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Geospatial Analysis of Predicted Tidal Flood Inundation (2024–2059) on Coastal Land Use in the Semarang-Demak Toll-Seawall Integration Plan, Central Java, Indonesia

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A B S T R A C T

The low topography of the Semarang – Demak coastal area makes it prone to tidal flooding, primarily caused by land subsidence. This study aims to model the existing tidal flood inundation area in 2024 and make predictions for 2054 and 2059, focusing on land use in coastal regions based on geospatial modeling before and after the construction of the Semarang-Demak toll road and sea wall integration. The data used include tidal levels, sea level rise, land subsidence, and land elevation, obtained from BMKG, CMEMS, SAR Sentinel 1-A, and Sentinel 2-A imagery. The least square method was used to analyze tidal components, while sea level rise was assessed using a linear approach. InSAR and DInSAR methods were used to process topographic and land subsidence data. The analysis results indicate that the coastal area of Semarang-Demak has a mixed semi-diurnal tidal type, with a Formzahl number of 0.68. The annual sea level rise is 4.7 mm/year, while the average land subsidence rates in Gayamsari, Genuk, and Sayung Districts are 14.16 cm/year, 15.5 cm/year, and 17.8 cm/year, respectively. In 2024, the tidal flood inundation area is 523.67 hectares. After the integrated toll road and sea wall construction in 2054, the inundation area is reduced to 19 hectares but increased to 5023.41 hectares in 2059 due to overtopping. The toll road-sea wall integration project is considered highly effective, successfully reducing tidal flooding by 96.37%.

Keywords: Land subsidence, Sea level rise, Seawall integration, Semarang-Demak Toll Road, Tidal flood

1. Introduction

The Semarang-Demak coast has a relatively flat topography with most of its coastal areas almost at the same elevation as sea level, making it vulnerable to tidal flooding. Tidal flooding occurs due to a combination of land subsidence and sea level rise and causes seawater to inundate land, especially in coastal areas (Hsiao *et al*., 2024). Coastal communities increasingly face recurring flooding hazards, exacerbated by the combined impacts of coastal storm surges and ongoing rising sea levels. These interconnected coastal threats jeopardize community resilience and pose significant risks to essential coastal ecosystems (Han *et al*., 2024).

Based on research conducted by Muldiyanto *et al*. in 2022, it is known that land subsidence generally ranges from 1 to 10 cm per year and can reach 20 cm in certain places, especially in the northern part of Semarang in recent years. Also conveyed by Dasanto *et al*. in the same year, the sea level rise in 2030 will reach 6 cm to 30 cm in the Indonesian region.

One of the solutions implemented by the government to overcome this tidal flood is to build a toll road-sea wall in 2022. This toll road-sea wall was built along 26.95 km to connect the cities of Semarang-Demak, with the height of the sea wall being 7 m from MSL with armorjack material to overcome tidal floods. Currently, the construction of the Semarang-Demak seawall toll road has reached 32.67%. Relevant officials emphasized that this toll road was designed as a long-term solution to overcome the problem of tidal flooding in the coastal areas of Semarang and Demak. This project also includes the construction of retention ponds and pump houses that function to regulate water flow and reduce inundation during high tides or extreme rain (BBPJN, 2025). This is supported by research by Hosseinzadeh *et al*. (2022); concrete seawalls are a common category of coastal protection structures designed with the primary objectives of absorbing wave action, preventing coastline erosion, and alleviating flooding.

Therefore, this study is expected to provide benefits to the community by providing a reference for mapping the area of existing tidal flood inundation in 2024. In addition, this study will predict changes in the area of tidal flood inundation and its impact on coastal land use in 2054 and 2059 in Gayamsari, Genuk, and Sayung Districts. This prediction will be carried out through geospatial analysis that considers factors such as land subsidence, sea level rise, and the existence of flood control infrastructure, including the integration of the Semarang-Demak toll road-sea wall. The results of this study are expected to be the basis for formulating policies and strategies for tidal flood mitigation, especially in planning sustainable coastal infrastructure development in the future.

2. Material and Method

This study was conducted in the integrated Semarang-Demak Sea Wall Toll Road area, which includes the coastal districts of Gayamsari, Genuk, and Sayung. The geographical coordinates of the study area range from -6.948674 S to -6.939550 S and 110.441498 E to 110.507153 E. Data processing was carried out from January to June 2024 at Diponegoro University. A field survey to determine the furthest extent of the inundation was conducted on June 19, 2024, in the city of Semarang, Central Java Province.

