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TSUNAMI HAZARD MAPPING BASED ON COASTAL SYSTEM ANALYSIS USING HIGH-RESOLUTION UNMANNED AERIAL VEHICLE (UAV) IMAGERY
(Case Study in Kukup Coastal Area, Gunungkidul Regency, Indonesia)

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ABSTRACT:
The Kukup Coastal Area is located in the southern part of Java's coastal area, which has an active megathrust subduction zone. The dynamics of tectonic activities in this zone trigger earthquakes with various intensities. Some of these earthquakes can trigger a tsunami threatening human activities in this area. Therefore, a detailed study of tsunami hazards by integrating physical and socio-economic aspects needs to be done to estimate disaster risk and determine spatial planning in coastal areas. The objectives of this study are (1) to identify the coastal system and (2) to create a tsunami hazard map in the Kukup Coastal Area. Coastal systems can be identified by analyzing the physical and socio-economic conditions. Physical conditions such as morphological and coastal typology can be extracted from Digital Elevation Model (DEM) from aerial photo processing. Socio-economic conditions such as land use analysis and tourism activities can be extracted from orthophoto, which is extracted from aerial photo processing using drones. The tsunami hazard can be analyzed using three modelling stages: earthquake source modelling, tsunami wave propagation modelling, and tsunami inundation modelling using Geographic Information System (GIS). The results show that the morphological conditions in the study area were dominated by the formation of conical hills with a firm lineament pattern causing the formation of elongated basins such as labyrinths. This basin is a place for developing socio-economic activities, especially tourism, which can be seen from a large amount of built-up land area. The presence of these basins causes the tsunami inundation pattern to extend perpendicular to the shoreline, causing the tsunami inundation in the study area to extend as far as 2 km from the shoreline.

Key-words: *Tsunami, GIS Modelling, Coastal System, Coastal Typology, Remote Sensing.*

1. INTRODUCTION

The coastal area is a transition zone from land and sea, which has a unique natural and social process. The interaction between land and sea makes the physical and social environmental conditions in coastal areas dynamic and interrelated. The dynamics of the physical environment will affect changes in the social environment and vice versa. Therefore, a study on the development of coastal areas needs to be carried out comprehensively by taking into all aspects of the environment, both physical and social, often known as coastal system analysis.

Coastal system analysis can be studied from three aspects: natural processes, population development, and socio-economic activities in coastal areas (Supriharyono, 2000). Natural processes can be studied regarding the potential of natural resources and the threat of natural disasters. The potential of natural resources in the coastal areas causes the increasing population and the socio-economic development activities. This condition occurs in coastal areas in Gunungkidul Regency, one of which is the Kukup Coastal Area. The Kukup Coastal area has a natural beauty with white sandy beaches between the karst conical hills, which are used for mass tourism activities. Tourism activities in the Kukup coastal area trigger an increase in socio-economic activities.

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It can be seen from the increasing number of tourist visits in Tanjungsari District, Gunungkidul Regency from 2011 to 2019 (see **Fig. 1**). The decline occurred in the 2019 to 2020 due to the policy of restricting public mobility due to the Coronavirus Disease 2019 pandemic (COVID-19).

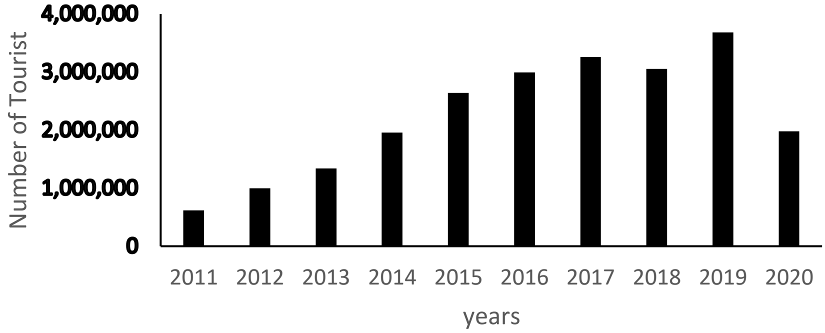

Fig. 1. The Number of Tourist in Gunungkidul Regency from 2011 to 2020
Source : Badan Pusat Statistik, 2021.

On the other hand, natural disasters can be a limiting factor in developing potential in coastal areas. Natural disasters often occur in coastal areas, such as land subsidence, abrasion, and tsunamis can be an inhibiting factor if they are not integrated into coastal area development planning. The occurrence of natural disasters not only changes the physical environment but also changes the pattern of socio-economic interaction (Rosselló, Becken, & Santana-Gallego, 2020) in coastal areas. Therefore, it is necessary to study the potential hazards of natural disasters by paying attention to the interaction of the physical and social environment (coastal system).

One natural disaster that potentially damages the Kukup Coastal Area is the tsunami. The Kukup Coastal Area is located in the southern coastal area of Java Island, which is close to the active megathrust subduction zone between the Eurasian Continental Plate and the Indo-Australian Ocean Plate in the Indian Ocean. Earthquakes still often occur in this subduction zone with varying intensities. Tectonic earthquakes with great intensity have caused tsunamis on the southern coast of Java Island in Banyuwangi in 1994 and Pangandaran in 2006 (Chaeroni, Hendriyono, & Kongko, 2013). The Pangandaran tsunami, with a height of 5-7 meters, surged along the southern coast of Java and was caused by an earthquake with a strength of > 7 Mw (moment magnitude) (Faiqoh, Gaol, & Ling, 2013; Widiyantoro et al., 2020). As a consequence of this incident, 664 people died, 498 people were injured, 1,623 houses were damaged, and economic loss reached 55 million US dollars (Anjar, Laksono, Widagdo, Aditama, & Fauzan, 2022). The southern coastal area of Java is the most at risk for tsunamis due to its dense population and proximity to an active subduction zone (Hall et al., 2017; Lavigne et al., 2007; Okamoto & Takenaka, 2009). Therefore, a study on the tsunami hazard is important to protect the socio-economic activities that develop in the Kukup Coastal Area and it also related to the opportunity to reduce the risk from tsunami.

The study of tsunami hazard has been widely studied, mainly in coastal areas in Indonesia with various approach methods such as in Cilacap Coast, Java, Indonesia (Anjar et al., 2022), Pangandaran Coast, Java, Indonesia (Faiqoh et al., 2013), Southern West Java Coast, Indonesia (Windupranata, Hanifa, Nusantara, Aristawati, & Arifianto, 2020), and Padang Coastal Area, Sumatra, Indonesia (Ashar, Amaratunga, & Haigh, 2018; Di Mauro, Megawati, Cedillos, & Tucker, 2013). Other research related to Tsunami risk and potential in this research such as from Mardiatno, Malawani, & Nisaa', (2020) The future tsunami risk potential as a consequence of building development in Pangandaran Region, West Java, Indonesia and Nisaa', Sartohadi, & Mardiatno, (2021) Participatory GIS Approach to Assessing Building Vulnerability to Tsunamis in Pangandaran Regency. The National Agency for Disaster Countermeasure, abbreviated (BNPB), as the state agency of disaster mitigation, has also produced a tsunami hazard map in the Southern Java coastal areas. However, most of the previous studies that have been carried out still utilize data with a medium to the small scale of detail. The inundation model provided by the government is based on national topographic maps/ *peta rupabumi indonesia* (RBI) with 12.5 meters contour interval and 1: 25,000 scale for land use identification, resulting inaccurate models (Marfai, Khakim, Fatchurohman, & Salma, 2021). Consequently, it will cause errors in tsunami inundation modelling in coastal areas with various topographical conditions. Some areas that should have been inundated were not flooded because of generalizations. This condition often occurs, especially in the karst coastal areas where small hills are located close to each other, such as in the Kukup Coastal Area.

