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Original Article

Flood Tidal Inundation Vulnerability Level in Pekalongan City, Central Java, Indonesia

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ABSTRACT
Pekalongan City is an area located on the northern coast of Java Island. This city often experiences flooding due to rain or tidal flooding due to its proximity to the sea and the very low altitude of the area. This makes Pekalongan City a dangerous place to live if the community is still vulnerable to flooding and tidal flooding. It is recorded that flooding in Pekalongan City always causes damage to houses and facilities, causing significant losses. This study was conducted to see the level of flood vulnerability in Pekalongan City. The study used BNPB regulation number 2 of 2012. The data used is secondary data taken through previous studies, data from related institutions in Pekalongan City, and data from related pages. The results of the study show that the flood vulnerability of Pekalongan City is still high, which means it is still very vulnerable and will always face losses every time a flood occurs. The results of the study on each index show that high vulnerability lies in economic vulnerability and physical vulnerability. Then environmental vulnerability and social vulnerability are at a moderate level. Further action needs to be taken by the government and local residents to increase community capacity in dealing with the high intensity of flood disasters.

KEYWORDS
Flood;
Vulnerability;
Pekalongan City

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INTRODUCTION

Indonesia is an archipelagic country with various landforms (Rohmah & Harianto, 2023). The diversity of landforms makes Indonesia have a variety of areas, including highlands and lowlands. Indonesia, which is also tropical, has fairly high rainfall every year. This condition causes lowlands to be prone to flooding. In addition to flooding caused by rain, there is flooding that can occur on the coast without rain, but rather due to

rising sea levels, known as tidal flooding (Macías-Tapia et al., 2021) . Coastal areas are regions with potential natural resources and economic benefits (Padungo et al., 2024) . This condition further increases the vulnerability of coastal areas to tidal flooding if not properly managed, which can cause significant losses.

Among the many areas prone to flooding in Indonesia, one of them is the city of Pekalongan. The city of Pekalongan has a flat topography, making it prone to tidal flooding (Miftakhudin, 2021) . The city of Pekalongan is only 0-1 meters above sea level, so when rainfall increases, it is very easy for water to overflow. Data from the Pekalongan City Disaster Management Agency (BPBD) in 2021 recorded that there were cases of flooding almost every day (Fernanda et al., 2022) . In addition to flooding caused by rain, Pekalongan City is also often affected by tidal flooding (Aini et al., 2024) ; (Ismanto et al., 2021) . Basically, tidal flooding often occurs and becomes a problem for areas with low elevation, making it very easy for seawater to rise onto land (Musarofa et al., 2024) ; (Muzakki et al., 2022) . In Pekalongan, tidal flooding has been occurring for more than 10 years (Utami et al., 2021) . Continuous tidal flooding will cause damage that requires extensive repairs and poses a risk of losing local wisdom (Falchi et al., 2024) . Moreover, the presence of poor communities can increase the risk of tidal flooding in the area (Handayani et al., 2021) .

Given this situation, the community needs to adapt to the conditions in order to continue living well, especially since flooding is a disaster that requires comprehensive management (Sinabutar et al., 2024) . In the effort to mitigate and plan for tidal flooding in the long term, in-depth research with various considerations is needed (Kang & Xie, 2025) . The community's high capacity in dealing with disasters of high intensity is necessary in order to minimize losses during a disaster (Wahyu et al., 2024) . Flood disasters can impact communities not only in terms of facilities and infrastructure but also in terms of property loss (Putri et al., 2024) ; (Enríquez et al., 2022) . Low capacity can cause communities in disaster-prone areas to become vulnerable. This condition will be very detrimental considering the high intensity of flooding that occurs in the city of Pekalongan.

Vulnerability is defined as a condition in society that causes a decline in capacity to deal with threats to life and well-being (Tidiesya et al., 2025) . Vulnerability in an area indicates the capacity of the community to deal with disasters when they occur. Vulnerability needs to be assessed to see if action is needed to increase capacity in the area so that when a disaster occurs, losses can be minimized or even eliminated. In calculating the vulnerability index based on Regulation of the Head of the National Disaster Management Agency No. 2 of 2012 concerning General Guidelines for Disaster Risk Assessment, vulnerability is divided into four elements, namely social vulnerability, physical vulnerability, economic vulnerability, and environmental vulnerability (BNPB, 2012).

Pekalongan City is one of the cities with very high tidal flood intensity, so vulnerability analysis will be needed as an effort to increase capacity (Hidayah et al., 2023) . Vulnerability analysis can be a primary consideration in development management and optimization of mitigation in a region.

METHOD

Research Location

This study was conducted in Pekalongan City (Figure 2), located in the northern part of Java Island. Topographically, Pekalongan City is located in a lowland area with an altitude of between 0 meters above sea level in the north and 6 meters above sea level in the south, with a relatively flat land slope (Miftakhudin, 2021) . As a result, the northern side of Pekalongan City, which borders directly with the coastal area, often experiences tidal flooding.

Research Procedure

This research was conducted in several stages, which can be illustrated specifically in Figure 1.

Research Approach

The method applied in this study is a quantitative method with a descriptive approach. This approach aims to explain the relationship between existing variables by analyzing numerical data. This article is based on spatial analysis using a Geographic Information System (GIS) with the help of ArcGIS software. The data used comes from the latest credible government agencies, namely the Central Statistics Agency (BPS), Disdukcapil, the Integrated Data Center, and websites related to Pekalongan City. Therefore, *ground checking* was not carried out because the accuracy of the data was guaranteed by these official sources.

