is sedimentation from solutional and marine activities. Scores on karst hills and depressions are the lowest compared to other landforms. Due to the terrain conditions, it is estimated that the tsunami did not significantly impact the karst hill, even though the location is directly adjacent to the sea (e.g., coastal cliff). The same applies to the karst depression because the surrounding hills protect the area.

Elevation is an attribute related to the difference in the vertical distance of a point to sea level. Tsunami easily inundates low-elevation areas. This study shows that the NPV for elevation ≤5.0 m is the highest compared to other elevation classes. At higher elevation classes, the NPV tends to decrease exponentially.

As one of the morphometric features, slope angle also has a crucial role in assessing tsunami susceptibility. According to (Safira et al., 2022), tsunami waves can hit land farther up to thousands of meters in areas with a low slope level. Meanwhile, the steep coast resists and reflects the waves from the sea. This scenario is applied to the acquisition of NPV slope, where the flat area is associated with the highest susceptibility. The score for each class decreases as the slope level increases.

Distance from the shoreline is a variable that is often considered in tsunami susceptibility modeling. In general, tsunami intensity is determined by the wave height scenario. However, it has been agreed by consensus that the closer an area is to the shoreline, the higher the level of tsunami susceptibility. Based on pairwise results, the highest NPV is found at a distance of ≤300.0 m from the shoreline. NPV tends to decrease with increasing distance to the shoreline.

Table 2. NPV Resulted from Pairwise Comparison

Variable	Class	NPV	Inconsistency Ratio
Landform	1. Karst Hill	0.111	0.001
	2. Alluvial Plain	0.953	
	3. Karst Depression	0.117	
	4. Beach	1.000	
	5. River	1.000	
Elevation	1. ≤5.0 m	1.000	0.060
	2. 5.1 – 10.0 m	0.538	
	3. 10.1 – 15.0 m	0.273	
	4. 15.1 – 20.0 m	0.090	
	5. >20 m	0.074	
Slope	1. Flat	1.000	0.043
	2. Gentle	0.562	
	3. More Gentle	0.304	
	4. Slightly Steep	0.097	
	5. Steep	0.080	
	6. Very Steep	0.075	
Distance from shoreline	1. ≤300.0 m	1.000	0.052
	2. 300.1 – 700.0 m	0.721	
	3. 700.1 – 1200.0 m	0.232	
	4. >1200.0 m	0.116	
Distance from river	1. ≤100.0 m	1.000	0.081
	2. 100.1 – 200.0 m	0.529	
	3. 200.1 – 300.0 m	0.267	
	4. 300.1 – 500.0 m	0.139	
	5. >500 m	0.054	

(Source: Data Analysis, 2023)

The last variable considered in this study is the distance from the river. Two rivers are identified in Watukarung: Kali Maron on the west side and Kali Cokel on the east side. Tsunami flows can easily infiltrate river bodies. When the river's capacity cannot accommodate the volume of water, the area around the river is estimated to be inundated with water overflow (Laksono et al., 2022). Therefore, the farther the distance from the river, the smaller the possibility of an area being affected by river overflow. Based on pairwise results, the highest NPV was found at a distance of ≤100.0 m from the river, while the lowest NPV was found at a distance of >500.0 m.

This study assumed that the importance of each tsunami susceptibility variable is not equal (Table 3). Of the five variables, landform has the highest weight (0.51), followed by distance from shoreline (0.23) and elevation (0.13). These results are consistent with the method design developed by (Hoppe and Spahn, 2008), where these three variables are critical parameters in village-level tsunami hazard zoning.

Table 3. Tsunami Susceptibility Variables Weights

Variable	Weight	Inconsistency Ratio
Landform	0.51	0.044
Elevation	0.13	
Slope	0.07	
Distance from shoreline	0.23	
Distance from river	0.06	

(Source: Data Analysis, 2023)

Landforms have been referred to as the most critical indicators in ecoregion-based tsunami susceptibility assessments because they can provide susceptibility information based on morphological aspects and the formation process (Husein et al., 2017). Distance from the shoreline plays a significant role in constructing the spatial distribution of coastal inundation since the tsunami waves first reached the area closest to the sea. Land elevation also directly influences the estimation of the impact of the tsunami hazard at a particular location (Lessy and Sabar, 2021).

