MAKARA, TEKNOLOGI, VOL. 16, NO. 2, NOVEMBER 2012: 163-170

COASTAL PHYSICAL VULNERABILITY OF SURABAYA AND ITS SURROUNDING AREA TO SEA LEVEL RISE

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Abstract

The study for coastal vulnerability to sea level rise was carried out in Surabaya and its surrounding area, it has focused on calculations of the physical vulnerability index were used coastal vulnerability index (CVI) methods. It was standardized by the multi criteria analysis (MCA) approach according to the study area. The score of each physical variable derived from remote sensing satellite data and the results of studies that have been done, such as modeling results and thematic maps, and then integrated into geographic information systems (GIS). Result of this study shows that the coastal areas of Gresik, Surabaya, and Sidoarjo in the very low to very high vulnerability level. Physically, the low land areas with open and slightly open coastal have a high vulnerability category. The high level vulnerability was found located in the northern of Madura Strait (Gresik Regency) that overlooks to the Java Sea is about 28.81% from the entire of study areas. Meanwhile, the moderate, low and very low levels of vulnerability were located on Surabaya and Sidoarjo Regency that have more protected coastal area, relatively. According to the physical condition, the coastal elevation is the most variable that contributes to the high of vulnerability index in the coastal of Surabaya City and Sidoarjo Regency.

Abstrak

Kerentanan Fisik Pesisir Surabaya dan sekitarnya terhadap Kenaikan Muka Air Laut. Penelitian kerentanan fisik pesisir Surabaya dan sekitarnya terhadap kenaikan muka air laut difokuskan pada perhitungan indeks kerentanan fisik dengan pendekatan metode *coastal vulnerability index* (CVI) yang distandarisasi dengan *multi criteria analysis* (MCA) sesuai daerah kajian. Nilai setiap variabel kerentanan fisik diperoleh dari data satelit penginderaan jauh serta hasil penelitian dan kajian yang sudah dilakukan berupa hasil pemodelan dan peta-peta tematik, kemudian diintegrasikan dalam sistem informasi geografis (SIG). Berdasarkan hasil analisis, daerah pesisir Kabupaten Gresik, Kota Surabaya dan Kabupaten Sidoarjo memiliki tingkat kerentanan fisik terhadap kenaikan muka air laut pada kategori sangat rendah hingga sangat tinggi. Wilayah dengan tingkat kerentanan tinggi secara fisik merupakan wilayah dataran rendah dengan kondisi pantai langsung menghadap Laut Jawa. Di seluruh daerah penelitian diketahui berada pada kategori kerentanan tinggi hingga sangat tinggi sebesar 28,81% yang sebagian besar terdapat di bagian utara Selat Madura (Kabupaten Gresik). Sementara itu, Kota Surabaya dan Kabupaten Sidoarjo yang kondisi pantainya relatif lebih terlindung memiliki tingkat kerentanan sedang, rendah dan sangat rendah. Kondisi fisik yang paling berkontribusi terhadap tingginya tingkat kerentanan pesisir di daerah kajian adalah elevasi pantai.

Keywords: coastal vulnerability, sea level rise, remote sensing, CVI, MCA

1. Introduction

The coastal area is very vulnerable towards the global warming phenomena causing sea level rise. The prediction by Intergovermental Panel on Climate Change (IPCC) in 2007 [1] shows that the sea level rise in average was 2.5 mm/year and it is estimated that it will reach 31 mm in the following decade. Diposaptono *et al.* In 2009 [2] mentioned that the sea level rise per year in Surabaya reaches 5.47 mm.

Surabaya as the second biggest city in Indonesia with the high population number and density and with the settlement area and the industrial city located on the coast has quite a big potential having the impact by sea level rise.This potential is supported by the topography of Surabaya city dominated by a lowland area (±80% of the area), so that it is vulnerable towards a physical change if sea level rise keeps happening.The condition can threaten and interrupt the socio-economic activities and infrastructure particularly in the coastal area[3-4].