This research uses high-resolution imagery from the unmanned aerial vehicle to model tsunami hazards in the Kukup Coastal Area. High-resolution aerial photography makes it possible to identify structural mitigation in coastal areas. The existence of a wave-retaining embankment on the shore will be well-modelled by utilizing An unmanned aerial vehicle (UAV) technology. UAV technology is expected to produce tsunami hazard modelling with detailed accuracy and pays attention to structural mitigation efforts carried out by communities in coastal areas. Based on the background of the problem described, this study aims (1) to identify the coastal system in the Kukup Coastal Area and (2) to create a tsunami hazard map in the Kukup Coastal Area.

2. STUDY AREA

The Kukup Coastal Area is one of the coastal in the southern region of Java Island, which is administratively located in Tanjungsari District, Gunungkidul Regency, D.I. Yogyakarta Province (see **Fig. 2.**). The Kukup Coastal Area is located near Baron Beach which is a favourite destination for tourists visiting. This beach can be accessed from the capital of Gunungkidul Regency, namely Wonosari, as far as 23 kilometres which can be reached in approximately 1 hour.

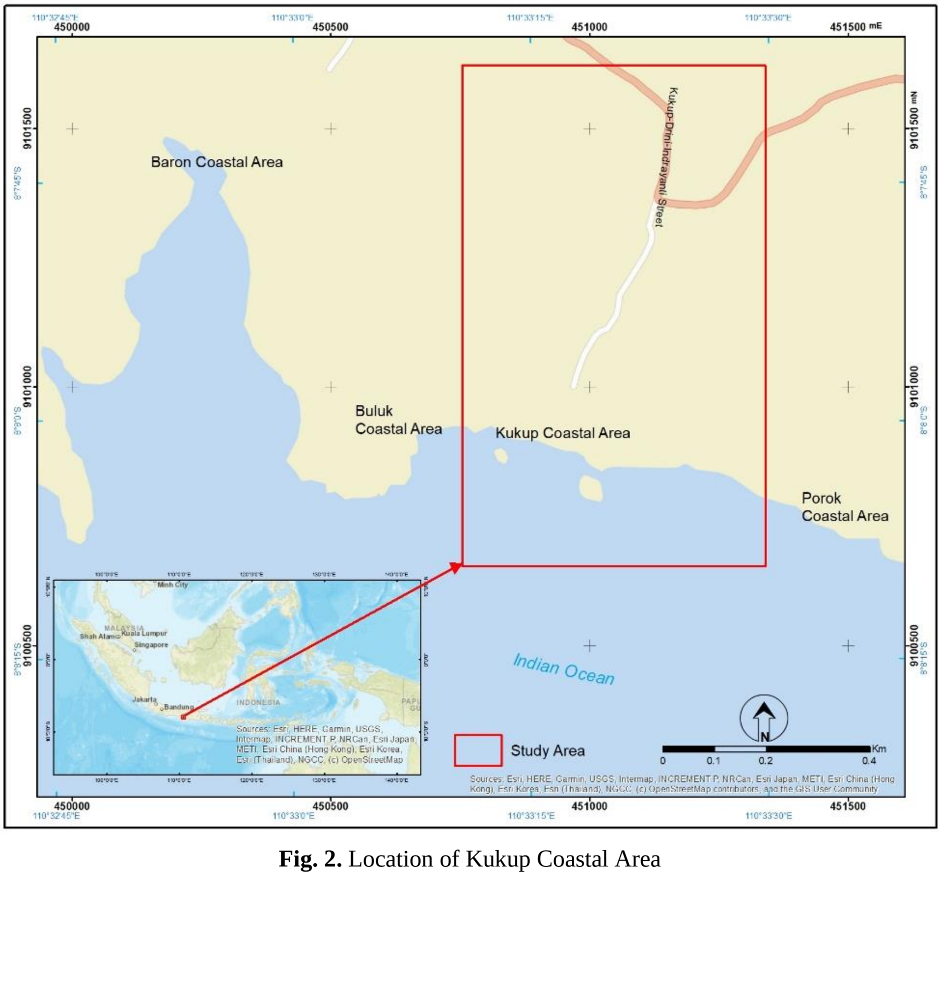

Fig. 2. Location of Kukup Coastal Area

The Kukup Coastal Area area has unique physical conditions in geology, geomorphology, and hydrology. Geologically, this coastal area is predominantly composed of reef limestone, characterized by the appearance of limestone with holes resembling coral reefs. Based on the geological map, this area is included in the Wonosari formation area, composed of reef limestone, calcarenite, and tuffaceous calcarenite. Calcarenite is a sandstone composed of carbonate minerals in it. The presence of reef limestones in the Kukup Coastal Area is in line with previous research, which states that the characteristics of the limestones in the Wonosari Formation are increasingly turning into hard reef limestones in the form of rudstone, framestone, and floatstone in the southern area (Bothe, 1929).

Geomorphologically, the Kukup Coastal Area area is controlled by two main processes, namely marine and structural processes. The structural process is seen by high cliffs directly adjacent to the sea around the Kukup Coastal Area, known as a cliff. The marine process is seen by the abrasion process caused by sea waves on the cliff. This process can be seen from the holes used by erosion from sea waves on high cliffs. In addition, the presence of beach sand with white sand material is a characteristic of deposition by sea waves resulting from erosion on limestone cliffs.

3. DATA AND METHODS

3.1. Coastal System Identification Using UAV Technology

UAV technology for aerial photo data acquisition has several advantages, including producing high-resolution aerial photos with relatively affordable costs or low costs. UAV technology for aerial photo data acquisition is suitable for detailed studies with a narrow area. This research has a narrow study area, namely the Kukup Coastal Area, which makes it easier for researchers to get detailed data. This study prioritizes detailed data to get a high accuracy of results. The utilization of UAV technology was chosen to obtain data with high accuracy. Utilization of GNSS technology with the Geodetic Global Positioning System (GPS) tool is also needed to improve the accuracy of the UAV result data. Geodetic GPS was used to obtain Ground Control Point (GCP).

Data that were obtained from UAV technology include orthophoto and Digital Elevation Model (DEM) data. The orthophoto data were used to interpret land use data and to analyze socio-economic data, especially the existence of built-up land. DEM data from UAVs were reprocessed into The Digital Terrain Model (DTM) data to obtain morphological and coastal typology data. Obtaining orthophoto and DTM data generally goes through two stages: field and post-field. Field observations, aerial photo data acquisition, and GCP acquisition were conducted during the field stage. After the field stage is complete, it proceeds to the aerial photo data processing stage. Aerial photo data was processed using the Agisoft PhotoScan Professional application.