Spatial Distribution of Tsunami-Prone Areas

Based on the results of the tsunami susceptibility assessment using SMCE, it can be seen that around 25.13 ha (3.83% of the total area of Watukarung mainland) is classified as high susceptibility, 23.92 ha (3.64% of the total area of Watukarung mainland) is classified as moderate susceptibility, 9.68 ha (1.47% of the total area of Watukarung mainland) is classified as low susceptibility and 598.40 ha (91.06% of the total area of Watukarung mainland) is included in the safe zone. The tsunami susceptibility map is illustrated in Figure 4. That is close to rivers with low elevations and gentle slopes also have a high potential for tsunami hazards. The high susceptibility zone is identified in the southern part of Watukarung. This area is dominated by alluvial plains landforms with low elevation and close to the shoreline. In addition, areas.

Areas with moderate and low susceptibility levels are dominated by land characteristics in the form of alluvial plains with elevations between 5-10 meters above sea level and within 300-700 meters of the shoreline. This area is located on the north side of the high susceptibility zone. The safe zone generally includes hills with steeper slopes and areas over 20 meters above sea level. Apart from inland, these hills can be found on the east, central, and west sides of the Watukarung coast so that they can act as natural tsunami barriers. On the one hand, the condition of the Watukarung area, which is dominated by karst hills, provides a distinct advantage because areas with the potential for a tsunami hazard only represent <10% of the total village area. On the other hand, the zone with higher susceptibility is an area that functions as a settlement center in Watukarung. In addition, this area also functions as a tourist spot, both beach and river tourism (in Kali Maron and Kali Cokel).

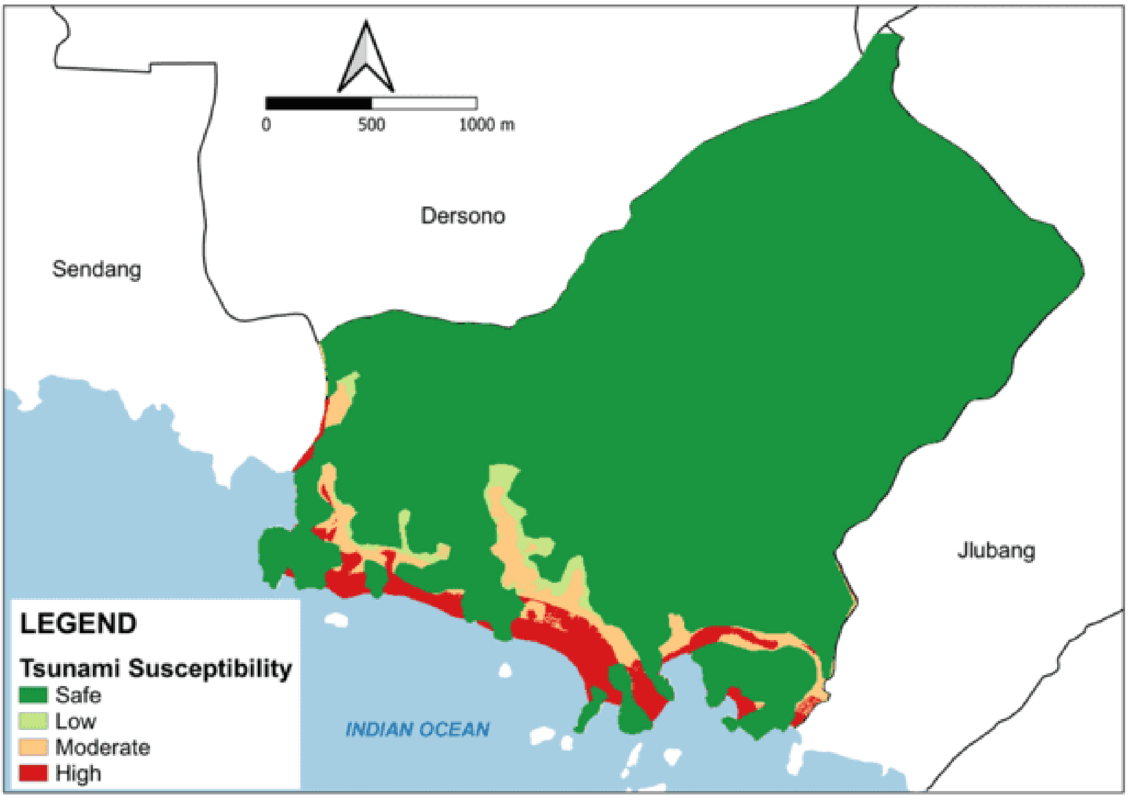

Figure 4. Tsunami Susceptibility Map (Source: Data Analysis, 2023)