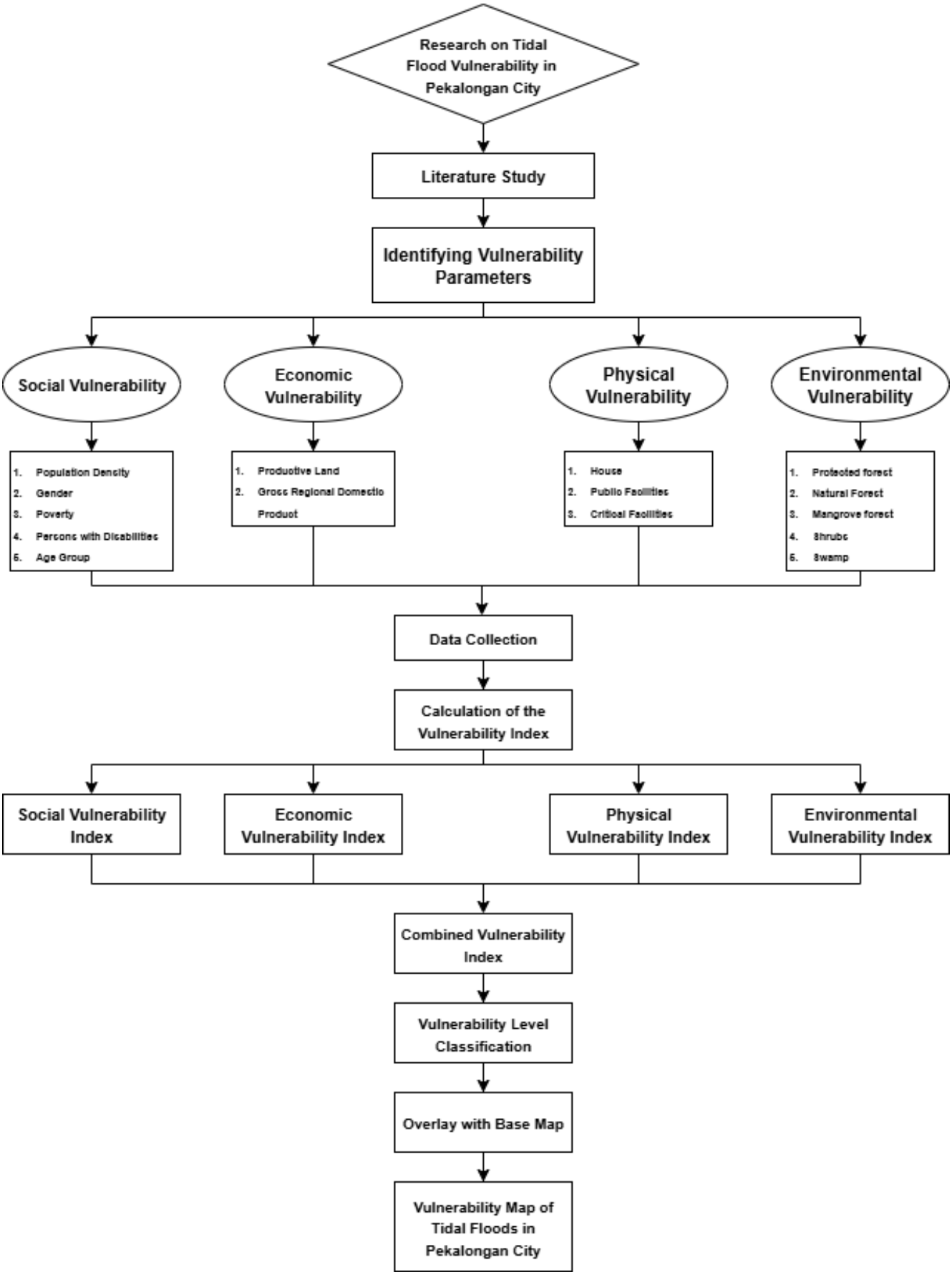

Figure 1. Research Procedure

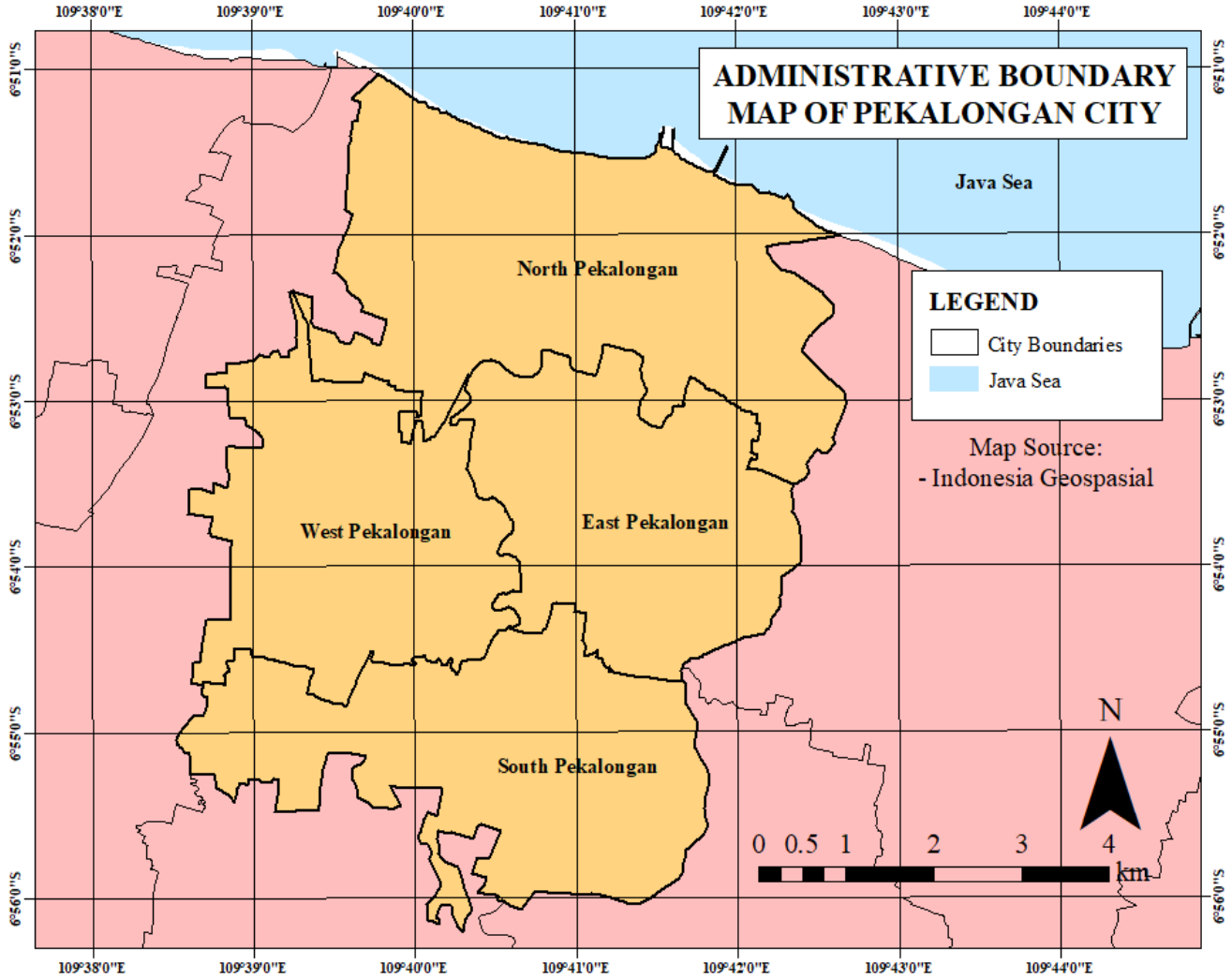

Figure 2. Administrative Map of Pekalongan City

Data Collection Instruments

In analyzing the vulnerability index, several vulnerability indices are required, consisting of social, economic, physical, and environmental indices (BNPB, 2016) . As in the research (Puspitotanti & Karmilah, 2022) ; (Pahleviannur et al., 2023) ; (Al-Amin & Chamid, 2022) ; (Ramadhanty et al., 2022) ;(Amin, 2024) ; (Balahanti et al., 2023) ; (Sauda et al., 2019) , vulnerability levels are analyzed in accordance with BNPB Regulation Number 2 of 2012, which consists of:

