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Mapping Tsunami Disaster Evacuation Routes Based on Geographic Information Systems (Case Study: Tambakrejo Village, Malang Regency, East Java)

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Abstract: Indonesia is situated amidst three major tectonic plates: the Indo-Australian Plate, Eurasian Plate, and Pacific Plate. As a consequence, the country is characterized by numerous volcanoes, frequent earthquakes in various regions, and the occurrence of tsunamis. Particularly in the southern region of Java Island, this coastal area is a disaster-prone area. One of the areas is Tambakrejo Village, which is located in the coastal area of Malang Regency, which has potential in the form of beautiful beaches, abundant fishery products and development of the tourist village. This research aims to create a tsunami evacuation route map using a GIS. The digital elevation model data was obtained from Geospatial Information Agency using reclassification based on variations in altitude levels. Distance data from the coastline is processed using a base map of the research location and assisted by the Multiple Ring Buffer Toolbox. Land use data is processed using the Maximum Likelihood Classification process, the data used is Landsat 8 imagery. Determination of tsunami evacuation routes is carried out by implementing the Network Analyst method. The Network Analyst method uses the starting point of the incident to the end point of the facility to produce an appropriate evacuation route. The results show four new gathering points and 6 recommended evacuation routes for Sendangbiru, Tamban and Sendiki Beaches respectively.

Keywords: Evacuation routes; Geographic information systems; Risks; Tsunami; Vulnerabilities

Introduction

Indonesia is located between three large plates: the Indo-Australian, Eurasian and Pacific plates. Therefore, Indonesia has many volcanoes which often cause earthquakes and tsunamis in various regions of the archipelago. The collision of these plates can cause local disturbances which can also cause ground movement (Susilo et al., 2018). Earthquakes can also generate massive ocean waves known as tsunamis, and these waves can traverse vast distances across the ocean before reaching and impacting coastal areas (Maryati et al., 2012). Tsunamis represent highly destructive incidents that pose a significant risk to numerous coastal communities globally. Given its extensive coastline, coupled with its position in the "ring of fire," Indonesia faces substantial exposure to the dangers associated with tsunamis (Marfai et al., 2021). Due to its high population density and many low-lying, coastal communities, the south coast of Java, in particular, is one of the most at risk areas in Indonesia (Hall et al., 2017).

Malang Regency is an area that has many beach tourist attractions that can be visited. Beach tourist attractions in Malang Regency are located in six sub-

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districts, namely Ampelgading, Bantur, Donomulyo, Gedangan, Sumbermanjing Wetan and Tirtoyudo sub-districts. Sumbermanjing Wetan District has a number of beach tourist attractions, especially in Malang Regency with a total of 12 beach tourist attractions in 15 villages. One of the villages that has the most beach attractions in this subregion is Tambakrejo Village which has six beach tourist attractions and one nature reserve (Karima et al., 2022).

According to the 2019 World Risk Index, Indonesia holds the 37th position, exhibiting a significant exposure of 21.20% to extreme natural events, high vulnerability at 49.93%, medium susceptibility of 26.63%, a substantial deficiency in coping capacity at 79.71%, and a considerable lack of adaptive capacity at 43.44%. Indonesia's World Risk Index stands at 10.58%, indicating that a mere 0.04% increase could propel it into the category of countries with a very high World Risk Index (10.62%). To avert this escalation, it is imperative to address and control factors such as exposure, vulnerability, susceptibility, coping capacity, and adaptive capacity to extreme natural events. Hence, concerted efforts in disaster management are crucial to prevent Indonesia from attaining a very high World Risk Index (Irma Alfie Yassin et al., 2022).

Pondokdadap, a Coastal Fishing Port (CFP) stands as one of the primaries for the landing of tuna, skipjack, and mackerel tuna in Malang, East Java. Pondadap Coastal Fishing Port (CFP) is one of Indonesia's fishing ports located in Malang, East Java, located in the waters of the Indian Ocean (WPP NRI 573) which is a fishing ground for tuna resources. The fishing port is part of the Technology Implementation Unit (UPT) of the East Java Maritime and Fisheries Service which provides port technical services, governance and business services. CFP Pondokdadap fishery production was 750,798 Kg with a production value of IDR 11,836,194,900, which is a 139% increase, compared to March 2021, where production of 314,694 kg was recorded. This makes CFP Pondokdadap the fishing port with the third-highest total fish production in East Java Province, after NFP (Nusantara Fishing Port) Brondong and CFP Muncar. Yellowfin tuna (Thunnus albacares) dominates the total fishery production, comprising 37% of the total production volume of 286.1 tons. As one of the largest tuna fishing ports on the south coast of East Java, CFP Pondokdadap has a target to improve the quality of port services. These services generally include providing required goods/services to fishers/fishery entrepreneurs and the public to enable them to advance their business using the facilities provided (Ningsih et al., 2022).

Great earthquakes close to the Java trench are typically interplate faulting events along the slab interface between the Australia and Sunda plates; these earthquakes generally have high tsunamigenic potential due to their shallow depths (Supendi et al., 2023). Especially the southern part of Java Island which is directly facing the meeting of the Eurasian and Indo-Australian plates under the Indian Ocean. This makes the southern part of Java Island not only prone to earthquakes, but also tsunamis. The southern part of Java Island can be divided into three large megathrust zones that have the potential for earthquakes and tsunamis, namely the Sunda Strait Megathrust, Central Java and East Java.

