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Participatory GIS Approach to Assessing Building Vulnerability to Tsunamis in Pangandaran Regency

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Abstract. Some cities in Indonesia which are located on Southern Java Island are susceptible to tsunamis. However, the application of participatory GIS for the assessment of building vulnerability to tsunamis remains rarely evaluated. The aims of this research are 1) to obtain the parameters of building vulnerability to tsunamis using the participatory approach, and 2) to evaluate the results of building vulnerability assessment using participatory GIS. A tsunami inundation map was constructed based on numerical modelling using the Hawke's Bay equation. Participatory approaches were taken to establish the parameters that affect the vulnerability of buildings to tsunamis using in-depth interviews. Respondents were selected using the purposive sampling technique. A geographic information system (GIS) was then applied to build a geodatabase and to perform analysis. The results show that six parameters were obtained from local people's participation, namely building materials, the number of stories of the buildings, orientation, preservation condition, building row, and natural barriers. All the parameters were identified and interpreted using aerial photos. A field survey was conducted to complete the information on building characteristics. Many buildings near the beach were classified as having high and moderate vulnerability. The main benefit of participatory GIS is that the role of the community makes a significant contribution to providing vulnerability information. It also raises public awareness and improves preparedness for disaster risk management. The drawback is that parameters based on participatory approaches are dynamic and may be different in other areas.

Keywords: tsunami, building vulnerability, PGIS, aerial photos.

1. Introduction

The southern part of Java island is an area that directly faces the subduction zone between the Indo-Australian and Eurasian plates. On 17 July 2006, a tsunami earthquake (Mw = 7.7) struck the southern coast of Java, Indonesia, affecting over 300 km of coastline and causing over 730 casualties. The triggering earthquake, located 225 km off the coast of Pangandaran (9.222◦ S, 107.320◦ E), occurred at 15:19 LT (Fritz et al., 2007; Lavigne et al., 2007; Mori et al., 2007; Reese et al., 2007). Around 3000 houses were destroyed by the flow depth, which reached 5 meters in Pangandaran (Fritz et al., 2007).

It is important to understand the related vulnerabilities and risks in order to increase the awareness of people affected by possible tsunami impacts (Arumugam et al., 2017; Dall'Osso et al., 2009b; Eckert et al., 2012; Suppasri et al., 2011). Risk is the interaction between hazard and vulnerability from the selected element at risk (UNDRR, 2021), while vulnerability consists of physical, social, economic and environmental factors. The physical factor in the form of building vulnerability is one of the important aspects in the context of tsunami risk reduction (Sathiparan, 2020). Besides having economic value, buildings also function as places for the community to live (Westen, 2013).

Several models and methodologies have been developed to evaluate tsunami vulnerability in recent years. The most popular model is the Papathoma Tsunami Vulnerability Assessment (PTVA), which was first proposed by Papathoma et al. (2003). It was then revised by Dominey-Howes & Papathoma (2007) as PTVA-2, by Dall'Osso et al. (2009a) as PTVA-3 and by Dall'Osso et al. (2016) as PTVA-4. Each of these has been successfully applied to various study areas, including PTVA-1 in Greece (Papathoma et al., 2003; Papathoma & Dominey-Howes, 2003). PTVA-2 in Seaside, USA (Dominey-Howes et al., 2010); PTVA-3 in Sydney (Dall'Osso et al., 2009b), in the Aeolian Islands, Italy (Dall'Osso et al., 2010), in Malaysia (Ismail et al., 2012), in Portugal (Santos et al., 2014), in Japan (Voulgaris & Murayama, 2014), in Chabahar Bay, Iran (Madani et al., 2017), and in Chile (Fritis et al., 2018); and PTVA-4 in Sydney, Australia (Dall'Osso et al., 2016), and in Chile (Fritis et al., 2018).