1. Social Vulnerability Index

The calculation of the social vulnerability index consists of parameters such as population density score, sex ratio, poverty ratio, disability ratio, and age group ratio. The weighting and classification of the social vulnerability index can be seen in Table 1 below.

Table 1. Social Vulnerability Index

Parameter	Weight (%)	Index Class		
		Low	Medium	High
Population Density	60	<500 people per km^2	500-1000 people/ km2	>1000 people/ km2
Gender (10%)	40	<20 %	20-40	>40%
Poverty (10%)				
People with disabilities (10%)				
Age group (10%)				

Source: BNPB Regulation No. 2 of 2012

In calculating the social vulnerability index, the following equation is used.

$$SV = 0.6 \times \frac{\log(PD/0.01)}{\log(100/0.01)} + 0.1 \times GR + 0.1 \times PR + 0.1 \times DR + 0.1 \times AR \quad (1)$$

Explanation:
SV = Social Vulnerability ; **PD** = Population Density; **GR** = Gender Ratio; **PR** = Poverty Ratio; **DR** = Disability Ratio; **AR** = Age Group Ratio

2. Economic Vulnerability Index

Economic vulnerability consists of the parameters of GRDP contribution and productive land. The productive land parameter consists of land in the form of rice fields, fields, and gardens, which are then converted into rupiah. Meanwhile, the GRDP used is the GRDP of Pekalongan City, which is converted into the GRDP of the sub-district. The rupiah value for the productive land parameter and the calculation of GRDP per sub-district are calculated based on the following equation.

$$\mathrm{RLP}_i = \frac{\mathrm{PLP}_{tot-i}}{\mathrm{LLP}_{tot-i}} \times \mathrm{LLP}_{village-i} \quad (2)$$

$$\mathrm{RPP}_{village-i} = \frac{\mathrm{RPP}_{KK}}{\mathrm{LKK}} \times \mathrm{LD}_i \quad (3)$$

Explanation:
RLP_i = Rupiah value of productive land for land use class *i* at the village/subdistrict level; **PLP_tot-i** = Total rupiah value of productive land based on sector *i* at the district/city level; **LLP_tot-i** = Total area of productive land of class *i* at the district/city level; **LLP_village-i** = Total area of productive land in sector *i* at the village/subdistrict level; **RPP_village-i** = Rupiah value of GRDP sector in village *I;* **RPP_KK** = Rupiah value of sectoral GRDP at the district/city level; **LKK** = Area of the district/city; **LD_i** = Area of the *i*-th village/subdistrict

Table 2. Economic Vulnerability Index

Parameter	Weight (%)	Index Class		
		Low	Medium	High
Productive Land	60	<50 million	50 – 200 million	>200 million
GRDP	40	<100 million	100– 300 million	>300 million

Source: BNPB Regulation No. 2 of 2012

Meanwhile, the economic vulnerability equation is as follows.

$$\mathrm{EV} = 0.6 \times PL + 0.4 \times GRDP \quad (4)$$

Explanation:
EV = Economic vulnerability index; **PL** = Score of productive land; **GRDP** = Score of Gross Regional Domestic Product (GRDP)

3. Physical Vulnerability Index

The physical vulnerability index consists of parameters for houses, public facilities, and critical facilities. Public facilities consist of markets, schools, places of worship, government buildings, and other buildings. Meanwhile, critical facilities consist of roads, bridges, PLN (cable) networks, PDAM networks, and health facilities (BPBD Kota Surakarta, 2020). These three parameters are then converted into rupiah based on current prices. With Folloeing equation:

$$\mathrm{PV} = 0.4 \times HS + 0.3 \times GF + 0.3 \times CF \quad (5)$$

Explanation:
PV = Physical Vulnerability; **HS** = Housing Score; **GF** = General Facilities Score; **CF** = Critical Facilities Score

Table 3. Physical Vulnerability Index

Parameter	Weight (%)	Index Class		
		Low	Medium	High
Housing	40	400 million	400 – 800 million	>800 million
Public facilities	30	<500 million	500 million – 1 billion	>1 billion
Critical Facilities	30	<500 million	500 million – 1 billion	>1 million

Source: BNPB Regulation No. 2 of 2012

4. Environmental Vulnerability Index

The environmental vulnerability index for tidal flooding is based on land cover maps consisting of protected forests, natural forests, mangrove forests, shrubs, and swamps. The weightings and index classes for environmental vulnerability are shown in Table 5. With the following environmental vulnerability equation.

$$\mathrm{ENV} = 0.3 \times PF + 0.3 \times NF + 0.1 \times MF + 0.1 \times SH + 0.2 \times SW \quad (6)$$

Explanation:
ENV = Environmental Vulnerability; **PF** = Protected Forest Score; **NF** = Natural Forest Score; **MF** = Mangrove Forest Score; **SH** = Shrubland Score; **SW** = Swamp Score

Table 4. Environmental Vulnerability Index

Parameter	Weight (%)	Index Class		
		Low	Medium	High
Protected Forest	10	<20 ha	20–50 ha	>50 ha
Natural Forest	30	<25 ha	25–75 ha	>75 ha
Mangrove forest	10	<10 ha	10 – 30 ha	>30 ha

Parameter	Weight (%)	Index Class		
		Low	Mediu m	High
Scrub	10	<10 ha	10 – 30 ha	>30 ha
Swamp	20	<5 ha	5 – 20 ha	>20 ha

Source: BNPB Regulation No. 2 of 2012

Data Analysis Techniques

Based on the equation 7 for each vulnerability parameter above, the results of the calculation are then categorized according to the following index classes.

$$\mathrm{VI} = 0.4 \times SV + 0.25 \times EV + 0.25 \times PV + 0.1 \times ENV \quad (7)$$

Explanation:
VI is the Vulnerability Index; **SV** is Social Vulnerability; **EV** is Economic Vulnerability; **PV** is Physical Vulnerability; **ENV** is Environmental Vulnerability.