Using the SMCE module for disaster susceptibility mapping has several advantages and disadvantages. According to (Waskita et al., 2020), the SMCE model can be used if there is limited data related to disaster history. SMCE is made based on experts' involvement to assess the study area's susceptibility. Although expert opinion is often subjective, inconsistency ratio measurements are believed to mitigate this issue. The results built using SMCE cannot produce a model based on variations in tsunami run-up, so this study recommends the need for comparison with other approaches.

Another issue relates to the inputs used in the susceptibility assessment, particularly the digital elevation model. The quality of geospatial data will influence the outcomes of the modeling process. DEMNAS is formed from several data: IFSAR, TerraSAR-X, ALOS-PALSAR, and mass point. One might argue that DEMNAS does not fully represent the actual terrain height in an area, thus, confident handling is needed to improve the accuracy of the model built (Julzarika & Harintaka, 2019). The use of a digital elevation model based on Light Detection and Ranging (LiDAR) or Unmanned Aerial Vehicle (UAV) is expected to provide better mapping results (Alwi & Mutaqin, 2022). Despite these limitations, higher-resolution data is much better for generating village-scale susceptibility maps than global elevation datasets. In addition, these results are similar to the regional tsunami hazard maps visualized in the disaster mapping portal developed by BNPB (i.e., InaRISK). Still, the spatial resolution is more adequate for local planning objectives.

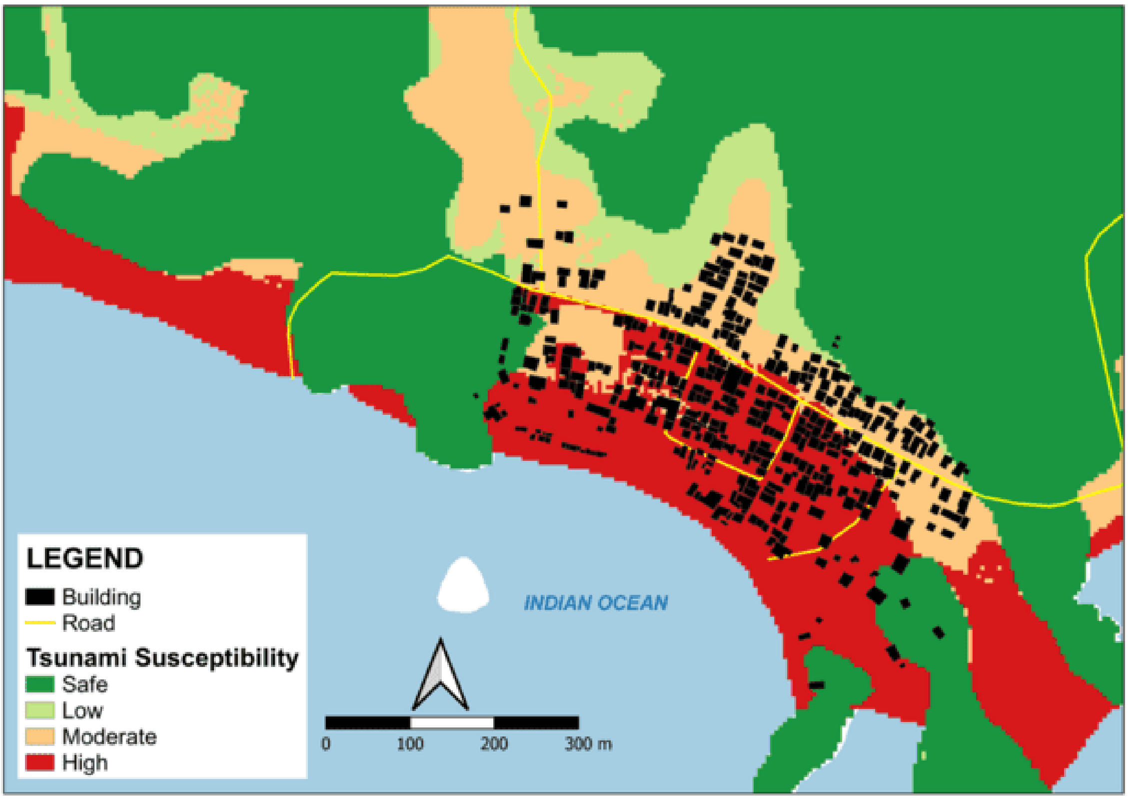

Figure 5. Major Element At-Risk in Tsunami-Prone Areas of Watukarung
(Source: Data Analysis, 2023)