The vulnerability evaluation of the coastal area is really required in the framework of the evaluation towards the impacts and possibilities of the response related to the phenomena change occurring. The evaluation which can be conducted includes the sensitivity of the coastal area towards sea level rise and the significant meaning of the coastal area from the social, economic, and ecological value. Various coastal vulnerability evaluation methods were done with the index-based approach. One of the general methods used to evaluate physical vulnerability such as erotion and/or inundation towards sea level rise was coastal vulnerability index (CVI) [5].

In general, the CVI method applies a simple approach in providing a ranking numeric base of the coastline sections towards a physical change so that it can be used for identifying the areas having high risks [6]. This method has been used in the coastal vulnerability evaluation national program towards sea level rise in the United States of America and the sea level coastal vulnerability evaluation in Indonesia [2].

Most of the coastal vulnerability level evaluations particularly in the coastal area of the big cities in Indonesia are solely based on the same CVI criterion system for a different scale scope. The method application like this causes the output obtained does not really represent the condition of the area scope studied so that it is necessary to do standardization of variable ranking and vulnerability index which are specific for each coastal area evaluated. The application of Multi Criteria Analysis method has some accessibility in analyzing index having different types, units, and weight of each index attribute analyzed [7].

The objective of this research is to spatially evaluate the coastal physical vulnerability of Surabaya and its surrounding area to sea level rise with the standardized CVI method, and to determine the most contributing factors towards the coastal vulnerability in Surabaya and its surrounding area.

2. Methods

Variable data gathering and management. The score of every physical vulnerability variable was obtained from remote sensing satellite data, research results, and the studies conducted such as modelling results and thematic maps. The score of vulnerability index obtained was then integrated in GIS (Geographical Information System) so that the spatial information of the coastal vulnerability level in Surabaya and its surrounding to sea level rise was obtained. The data processing and analysis for vulnerability evaluation were done with the assistance of the software ER Mapper 6.4, Arc View 3.4, and Microsoft Excel 2007.

The physical variables used in the coastal vulnerability study are geomorphology (landform), elevation or height (m), coastal line change rate (m/year), the mean tidal range (dm), sea level rise rate (mm/year), the mean wave height (m).The analysis unit which becomes the vulnerability evaluation unit of every variable was determined with the buffer in line with the (longshore) coastal line with the distance of 1 km seaward and landward, while the limit of the cross shore used the village administrative boundaries located on the edge of a shore.The number of analysis units along the research areas of Gresik Regency, Surabaya City, to Sidoarjo Regency is ±172 km consisting of 59 units suitable with the number of subdistricts located on the edge of a shore.

This research is the development from the previous research at [7] and [8], where at those studies the elevation variable is more preferred than the slope, with the elevation variability consideration higher than the slope in the sloping coastal area.The coastal line change analysis was also developed by doing tidal correction first to reduce coastal line shift mistakes because of the tidal differences during the satellite data acquisition. The development at the village administrative based analysis unit with the 1 km buffer in line with the coastal line was used with the consideration of the analysis unit measure representative for variation observation of each variable in the study area with the length of ±172 km, and the identification accessibility in the administrative area. The variable types and the data gathering and management are shown in Table 1.

Data analysis. Physical vulnerability analysis started with Multi Criteria Analysis (MCA) to do variable ranking standardization based on the CVI method and vulnerability index score normalization. The data standardization of every variable started by searching for the lowest and the highest scores of every variable gathered from the data extraction results of the six variables in the study area.The standard score of every variable in the next analysis unit was determined to use the following equation [9]:

$$X_{in} = (x_{in} - \min x_{in}) / (\max x_i - \min x_i) \quad (1)$$

where:
X_i = the standard score of variable number order *i* in the analysis unit number order *n*
x_{in} = the original score of the variable number order *i* in the analysis unit number order *n*
$\max x_i$ = the highest variable score
$\min x_i$ = the lowest variable score