Table 5. Index Classes

Index Class	Value
Low	0.00 – 0.33
Medium	0.34 – 0.66
High	0.67 – 1.00

Source: BNPB Regulation No. 2 of 2012

Next, the results of the calculations are *overlaid* using ArcMap software, which then produces a map of flood vulnerability in Pekalongan City.

RESULTS AND DISCUSSION

Social Vulnerability

Based on Equation 1, the social vulnerability index values use indicators such as population density, sex ratio, poverty ratio, disability ratio, and age group ratio in each subdistrict in Pekalongan City. The calculation results can be seen in Table 6. The calculation of the social vulnerability index from the five indicators produced an average score of 0.41, indicating that Pekalongan City has a moderate level of social vulnerability, with the social vulnerability profile for each subdistrict as shown in Figure 3.

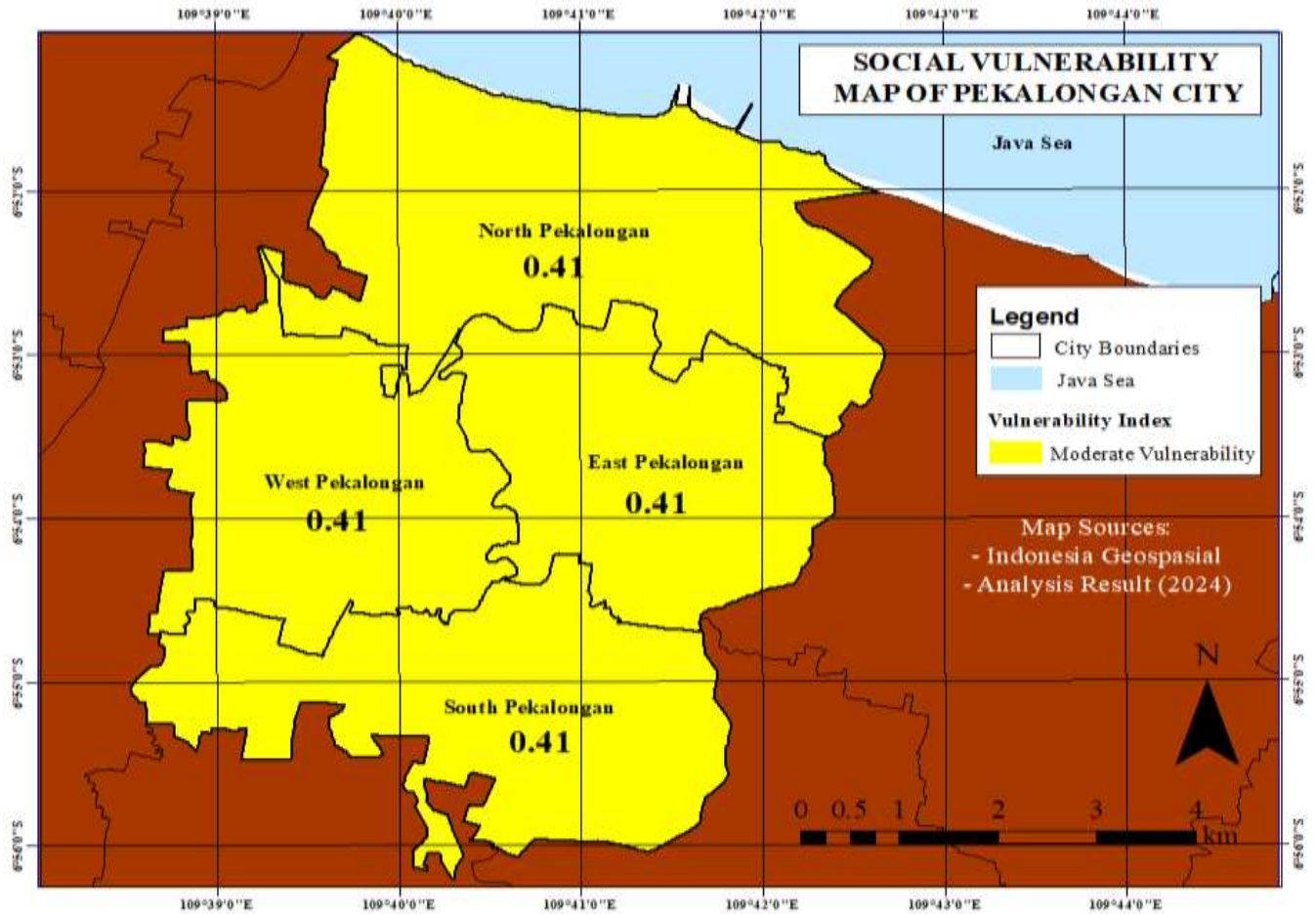

Figure 3. Social Vulnerability Map

Population density and non-productive age groups (children and the elderly) are major contributors to high social vulnerability (Mukhtar & Zuhdi, 2023) . The moderate level of social vulnerability remains a concern because the Pekalongan City area has been empirically proven to experience vulnerability due to these demographic characteristics.

Table 6. Social Vulnerability Index Calculation Results

District	Population Density	Sex Ratio	Poor Population	Disability	Age	**Social Vulnerability**
West Pekalongan	0.3	0.01	0.1	0.003	0.03	**0.41**
North Pekalongan	0.30	0.01	0.1	0.003	0.03	**0.41**
South Pekalongan	0.30	0.01	0.1	0.003	0.03	**0.41**
East Pekalongan	0.30	0.01	0.1	0.003	0.03	**0.41**
Average						**0.41**

Source: Analysis Results (2024)