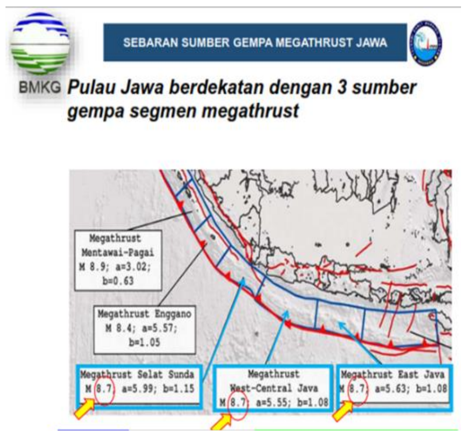

Figure 1. BMKG Earthquake & Tsunami Socialization Team, 2021

A Geographic Information System (GIS) is a computer-based system comprising hardware, software, and human expertise designed for the processing and analysis of geographic data. Its widespread application in diverse fields, including land resource management, forestry, agriculture, marine and fisheries, infrastructure, tourism, plantation, mining, and economics, stems from its capacity to process both spatial and attribute data related to geographic phenomena (Maryati et al., 2012). Satellite remote sensing and GIS have emerged as highly effective tools in disaster research, assisting in risk management and mitigation. The focus on remote sensing satellite data makes it easier to identify tsunami-affected areas, thereby utilizing simultaneous image transmission over a wide area. Satellite imagery has the advantage of being able to transmit images over a large area simultaneously (Sambah et al., 2018). Examining the spatial distributions of tsunami occurrences and assessing their impact on vulnerable elements can be accomplished through the utilization of Geographic Information Systems (GIS) and Remote Sensing. The research involving Remote Sensing and GIS data yields valuable insights for in-depth evaluations, contributing to both pre-tsunami preparedness and understanding the aftermath of tsunamis (Wiguna, 2014).

A tsunami refers to a sequence of waves triggered by the sudden vertical displacement of a body of water. Tsunamis are the outcome of sudden shifts in tectonic plates beneath the ocean surface. When these plates move, the water above the point of movement is disturbed, leading to the formation of waves. Subsequently, these waves travel in diverse directions and ultimately reach coastal regions (Armono et al., 2021). The tsunami disaster has been considered a major disaster so that many types of research have been carried out to assess its vulnerability and risk to coastal areas (Sambah et al., 2019). Coastal areas frequently experience both tsunamis and floods, facing numerous challenges from both land and ocean influences. It is evident that the vulnerability of these zones is considerable, with tsunamis posing significant risks such as loss of life, property destruction, and damage to coastal infrastructure (Manikandan et al., 2010).

Settlement patterns typically follow natural features, with coastal areas experiencing development towards the shoreline. In regions susceptible to tsunami hazards, settlements located along the coastline face a heightened risk of tsunami disasters. The impact of tsunamis is more severe for settlements along the coast, and the level of risk is influenced not only by the distance between the settlement and the beach but also by the absence of coastal barriers (Soviana et al., 2023). To effectively mitigate the risk of tsunami disasters, it is essential to understand the community's coping capacity through a thorough assessment of their vulnerability to such events.

Based on earthquake risk index data per district in 2011, Malang Regency is in the medium risk class. Indonesian Tsunami Potential and Inundation Reference Data for Malang Regency is 11 meters with a tsunami arrival time of 29 minutes (BNPB, 2012). Tsunami run-up can be severe depending on areas with relatively flat topography because tsunamis can flow more easily into flat areas, but can be deflected by hills bordering the coast (Sambah et al., 2019).

Natural disaster vulnerability is needed in determining other regional development options, especially determining limited or barrier areas (areas with a high-quality level of natural disaster vulnerability need to be avoided). The increasing concentration of population, together with the high density of assets and the socio-economic and spatial vulnerabilities that characterize many cities, makes more susceptible to the risk of being severely affected by natural hazards (Gu, 2019). Survivors of natural disasters may undergo trauma, and this traumatic experience can impact their adjustment over time (Surjono et al., 2021).

The aim of this research is to create a regional tsunami evacuation route map in the coastal area of Tambakrejo Village, Malang Regency using a Geographic Information System and new gathering points in areas with safe areas from potential impacts.

Method

The location of this research is in the Coastal Area of Tambakrejo Village in Sumbermanjing Wetan District, Malang Regency, East Java Province. This area has several beaches designated as tourism desti s and several important places such as fishing ports and fish auction sites.

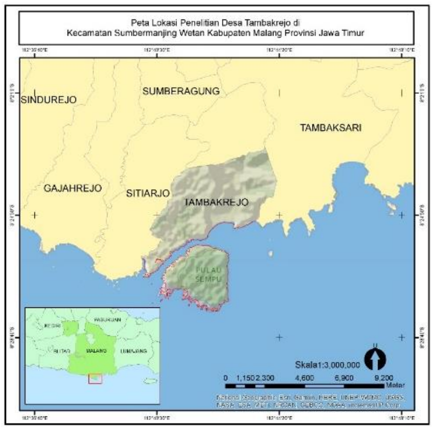

Figure 2. Research location map

Field data collection was carried out for validation of the results of processing tsunami evacuation route data using a Network Analyst. Validation is done to measure the effectiveness of the data that has been processed. Adequate road access and road conditions affect in accelerating the evacuation process. The width of the road will be measured using a roll meter assuming that one-meter-wide road can be traversed by two adults. Road width data is used as additional information for the estimation of capacity and means of transportation used when carrying out evacuation actions. Road conditions will be visually analyzed for feasibility values so that it can be decided whether the road is in good condition or not. If the road proves to be not good for evacuation routes, the data can be used for additional information on improving facilities and infrastructure so that they become suitable for evacuation routes.