Table 1. Data Gathering and Management of Variables

Data Type	Ways to Gather and Manage Data
Coastal line change rate	Obtained through image visual interpretation of Landsat time series in the period of 32 years (1979-2011). The coastal line change was calculated with a transec connecting coastal lines at different time and its shift was calculated in a meter/year unit, by first doing the tidal correction in accordance with the satellite data orbit time.
Geomorphology (landform)	Obtained through image visual interpretation of Landsat ETM+ (in the years 2003 and 2011) and DEM data from RBI topography. Classification refers to the resistance power of the land form types towards erotion suitable with the CVI model [6], with the vulnerability ranking from 1 to 5.
Elevation	Obtained from the elevation point interpolation of RBI (Indonesian Land Image) digital map with the scale 1:25,000. The extraction of mean elevation variable at the analysis unit was done using zonal statistic tool.
Meantidal range	The tidal data are obtained from the 2005–2011 tide gauge measurement results. The tidal range was calculated from the mean differences of the highest tide and the lowest tide.
Mean sea level rise rate	The sea level rise data were obtained from AVISO which is the Topex/Poseidon altimeter satellite observation data, downloaded from http://www.aviso.oceanobs.com. The sea level rise trend data were available from 1992 to 2011.The data are in a form of the interpolated and resampled grid, and then the meanscore was extracted into every analysis unit.
Mean wave height	The data were obtained from BMKG based on the wind data estimation by using the wave model of Windwaves-05 in the time period of 2000-2010. The mean annual wave height was then interpolated and resampled, and then extracted into every analysis unit.

The standardization results made the score of every variable have the minimum and maximum range between 0 and 1.Based on the approach in the CVI method dividing the variable ranking interval into 5 categories, the variable score division of the standardization results (CVI-MCA) was also divided into 5 categories using the percentile distance rule with the variable vulnerability category:very low (<0.2), low (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), and very high (>0.8). From the ranking system, the vulnerability index score calculation refers to the same approach with the CVI equation:

$$CVI = \sqrt{(a * b * c * d * e * f) / 6} \quad (2)$$

where:
a, b, c, d, e,and f : vulnerability ranking of each variable

If the ranking of all variables in the CVI method is simulated with the lowest score, which is 1, or the highest score, which is 5, then the index output range will be obtained with the lowest, which is 0.41, and the highest, which is 51.03. By applying the CVI method in the coastal area wherever, it will produce the minimum and maximum index range output completing a relation as follows:

$$0.41 \leq \min \leq \text{index CVI} \leq \max \leq 51.03 \quad (3)$$

From the index score relation in the equation (3), the index score standardization with the CVI-MCA approach can be done using the index score normalization approach formulated as follows [7,10]:

$$NS = (nub - nlb / oub - olb)*(OS - olb) + nlb \quad (4)$$

where:
NS = new index score
OS = original index score
nub = the highest limit of the new index score
nlb = the lowest limit of the new index score
oub = the highest limit of the original index score
olb = the lowest limit of the original index score

With normalization, the minimum (0.41) and maximum (51.03) index scores of each will become 0 and 1. Thus, the vulnerability index category division based on the percentile distance will complete a relation as follows starting from very low to very high vulnerability:

$$0 \leq \min \leq \text{index CVI MCA} \leq \max \leq 1 \quad (5)$$

3. Results and Discussion

Coastal line change rate. In the vulnerability analysis, how fast a part of the coastal line has experienced abrasion or accretion can become the vulnerability indicator of the area. The area experiencing the fastest abrasion will add the vulnerability level towards sea level rise.

Based on the coastal line change analysis for the time period of 32 years (1979-2011), it is showed that an area experiencing the biggest change such as accretion or moving forward shore is the coastal area of Kalisari Village, Mulyorejo Subdistrict, Surabaya City with the coastal line change rate as much as 38.9 m/year (Figure 1). Other areas which also experience quite a fast accretion are Keputih Village, Surabaya City (Keputih river mouth), and Kedungpandan Village, Sidoarjo Regency which is Porong river mouth. Meanwhile, the areas experiencing the fastest abrasion are Tanjungwidoro and Bedanten Village, Bungah Subdistrict, Gresik Regency with the coastal line moving backward rate reaching 22 m/year.