There were several stages in processing aerial photo data using the Agisoft PhotoScan Professional application, including Align Photos, Inputting GCP coordinate to aerial photo, Build Dense Cloud, Build Mesh, Build Orthomosaic, and Build DEM. Align Photos is the process of identifying the points on each photo, and then a matching process is carried out between the same points. The following process is to build Dense Point Clouds. Dense Point Clouds are a collection of high points in thousands to millions resulting from photogrammetric processing of aerial photographs. This processing principle used structure from motion (SFM) which generated point cloud data from the reconstruction of patches between photos (Pranata & Cahyono, 2016). Point cloud data has 3D coordinate information (x, y, and z). Mesh, also called a 3D model, was the main processing output at Agisoft. The mesh data were used to generate DEM and Orthophoto data.

Output DEM data from UAV is Digital Surface Model (DSM). DSM data must be processed into Digital Terrain Model (DTM) data to obtain coastal morphology data. DTM is digital elevation data that eliminates the appearance of objects on the earth's surface, such as vegetation and buildings, so the surface relief is the actual condition of the relief above the earth's surface. The processing of DSM into DTM in this study was carried out in all study area both flat and hilly areas.DSM data processing into DTM data has been carried out using the PCI Geomatics application with the Terrain Filter (Flat) method.

Beside the DEM data, bathymetry data is also needed to create tsunami hazard modeling. There are two kinds of bathymetry data used in this research, namely GEBCO bathymetry data and BATNAS bathymetry data. GEBCO bathymetry data has a resolution of 30 arc seconds or around 1 km. BATNAS bathymetry data has a resolution of around 185 m. The BATNAS bathymetry data is used for modelling in the Indian Ocean region to the coastal areas. Meanwhile, GEBCO bathymetry data is used for modelling in the Indian Ocean region which is not covered by BATNAS bathymetry data.

3.2. Tsunami Hazard Modelling

One of the reasons that caused tsunami disasters in Southern Java Island is seabed dislocations that produce earthquakes (Wibowo, Marfai, Kongko, Mardiatno, & Nurwijayanti, 2019). The numerical modelling of tsunami wave processing was divided into three stages: earthquake source modelling, tsunami wave propagation modelling, and tsunami inundation modelling (Hasan, Rahman, & Mahamud, 2015). Massive earthquakes can occur because of the subduction zone of the Indo-Australian oceanic plate under the Eurasian continental plate in the south of Java Island. According to the 2017 Indonesia Earthquake Source and Hazard Map, the highest potential earthquake in the southern fault zone of Gunungkidul is 8.9 MW. This data is used by researchers to model the potential for a tsunami in the Coastal Area around Kukup Beach, Gunungkidul.

The following process was reconstructing the fault or vertical deformation, which could produce an 8.9 MW earthquake. Tsunami source construction was carried out by identifying earthquake parameters due to vertical deformation on the seabed surface. The dimensions and characteristics of deformation in this study were modelled based on the scaling law. Scaling law is a comparison of earthquake-triggering parameters used to estimate fault geometry. These parameters are magnitude, epicentre, depth, strike, dip, slip, L (length of the fault area), W (width of the fault area), and dislocations.

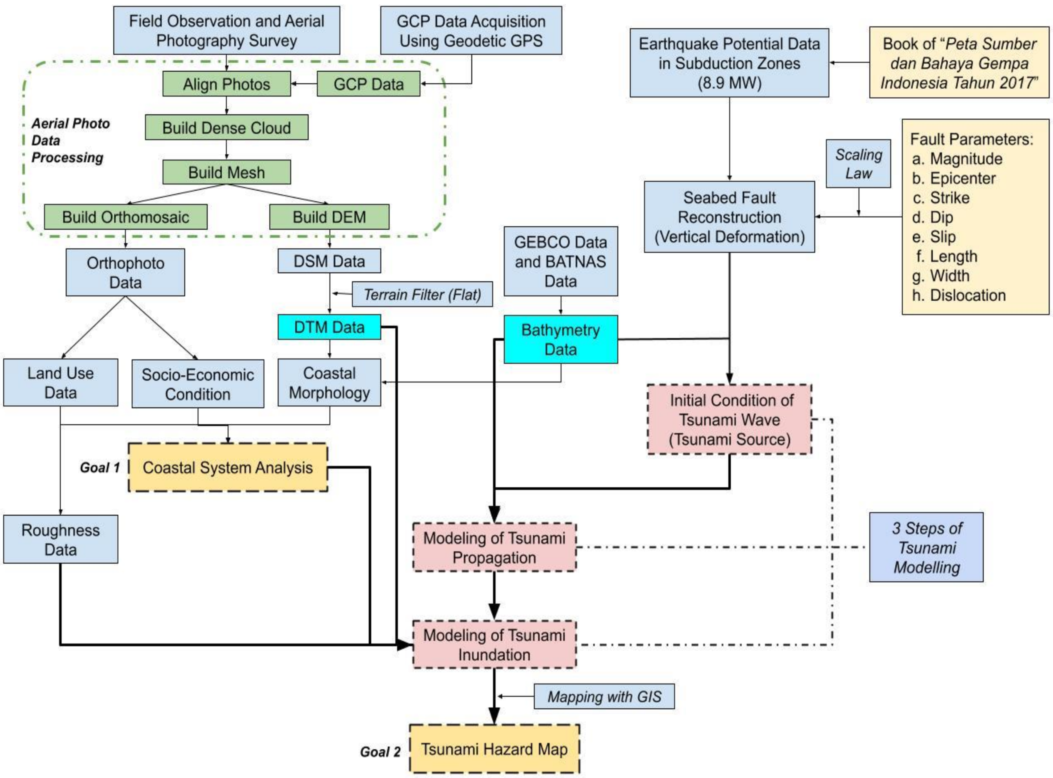

Fig. 3. Flowchart of Research Methodology.

After determining the earthquake source parameters, a tsunami source model was created to create a tsunami propagation and inundation model. The modelling of tsunami propagation and tsunami inundation was carried out using TUNAMI N3 software. Tsunami inundation modeling used a two data from UAV photo processing, namely DTM data and surface roughness from landuse interpretation and processing data. The modelling results were in the form of a tsunami inundation map of the potential of the highest waves. Next, the tsunami inundation map was classified to produce a tsunami hazard map based on the classification in the Head of BNPB Regulation No. 2 of 2012 (Perka BNPB No. 2 Tahun 2012). Overall, the research process is presented in **Fig. 3.**

4. RESULTS

4.1. Coastal System in Kukup Coastal Area

Coastal system analysis is important to study the dynamics that occur in coastal areas, especially for tsunami disaster identification. Identification of the coastal system can be made by utilizing remote sensing technology such as aerial photography imagery using drones. The results of aerial photography with drones can produce orthophoto and digital elevation model (DEM) data. The orthophoto was used to identify coastal areas' land cover and socio-economic activities. DEM can be used to describe the morphological conditions and physical environment characteristics in coastal areas.

4.1.1. Morphology and Physical Characteristics in Kukup Coastal Area

The results of processing aerial photos can produce Digital Surface Model (DSM) data using Agisoft Photoscan software. DSM is digital height data in the form of the height of objects that cover the earth's surface, so the presence of vegetation and building objects is identified as the height of the earth's surface. The results of DSM from aerial photo processing can be seen in **Fig. 4**. Furthermore, the DSM data can be modelled to produce a digital terrain model (DTM).