In this research, spatial data from the RBI Map (Earth Map) 1:25,000 by the Geospatial Information Agency, road network data from OpenStreetMap, DEMNAS from the Geospatial Information Agency, and tsunami run-up elevation data for Malang Regency in 2012 from the National Disaster Management Agency (BNPB) were utilized.

Data processing is conducted with the aid of computers and ArcGIS 10.8 software. Processing of data, which includes Landsat 8 imagery, DEMNAS (Seamless Digital Elevation Model (DEM) and National Bathymetry) from Geospatial Information Agency Indonesia, and the topographic map of Indonesia, is performed to compile parameters. These parameters are subsequently processed using ArcGIS 10.8 software. In a general sense, the utilized steps encompass the following phases.

Extraction of spatial data from satellite imagery, topographic maps, DEM (Digital Elevation Model), and additional supporting data. DEM data is acquired from DEMNAS BIG 2022, the high spatial resolution of the satellite technology employed allows for the selection of smaller-scale objects in images, provided there are small plots and low survey frequencies (Yussupov & Raya Z. Suleimenova, 2023) and processed using ArcGIS 10.8 software, involving reclassification based on variations in elevation levels. The distance data from the coastline is handled using the base map of the research location, aided by the Multiple Ring Buffer Toolbox in ArcGIS 10.8 software. ArcGIS 10.8 is employed for processing land use data through the Maximum Likelihood Classification process, with Landsat 8 imagery as the primary data source. Image classification is used to obtain geological interpretation results and determine regional zones with certain geological conditions. The classified images are then combined with the vector map digitised by the RBI map to get maximum classification results (Kausarian et al., 2023). The determination of tsunami evacuation routes is executed through the implementation of the Network Analyst method.

The utilization of ArcGIS Network Analyst Extension facilitated the execution of road network analysis. This extension, a robust component of ArcGIS, is dedicated to spatial analysis based on networks, encompassing functionalities such as route analysis, travel directions, closest facility analysis, and service area analysis. It empowers users to dynamically simulate real-world factors within road networks, such as turn restrictions, speed limits, and varying traffic conditions throughout different times of the day. Employing the standard Dijkstra's algorithm, the ArcGIS Network Analyst Extension computes the minimum accumulated cost between the destination node and every other node in the network. Two specific types of network analyses were conducted: the best route analysis and the closest facilities analysis (Ahmed et al., 2018).

Topographic maps portray detailed information about the landscape of both natural and man-made features, incorporating elevation details depicted through contour lines. They are an indispensable tool for government, science, industry, and leisure for a wide variety of purposes (Pavlicko & Peterson, 2005). The forecasted maximum tsunami height data, based on BNPB Regulation No. 4 of 2012 for Malang Regency or City, is 11 meters. Referring to the BNPB's projections, this study will categorize the data into various class ranges through the reclassification process. Each class represents different levels of vulnerability to tsunamis, with higher elevations indicating lower vulnerability, and vice versa.

Secondary data in the form of elevation data for this study can be downloaded from the website https://tanahair.indonesia.go.id/demnas. The data processing is conducted using the ArcGIS 10.8 application, with the input data being the Seamless Digital Elevation Model (DEM). ArcGIS it is the main component of a suite of geospatial processing programs and is primarily used to view, edit, create, and analyze geospatial data (Bağdatlı & Ballı, 2021). DEM represents spatial variation in altitude and is used in producing slope gradient and slope shape (Harist et al., 2018). The topographic data processing involves reclassification based on variations in elevation levels. The class ranges of elevation values are also termed reclassification. The outcomes of the topographic data processing serve as reference data for identifying safe points or areas for tsunami evacuation. The class ranges of elevation values are also referred to as reclassification, as detailed in Table 1.

Table 1. Altitude classification by elevation (Sambah & Miura, 2014)

Elevation (m)	Vulnerability Class
<5	High
5 – 10	Slightly High
10 – 15	Medium
15 - 20	Slightly Low
>20	Low

The alteration of the Earth's terrestrial surface resulting from human activities is known as land use/land cover change. The land use analysis allows the identification of the main soil occupations in an area of interest and provides important information related to the environmental characteristics of the area (Piroli & Campos, 2010). This process has adverse effects on biodiversity, climate, soil, air, and the overall ecosystem, making it a significant environmental issue in recent years. Land use analysis serves as a valuable tool for evaluating changes in ecosystems and their environmental consequences across different temporal and spatial scales, providing insights into broader environmental transformations (Anteneh, 2022). The creation of land use maps involves leveraging remote sensing technology, such as the analysis of satellite imagery. In this study, Landsat 8 satellite imagery is utilized.

The processing of land use data in this research involves the utilization of Landsat 8 imagery, processed subsequently using ArcGIS 10.8. The classification of land use is determined based on satellite imagery downloaded on July 7, 2022. In ArcGIS, data processing utilizes the Iso Cluster Unsupervised tool to understand the existing land use. Following that, the Clip tool is applied to the processed area, and Image Classification is selected to generate polygons or areas for each class. The classes formed are then visible in the Training Sample Manager for consolidation into separate classes by choosing Merge Training Sample. Subsequently, the Maximum Likelihood Classification is applied to assign each pixel to different classes based on the characteristics and variations of the class indicators.