Besides that, the areas which are also very dynamic are Pangkah Kulon and Pangkah Wetan Village, Gresik Regency, which, on one side, their area experiences abrasion, but on the other side there is a fast accretion happening. This occurs because of the sedimentation activity at the Bengawan Solo river mouth. According to Pariwono [11], with the occurrence of erotion in an area, it means the sedimentation process is happening (the coastal line moving seaward) in another area.This phenomenon is also seen at the Keputih river mouth on its northern part, which is Keputih Village experiencing high accretion, yet on its southern part, which is Wonorejo Village experiencing quite a high abrasion. In the urban and port areas, such as Gresik Town and Surabaya City, there is a coastal line moving forward change which is mostly caused by reclamation along the coast.

Elevation. Figure 2 shows the height condition of all the coastal areas of Gresik, Surabaya to Sidoarjo. Generally, almost all coastal areas are sloping areas with the height between 0 and 5 meters. On the coastal area 1 km from the coastal line having the height to 15 meters it is found in Kramat, Manyar, and Indro Village, Gresik Regency. Meanwhile, the coastal areas having the height more than 20 meters, among others, are in Prupuh and Banyuurip Village, Gresik Regency,which are hilly areas along the coast.

Based on the results of the mean area height in every analysis unit, it is discovered that the area having the mean height of the biggest land is Banyuurip Village with the height of 10.9 meters.The low areas with the mean height of 1 meter which are mostly found along the coastal areas of Gresik to Sidoarjo are areas vulnerable towards sea level rise. Based on its land height factor, the high areas, such as Banyuurip Village, are the areas which are not vulnerable to sea level rise phenomena.

Geomorphology. Based on the coastal land form visual analysis of Gresik, Surabaya, and Sidoarjo, there are nine coastal geomorphological units, which are alluvial land, coastal alluvial land, tidal land, delta, estuary, lagoon, low hills, moderate hills, and high hilly areas (Figure 3). In general, the geomorphology in the coastal area of those three regions is dominated with coastal alluvial land and alluvial land alternated with low hilly morphology and moderate hills on the north and east coast parts of Gresik Regency. Geomorphology like low, moderate, to high hills is located on the western part of Surabaya City, and on the north and south of Sidoarjo Regency. A form of delta is found in the area of Ujung Pangkah, Gresik (Bengawan Solo Delta), and

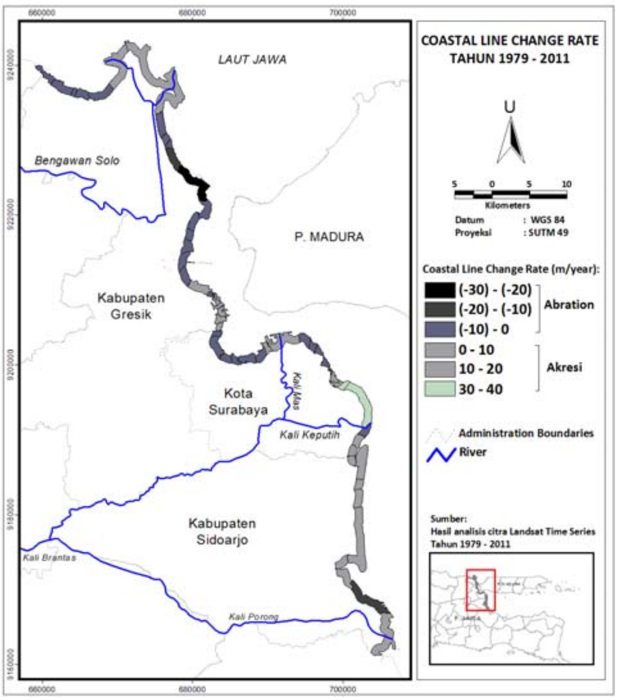

Figure 1. Coastal Line Change Rate of Surabaya and its Surrounding Area of the Years 1979-2011