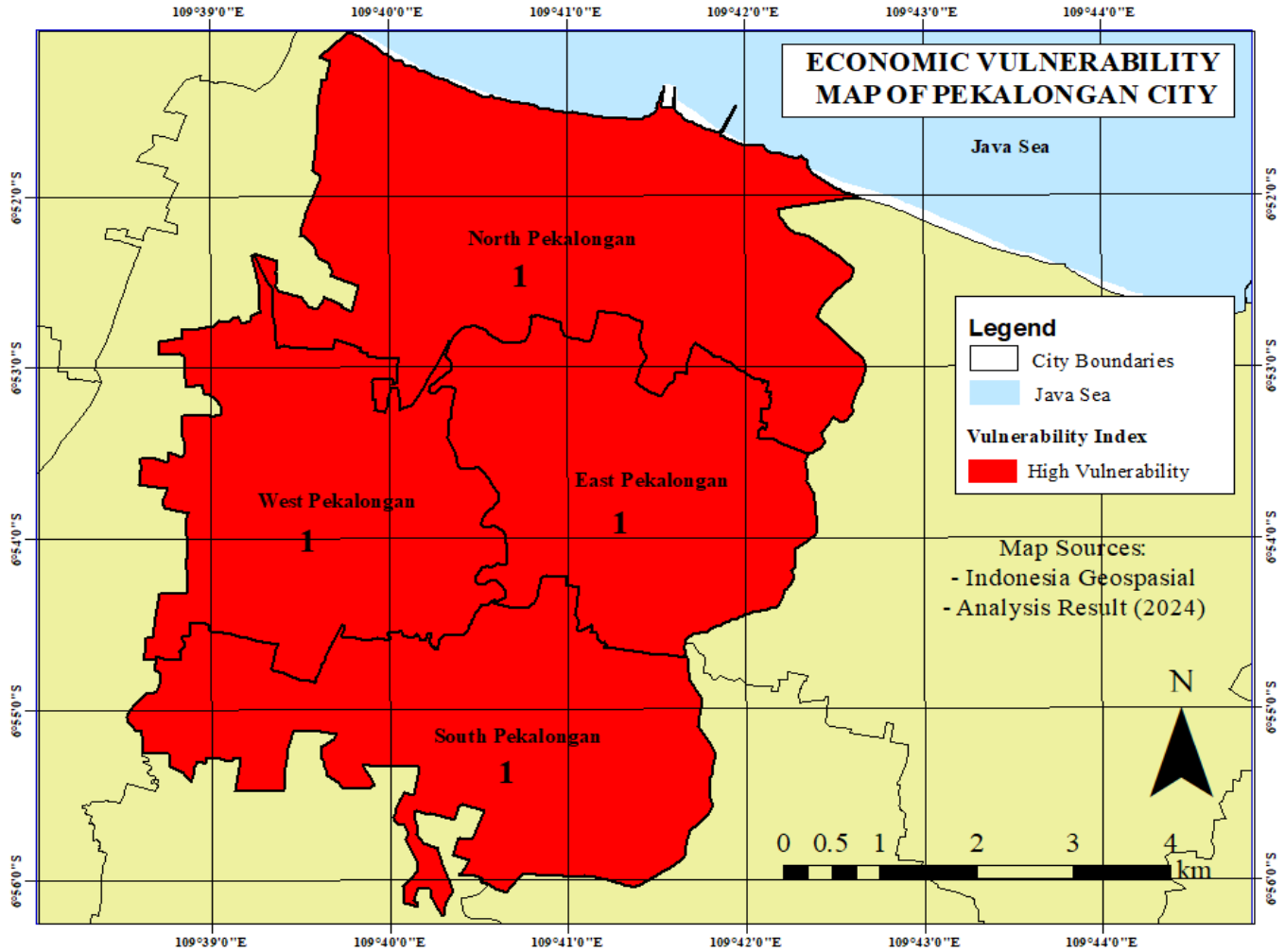

Figure 4. Economic Vulnerability Map

Economic Vulnerability

Economic vulnerability is derived from the results of Equation 4, which uses two indicators: productive land and GRDP. The results of the economic vulnerability calculation can be seen in Table 7, and the economic vulnerability map can be seen in Figure 4.

Table 7. Results of Economic Vulnerability Index Calculations

District	Productive Land	GRDP	Economic Vulnerability
West Pekalongan	0.6	0.4	**1**
East Pekalongan	0.6	0.4	**1**
South Pekalongan	0.6	0.4	**1**
North Pekalongan	0.6	0.4	**1**
Average			**1**

Source: Analysis Results (2024)

The calculation of the economic vulnerability index from both indicators resulted in an average score of 1, which indicates that the economic vulnerability of Pekalongan City is at a high level.

Based on the above calculations, the high amount of productive land, such as fish ponds and agriculture, tends to increase economic vulnerability. This is because tidal flooding can disrupt activities or the quality of produce on such productive land (Mukhtar & Zuhdi, 2023) . This, together with the calculation results, means that special measures are needed to deal with tidal flooding in order to avoid economic losses.

Physical Vulnerability

The physical vulnerability index consists of three parameters calculated based on Equation 5 using indicators for housing, public facilities, and critical facilities. The results of the physical vulnerability calculation can be seen in Table 8, and the physical vulnerability map can be seen in Figure 5.