The comparison of DSM and DTM conditions in the Kukup Coastal Area can be seen in **Fig. 5**. Based on **Fig. 5**, the roughness of the surface relief of the plains in the DSM looks rougher, while the DTM data, the surface relief looks smoother.

Based on DTM, it can be seen that the Kukup Coastal Area has a morphology with various conical hills resembling a dome with closed basins, namely a cockpit. It is a characteristic of the karst landscape area in the southern part of Gunungsewu, namely the conical karst landscape. Some hills are also directly adjacent to the sea, so there are abrasion marks by sea waves known as cliff landforms. In addition, it can be seen that there is a straightness pattern on the karst hills in the coastal area of Kukup Beach with a northwest-southeast direction (see **Fig. 4.**). The existence of straightness causes the conical hills to become interconnected so that the closed basin pattern forms labyrinths. It is also a characteristic of the karst formation on the south side of Gunungsewu, namely the labyrinthic karst type. The labyrinth extending north-south becomes the centre of tourist activities and is the only access to the Kukup Coastal Area. It needs to be a concern because this labyrinth can be the location of a water passage when a tsunami occurs. In addition to tsunami hazard processing, DTM can be used to classify the typology of the Kukup Coastal Area. The coastal typology is influenced by several factors, namely genesis, coastal dynamics, and the current dominant geomorphological process. The coastal typology classification in this study was determined based on the tidal range, the main material, the genesis process, the slope, and the shape of the beach (Khakim, Soedharma, Mardiastuti, Siregar, & Boer, 2008; Malawani & Mardiatno, 2015; Shepard, 1973).

Tidal range data was obtained from previous research according Wibowo (2019) which *"Data from Tidal Model Driver (TMD) was taken around the area of interest, namely between the Baron and Sepanjang Coastal Area. One of the results of data extraction from TMD was tidal constant data. Tidal constant data was used to calculate the value of each vertical datum. Datum Highest Astronomical Tide (HAT) is the highest tide condition in about 20 years. On the other hand, the Lowest Astronomical Tide (LAT) datum is the lowest condition during that period. The Tidal Range value shows the difference between the mean high-water level (MHWL) and the mean low water level (MLWL), which is 1.719 meters located in Kukup Coastal Area."* (2019, pp 73-74).

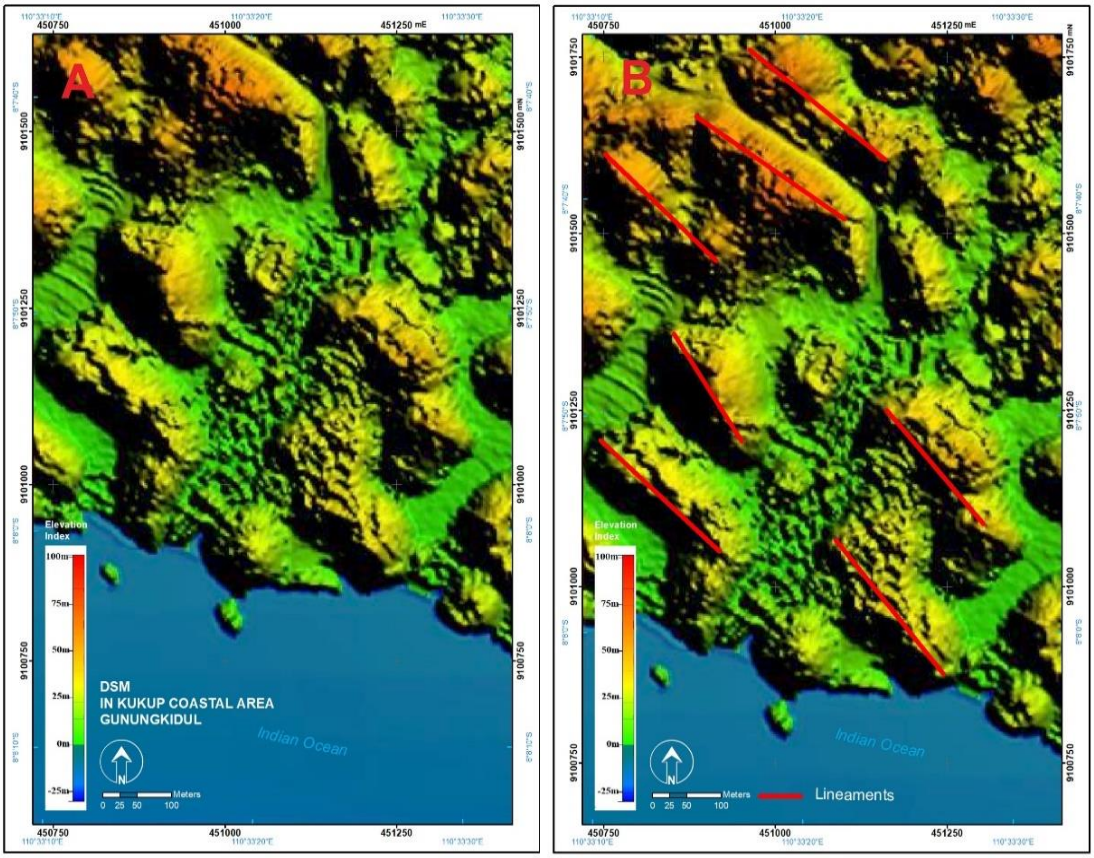

Fig. 4. DSM from UAV Foto Analysis (A) and Lineaments Identification Based on DSM Data in Kukup Coastal Area (B)

Tidal data range around Kukup Coastal Area was 1,719 meters (Wibowo, 2019). This value is similar to previous research (Khakim et al., 2008), which states that the tidal range on one of the beaches in Gunungkidul (Ngungap Beach) is less than 2 meters. The value of the tidal range of fewer than 2 meters indicates that the typology of the southern coast of Gunungkidul Regency, especially Kukup Beach, is dominated by the influence of waves (wave erosion coast).

Other parameters besides the tidal range are slope, constituent material, genesis, and beach shape. The Kukup Coastal Area is dominated by flat and steep slopes. In the flat area, the material is white sand with the primary dominant process, namely the deposition of marine deposits carried by longshore currents due to erosion on limestone cliffs. In the steep area, the material is hard reef limestone with the dominant processes in the form of structural and solutional. When viewed from the beach shape, all of the Kukup Coastal Areas have a concave shape. Based on these conditions, it can be concluded that there are two coastal typologies in the Kukup Coastal Area according to Shepard, (1973) classification, namely the Marine Deposition Coast on the flat area and the Wave Erosion Coast on the steep slope area (see **Table 1.**).

Meanwhile, according to the local scale (1:15,000), the Kukup Coastal Area has two typologies: the Sandy Coast in the flat area and the Rocky Erosion Coast in the steep slopes area. Based on previous research, the coastal typology of karst areas begins with a structurally shaped coast typology, becomes a wave erosion coast, and ends as a marine deposition coast (Marfai, Cahyadi, & Anggraini, 2013). It implies that the coastal typology at Kukup Coastal Area in the steep slope area will eventually turn into a coastal typology as in the flat area in the future.