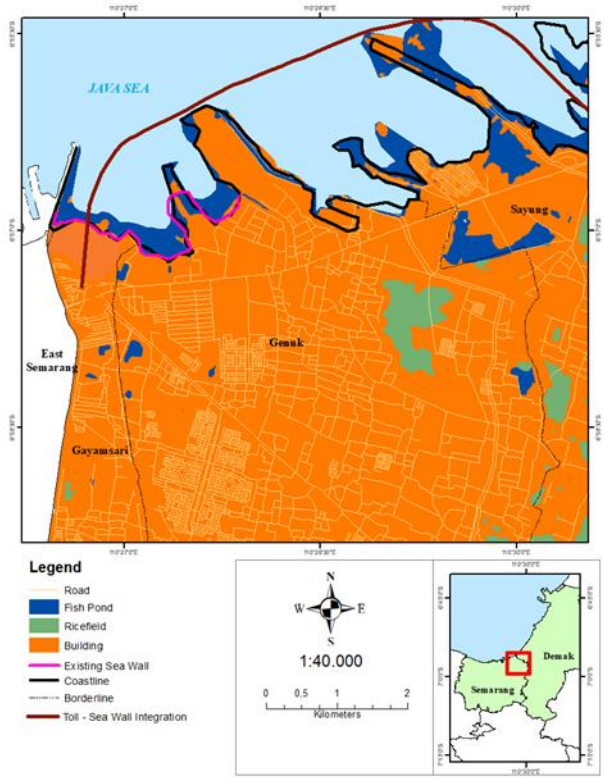

Figure 1. Research Location

Determining the Furthest Extent of Flood Inundation

The furthest extent of tidal flood inundation was determined through direct field observations and in-depth interviews based on existing tidal flood modeling results. Interviews with residents were conducted to gather information about the furthest points of tidal flooding. Several research sites were marked using GPS to record the coordinates of these flood points (Griselda *et al*., 2021).

Tidal Data Analysis Using the Least Squares Method

The tidal analysis process utilized the least squares method using Matlab software. This method generates tidal components, tidal predictions, and an analysis of sea level rise that contributes to tidal flooding. The number of tidal components that can be identified depends on the duration of the observation. Longer observation periods allow for identifying more tidal components, leading to a more comprehensive analysis. Tidal components are determined using the Formzahl formula as follows:

$$F = \frac{(AK1 + AO1)}{(AM2 + AS2)}$$

K1 and O1 are the amplitudes of the tidal component caused by solar and lunar gravitational forces, respectively. S2 and M2 are the amplitudes of the semidiurnal tidal component caused by solar and lunar gravitational forces, respectively.

Further, according to Pasomba *et al*. (2019), based on the Formzahl value (F), there are four categories of tidal types. Tidal in a sea is classified as a regular semidiurnal tide type if $F<0.25$ (low Formzahl), a mixed mainly semidiurnal tide type if $0.25<F<1.50$ (moderate Formzahl), a mixed mainly diurnal tide type if $1.50<F<3.00$ (high Formzahl), and a diurnal tide type if $F>3.00$ (very high Formzahl).

Analysis of Predicted Sea Level Rise

The analysis of predicted sea level rise is based on HHWL (Highest High Water Level). Once the sea level rise value is obtained, the next step is to perform a linear regression calculation using the equation provided by El-Fath *et al*. (2022), as follows:

$y = ax+b$

Where y is the sea level height, x is the year i, a is the coefficient of sea level rise, and b is the constant term.

The predicted value of the highest tide for the next year can be estimated linearly using the following equation:

$$TL\,max = HHWL + (SLR\,(Yp - Yb))$$

Where TLmax is the height of predicted highest tide for the next year, HHWL is the average of the highest high waters, one from each of 19 years of predictions, SLR is the sea level rise rate, Yp is the prediction year, and Yb is the current year.

Digital Elevation Model Analisis Using SAR Interferometry SAR (InSAR)

Topographic analysis of land surface elevation was conducted using SNAP software with Sentinel 1-A imagery, with recordings from March 30, 2022, and October 15, 2023, for land subsidence data, and recordings from November 8, 2023, and November 20, 2023, for land elevation data. This method produces a Digital Surface Model (DSM), which is then interpolated using the topo-to-raster method to generate a Digital Terrain Model (DTM) (El-Fath *et al*., 2022).