The proximity to the coastline, known as Coastal Proximity, is linked to the potential reach of tsunami waves towards the land. The computation of this distance from the coastline involves the utilization of the multiple ring buffer toolbox found in the ArcGIS 10.8 software. This distance is determined based on historical records of maximum run-up in the research area, as expressed by the formula outlined by (Sambah & Miura, 2014).

$$\log X_{\max} = \log 1400 + \frac{4}{3}\log\left(\frac{Y_o}{10}\right) \tag{1}$$

$X_{\max}$: Maximum tsunami run-up on land.
Y_0: High of tsunami in beach

Notably, Tambakrejo Village's coastal area has never experienced a tsunami historically. Consequently, for the Coastal Proximity calculation in this study, predicted tsunami run-up data is used as a reference, obtained from BNPB Regulation No. 4 of 2012 (BNPB, 2012), indicating a value of 11 meters. The classification of vulnerability levels based on coastal proximity is detailed in Table 2.

Table 2. Vulnerability class distance from coastline

Coastal Proximity (m)	Vulnerability Class
0-281	Extremely Vulnerable
281-556	Vulnerable
556-870	Moderately Vulnerable
870-1217	Less Vulnerable
>1540	Not Vulnerable

The presence of roads is a critical element in establishing evacuation routes, and the study relies on data obtained through the InaSAFE tool within the QGIS software. The functionalities provided by the OpenStreetMap Downloader in InaSAFE enable the visualization of maps and access to current road network data. Following the acquisition of road shapefile data, adjustments are made to the road network data in ArcGIS 10.8 to ensure precision that aligns with the specific conditions at the research site.

The existence of tsunami evacuation routes will facilitate people to make the best choices during evacuation. Therefore, an effective evacuation plan must consider both local communities and visitors (Marfai et al., 2021).

The subsequent step involves identifying new assembly points in areas deemed safe from tsunami risks. After selecting these points as new assembly locations, on-site surveys are conducted to assess road access conditions and the surrounding environment of these assembly points. The application of the Network Analyst method results in determining the location of Temporary Evacuation Sites (TES) through network analysis. The road network data obtained from OpenStreetMap (OSM) is preferred due to its real-time updates, providing flexibility and prompt adjustments to field changes, in contrast to government maps updated at fixed intervals.

To validate the outcomes of processing tsunami evacuation route data, a field investigation was conducted using a network analyst tool. To assess the efficiency of evacuation routes, on-site inspections are necessary. A critical aspect of the evacuation process is the presence of suitable road conditions, which significantly impact the speed of evacuation. The width of the road is gauged using a tape measure, assuming that two adults can pass through one meter of road width. Details about road width provide supplementary insights when evaluating the capacity and modes of transportation employed during the execution of evacuation measures.

The state of the roads is also regarded as a facilitating factor for seamless transportation during evacuation operations to ensure their effective execution. Road conditions play a key role in determining the effectiveness of the utilized evacuation routes. A visual analysis is conducted on road conditions to ascertain whether the roads are in good or poor condition. If it turns out that a road is unsuitable for an evacuation route, this data can offer additional insights to enhance the facilities and infrastructure necessary for a viable evacuation route.

Result and Discussion

Elevation information stands as a crucial dataset needed for models to produce assessments of tsunami susceptibility and aggregation. In order to derive parameters describing physical vulnerability, a digital elevation model is created through elevation maps utilizing DEM data (Sambah & Miura, 2014). The elevation of the terrain plays a significant role in influencing the vulnerability to tsunami disasters. Lower-lying areas are more susceptible to tsunami impact, while higher elevations correspond to a reduced risk of tsunami disasters. The altitude of the land is a key factor determining the extent of a tsunami's reach. This data was obtained from the BIG website on May 30 2023. The DEMNAS data published by BIG has undergone classification and processing according to the guidelines of PERKA BNPB No. 11 meters in the Malang Regency area. Height categories are defined, dividing the terrain into five classes: <5 meters (High), 5-10 meters (Moderately High), 10-15 meters (Medium), 15-20 meters (Moderately Low), and >20 meters (Low).

The processed data indicates that the coastal region of Tambakrejo Village is predominantly characterized by elevations falling within the 5-10 meter and 10–15-meter classes, with some locations featuring elevations in the 15-20 meter and >20-meter categories. Certain beach areas fall within tsunami-prone zones, specifically with heights ranging from 5-10 meters and 10-15 meters. These areas encompass the tourist and economic hubs of Tambakrejo Village. Regions marked in yellow have the potential to serve as Gathering Points. Those in green can be designated for Evacuation Protection Buildings, while those in orange are considered the initial points of an incident. Topographic maps prove useful as references for tsunami preparedness efforts, aiding in the planning and enhancement of safety measures, including the expansion of residential areas to higher, safer elevations.