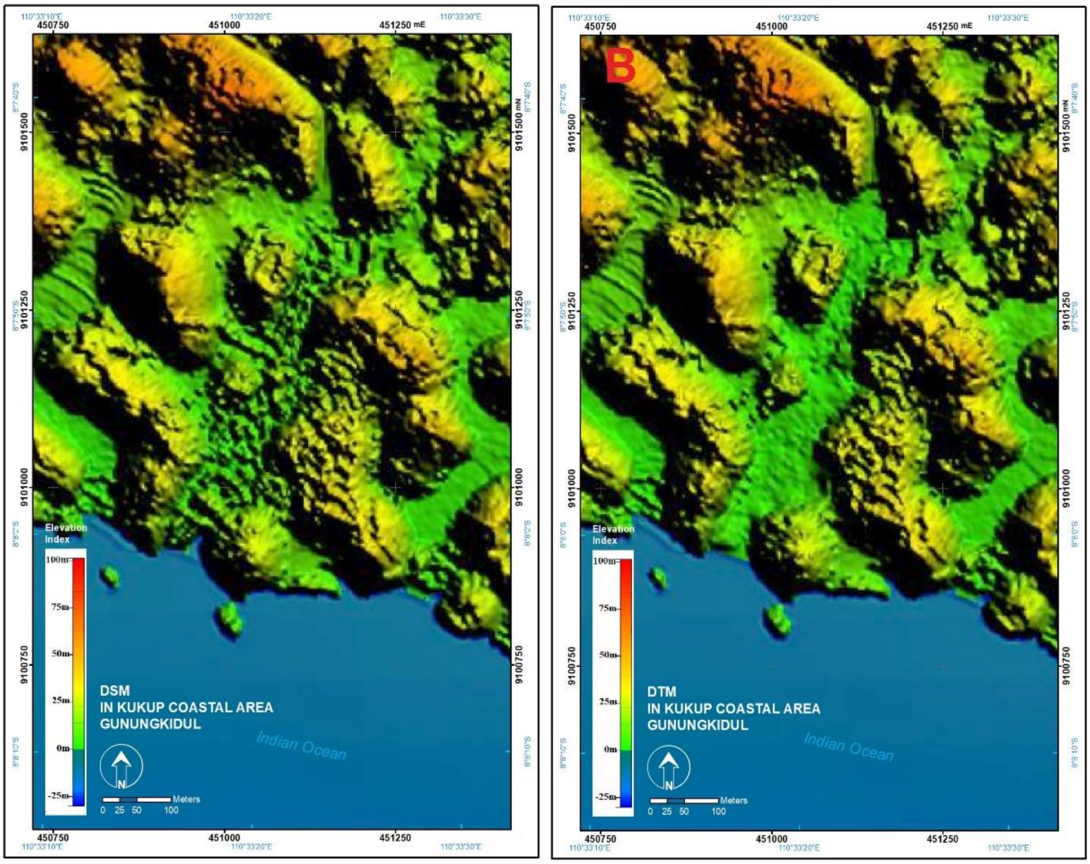

Fig. 5. Comparison of DSM and DTM Results Modelling.

Table 1.
Coastal Typology Classification in Kukup Coastal Area.

Coastal Area	Identification Parameters				Typology Classification	
	Slope	Parent Material	Genesis	Coastal Shape	Shepard (1973)	Local Scale (1:15,000)
Kukup	Flat-Undulating	Sand	Deposition	Concave	Marine Deposition Coast	Sandy Coast
	Steep	Calcareous Limestone	Erosion & Solutional	Concave	Wave Erosion Coast	Rocky Erosion Coast

4.1.2. Land Cover and Social-Economic Activities in Kukup Coastal Area

Land cover data can be extracted from orthophoto (see **Fig. 6.**) through manual digitization on screen. Visual interpretation was used to extract land cover data because it is more appropriate for narrow areas with higher accuracy, better data completeness, and accuracy of area calculation (Sari, Weston, Newnham, & Volkova, 2021; Zanella, Sousa, Souza, Carvalho, & Borem, 2012). Visual interpretation is an approach based on the recognition of spatial characteristics of objects such as hue/color, size, shape, texture, pattern, height, shadow, location, association, and convergence of evidence (Sutanto, 1994). The interpretation results show that there are 11 types of land cover: road networks with pavement, house yards, mixed gardens, built-up land, buried land, sandy land, grass, shrubs, dry land, agricultural land, and ponds. The land cover map in the Kukup Coastal Area can be seen in **Fig. 6**. Mixed gardens and dry fields are the dominant land cover in the Kukup Coastal Area, with an area of more than 50% of the total study area.

Mixed gardens are primarily found in areas with steep slopes on the hills, while dry fields are mostly found in plains or basins between karst hills. Sandy land or buried land is found only in areas near the shoreline known as sandy beaches. Built-up land and roads are found in an elongated pattern along the valley in the middle of the hill, with the main dominance of buildings for trade, lodging, public facilities, and buildings to support other tourism activities. The dominance of built-up land indicates that socio-economic activities in the Kukup coastal area have developed. The main socio-economic activities in the study area are tourism activities. The land use data results were used to classify the roughness class.

The surface roughness condition was interpreted as the fundamental friction value possessed by each land cover. Surface roughness values in tsunami hazard studies were used to minimize the tsunami inundation area and its maximum range (Kongko & Schlurmann, 2011). Surface roughness values can be classified by various approaches. The classification approach used in this study is the Chow classification (Chow, 1959). Surface roughness is divided into 13 classes based on land cover: house yards, road, mixed garden, ponds/ water bodies, buried land, built-up land, dry land, sandy land, grass, agricultural land, and shrubs. The surface roughness value in the Kukup Coastal Area was derived from land cover data previously processed using orthophoto data from aerial photo processing. Based on the classification results, it was found that there are seven classes of classification of surface roughness values in the Kukup Coastal Area. The lowest value, 0.007, is in the waterbody in the form of a pond. Meanwhile, the highest value, 0.05, is on the built-up land area for settlements. The distribution of surface roughness values follows the pattern formed by the land cover, which can be seen in **Fig. 6**.