Exposures of Built-up Land

For further discussion, this study simulated a simple tsunami exposure analysis in a part of the Watukarung coastal area through an overlay between the built-up land and the tsunami-prone zone layer. The building site vector data were digitized on-screen from the high-resolution imagery base map available in the QGIS software. Administratively, two hamlets (Dusun) are directly adjacent to the shoreline and have a relatively high population density in Watukarung, namely Ketro and Gumulharjo. Both areas are mainly positioned in a flat and low-elevation alluvial plain environment.

This study successfully identified at least 381 buildings in the coastal areas of Ketro and Gumulharjo (Figure 5). Based on field observations, land use, according to its function, is a mixture of housing, tourist accommodations, small shops, restaurants, and public facilities. The results of the overlay analysis revealed that most of the built-up land is situated in a high susceptibility zone for tsunamis, indicated by 216 structures or approximately 68% of the total buildings. There are 141 structures located in a moderately susceptible zone, while only three structures are found in a zone with low susceptibility. The quantity of buildings unexposed to tsunami hazards is comparatively limited (21 structures), predominantly situated at elevated locations. This situation calls for promoting serious mitigation initiatives to prevent future catastrophes.

Apart from Watukarung, the exposure of buildings to tsunamis in other parts of Indonesia has also been studied in several latest studies. Mardiatno et al. (2020) investigated the number of buildings in areas that could be inundated by a tsunami in Pangandaran (West Java), which experienced a significant increase over ten years after the 2006 large-scale tsunami. On the coast of Bengkulu City and Central Bengkulu Regency, (Akbar et al., 2020) also found that many settlements are in the high tsunami hazard zone, especially in the western part. Amri and Giyarsih (2022) evaluated the existing urban physical growth in areas affected by the 2004 tsunami of Banda Aceh, which occurred again at a high rate and intensity.

Mitigation strategies are essential steps to support tsunami risk reduction efforts. This study has provided essential information to achieve this goal. Subsequent studies are needed to investigate the element at risk in detail regarding its vulnerability and capacity (Amri et al., 2023). On the governance side, several aspects of tsunami risk reduction should be reviewed, such as regional planning, regulations, institutions, and preparedness schemes.

CONCLUSION

Geographical information systems have been widely utilized for disaster risk management purposes. This study applied the SMCE framework to assess tsunami susceptibility patterns in Watukarung Village, Pacitan Regency. A multi-criteria evaluation approach was chosen because of its benefits in integrating qualitative and quantitative data. Several physical factors that contribute to identifying tsunami-prone areas have been included in the modeling, such as landform, elevation, slope, distance from the shoreline, and distance from the river. This article presented geomorphological features (i.e., landform) as the most influential aspects of tsunami susceptibility, followed by distance from shoreline and elevation.

The results indicated that the areas with high, moderate, and low levels of tsunami susceptibility were 25.13 ha, 23.92 ha, and 9.68 ha, respectively. Meanwhile, the safe zone area covers most of the Watukarung area, i.e., 598.40 ha. Regardless of this situation, the research found that the densest population concentration in Watukarung was identified as a tsunami-prone area. Given the high level of economic development (especially for tourism), managing coastal resources must be integrated with tsunami risk reduction measures to mitigate the consequences of disasters as much as possible.

Higher spatial resolution data is crucial in providing more reliable coastal hazard information. For example, an onshore digital elevation model derived from LiDAR or UAV is expected to produce a more reliable tsunami susceptibility mapping. Also, it is essential to compare this result with other approaches, such as tsunami propagation models, which involve bathymetry data and earthquake magnitude scenarios. Further research must examine coastal community and tourism resilience in anticipating tsunami risk.