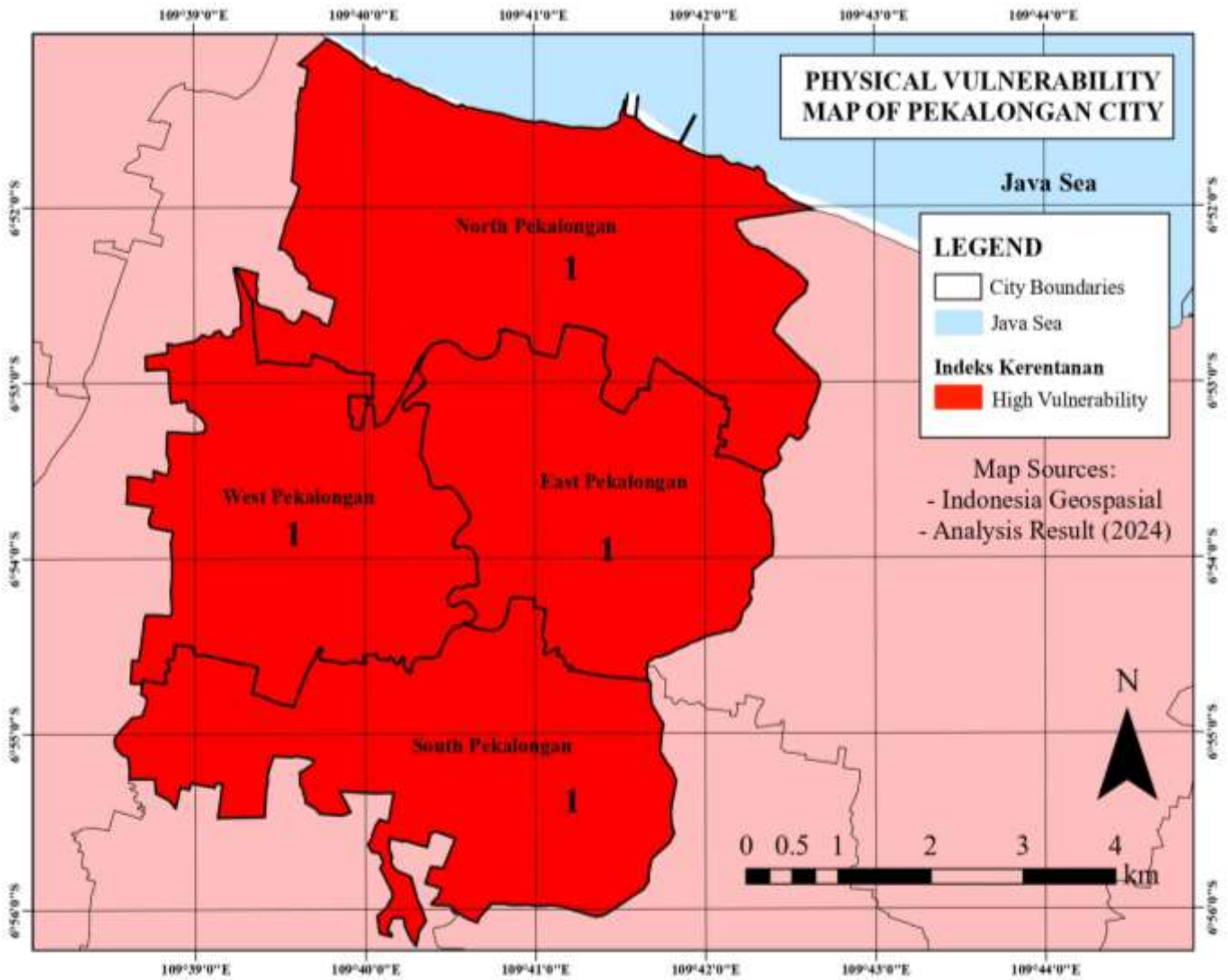

Figure 5. Physical Vulnerability Map

The results of the physical vulnerability calculation based on the three factors are at a score of 1, which indicates that the physical vulnerability in Pekalongan City is high.

Table 8. Results of Physical Vulnerability Index Calculations

District/City	Housing	Public Facilities	Critical Facilities	**Physical Vulnerability**
West Pekalongan	0.4	0.3	0.3	**1**
East Pekalongan	0.4	0.3	0.3	**1**
North Pekalongan	0.4	0.3	0.3	**1**
South Pekalongan	0.4	0.3	0.3	**1**
Average				**1**

Source: Analysis Results (2024)

High physical vulnerability is inevitable as the city progresses. The increasing number of houses, public facilities, and critical facilities means that Pekalongan City could face maximum impact. Similar conditions can be found in the study Sauda et al,(2019) which calculates physical vulnerability in Pekalongan Regency. The study mentions that this condition is exacerbated by poor topography and drainage. Similar results were found in the study Refnitasari et al ,(2022) in Surabaya City, which states that the highest physical vulnerability is due to the large number of important buildings such as housing and ports. Another condition was also found in the study Ramdhany et al,(2021) in Semarang City, which states that physical vulnerability is exacerbated by the very low elevation and proximity to the coast, as well as land subsidence.