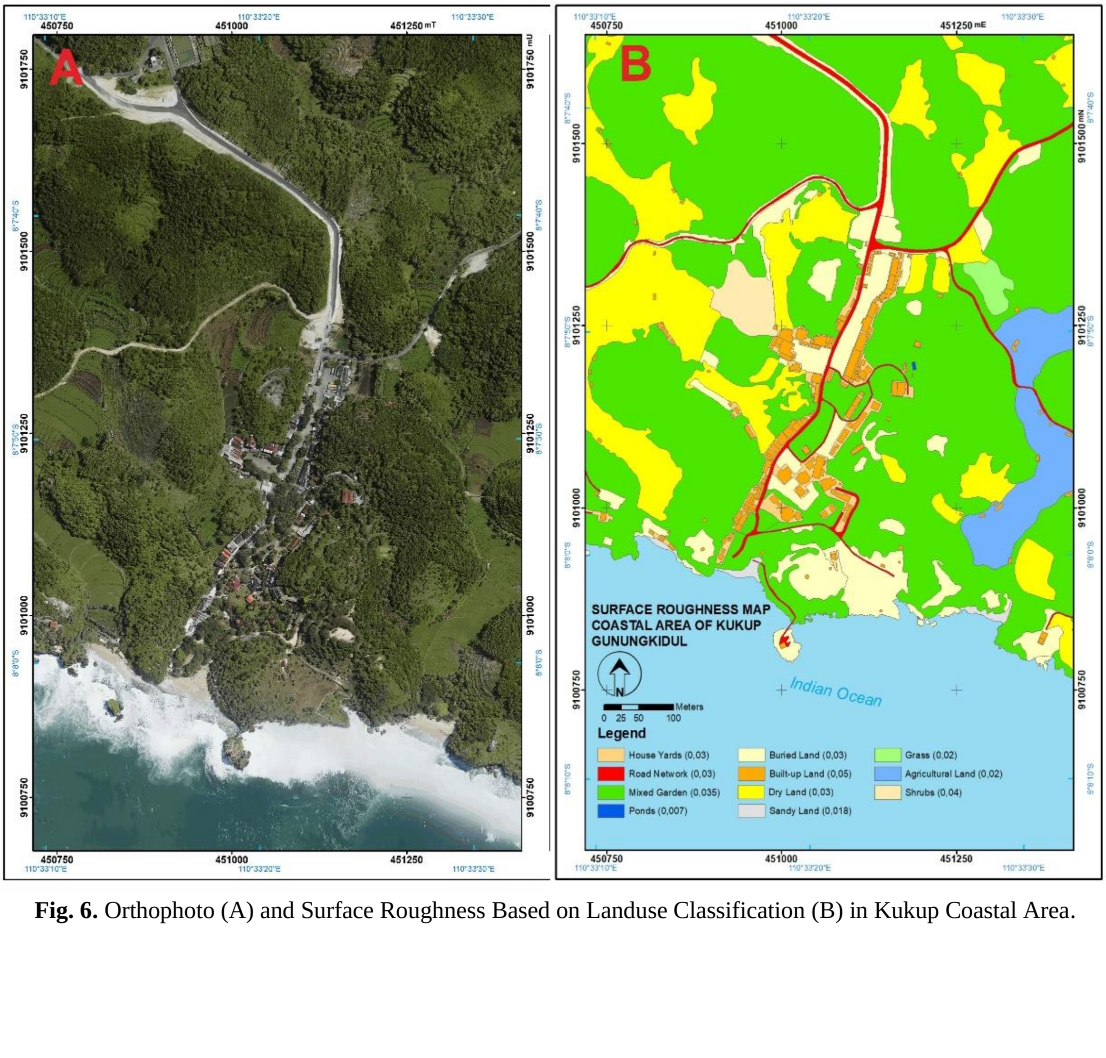

Fig. 6. Orthophoto (A) and Surface Roughness Based on Landuse Classification (B) in Kukup Coastal Area.

4.2. Tsunami Hazard in Kukup Coastal Area

The tsunami model created in this study uses earthquake data with a magnitude of 8.9 Mw. This magnitude was chosen based on the maximum earthquake potential in the southern megathrust segment of eastern Java (Tim Pusat Studi Gempa Nasional, 2017). This model also considers the suitability of the tsunami propagation into the mainland (run-up). Parameters that influence the suitability of tsunami run-up are DTM data and surface roughness. The DTM data has been processed based on aerial photography data, so it has a high spatial resolution. Meanwhile, the surface roughness data used in the modelling is non-uniform roughness based on the actual land cover conditions in the Kukup Coastal Area.

Based on the modelling results, there was an initial rise in sea level due to an earthquake with a magnitude of 8.9 Mw, as high as 6.7 meters, with a maximum decrease of 3.0 meters. Furthermore, a tsunami propagation model can be developed. Tsunami propagation modelling describes the process of tsunami propagation from the initial sea level condition after the earthquake and its distribution in all directions. This propagation is described as the relationship between tsunami height and time. Based on the modelling results, it was found that the tsunami reached the Kukup Coastal Area with a height of 5 cm in about 1,400 seconds (23 minutes). Next, the tsunami event was modelled for 90 minutes to determine the dynamics of the tsunami height for 90 minutes. Based on the modelling results, three high waves hit the Kukup Coastal Area. The first high waves came with a height of 10-12 meters at 23–25-minute intervals lasting 15 minutes. The second high wave came at 53-55 minutes intervals with a height of 12-14 meters for 5 minutes. The third wave is the highest compared to the two previous waves. The height of the third wave is 14.7 meters which occurred at 78-79 minutes.

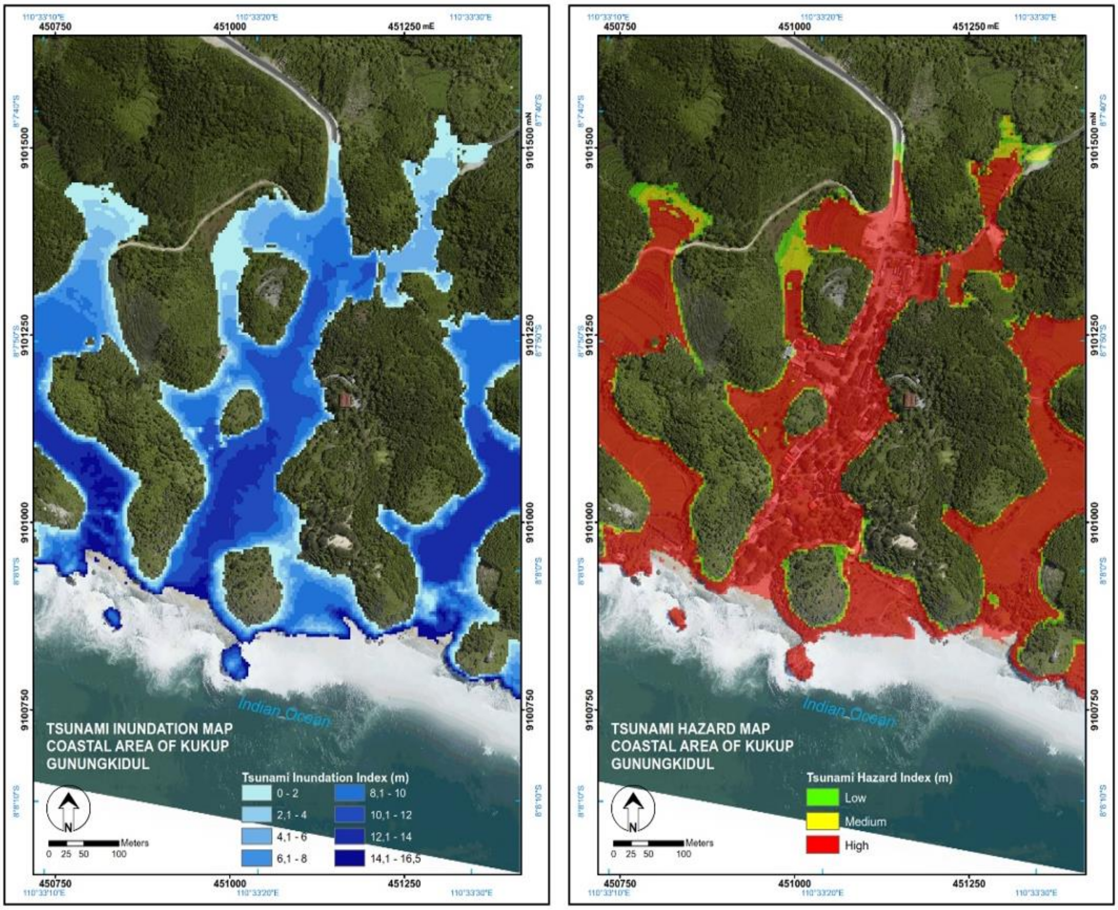

Fig. 7. Inundation (A) and Tsunami Hazard Maps (B) in Kukup Coastal Area.