Land Subsidence Analysis Using Differential Interferometry SAR (DInSAR)

Land subsidence analysis was performed using SNAP software with Sentinel 1A satellite imagery. This process used the Differential Interferometry SAR (DInSAR) methodology, which efficiently and systematically determines the rate of land subsidence and provides high spatial resolution data. The processed data from SNAP was then corrected using the Raster Calculator Tool in ArcGIS 10.8. The formula used is based on the research by Griselda *et al*. (2021) as follows:

$$\text{Land Subsidence} = \frac{Subsidence\ Value * 365}{Time\ Interval\ Between\ Image\ Acquisitions\ (in\ days)}$$

Prediction of Land Subsidence

The value of land subsidence for both existing conditions and predictions is determined using Sentinel 1A satellite imagery. According to Khrisnamurti *et al*. (2021), the predicted land subsidence for the following year can be estimated linearly using the following equation:

$LSp = LS\,(Yp-Yb)$

Where LSp is the predicted land subsidence for the forecast year, LS is the land subsidence in the current year, Yp is the prediction year, and Yb is the current year.

Geospatial Modeling of Tidal Flood Inundation Extent

Geospatial modeling is performed to determine the extent of existing tidal flood inundation using ArcMap software with the Raster Calculator Tool method. The geospatial modeling of tidal flood inundation is created by inputting the difference between the Highest High Water Level (HHWL) and the Mean Sea Level (MSL) into the Raster Calculator Tool. The equation used in the Raster Calculator is based on the methodology of Iskandar *et al*. (2020) as follows:

$WD = Con(Con([DEM] \leq Elevation, Elevation), Con[DEM] \leq Elevation, Elevation) - [DEM],0)$

Where WD is the depth of tidal flood inundation, DEM is the Digital Elevation Model (Land Elevation Data), and Elevation is HHWL (Highest High Water Level) – MSL (Mean Sea Level).

Geospatial Modeling of Predicted Tidal Flood Inundation Extent

To map the predicted tidal flood inundation areas for the years 2054 and 2059, data on land elevation, land subsidence, and maximum sea level are used. Iskandar *et al*. (2020) assume that land subsidence and sea level rise occur linearly. The equation used to calculate the extent of tidal flood inundation is:

Flood Year Prediction =CON([RasterDEM - Land Subsidence]<=[Tidal Height fod Prediction Year],1,0)

The value "1" in the raster indicates areas that are inundated, while "0" indicates areas that are not inundated.

3. Results and Discussion

Based on tidal data from the BMKG Tanjung Mas station for December 2023, the tidal type observed is a mixed tide leaning towards semidiurnal, with a Formzahl value (F) of 0.68. This tidal type indicates that there is typically one high tide and one low tide each day, though occasionally there may be two high tides and two low tides at varying heights and times. During the western monsoon season, specifically in December, the Highest High Water Level (HHWL) reached 177 cm. Calculations using the least squares method yielded an average Mean Sea Level (MSL) of 123 cm and a Lowest Low

Water Level (LLWL) of 64.4 cm. These results are consistent with the findings of Shalsabilla *et al.* (2022), who reported that this tidal type occurs in the Semarang area.

Table 1. Harmonic Tidal Components for Semarang City, December 2023

No	Harmonic Component	Amplitude	Phase (g°)
1,	O1	0.047	156.7
2.	P1	0.028	349.17
3.	K1	0.226	344.77
4.	N2	0.028	82.26
5.	M2	0.119	204.34
6.	S2	0.065	173.47
7.	K2	0.073	354.46
8.	M4	0.001	222.23
9.	MS4	0.006	132.51