REFERENCES

Akbar, F. S., Vira, B. A., Doni, L. R., Putra, H. E., & Efriyanti, A. (2020). Aplikasi Metode Weighted Overlay untuk Pemetaan Zona Keterpaparan Permukiman Akibat Tsunami (Studi Kasus: Kota Bengkulu dan Kabupaten Bengkulu Tengah). Jurnal Geosains Dan Remote Sensing, 1(1), 43-51. https://doi.org/10.23960/jgrs.2020.v1i1.17

Alwi, M., & Mutaqin, B. W. (2022). Geospatial Mapping of Tsunami Susceptibility in Parangtritis Coastal Areas of Yogyakarta, Indonesia. Arabian Journal of Geosciences, 15, 1332. https://doi.org/10.1007/s12517-022-10608-2

Amri, I., Alami, R. R., & Serlia, A. (2023). Population Distribution Analysis in Banda Aceh City for Tsunami Disaster Risk Reduction. IOP Conference Series: Earth and Environmental Science, 1173(1), 012052. https://doi.org/10.1088/1755-1315/1173/1/012052

Amri, I., & Giyarsih, S. R. (2022). Monitoring Urban Physical Growth in Tsunami-Affected Areas: A Case Study of Banda Aceh City, Indonesia. GeoJournal, 87(3), 1929-1944. https://doi.org/10.1007/s10708-020-10362-6

Berryman, K. (2006). Review of Tsunami Hazard and Risk in New Zealand. New

Zealand: Institute of Geological and Nuclear Science.

Biswas, S., & Sil, A. (2023). Tsunami Vulnerability Assessment and Multi-Criteria Decision Making Analysis of Eastern Coast of India Using GIS-Based Tools. KSCE Journal of Civil Engineering, 27, 1270-1287. https://doi.org/10.1007/s12205-023-1493-y

BNPB. (2018). Modul Teknis Penyusunan Kajian Risiko Bencana Tsunami Versi 1.0. Jakarta: BNPB.

BPS Kabupaten Pacitan. (2022). Kecamatan Pringkuku Dalam Angka 2022. Pacitan: BPS Kabupaten Pacitan.

Cutter, S. L. (2013). Vulnerability. 1088-1090 pp. In Bobrowsky, P.T. (eds) Encyclopedia of natural hazards. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4399-4_40

De Reu, J., Bourgeois, J., Bats, M., Zwertvaegher, A., Gelorini, V., de Smedt, P., Chu, W., Antrop, M., de Maeyer, P., Finke, P., van Meirvenne, M., Verniers, J., & Crombe, P. (2013). Application of the Topographic Position Index to Heterogeneous Landscapes. Geomorphology, 186, 39-49. https://doi.org/10.1016/j.geomorph.2012.12.015

Domínguez-Cuesta, M. J. (2013). Susceptibility. 98 pp. In Bobrowsky, P.T. (eds) Encyclopedia of natural hazards. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4399-4_340

Harahap, R. G., Adnyani, L. P., Dianiswara, A. (2019). Rekonstruksi dan Simulasi Penjalaran Tsunami Banyuwangi 1994 Menggunakan Mike 21 Flow Model. Jurnal Inovtek Polbeng, 9(1). https://doi.org/10.35314/ip.v9i1.900

Hidayah, Z., Rohmah, N. N., & Wardhani, M. K. (2022). Coastal Vulnerability Study on Potential Impact of Tsunami and Community Resilience in Pacitan Bay East Java. Forum Geografi, 36(1), 66-79. https://doi.org/10.23917/forgeo.v36i1.17160

Hoppe, M. W., & Spahn, H. (2009). Guidebook Tsunami Hazard Mapping for the District Level. Jakarta: GITEWS.

Husein, Z., Tjahjono, B., & Nurwajedi. (2017). Analisis Zona Bahaya Banjir dan Tsunami Berbasis Ekoregion di Provinsi Banten. Jurnal Ilmu Tanah dan Lingkungan, 19(2), 60-67. http://dx.doi.org/10.29244/jitl.19.2.60-67

Jamilah, Z., Widodo, A., & Ariyanti, N. (2021). Mapping Tsunami Hazard Levels in Pacitan Beach Using Remote Sensing Methods. Journal of Marine-Earth Science Technology, 2(1), 1-4. https://doi.org/10.12962/j27745449.v2i1.64