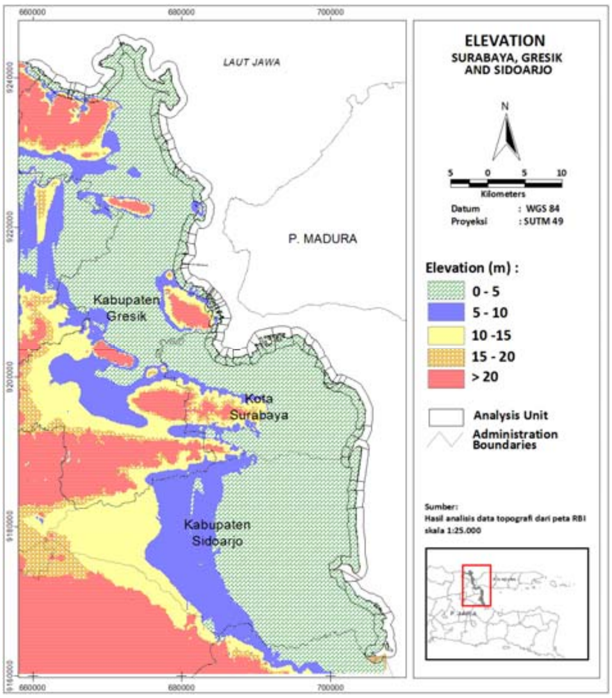

Figure 2. Coastal Line Change Rate of Surabaya and its Surrounding Area of the Years 1979-2011

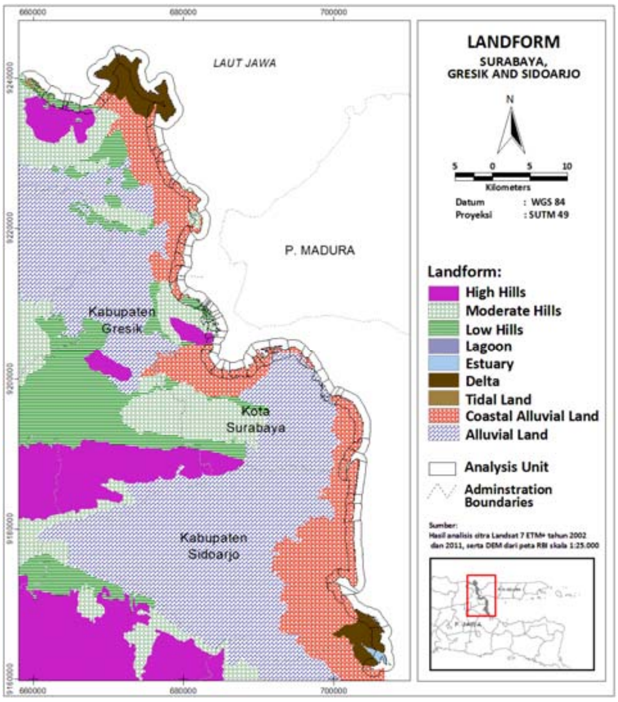

Figure 3. Land Form of Gresik Regency, Sidoarjo Regency, and Surabaya City

Porong River Mouth (Brantas Delta), Sidoarjo, besides, the estuary is also located on Porong River Mouth.

Based on the land form analysis result, the area width of every land form class in every analysis unit is transformed to become ranking/score with a ranking reference based on the vulnerability level according to CVI criteria. Based on the calculation result of the land form ranking using the equation (1) in every analysis unit, it shows that the highest score which is 5 is found in most coastal areas covering 27 Subdistricts. The areas with the highest score have a higher vulnerability level if seen from its geomorphological aspect.

Sea level rise rate. Figure 4 shows the sea level rise trend per year in Surabaya waters and its surrounding area, which in general ranges from 5.4 to 5.8 mm/year.The highest sea level rise lies on the northern part of Gresik's waters and the lowest lies on the waters of Sidoarjo. The sea level rise score in the waters of Gresik to Sidoarjo is bigger than the sea level rise globally, which ranges 3 mm/year [12].