None of the PTVA models involves the local people/community in determining the parameters of building vulnerability; instead, the parameters are based on a subjective procedure that relies heavily on the "expert judgment" of the authors (Tarbotton et al., 2012). Community and individual local spatial knowledge have considerable value-added for understanding disaster risk situations and designing community-based improvements (Bollin & Hidajat, 2006; McCall, 2008). Involving communities in preparing vulnerability assessments can increase their effectiveness and ensure that the assessment is relevant to those who are most at risk (Rasheed, 2021), while meaningful community engagement helps improve awareness of the risks posed by certain hazards (Barua et al., 2020; Hosseini & Izadkhah, 2020). Participatory GIS is a useful tool for extracting people's knowledge and perceptions of environmental problems and hazards, and for presenting and communicating these to environmental scientists and local authorities (Westen et al., 2011).

The two main aims to conduct this research were: 1) to obtain the parameters of a building vulnerable to a tsunami using a participatory approach; and 2) to evaluate the results of the building vulnerability assessment using participatory GIS.

2. Research method

The study area was located in Pangandaran Regency, specifically in Ciliang Village, Parigi Subdistrict, approximately 14 km from Pangandaran City called Batuhiu tourist area. The total area is around 34.75 ha, with a total of 180 buildings and different types of landcover, such as built-up areas, agriculture, plantations, shrubs, bare land/open land, and fishponds (Figure 1).

The tourist attractions of Batuhiu are one of most well-known destinations in Pangandaran Regency. The number of visitors has increased two-fold since 2013, from around 60,000 to approximately 155,000 in 2017 (Dinas Pariwisata Kabupaten Pangandaran, 2018).

Batuhiu was chosen to conduct the tsunami vulnerability assessment because: (1) the area was seriously affected by the 2006 tsunami; and (2) the area has experienced significant development since the event.