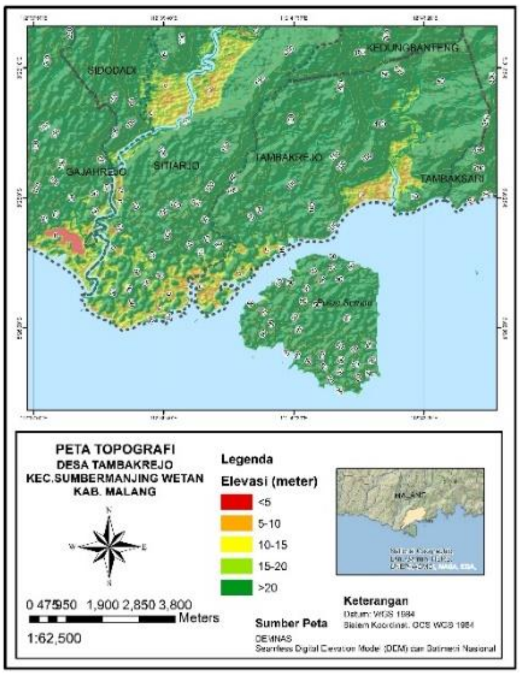

Figure 3. Elevation of Tambakrejo Village, Malang Regency

The inclination of a flat surface, known as land slope, is commonly measured in degrees or as a percentage. The Slope is the appearance of the natural surface because of the high difference if the height difference between the two places is compared with the horizontal straight distance so that the slope will be obtained (Harist et al., 2018). The utilization of the slope parameter is crucial as it determines the extent to which a tsunami can reach the land. The slope of the terrain significantly influences the vulnerability of an area to tsunami disasters. Steep coasts can mitigate the impact of a tsunami, preventing it from advancing inland. Conversely, a sloping coast allows a tsunami to reach the land. The outcomes derived from a land slope map play a vital role in assessing the flatness or steepness of the terrain, aiding in the identification of suitable evacuation routes.

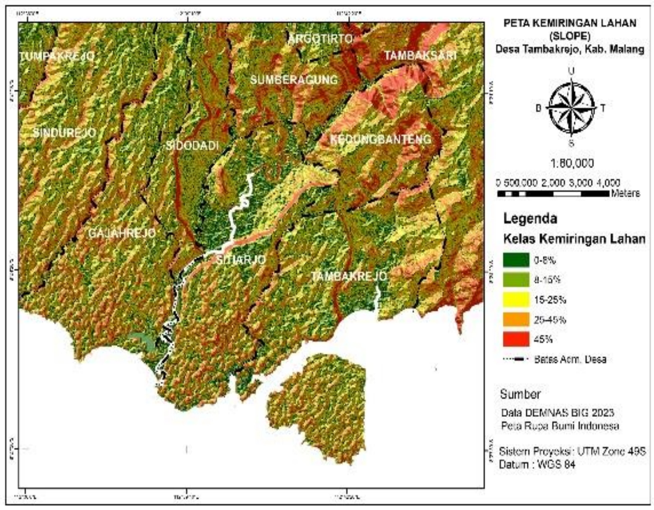

Figure 4. Slopes of Tambakrejo Village, Malang Regency

The outcomes of processing land use data in Tambakrejo Village, Malang Regency are illustrated in Figure 5. The processing results reveal that the predominant land use in Tambakrejo Village consists of plantation forests and secondary dry land forests. It is essential to differentiate various categories of forests, such as secondary forests and forest plantations, in the context of restoration and rehabilitation programs aimed at addressing climate change (Noviar & Kartika, 2017). Plantation forests are areas managed and cultivated with a focus on optimal utilization, considering environmental sustainability and natural resources. Secondary dry land forest encompasses areas categorized by the distribution of lowland, hilly, and mountainous forest features with visible logging scars, groves, and logging patches. The detailed breakdown of land use in Tambakrejo Village following the processing can be found in Table 3.

Table 3. Distribution of land use

Land Use	Area (ha)
Secondary Dryland Forest	1083.525411
Secondary Mangrove Forest	52.682269
Plantation Forest	1409.270982
Settlement	297.727697
Mixed Dry Land Agriculture	105.886091
Ricefield	223.879384
Open Land	433.973281

The largest distribution of settlements close to the coastal area is around the Sendangbiru Beach area. The distribution in this area is due to the existence of local population activity centers such as; buying and selling activities, tourist locations, and fish auction places. Apart from that, there is a distribution of secondary mangrove forests on Gatra, Tiga Warna and Tamban Beaches. Secondary dry land forests are classified in the area around Sendiki Beach and Sempu Beach. The open land on the coast is located between Jalan Kondang Bajol and Jalan Makam, while other vegetation is assumed to be plantation areas and rice fields which are influenced by the presence of people who use the land. The results of land use processing can be seen in Figure 5.