Based on the above altimeter satellite data, the sea level rise rate (of the years 1992-2011) in Surabaya City was around 5.69 mm/year. Meanwhile, from the research conducted by Abdurrahchim [13] in his calculation using the benchmark observation on land that the sea level rise rate in Surabaya City was around 5.47 mm/year so that there is a slight difference which is around 0.22 mm between those two calculations.The difference is relatively small so that the sea level rise rate score from the altimeter satellite can be used in this research.The observation result of the sea level rise from the altimeter satellite published by AVISO of France shows that there is consistency with the sea level rise data from the observation result of National Tide Station Network operated by Bakosurtanal [14].

The difference which may happen can be caused by the difference of the calculation method and by also the difference of the time period of the observation conducted. Besides that, in this research the observation of the sea level rise has not taken into account that there are local factors, such as land subsidence or up lift, the ground water consumption level, and other factors.

Mean wave height. Figure 5 shows the analysis result of the mean annual wave height in the period of time of 2000–2010. Based on the mean annual wave height, it can be discovered that the wave height in all research areas ranges between 0.1 and 0.8 meter. The highest wave happens on the north waters of Gresik and the lowest on the waters around Surabaya City. This can be caused by the location of Surabaya area on the Madura Strait which is quite protected. The higher the wave, the

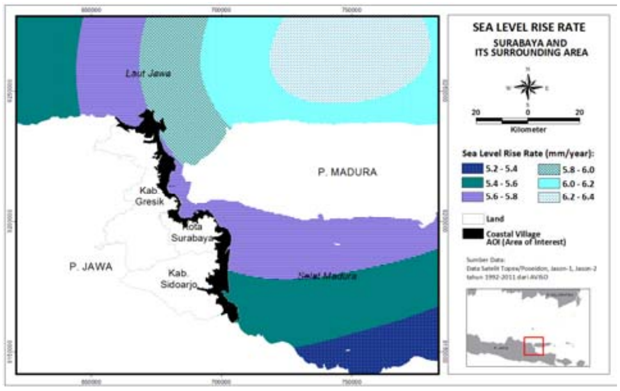

Figure 4. Mean Sea Level Rise Rate of Surabaya Waters and its Surrounding Area

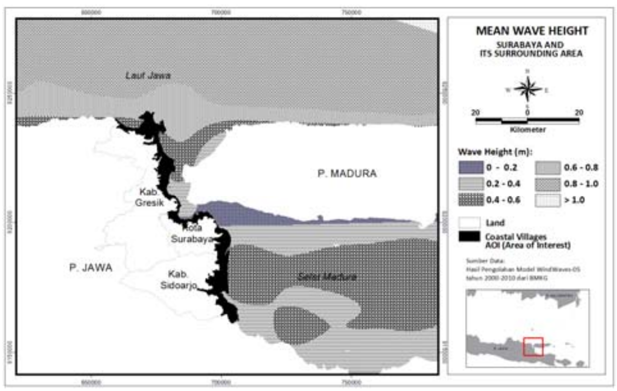

Figure 5. Mean Annual Wave Height of Surabaya Waters and its Surrounding Area

more it will influence the coastal line change and the area geomorphological condition so that it will add vulnerability in the coastal area.

Mean tidal range. Based on the data from Tanjung Perak Maritime BMKG, the condition of tide in the research areas is divided into two parts, which are the west zone covering western part of Surabaya to Gresik and Tuban, and the east zone covering the eastern part of Surabaya to Sidoarjo. In Imaduddina [15], it is also mentioned that the west zone division starts from Semampir subdistrict, Surabaya City to the north direction, which includes Gresik Regency and Tuban Regency. Meanwhile, the west zone starts from Kenjeran subdistrict to Sidoarjo Regency.

Based on the daily pattern, it is discovered that in the west zone the daily tide pattern is diurnal, which means it expeciences one high tide and one low tide on one day. Meanwhile, in the east zone covering the eastern part of Surabaya to Sidoarjo, the daily tide pattern is a combination having an inclination to be double, which means it experiences twice high tides and twice low tides on one day.

From the daily tide data, we then analyzed until we obtained Mean Highest Water Level/MHWL, Mean Lowest Water Level/MLWL, and Tidal Range. In determining the coastal vulnerability index, the score required was the mean tidal range in the study area. Based on the calculation, it is discovered that the mean tidal range for the west zone areas was 1.87 m, while the mean tidal range for the east zone was 2.91 m so that the tidal range of the east zone was higher than the tidal range of the west zone.