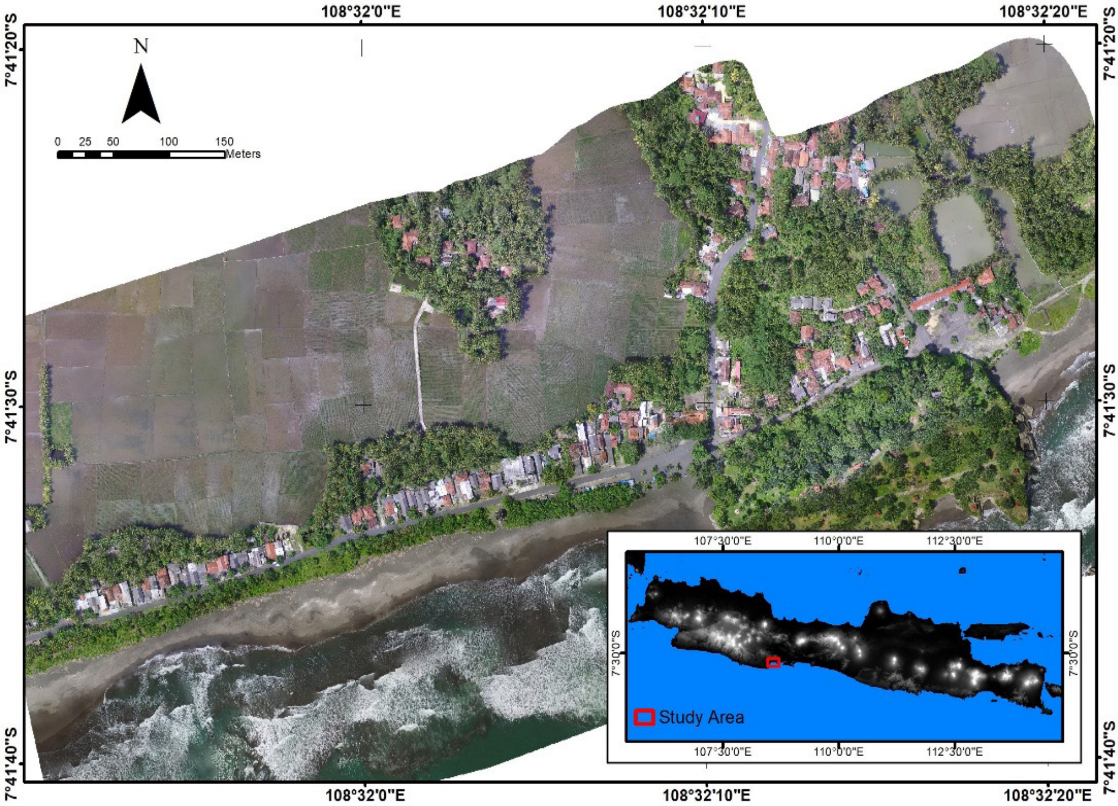

Figure 1. Study area

2.1 Tsunami inundation model

The tsunami inundation map was created based on numerical modelling using the Hawke's Bay equation developed by Berryman (2006). This model requires three main inputs: the wave height on the coastline, the roughness coefficient (Manning's coefficient), and the slope (see Table 1). The hazard scenario employed data from Reese et al. (2007), specifically for the Batuhiu area, where the wave height on the shoreline was 5 m. Roughness data were created by extracting land-use data from the manual digitization of aerial photos of the study area. The slope was derived from DEM downloaded through the website http://tides.big.go.id/DEMNAS/ provided by government agencies (BIG) (see Table 1). The Hawke's Bay equation is

$$H_{loss} = \left(176\, n^2 \div H_0^{1/3}\right) + 5\, sinS$$

where H_{loss} is the loss in wave height per meter of inundation distance; H_0 is the wave height at the coast; n is the surface roughness coefficient; and S is the slope.

The equation can be implemented using the ArcGIS cost-distance function, which determines the least cumulative cost to travel over a cost surface.

Table 1. Data required to produce the hazard map

Data type	Source	Resolution
Tsunami height scenario	Reese et al. (2007)	
DEM	DEMNAS BIG (http://tides.big.go.id/DEMNAS/)	0.27-arcsecond
Land-use	Aerial photos	0.04m

2.2 Participatory approach and data collection

Participatory approaches are valuable in assessing the vulnerability and capacity of communities (Twigg, 2015). They allow experts to learn from local communities that have different perspectives on vulnerability assessment (De Brito et al., 2018). Working with local communities can help professionals gain greater insight into those they meet, enabling them to work more effectively and produce better results (Twigg, 2004).

Participatory approaches were conducted to establish the parameters that affect the vulnerability of buildings to tsunamis, using in-depth interviews and purposive sampling. The emphasis of the purposive sampling technique is on the character of the sample member, which is considered to represent the character of the population. The sample members were considered to understand the circumstances of the surrounding environment, such as the local government and/or local people, who potentially know about building vulnerability. Five participants were selected: the village secretary, sub-village head, head of the village administration, the head of RT, and resident. Both the head of the village administration and the head of RT were local people who were affected by the tsunami in 2006.

Previously, we made preliminary parameters based on the existing model. We choose PTVA-4 because it is the latest update of the PTVA model and it has many attributes compared to other models. These preliminary parameters aim to give a framework and general description of building vulnerability. They facilitated the interviews and reduced any dialogue that was not relevant to the main topic.

Data collection was based on an aerial photos (0.04m resolution) and a field survey. We attempted to compile data based on participatory interpretation. For the parameters that could not be identified from the aerial photos, we gathered building detail information by the field survey.

2.3 Participatory GIS modelling and evaluation

We utilized a geographic information system (GIS) to build a geodatabase and to perform the modelling. The criteria for each parameter and its weighting factors are defined base on previous research. For the evaluation, we compared the results of the PGIS modelling with existing modelling (PTVA-4).

3. Results and Discussion

3.1 Tsunami inundation model

The tsunami inundation model was developed based on previous models. The total affected area was 24.88 ha. As can be seen in Figure 2, the eastern part of the study area was a slightly inundated area that protected by small hill from the sea (Mardiatno et al., 2020).

A tsunami inundation map is important to obtain the flood depth value for each assessed building along the affected area. This is very influential on the vulnerability of buildings; the greater the danger, the higher the vulnerability.

3.2 Participatory approach

Based on the interviews, most of the participants had the same opinion, that the building material, number of building stories, natural barriers, and building location have a very important effect on the vulnerability of buildings. From their experience of the tsunami in 2006, the majority of buildings made of timber or bamboo suffered severe damage. Building made from traditional brick were also damaged because they were built without reinforced columns. This is consistent with the findings of Reese et al. (2007) in their research on damage observation. In addition, the number of floors has a significant effect on vulnerability. In the 2006 tsunami, only two buildings survived, one of which was a building with two floors. Buildings with more than one floor use reinforced concrete in their construction, which is considered more robust. Dall'Osso et al. (2016) state that the number of floors is proven to be directly correlated with the level of damage.