Based on the tsunami source and propagation model, a tsunami inundation map can be made in the Kukup Coastal Area. This tsunami inundation map shows the inundation area due to the tsunami with an earthquake-triggering scenario of 8.9 Mw. The results show that the inundated area in the Kukup Coastal Area due to the tsunami was 23.53 hectares. The maximum height of tsunami inundation is 16.5 meters. The tsunami-formed inundation pattern shows a longitudinal pattern in the elongated basin between conical hills. This condition happens because the tsunami waves are concentrated at one point so that the run-up of the tsunami becomes elongated. Therefore, it can be concluded that the morphology in the coastal area also affects the propagation of tsunami inundation to the mainland. Understanding tsunami generation and subsequent inundation are needed in addition to the tsunami propagation model (Dias, Dutykh, O'Brien, Renzi, & Stefanakis, 2014). The tsunami inundation map in Kukup Coastal Area can be seen in **Fig. 7**.

The tsunami hazard map was made based on the tsunami inundation modelling in the Kukup Coastal Area. The assumptions used to create a tsunami hazard map follow BNPB regulations through the Head of BNPB Regulation No. 2 of 2012. This regulation has provided a standard for compiling disaster vulnerability classes, especially tsunami disasters, based on inundation heights. A tsunami inundation height of 0 - 1 meter is included in the low hazard index class, 1 - 3 meters is included in the medium hazard index class, and more than 3 meters is included in the high hazard index class.

ased on the results, it was found that the Kukup Coastal Area has a high tsunami hazard index, even far inland (see **Fig. 7**.). The low and moderate tsunami hazard index values are only found in a few areas adjacent to the hill or already on the hill ridge. This condition happens because the value of the tsunami run-up height in the shoreline is 15 - 20 meters, so the tsunami inundation still has a height of more than 3 meters when it reaches the mainland.

5. DISCUSSION

The tsunami hazard pattern formed in the Kukup Coastal Area extends south-north in the elongated basin between the karst hills. This condition should be a concern, mainly when a tsunami occurs; all forms of tourist and human activities in the elongated basin can become elements at risk of being affected by a tsunami. Therefore, it is necessary to develop a good tsunami disaster mitigation strategy to reduce the risk of a tsunami disaster in the Kukup Coastal Area. In addition, it is also necessary to determine the appropriate evacuation points and routes, considering that there is only one access road to Kukup Beach through the elongated basin.

The results of the tsunami inundation model in the Kukup Coastal Area show a unique pattern. The maximum tsunami height generated by the 8.9 Mw earthquake scenario is 16.5 meters on the Kukup Shoreline. The results of the tsunami inundation model in the coastal area are similar to previous studies conducted in the southern coastal areas of Java Island as high as 12-16 meters (Horspool et al., 2014); Cilacap, Central Java as high as 10-15 meters (Gayer, Leschka, Nöhren, Larsen, & Günther, 2010); Pandeglang, West Java as high as 15 meters (Lestari, Fitriasari, Ahmad, Rais, & Azhari, 2021); Blitar and Malang, East Java as high as 17.5 meters (Armono, Putra, & Wahyudi, 2021).

The height of the tsunami inundation in the Kukup Coastal Area decreased in areas far from the coastline. The decrease in tsunami inundation occurred due to differences in slope conditions at locations near the shoreline, which were relatively flat. In contrast, it was relatively wavy or wavy in areas far from the shoreline. Previous studies on tsunamis have also shown this condition based on tsunami inundation modelling (Hebert et al., 2012; Smart, Crowley, & Lane, 2015). The inundation pattern in the Kukup Coastal Area extends perpendicular to the shoreline, with a range of about 2 km from the shoreline. It is very different from the pattern of tsunami inundation that was modelled in the Pelabuhan Ratu Coastal Area, West Java (Setiyono, Gusman, Satake, & Fujii, 2017); Kuta, Bali; Padang, Sumatra (Gayer et al., 2010); Wediombo, Gunungkidul, Central Java (H Fatchurohman & Handayani, 2022); Palu, Central Sulawesi (Mikami et al., 2019); Banda Aceh, Sumatra (Prasetya, Borrero, de Lange, Black, & Healy, 2011) which extend parallel to the shoreline. Differences in tsunami inundation patterns occur due to coastal typology and morphological conditions (Hendy Fatchurohman, Cahyadi, & Purwanto, 2022; Takabatake, Chenxi, Esteban, & Shibayama, 2022).