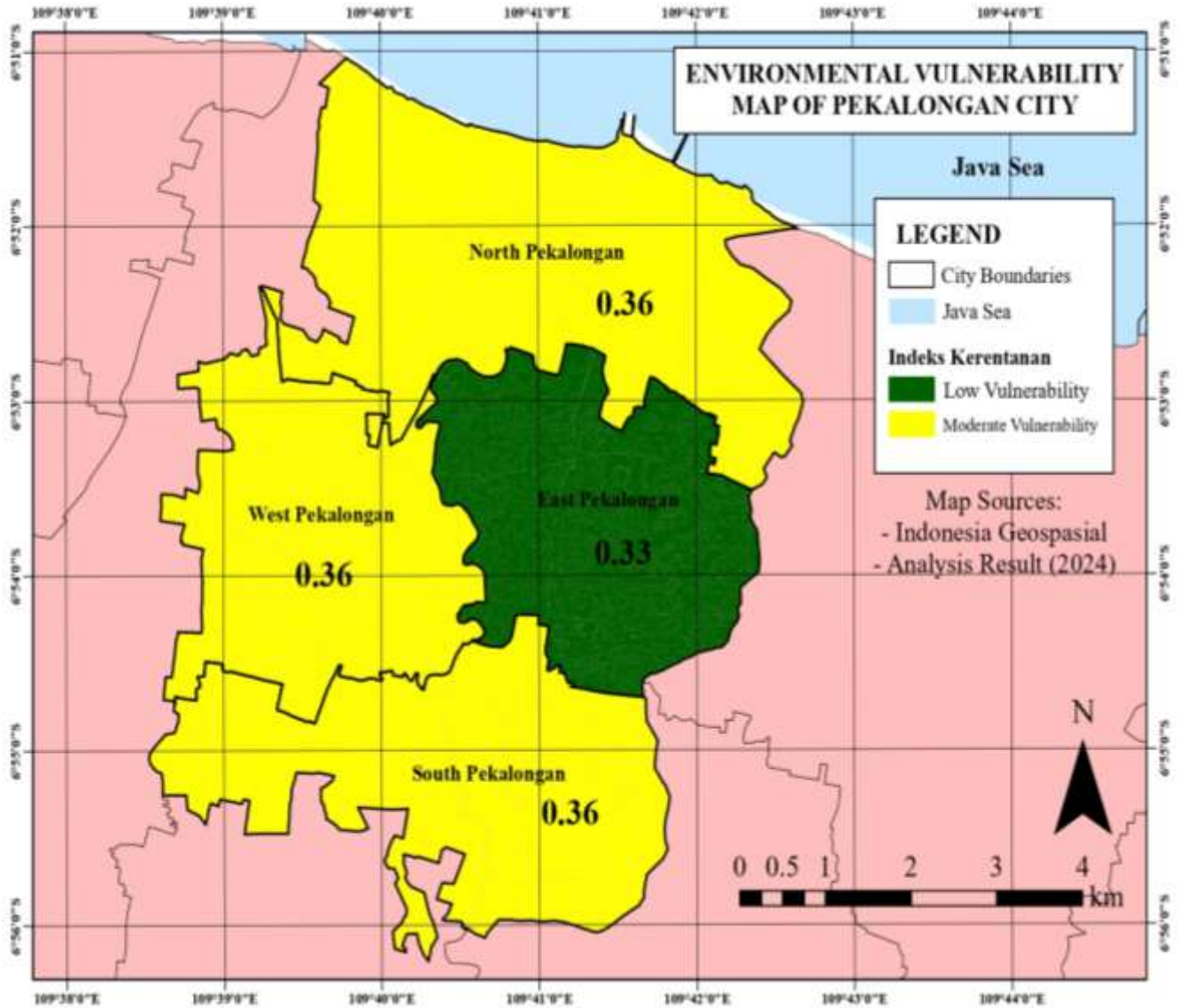

Figure 6. Environmental Vulnerability Map

Environmental Vulnerability

The environmental vulnerability index consists of five parameters which are then calculated based on Equation 6, yielding the following results (Table 9). The results of the environmental vulnerability calculation using the five factors indicate that the subdistricts of West Pekalongan, North Pekalongan, and South Pekalongan have a moderate level of environmental vulnerability. This is in contrast to the subdistrict of East Pekalongan, which has a low level of vulnerability. The average result is 0.36, which means that the environmental vulnerability of Pekalongan City is at a moderate level. The results map can be seen in Figure 6.

Table 9. Environmental Vulnerability Index Calculation Results

District	Protected Forest	Plantation Forest	Mangrove Forest	Scrub	Swamp	**Environmental Vulnerability**
West Pekalongan	0.33	0.33	0.33	0.67	0.33	**0.36**
East Pekalongan	0.33	0.33	0.33	0.33	0.33	**0.33**
North Pekalongan	0.33	0.33	0.33	0.67	0.33	**0.36**
South Pekalongan	0.33	0.33	0.33	0.67	0.33	**0.36**
Average						**0.36**

Source: Analysis Results (2024)

Unlike Pekalongan Regency in the study by Sauda et al. (2019), which has low vulnerability in all villages, Pekalongan City has moderate vulnerability and only one subdistrict has low vulnerability. This condition is due to the higher number of shrubs, which are the main driver of vulnerability in this aspect.

Flood Vulnerability

The total tidal flooding vulnerability index can be calculated based on the sum of the four indices, as shown in Equation 7. The calculation results can be see Table 10.

Table 10. Results of Tidal Flood Vulnerability Calculations

District	Social (40%)	Economic (25%)	Physical (25%)	Environment (10%)	**Flood Disaster Vulnerability**	**Class**
West Pekalongan	0.45	1.00	1.0	0.36	**0.716**	**High**
East Pekalongan	0.45	1.00	1.00	0.33	**0.713**	**High**
North Pekalongan	0.45	1.00	1.00	0.36	**0.716**	**High**
South Pekalongan	0.45	1.00	1.00	0.36	**0.716**	**Height**
Average					**0.715**	**High**

Source: Analysis Results (2024)

Based on the calculation results, it was found that the average vulnerability to tidal flooding in Pekalongan City was 0.715, indicating high vulnerability. This is compounded by the fact that Pekalongan City is dominated by residential areas, with a population density of over 1000 people/km2 (Table 11), making the population density in Pekalongan City relatively high. This figure has an impact on economic and physical vulnerability, increasing the number of people affected by flooding and potentially causing high losses due to the large number of economic activities that support Pekalongan City's GRDP.

Table 11. Population Density of Pekalongan City

District	Population Density (People/km^2)
West Pekalongan	10019
East Pekalongan	7798
South Pekalongan	6234
North Pekalongan	5239
Pekalongan City	**7027**

This situation can be exacerbated by the low topography of Pekalongan City, which is dominated by elevations of less than 10 m. With such low elevations, the likelihood of seawater overflowing and causing tidal flooding will be even higher (Figure 7).