Natural barriers are an important parameter; in this case the presence of a small hill on the eastern side, which gave protection to the area behind it from the tsunami. It can be seen that the buildings located behind the hill was not damaged. On the other hand, buildings that were surrounded by shrubs suffered significant damage. Furthermore, building rows have an important effect on building vulnerability. The interviews indicated that buildings close to the shoreline or in the first row after the coastline tended to experience severe damage. Buildings located far from the coastline are potentially safe from the tsunami threat.

The orientation parameters of buildings are characteristics that fairly influential on the vulnerability of buildings. Ismail et al. (2012) and Mück et al. (2013) show that if the main side of a building is parallel to the shoreline, it is highly vulnerable. On the other hand, buildings perpendicular to the coastline are less at risk. This was pointed out by the respondents. Evidence shows that a building with a door facing the sea will be perforated in the middle, but can still be repaired. A moderately important criterion is the preservation condition; newer buildings have the benefit of good construction using simple reinforced concrete and are better maintained.

According to the respondents, two unimportant criteria are the foundations and artificial barriers. Most of the buildings have a foundation with a height of 80-100 cm for the masonry and simple reinforced concrete. Furthermore, artificial building like a brick wall is rarely found due to building function which used for shops or cafés. The scores and criteria of the participatory approach parameters are based on previous research as explained in Table 2.

It is clear that the parameters derived from the participatory approach have fewer criteria than the existing model (see Table 3). PTVA-3, which was developed into PTVA 4, has a variety of parameters. The advantages of the current models are the form of universal parameters, which can be applied anywhere. On the other hand, the participatory approach was conducted to reveal local criteria. It can be seen that participatory criteria can only be adjusted to the local area