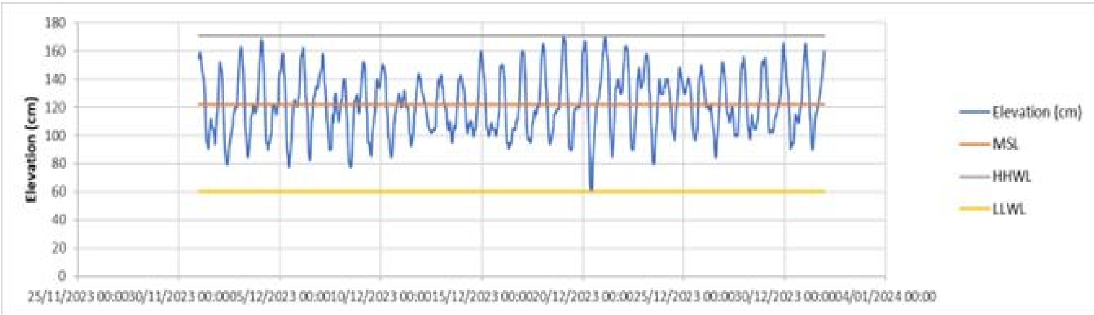

Figure 2. Tidal Graph for Semarang City, December 2023

Based on the data processing results, a trend analysis of sea level rise from 1993 to 2022 using linear regression shows an increase in sea level of 4.7 mm per year **(Figure 3)**. The rise in sea levels due to global warming will lead to long-term increases in sea levels. This will result in coastal erosion, tidal flooding, land inundation, and the potential submersion of small islands, with more intense and frequent flooding (IPCC, 2010, as cited in Nadya and Salim, 2023). Linear regression analysis estimates the highest tide levels for prediction years 30 and 35 years into the future, as shown in the following table **(Table 2)**. The values for HHWL and sea level rise serve as initial references for creating maps of existing tidal flood inundations in the study area. Research has shown that global sea level rise (SLR) will cause 100-year return period (RP) flood events, currently considered rare, to occur more frequently, potentially becoming common by 2100 (Garner *et al*., 2017; Amoura & Dahmani, 2022). Extreme water levels not only have the potential to overtop coastal defenses but also reduce river drainage capacity, leading to backwater effects and urban flooding (Hadipour *et al*., 2020; Hsiao *et al*., 2021; Wang & Marsooli, 2021). Therefore, accurately modeling and quantifying the combined effects of multiple flood drivers is essential for improving our understanding and preparedness for future coastal flood risks.

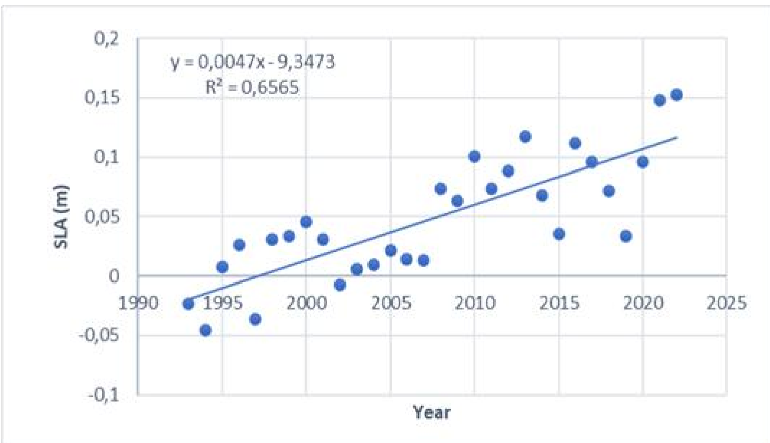

Figure 3. Sea Level Rise Trend Graph for 1993 – 2022

Table 2. Predicted Highest Sea Levels for Forecast Years

No	Year	Max Sea Level (m)	MSL (m)	Fluctuation (cm)
1.	2024	178	124	54
2.	2054	191	137	54
3.	2059	193	140	53

The processing of land subsidence data used Sentinel-1A SAR imagery and applied the DInSAR method. Before the construction of the seawall, the land subsidence rates in the Semarang-Demak area, specifically in the Gayamsari, Genuk, and Sayung districts, were 14.16 cm/year, 15.5 cm/year, and 17.8 cm/year, respectively **(Figure 4)**. The data analysis indicates land subsidence increases as one approaches the Northern Coast or shoreline. This subsidence is attributed to factors such as tectonic activity, excessive groundwater extraction, tidal effects, rising sea levels, and soil type. In Semarang, the predominant soil type is alluvial, which supports findings by Ramadhan *et al*. (2021) that land subsidence in Semarang is associated with alluvial deposits. The model demonstrates that the area of inundated land is expanding over time. The seemingly sharp transition between blue (low subsidence) and orange (high subsidence) zones near the shoreline occurs because the blue represents water with naturally low subsidence rates. Land areas, especially those with loose alluvial soil and heavy groundwater extraction, experience much higher subsidence. Additional factors like coastal protections and tidal pressure differences further contribute to this contrast. Based on the predicted rate of land subsidence that has been calculated, it can be seen that the rate of land subsidence will be higher in the coming years. This is supported by Shidik *et al.* (2019), which states that there is a correlation between continuous land subsidence causing the topographic height of an area to be lower. The type of alluvial soil is clay and easy to consolidate so that it greatly affects land subsidence (Khoirunnisa *et al*., 2015). Moreover, the interaction between tropical cyclones and relative sea level rise exacerbates the complexity of compound flooding, making it increasingly difficult to manage in the context of global warming (Wu *et al*., 2024). Additionally, coastal regions are particularly vulnerable due to the intricate interplay between human activities and natural environmental dynamics (Fang *et al*., 2020; Zhao & Liu, 2020).