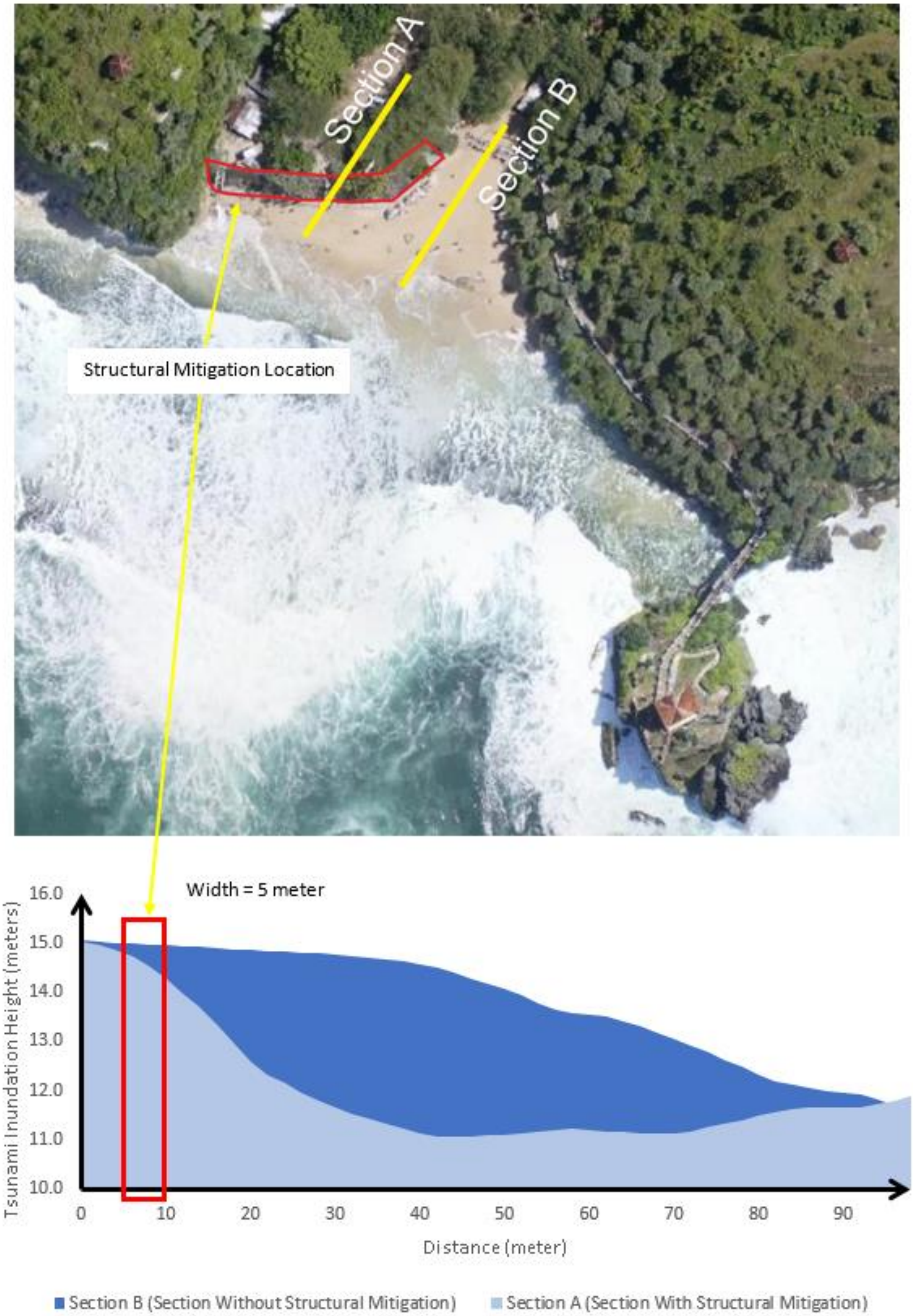

Fig. 8. Tsunami Inundation Slope Pattern in Segments with Barrier and Without Barrier.

The coastal typology of the Kukup Coastal Area, which is dominated by wave erosion, causes tsunami inundation concentrated in flat areas with a marine deposition coast typology. In addition, the morphological condition of the Kukup Coastal land, which is dominated by the appearance of conical hills with a firm lineament pattern, causes tsunami inundations concentrated lengthwise in the basins between these hills. It shows that the pattern of tsunami inundation is strongly controlled by physical conditions in the coastal area, mainly related to morphological conditions.

The accumulation of tsunami inundation concentrated and elongated in the inter-hill basin makes the risk in the Kukup Coastal Area relatively higher than other coastal areas because the nodal of human activity is in this elongated basin. The built-up land area has an elongated pattern in this basin which is also a place for the accumulation of tsunami inundation. This condition indicates that all human activities in the Kukup Coastal Area will be directly affected when a tsunami occurs. Therefore, it is necessary to carry out mitigation efforts to reduce the risk caused by a tsunami in this area.

One disaster mitigation that has been carried out in this coastal area is by making a long embankment near the shoreline. This embankment is made extending along the shoreline of the Kukup Coastal Area, which has the function of preventing coastal abrasion and preventing the big waves that will hit Kukup Beach. This building turned out to be quite effective in withstanding tsunami waves, as evidenced by the results of the inundation modelling. On the shore where there are embankments, the deflation of the tsunami inundation tends to be relatively fast compared to the tsunami inundation deflation on the shore without the embankment (see **Fig. 8.**).

The role of tsunami barrier buildings in disaster risk reduction could be identified in detailed tsunami modelling using drones using high-resolution aerial photo data. Drone photography data could produce elevation data that can describe the details of the wave-retaining embankment in the study area. It is one of the advantages of using aerial photography data by using a drone in tsunami modelling, which could describe the effectiveness of tsunami mitigation buildings to withstand big waves in coastal areas. The role of tsunami mitigation buildings will not be modelled if the tsunami modelling is carried out using medium or small-scale DEM data (Takabatake et al., 2022; Yamanaka & Shimozono, 2022). Therefore, it is crucial to use aerial photography data using a drone in tsunami studies, significantly to develop detailed mitigation planning in coastal areas, such as spatial planning for coastal areas, planning for evacuation points and routes, constructing wave retaining structures (Strusińska-Correia, 2017), and the use of wave-retaining vegetation (Wanger et al., 2020).

The results of this study indicate that structural mitigation by constructing a structural embankment is effective to reduce tsunami inundation in the Kukup Coastal Area. However, the construction of a structural mitigation for tsunami disaster mitigation has several weaknesses. First, the cost to build structural mitigation such as structural enbankment is expensive. Second, the existence of additional buildings in coastal areas can change the dynamics of the abiotic and biotic environment such as changes in ecosystem conditions, especially natural vegetation and changes in patterns of physical distribution of sand in coastal areas. There is another alternative for mitigating tsunami, namely by utilizing natural embankments in the form of natural ecosystems such as mangroves, sand dunes, greenbelt, or other natural vegetation which can lives in coastal area. Utilization of natural embankments is also effective to reduce the risk of a tsunami without changing the dynamics of the abiotic and biotic environment in coastal areas (Harada1 & Imamura, 2005). However, natural enbankment has several disadvantages. First, The effectiveness of vegetation also changes with the age and structure of the forest (Tanaka & Sasaki, 2007). Second, the nature enbankment is fragile due to antropological activities such as land conversion and ecosystem exploitation (Tanaka, 2009). Apart from that, establishing evacuation points and routes as well as socializing the tsunami disaster to the public and tourists is also important to reduce the risk of tsunami by increasing community capacity in dealing with tsunami disasters (Agussaini, Sirojuzilam, Rujiman, & Purwoko, 2022; Baeda, Suriamihardja, Umar, & Rachman, 2015).

6. CONCLUSIONS

The Kukup Coastal Area has very complex and interrelated physical and socio-economic conditions. The physical environment, dominated by conical hills with a firm lineament pattern, causes the formation of elongated basins between the conical hills. This elongated basin is a place for human activities, as indicated by the density of built-up land area for trading and supporting coastal tourism activities. In addition, this elongated basin also became a passageway for waves when the tsunami hit this area. The existence of longitudinal basins between the conical hills causes the tsunami inundation pattern to extend perpendicular to the shoreline, causing the tsunami inundation to extend as far as 2 km from the shoreline. The existence of community activities that are also concentrated in this basin causes an increased risk of a tsunami disaster in the Kukup Coastal Area.

The tsunami inundation in the Kukup Coastal Area has a unique pattern caused by a morphological condition in this coastal area. Based on the tsunami inundation model, it shows that all of the plain areas in the Kukup Coastal Area were inundated with heights between 2 – 16 meters. In fact, most of the plain area in the Kukup Coastal Area were inudated with a height of more than 8 meters. Therefore, most of the plain area in the Kukup Coastal Area have a high tsunami hazard. Meanwhile, moderate and low tsunami hazard areas are only found on the lower slopes of the hills in the Kukup Coastal Area with an inundation of 0 – 6 meters. Conditions of plain areas with a high tsunami hazard that are widely used for tourism and economic activities make it necessary to plan a tsunami hazard mitigation to reduce the risk of a tsunami in the Kukup Coastal Area. However, the determination of tsunami hazard mitigation efforts needs to be based on several tsunami hazard scenarios with various magnitudes of earthquake as a source values. This is the limitation of this research. This research was modelled tsunami hazard only with one magnitude of earthquake source, so it needs to create a tsunami hazard model by using other scenario to produce more effective and efficient mitigation efforts.

This study also found that using aerial photographic data with drones was very helpful in making detailed studies on tsunami hazards and inundation modelling. The existence of structural mitigation can be modelled with drone aerial photography so that the role of structural mitigation in tsunami hazards can be known directly. The presence of a wave retaining structure can speed up the tsunami inundation sloping process so the height of the tsunami inundation can be minimized. Therefore, it is crucial to use drone aerial photo data for tsunami inundation modelling to develop detailed mitigation directions for various coastal typologies.

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