The high tidal range can cause inundation permanently or episodically. The area with a high tidal range is very vulnerable towards permanent inundation. That area is also vulnerable towards periodical inundation, so the coast with macrotidal tide will be more vulnerable than the area with lower tidal range [16]. Based on the tidal range data along the Gresik coastal area to Sidoarjo, it can be showed that the east zone coastal areas, which are from the eastern part of Surabaya to Sidoarjo, have a more vulnerable condition than the northern part of Surabaya to Gresik because these areas have a higher tidal range.

Coastal physical vulnerability. The ranking/score system of each variable in determining the coastal vulnerability was decided based on the data range of each variable. In this research, the lowest score (the best potential) and the highest score (the worst potential) of every variable were collected from the extraction results of all variables in the study area, which consist of six physical variables.The data in Table 2 are the highest and the lowest scores of every variable from the extraction results in every analysis unit in the entire study areas.

By making the variable score standardization in every analysis unit based on the lowest and the highest scores above, the score range of all variables was between 0 and 1. The variable standardization results were then divided into 5 discretes using the percentile distance rule with the variable vulnerability categories: very low (<0.2), low (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), and very high (>0.8). Afterwards, overlay of all variables was made, and its index calculation used the CVI equation, index normalization was also done.

Based on the CVI index score normalization in this research, we obtained the CVI minimum index score which was 0.05, while the maximum index score was 0.56. The physical vulnerability index category based on the percentile distance starting from very low

Table 2. The Lowest and Highest Score of Every Variable

Variable	Variable Value	
	Lowest Rangking	Highest Rangking
Coastal line change rate (m/year)	38.92 (accretion)	-22.31 (abration)
Elevation (m)	10.89	1
Geomorphology	1.27	5
	(Ranking based on Gornitz, 1997; Pendleton, 2005	
Sea level rise ratet (mm/year)	5.48	5.80
Mean wave height (m)	0.16	0.59
Mean tidal range (m)	1.87	2.91

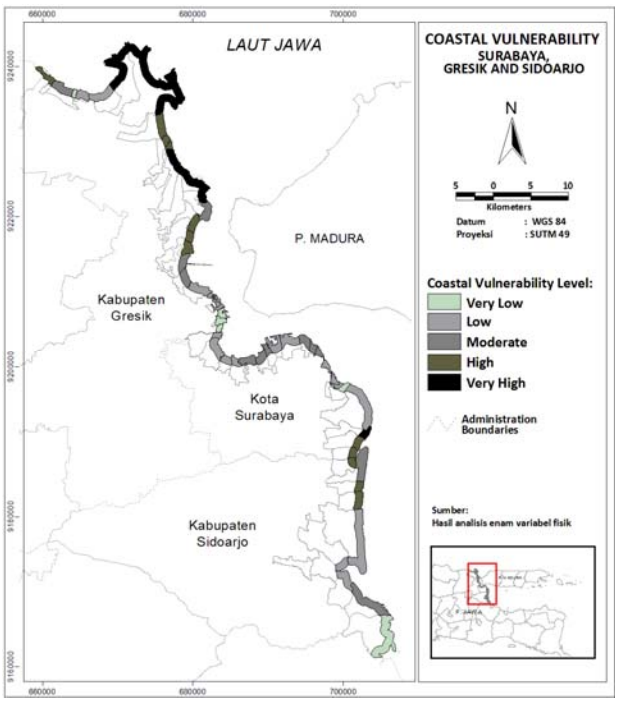

Figure 6. Physical Vulnerability Level of the Coastal Areas of Gresik, Surabaya, and Sidoarjo

Table 3. Regions with Physical Vulnerability at the Levels of Moderate to Very High