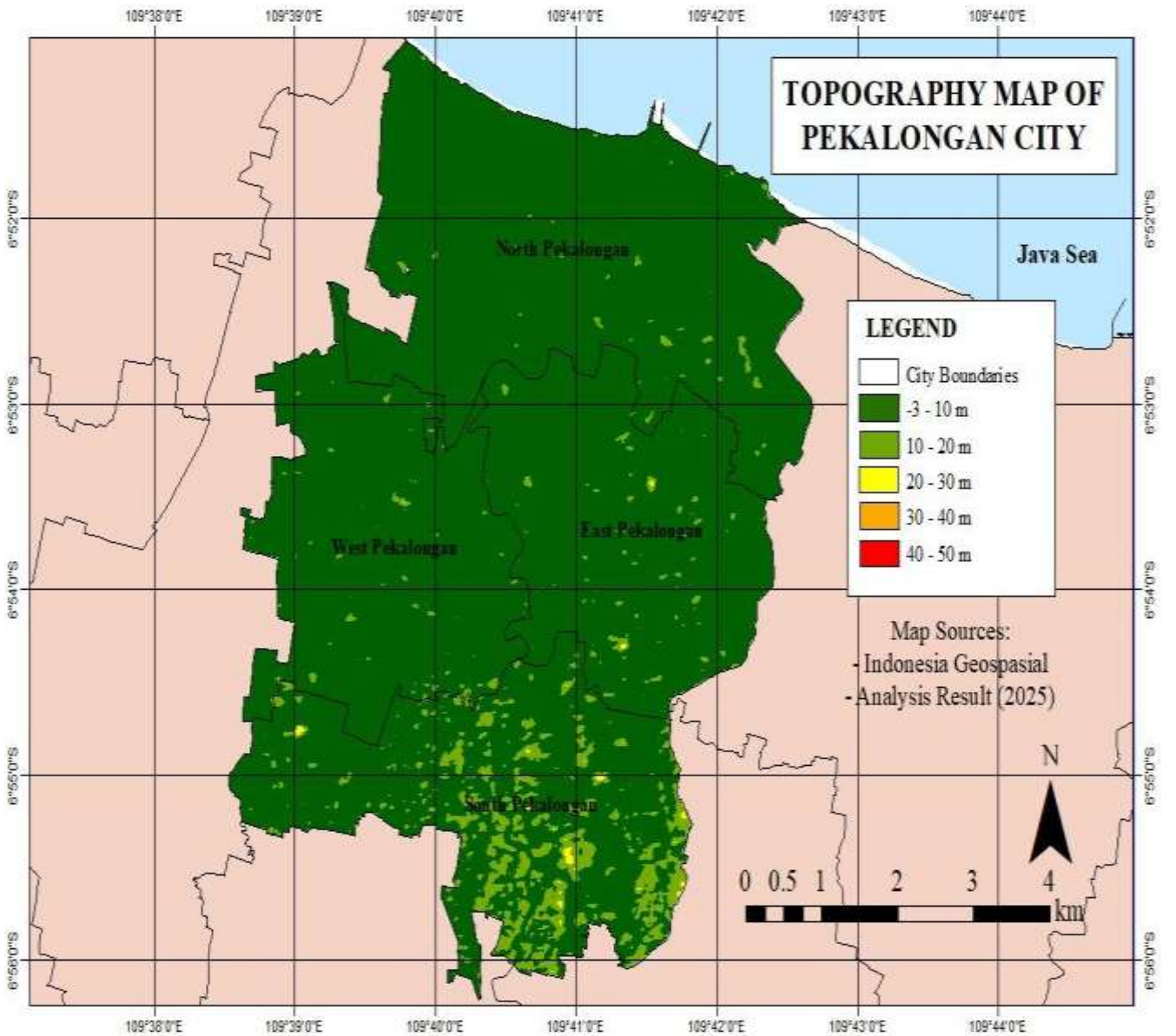

Figure 7. Topographic Map of Pekalongan City

Additionally, there are other factors outside the parameters that contribute to this condition, namely the high e of tidal flooding intensity. The tidal flooding vulnerability map for Pekalongan City can be seen in Figure 8.

CONCLUSION

Pekalongan City is one of the cities located in the north of Java Island. This city has an elevation ranging from 0-1 MDPL, making it highly prone to flooding. With the high vulnerability to flooding, the community in the city must be able to cope with the floods that often hit the city. After the analysis was conducted, it was found that the vulnerability in Pekalongan City is at a high level, partly due to dense settlements and economic and physical conditions that can cause maximum losses if not handled. Therefore, efforts need to be made to increase the capacity of the community so that they can reduce the impact of the high intensity of flooding they face.

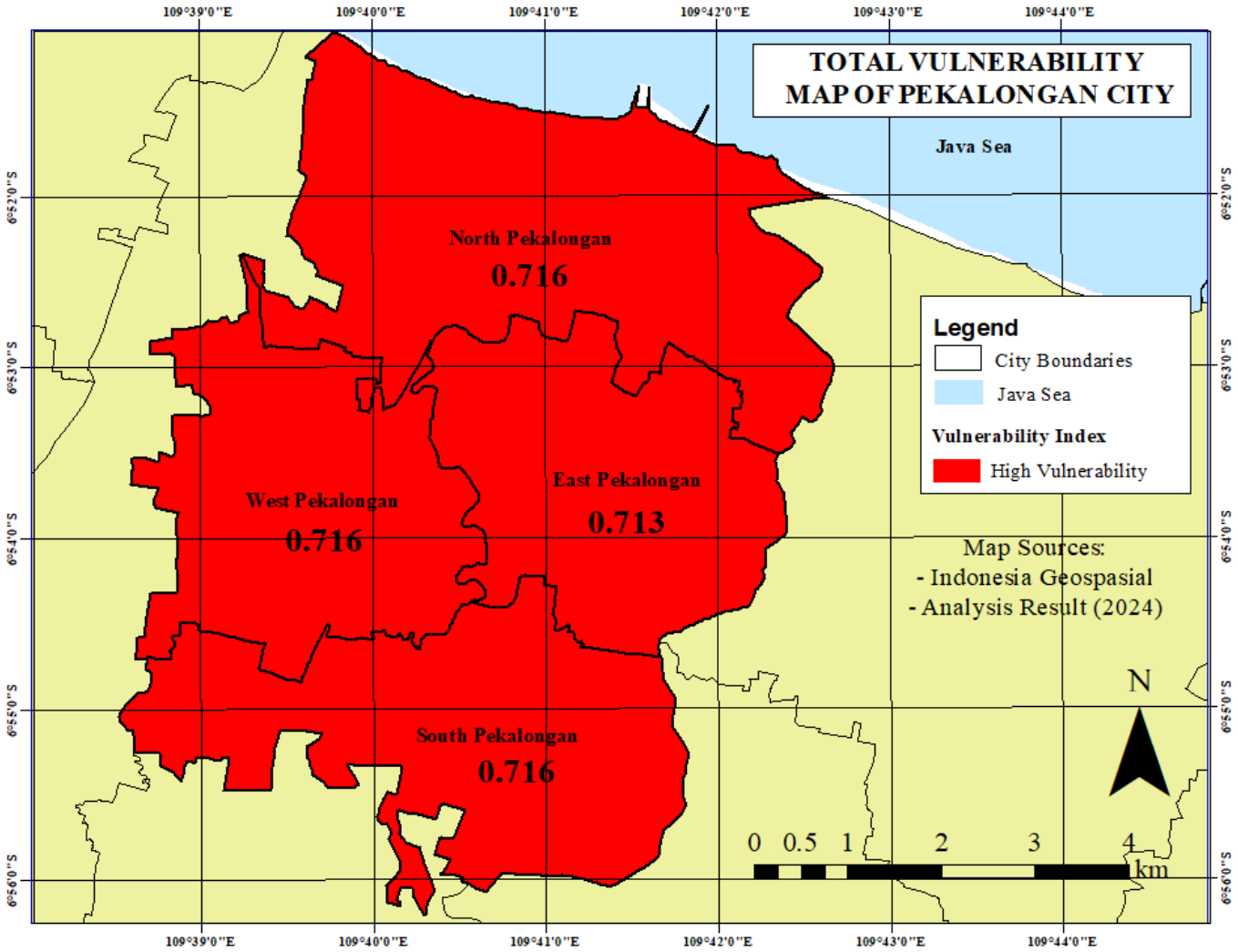

Figure 8. Tidal Flood Vulnerability Map

For further study and research, it is recommended to deepen the data used and continue the analysis of the relationship between the four factors or analyze vulnerability. This can deepen the study of disasters in Pekalongan City so that maximum results can be achieved in relation to the development of mitigation and adaptation efforts against tidal flooding. The limitations of this study lie in the difficulty of finding data on house prices, which tend to be dynamic. This study uses data obtained from relevant agencies through websites available on the internet and not from direct collection or measurement in the field.

Conflict of Interest The author has no competing interests to declare that are relevant to the content of this article.

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