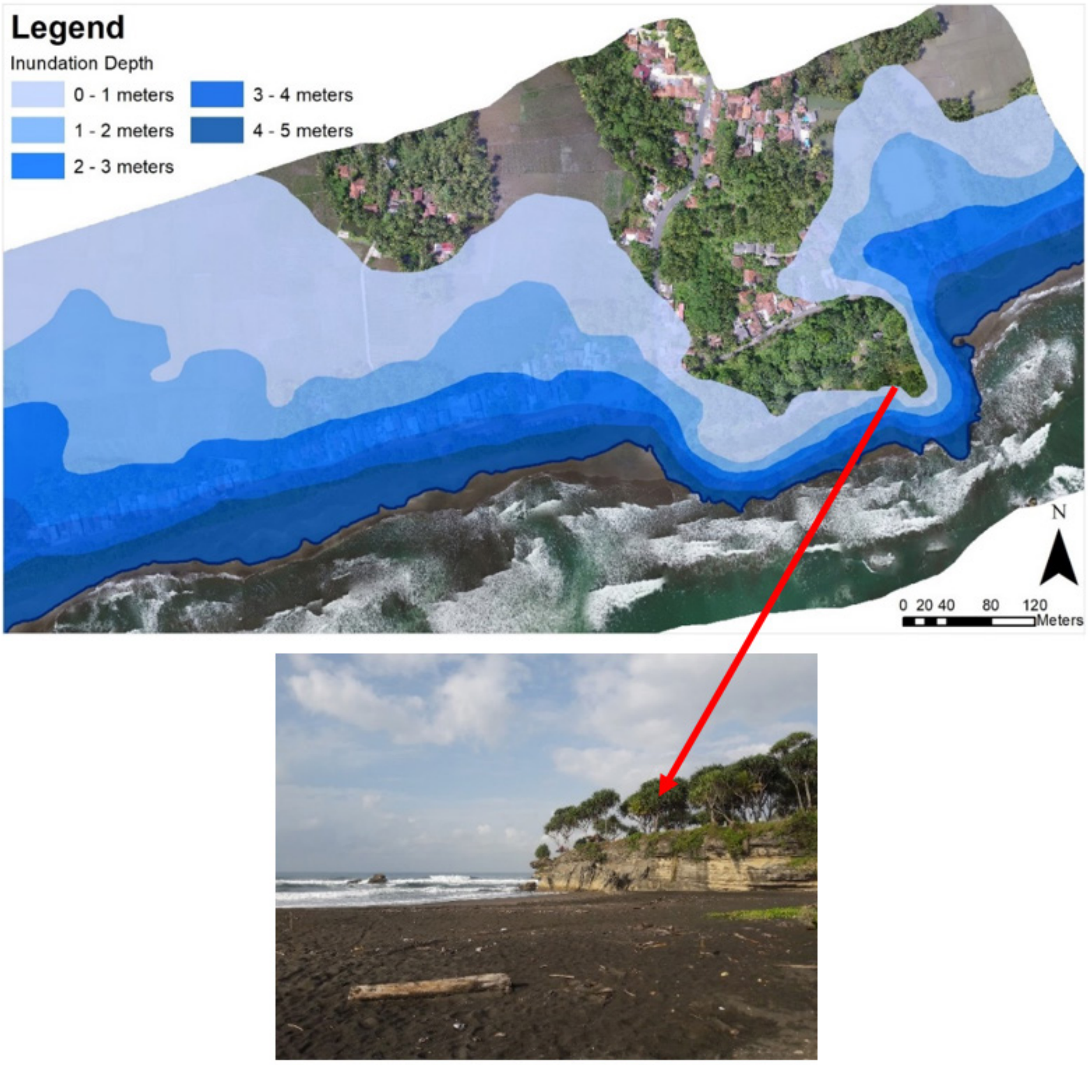

Figure 2. Tsunami inundation in the study area and the small hill that protects the area from the sea.

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Table 2. Scores and criteria of the participatory approach parameters

Parameter	Score and Criteria				Sources
	4 (Very high vulnerability)	3 (High vulnerability)	2 (Moderate vulnerability)	1 (Low vulnerability)	
Building material	Timber and/ or bamboo	Timber or bamboo with few bricks	Masonry	Brick with simple reinforced concrete	(Reese et al., 2007); PTVA-3 (Dall'Osso et al., 2010); PTVA-4 (Dall'Osso et al., 2016)
Parameter	**Score and Criteria**				**Sources**
	4 (Very high vulnerability)	**3 (High vulnerability)**	**2 (Moderate vulnerability)**	**1 (Low vulnerability)**	
Number of stories		1	2	>2	(Reese et al., 2007); PTVA-3 (Dall'Osso et al., 2010); PTVA-4 (Dall'Osso et al., 2016)
Orientation		Main side parallel to the shoreline		Main side perpendicular to the shoreline	PTVA 2 (Dominey-Howes & Papathoma, 2007); (Ismail et al., 2012; Mück et al., 2013)
Preservation condition	Poor	Average	Good	Excellent	PTVA-3 (Dall'Osso et al., 2010); PTVA-4 (Dall'Osso et al., 2016)
Building location	1st row	2nd and 3rd	4th – 6th	>6th	PTVA-3 (Dall'Osso et al., 2010); PTVA-4 (Dall'Osso et al., 2016)
Natural barrier	No protection	Low protection	Moderate protection	High protection	PTVA 1 (Papathoma et al., 2003); PTVA 2 (Dominey-Howes & Papathoma, 2007); PTVA-3 (Dall'Osso et al., 2010); PTVA-4 (Dall'Osso et al., 2016)

Table 3. Comparison of the number of criteria to define tsunami vulnerability

Participatory approach	PTVA-1 (Papathoma et al., 2003)	PTVA-2 (Dominey-Howes et al., 2010)	PTVA-3 (Dall'Osso et al., 2010)	PTVA-4 (Dall'Osso et al., 2016)
- Building material - Number of stories - Orientation - Preservation condition - Building location - Natural barriers	- Building material - Building row - Surroundings - Condition of the ground floor - Number of floors - Sea defence - Natural environment	- Water depth above the ground surface - Building row number (from the sea) - Building material - Number of floors - Orientation of building - Condition of building - Building surroundings - Land cover	- Number of stories - Material - Ground floor hydrodynamics - Foundation strength - Shape and orientation - Moveable objects - Preservation condition - Building row - Natural barriers - Seawall - Surrounding wall	- Number of stories - Material - Ground floor hydrodynamics - Foundation strength - Shape of the building footprint - Preservation condition - Building row - Natural barriers - Seawall height and shape - Brick wall around the building - Sources of large movable objects

3.3 Participatory GIS analysis and evaluation

The geographic information system (GIS) was an amazingly powerful tool to establish a geodatabase of the six main parameters obtained from the participatory approach. For all the attributes collected, we conducted scoring and weighting. Determination of the weighting factor was based on Dall'Osso et al. (2016) and Mück et al.(2013). Table 4 shows that building materials and building location have higher values, while preservation condition has a lower weighting value. This is corroborated by Reese et al. (2007), who found that semi-permanent constructions near the beach suffered severe damage.