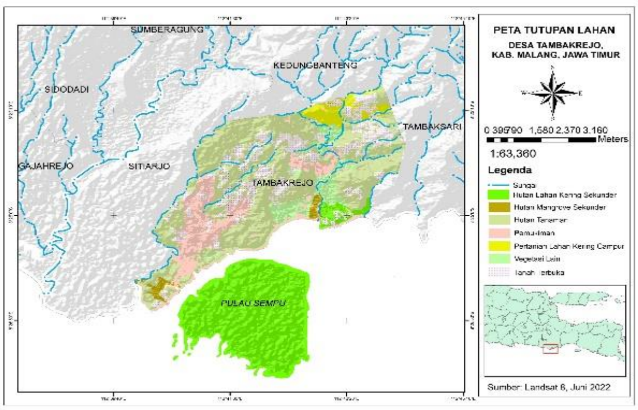

Figure 5. Land use map

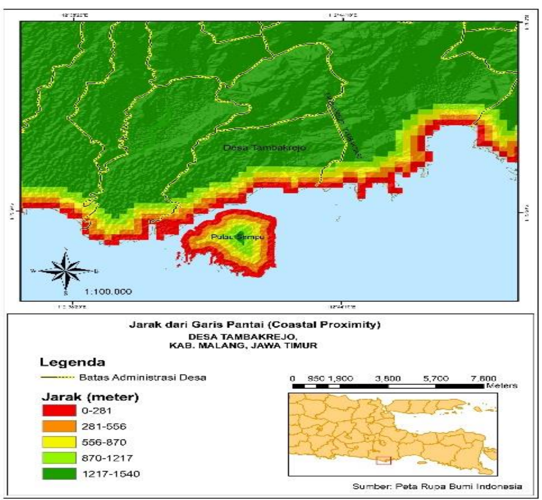

Figure 6. Coastal proximity map

Coastal proximity is linked to land use and plays a crucial role in mitigating regional susceptibility to tsunami disasters. Strategic land use along coastal areas, taking into consideration the proximity to the coastline, has the potential to diminish vulnerability. The height of tsunami waves approaching land tends to diminish with increasing distance from the coastline. Figure 9 illustrates a map detailing the distances from the coastline.

Population data for Sumbermanjing District in Malang Regency in 2021 was sourced from the official publication of agency data by the Malang Regency Central Statistics Agency. The significance of population data in development planning and evaluation cannot be overstated, as the population serves both as the object and subject of development. In the object function, the population is the target and recipient of development efforts, while in the subject function, the population is the primary actor in the development process. The harmonious alignment of these two functions is crucial.

Table 4. Population Data, Population Growth Rate, Population Percentage Distribution, Population Density, Sex Ratio by Village/Subdistrict in Sumbermanjing Wetan District, BPS, 2020 Population Census

Village/Subdistrict	Population (thousand)	Population Growth Rate per Year (%) 2010-2020
Sitiarjo	7561	0,68
Tambakrejo	7193	0,72
Kedungbanteng	7241	0,92
Tambaksari	9125	1,84
Tegalrejo	2513	0,38
Ringinkembar	4998	0,60
Sumberagung	6025	0,80
Harjokuncaran	9779	0,78
Argotirto	7721	0,76
Ringinsari	4796	2,24
Druju	11785	1,71
Sumbermanjing Wetan	3958	2,56
Klepu	8397	(0,03)
Sekarbanyu	2770	0,15
Sidoasri	4785	1,20
Sumbermanjing Wetan District	98647	1,00

Source: BNPB Tsunami Contingency Plan, 2021

Table 5. Number of Population According to Age Group and Gender in Sumbermanjing Wetan District, BPS, 2020 Population Census

Age group	Male	Female	Total
0-14	10499	9886	20385
15-64	34843	34385	69228
65+	4420	4614	9034
Sumbermanjing Wetan District	49762		98647

According to BPS Malang Regency's 2020 records, Tambakrejo Village had a population of 7,193 residents, with an annual population growth rate of 0.72% from 2010 to 2020. Population of 8,424 in Tambakrejo Village in 2018, comprising 4,320 males and 4,104 females. Notably, a significant portion of the population in Tambakrejo Village falls within the productive age range of 18 to 56 years, accounting for 48.7%.

The residents of Tambakrejo Village engage in the residents of Tambakrejo Village engage in various occupations, including private employment, particularly as crew members on fishing boats. Additionally, some individuals are employed in formal institutions like PKK, KUD Cooperatives, and similar organizations. The village benefits from essential facilities and infrastructure, including those supporting activities related to capture fisheries, such as a fish market and a fish auction place known as TPI (fish auction place).

Table 6. Sex Ratio in Sumbermanjing Wetan District, BPS Kab. Malang 2020

Village/Subdistrict	Sex Ratio
Sitiarjo	99.9
Tambakrejo	102.2
Kedungbanteng	101.4
Tambaksari	102.4
Tegalrejo	103.3
Ringinkembar	104.2
Sumberagung	104.0
Harjokuncaran	101.3
Argotirto	103.0
Ringinsari	98.3
Druju	102.1
Sumbermanjing Wetan	98.0
Klepu	103.5
Sekarbanyu	95.9
Sidoasri	103.4
Sumbermanjing Wetan District	101.8

Source: BNPB Tsunami Contingency Plan, 2021

The processing of data, which involved topographic maps, land use, coastal proximity, and the network analyst tool, yielded four designated gathering points and identified two proposed evacuation protection buildings, as outlined in Table 5. The suggested gathering points encompass two temporary locations near the Sendangbiru Beach settlement, while the recommended evacuation protection buildings are strategically placed near the Tamban Indah and Sendiki Beach settlements.

The selection of evacuation protection building points carefully considers accessibility factors, emphasizing convenient location access. These points are situated in close proximity to the main road within Tambakrejo Village. Moreover, the chosen locations for evacuation protection buildings are carefully situated in safe areas, away from potential tsunami hazard zones. Adhering to guidelines for tsunami evacuation planning, the recommended height for these rescue buildings in evacuation zones exceeds 3 meters (Usman & Sari, 2019).