Regency/City	Subdistrict	Village		
		Moderate	High	Very High
Gresik	Panceng	Dalegan	Campurejo	-
	Ujungpangkah	-	Ketapanglor	Pangkahkulon, Pangkahwetan
	Sidayu	-	Randuboto	-
	Bungah	Kramat	Gumeng	Sungonlegowo, Badanten, Tanjungwidoro
	Manyar	Manyarsidomukti, Sukomulyo	Manyarejo, Manyarsidorukun	-
Surabaya	Asemrowo	Kalianak	-	-
	Krembangan	Morokrembangan, Perakbarat	-	-
	Kenjeran	Bulakbanteng, Tambakwedi	-	-
	Bulak	Kedungcowek	-	-
	Rungkut	-	Medokanayu	Wonorejo
	Gununganyar	-	Gununganyar tambak	-
Sidoarjo	Waru	-	Tambakoso	-
	Sedati	Segorotambak	Banjarkemuning, Tambakcemandi	-
	Jabon	Kupang	-	-

Table 4. Mean Variable Score Standardized

Variable	Standardized Score	
	Mean	SD
Coastal line change rate	0.61	0.17
Elevation	0.86	0.24
Geomorphology	0.77	0.28
Sea level rise rate	0.68	0.21
Mean wave height	0.37	0.23
Mean tidal range	0.34	0.48

vulnerability to very high vulnerability will complete a relation as follows:

$$0.05 \leq \text{index CVI MCA} \leq 0.56 \quad (6)$$

The coastal vulnerability index analysis results to sea level rise can be seen in Figure 6. Based on the analysis results of the six physical variables in the research areas, it is discovered that the areas having high and very high physical vulnerability are located in Ujungpangkah, Bungah, Sidayu, Manyar Subdistrict, Gresik Regency, Rungkut, Gununganyar Subdistrict, Surabaya City and Sedati Subdistrict, Sidoarjo Regency. Meanwhile, the other areas consist of the moderate, low, and very low vulnerability levels. Table 3 completely shows the regions having physical vulnerability to sea level riseat the moderate, high, and very high levels. Along the study areas starting from Gresik Regency to Sidoarjo Regency, it is discovered that their physical vulnerability is at the very-high category with 10.17%, the high category with 18.64%, the moderate category with 20.34%, the low category with 40.68%, and the very-low category with 10.17%.

Coastal vulnerability to sea level rise along the coastal areas of Gresik, Surabaya, to Sidoarjo is influenced by the geological variables consisting of a land form, elevation, and the coastal line change rate, and the oceanographical variables consisting of the mean tidal range, the mean wave height, and the mean sea level rise. Based on the mean variable score standardized (Table 4), the mean variable score can be seen from the biggest to the smallest, which are elevation (0.86) and the lowest mean tidal range (0.34).

From the analysis result, it can be discovered that the elevation condition provides the highest contribution towards the high physical vulnerability level in the study areas; besides that, the sea level rise rate which is one of the oceanographical variables also provides a high contribution towards the physical vulnerability in the study areas. Meanwhile, overall the smallest contribution is at the mean tidal range.

4. Conclusions

The coastal areas of Gresik Regency, Surabaya City, and Sidoarjo Regency have coastal physical vulnerability to sea level rise in the categories from very low to very high.The area with the high vulnerability level physically is the lowland area with the coastal condition directly facing Java Sea. All study areas are known to be at the vulnerability categories from high to very high with 28.81% where most areas are located on the northern part of Madura Strait (Gresik Regency) directly facing to Java Sea. Meanwhile, Surabaya City and Sidoarjo Regency whose coastal condition is relatively more protective because they are located on Madura Strait have the moderate, low, and very low vulnerability levels. The physical condition which mostly contributes to the high coastal area vulnerability level in the study areas is the coastal elevation.

Gratitude Remarks

This writing is part of the research for Master's Thesis at the Geography Science Master's Degree Program, FMIPA (the Faculty of Maths and Natural Sciences), Universitas Indonesia.

We express gratitude to LAPAN (Indonesian National Institute of Aeronautics and Space), Bakosurtanal, and BMKG which have helped a lot in the data collection required in this research, and the Ministry of Research and Technology that has provided the scholarship.

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