The participatory GIS model (Figure 3) shows that most of the buildings near the shoreline have high and moderate vulnerability, while those away from the coast and protected by small hills have low vulnerability. The results from the PGIS model were compared with models from PTVA-4 (Figure 4) for evaluation purposes. There is a considerable difference between the high and low classes, while the moderate classes have slight difference (Figure 5). Both use Jenks' natural breaks classification with a different value.

Participatory GIS implementation is still dynamic; the parameters of building vulnerability in one region will differ from another depending on the knowledge and experience of the community. Participatory GIS application will excel when the area studied has experienced a tsunami disaster. People have a significant influence on the provision of vulnerability information because they already have experience related to the homes they live in. The application of participatory approaches to areas that have never experienced a tsunami can be made by applying the results of participatory GIS parameters in other regions that have the same physical or social characteristics.

Table 4. Weighting factors of building vulnerability parameters

Parameter	Weighting	Source
Building material	100	PTVA-4 (Dall'Osso et al., 2016)
Number of stories	85	PTVA-4 (Dall'Osso et al., 2016)
Orientation	25	Mück et al. (2013)
Preservation condition	34	PTVA-4 (Dall'Osso et al., 2016)
Building location	100	PTVA-4 (Dall'Osso et al., 2016)
Natural barriers	72	PTVA-4 (Dall'Osso et al., 2016)
Total	**416**	

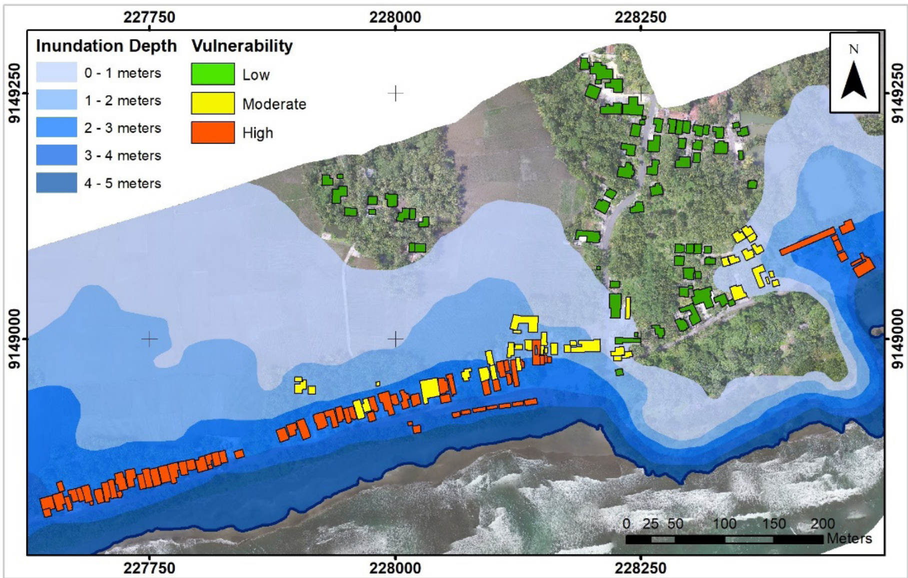

Figure 3. Map of building vulnerability to tsunamis based on the participatory approach