Table 7. Recommended evacuation locations

Location	Gathering Point	Evacuation Shelter Buildings
Pantai Sendang Biru	A. -8.430301, 112.678477 B. -8.429942, 112.681751	-8.426122, 112.679644
Pantai Tamban Indah	C. -8.411254, 112.712001	-8.402556, 112.717878
Pantai Sendiki	D. -8.410727, 112.716477	-8.402556, 112.717878

The employment of the Closest Facility tool in Network Analyst yielded five evacuation routes for the residential areas of Sendangbiru Beach, Tamban Indah, and Sendiki. These routes were distributed with three in the Sendangbiru residential area and two in the Tamban Indah and Sendiki residential areas. The selection of routes and gathering points was guided by the residential distribution and available open land, ensuring that evacuation protection buildings were strategically placed in locations safe from potential disasters. The initial evacuation protection building was identified at UPT Marine Station FPIK UB for evacuees from the Sendangbiru gathering point, while the second building was designated as SDN Tambakrejo II for evacuees from gathering points in Tamban Indah and Sendiki. The contingency plan for tsunamis by the National Disaster Management Agency (BNPB) in 2021 contains various gathering points along the coastal regions of each beach on the evacuation route map.

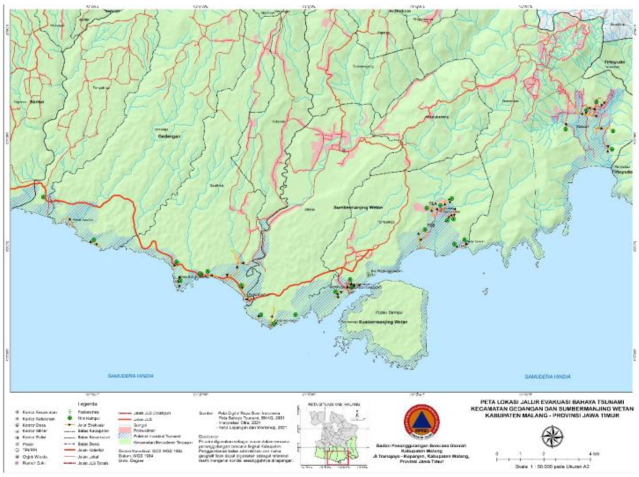

Figure 7. Map of Tsunami Evacuation Route in Gedangan and Sumbermanjing Wetan Districts, Malang Regency, East Java Province

Two gathering points were established in the Sendangbiru area, with the first situated in an open land area near plantation forests and a small number of settlements, and the second located in a settlement area. In Tamban Indah and Sendiki, two gathering points were designated, each positioned in open land areas near a few settlements and open land adjacent to other vegetation areas.

The determined evacuation route features an average asphalt road width ranging from 2.5 to 5 meters, with an additional dirt road of +1 meter on both the right and left sides. The selection of roads was influenced by factors such as road capacity, condition, and width, ensuring they could effectively accommodate refugees and vehicles. These considerations were particularly pertinent as the routes were intended for use as tsunami evacuation routes. Detailed maps of the tsunami evacuation routes for Sendangbiru Beach, Tamban Indah, and Sendiki can be found in Figure 9 and Figure 10.

The assessment of the effectiveness of tsunami evacuation routes is conducted by analyzing the travel time to the designated evacuation points. The evaluation of travel time to these points employs the evacuation speed determined by researchers, assuming the average speed of adults, which is 13 km/h, on those routes. All specified routes are in good condition, and the presence of severe potholes is uncommon. Nevertheless, as the evacuation approaches the recommended assembly point, the speed of evacuees may decrease due to the increasingly steep road conditions.

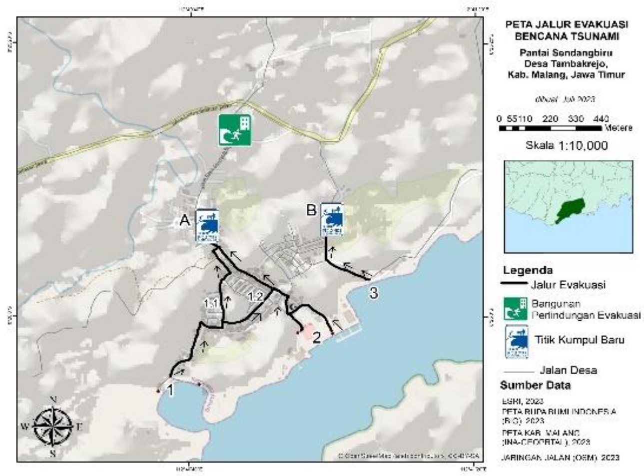

Figure 8. Map of Sendangbiru Beach Tsunami Evacuation Route

Route 1.1 can be easily traversed by running and utilizing two motorcycles simultaneously. Route 1.2 can be easily traversed by running, and for motorized vehicles, it is efficient to pass with a maximum of one single car, similar in size to a Small/Compact SUV/LMPV, or two motorcycles running simultaneously. Hence, evacuation route 1.1 to Assembly Point A at Sendangbiru Beach, useing a distance of 900 m, can be used within an estimated time of 4 minutes and 15 seconds. Evacuation route 1.2 to Assembly Point A, spanning a distance of 1.2 km, can be used within an estimated time of 5 minutes and 54 seconds.

Route 2 can be easily traversed by running, and for motorized vehicles, it is efficient to pass with a maximum of one single car, comparable in size to a Small/Compact SUV, or two motorcycles running simultaneously. Consequently, evacuation route 2 to Assembly Point A at Sendangbiru Beach, with a distance of 750 m, can be useed within an estimated time of 3 minutes and 46 seconds. Route 3 to Assembly Point B at Sendangbiru Beach, useing a distance of 322 m, can be reached within an estimated time of 1 minute and 29 seconds.