Julzarika, A., & Harintaka (2019). Indonesian DEMNAS: DSM or DTM? IEEE Asia-Pacific Conference on Geoscience, Electronics and Remote Sensing Technology (AGERS), 31-36. https://doi.org/10.1109/AGERS48446.2019.9034351

Laksono, F. A. T., Widagdo, A., Aditama, M. R., Fauzan, M. R., & Kovács, J. (2022). Tsunami Hazard Zone and Multiple Scenarios of Tsunami Evacuation Route at Jetis Beach, Cilacap Regency, Indonesia. Sustainability, 14, 2726. https://doi.org/10.3390/su14052726

Latifah, A. (2022). Pemodelan Tsunami pada Zona Megathrust Pantai Selatan Jawa menggunakan Community Model Interface for Tsunami (ComMIT). Unnes Physics Education Journal. 11(1), 78-87. https://doi.org/10.15294/upej.v11i1.59054

Lessy, M. R., & Sabar, M. (2021). Mapping Tsunami Vulnerability Area for Bacan Sub-District and Its Surroundings – North Maluku Province. E3S Web of Conferences, 328, 04024. https://doi.org/10.1051/e3sconf/202132804024

Mardiatno, D., Malawani, M.N., & Nisaa', R.M. (2020). The Future Tsunami Risk Potential as a Consequence of Building

Development in Pangandaran Region, West Java, Indonesia. International Journal of Disaster Risk Reduction, 46, 101523. https://doi.org/10.1016/j.ijdrr.2020.101523

Mutaqin, B.W., Amri, I., & Aditya, B. (2020). Pola Kejadian Tsunami dan Perkembangan Manajemen Bencana di Indonesia Setelah Tsunami Samudra Hindia 2004: Sebuah Tinjauan. Jurnal Lingkungan dan Bencana Geologi, 11(2), 73-86. http://dx.doi.org/10.34126/jlbg.v11i2.302

Nadim, F. (2013). Hazard. 425-426 pp. In Bobrowsky, P.T. (eds) Encyclopedia of natural hazards. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4399-4_164

Nur, A. M. (2010). Gempa Bumi, Tsunami dan Mitigasinya. Jurnal Geografi, 7(1), 66-73. https://doi.org/10.15294/jg.v7i1.92

Oktaviana, Dewi, P. U., Wahdini, M., Prasiamratri, N., Alghifarry, M. B., & Utami, N. A. (2020). Aplikasi SIG untuk Pemetaan Zona Tingkat Bahaya dan Keterpaparan Permukiman Terhadap Tsunami Kota Denpasar. Jurnal Geosains dan Remote Sensing, 1(2), 80-88. https://doi.org/10.23960/jgrs.2020.v1i2.28

Pratiwi, D. (2016). The Evaluation of Coastal Vegetation Structures and Their Function to Reduce Tsunami Hazard in Pacitan Bay. Thesis. Yogyakarta: Universitas Gadjah Mada.

Safira, F. A., Muryani, C., & Tjahjono, G. A. (2022). Tsunami Susceptibility Analysis in Coastal Area Petanahan District, Kebumen Regency. Jambura Geoscience Review, 4(2), 110-122. https://doi.org/10.34312/jgeosrev.v4i2.13938

Surono, Toha, B., & Sudarno, I. (1992). Peta Geologi Lembar Surakarta – Giritontro, Jawa. Bandung: Pusat Penelitian dan Pengembangan Geologi.

Van Bemmelen, R. W. (1949). The Geology of Indonesia. The Hague: Nijhoff.

Waskita, T. B., Zahra, R. A., Biladi, M., Isnain, M. N., Melati, P., Insani, A. A., Amri, I., Mardiatno, D., & Putri, R. F. (2020). Susceptibility Distribution Analysis of Tsunami using Spatial Multi-Criteria Evaluation (SMCE) Method in Parangtritis, Indonesia. 2020 6th International Conference on Science and Technology, 1-6. https://doi.org/10.1109/ICST50505.2020.9732883

Widiyantoro, S., Gunawan, E., Muhari, A., Rawlinson, N., Mori, J., Hanifa, N. R., Susilo, S., Supendi, P., Shiddiqi, H. A., Nugraha, A. D., & Putra, H. E. (2020). Implications for Megathrust Earthquakes and Tsunamis from Seismic Gaps South of Java Indonesia. Scientific Reports, 10(1), 15274. https://doi.org/10.1038/s41598-020-72142-z