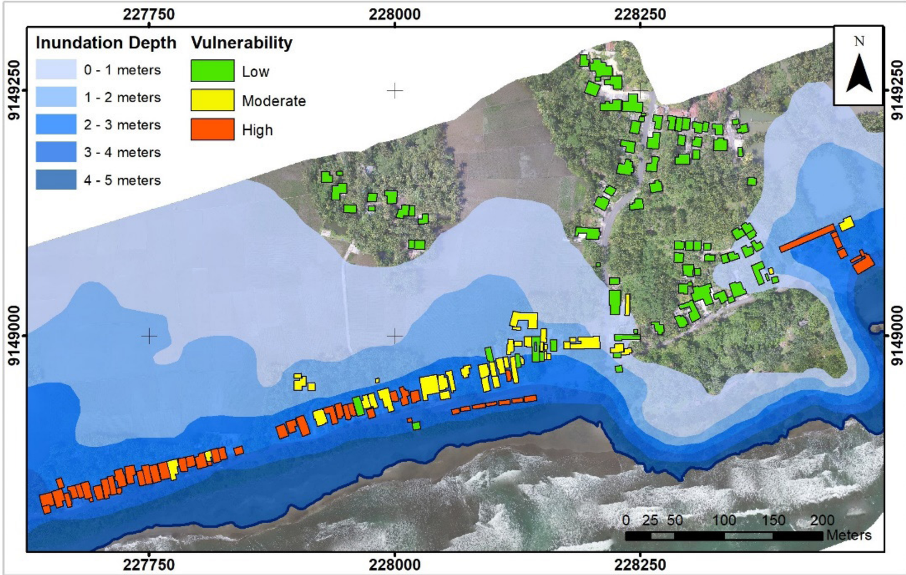

Figure 4. Map of building vulnerability to tsunamis based on PTVA-4 models (**Nisaa' et al., 2019**)

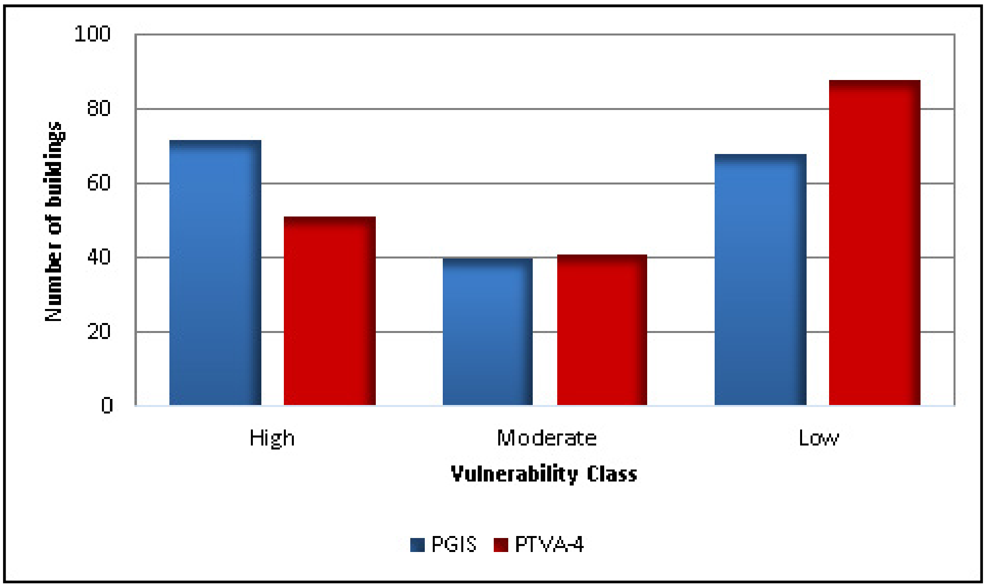

Figure 5. Comparison of the number of buildings in each class between PGIS and PTVA

4. Conclusion

The Batuhiu tourism area in Pangandaran Regency needs to be considered further by the government due to the lack of awareness of the tsunami threat. It can be seen clearly that the buildings near the beach are classified as highly vulnerable. Furthermore, the role of the community has a significant influence on providing vulnerability information. It also raises public awareness and improves preparedness for disaster risk management. Participatory GIS is fairly successful for effective application to rural areas. The criteria of participatory approach parameters, such as building material, number of stories, orientation, preservation condition, building location, and natural barriers, can be processed and represented by the GIS. However, this study only used previous research on determining weight parameters. It would be better if the community was also involved in determining the weight of each parameter. Besides, parameters based on participatory approaches are dynamic and can change in other areas. This relates to the knowledge of the community and the characteristics of the region.

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