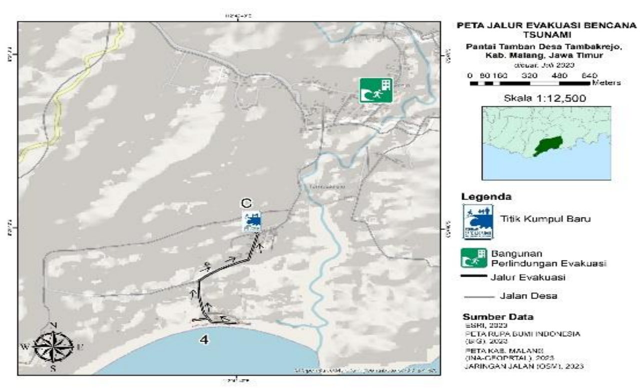

Figure 9. Map of Evacuation Routes at Tamban Beach

Tamban Indah Beach and Sendiki Beach each have one evacuation route and one gathering point. At Tamban Indah Beach, evacuation route 4, which leads to Assembly Point C, has a road capacity sufficient for easy traversal by running. For motorized vehicles, it is efficient to pass with a single Small SUV or two motorcycles running simultaneously. The distance to Assembly Point C from evacuation route 4 is 950 m, with an estimated travel time of 4 minutes and 39 seconds. Sendiki Beach, with evacuation route 5 leading to Assembly Point D, features a very steep terrain and narrow roads. Therefore, visitors entering this area will walk to the beach, while motorized vehicles can only access the entrance to Sendiki Beach. The distance to Assembly Point D from evacuation route 5 is 409 m, with an estimated travel time of 2 minutes and 13 seconds.

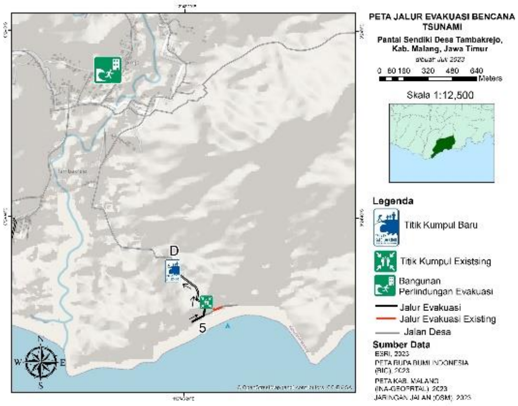

Figure 10. Map of Evacuation Routes at Sendiki Beach

Both Tamban Indah Beach and Sendiki Beach are equipped with a single evacuation route and an assembly point each. The route 4 at Tamban Indah Beach, leading to Assembly Point C, has a road capacity suitable for easy pedestrian movement, and for motorized vehicles, it is recommended to use a single Small SUV or two motorcycles traveling simultaneously. The distance to Assembly Point C from evacuation route 4 is 950 m, and the estimated travel time is 4 minutes and 39 seconds. On the other hand, Sendiki Beach has evacuation route 5 leading to Assembly Point D, characterized by a steep terrain and narrow roads. Visitors entering this area are advised to walk to the beach, while motorized vehicles can only access the entrance to Sendiki Beach. The distance to Assembly Point D from evacuation route 5 is 409 m, with an estimated travel time of 2 minutes and 13 seconds.

Field investigations using network analysis tools were carried out to validate processed data related to tsunami evacuation routes. On-site assessments are essential to evaluate the effectiveness of these routes. Road conditions play an important role in the smooth implementation of an evacuation. The width of the road is measured using measuring tape, assuming two adults can cross one metre. Information on road width provides additional insight into the capacity and type of transportation used in evacuation actions. Road conditions are also considered a key factor in ensuring transportation efficiency during evacuation. The effectiveness of evacuation routes is directly influenced by road conditions, which are analyzed visually to determine their suitability. If a road is deemed unfit for evacuation, additional data can be used to improve the facilities and infrastructure supporting the evacuation route.

On the topographic map shown are the areas included in the tourist and economic destinations in Tambakrejo Village. Areas with a moderate level of vulnerability can be recommended as safe places for tourism activities. Roads from coastal beaches can also be built better to make it easier for visitors to evacuate to the nearest gathering point.

Conclusion

Upon analyzing and discussing the findings, this research yields several conclusions. The data processing revealed four recommended assembly points and two designated evacuation shelters. The suggested temporary gathering points are strategically positioned near the settlements of Sendangbiru Beach, Tamban Indah, and Sendiki, while two evacuation shelters are specifically designated for Sendangbiru Beach and Tamban Indah Beach, as well as Sendiki Beach. These designated gathering points can serve as options or recommendations for effective tsunami disaster mitigation, ensuring sufficient access and capacity. The data analysis also identified six evacuation routes, situated close to residential areas in Sendangbiru Beach and Tamban Indah Beach, while in Sendiki Beach, they are positioned near other vegetative areas. The recommended evacuation routes are influenced by the environmental and social conditions of the surrounding community, leading to variations in the capacity and effectiveness of these routes. Drawing from the research on Geographic Information System-based Tsunami Disaster Evacuation Route Mapping, recommendations for future studies can be outlined. One crucial suggestion is to conduct on-site surveys to assess the conditions of locations, including their capacity, width, and road conditions, to identify effective evacuation routes. Obtaining more precise data on the tsunami-vulnerable population in coastal areas is necessary for reducing and estimating the number of lives at risk, consequently prioritizing evacuation plans. Accurate estimation data for the capacity and area of evacuation shelters is essential to predict the capacity to accommodate victims, considering age-related variations in running speed to derive more effective estimates of travel time based on individual conditions and physical differences.

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Conflicts of Interest
The authors declare no conflict of interest.

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