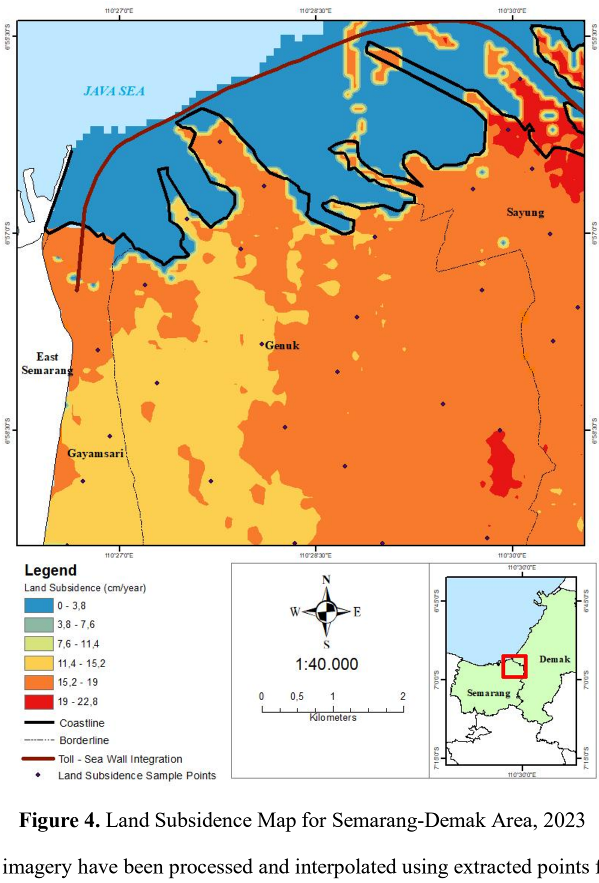

Figure 4. Land Subsidence Map for Semarang-Demak Area, 2023

The elevation data from Sentinel-1 SAR imagery have been processed and interpolated using extracted points from the Digital Surface Model (DSM) to convert it into a high-resolution Digital Terrain Model (DTM). The Semarang-Demak coastline has an elevation range from 0 meters to 3.21 meters **(Figure 5)**. This aligns with data from the Central Statistics Agency in 2021, where the elevation in Genuk to Sayung districts ranges from 1 to 3.5 meters above sea level. The processed data show that as one moves north or closer to the coast, the elevation decreases. This variation in land elevation is due to land subsidence, which results in differing levels of subsidence at various locations (Griselda *et al*., 2021). This finding is supported by Shidik *et al*.. (2019), who state that ongoing land subsidence correlates with lower topographic elevations in a region.

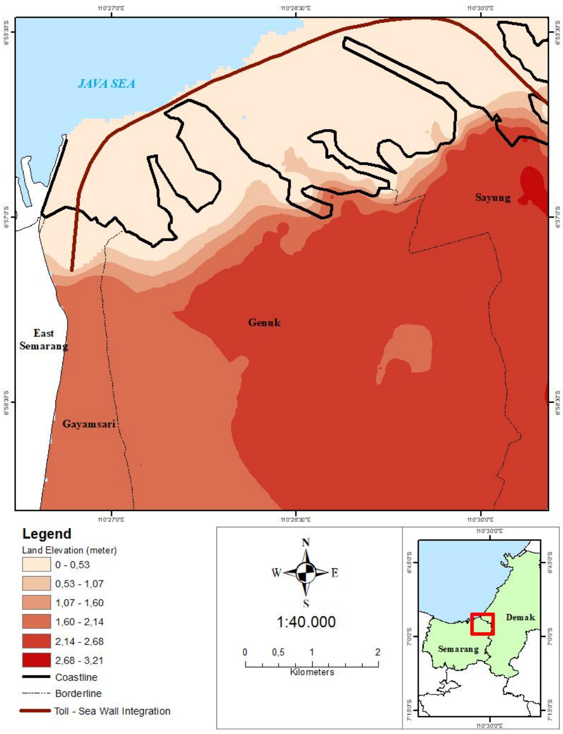

Figure 5. Land Elevation Map for the Semarang – Demak Area

Based on the spatial modelling of existing tidal flood inundation for Semarang-Demak, the flood area in 2024 is projected to cover 523.67 hectares **(Figure 6)**. In 2024, the seawall-toll road construction is still ongoing and not fully operational, and the inundation in Sayung District could still occur. Sayung District will experience the largest inundated area, with 345.97 hectares, followed by the Genuk and Gayamsari districts with 144.9 hectares and 32.8 hectares, respectively. Most of the inundated land is aquaculture ponds. In the Gayamsari and Genuk districts, the risk of water overflowing onto land is relatively low due to the presence of seawalls along the coast. However, in the Sayung District, areas with buildings (residential and industrial) are highly vulnerable to tidal flooding. According to residents, tidal flooding can occur daily, and no effective solutions have yet been implemented to address this issue.

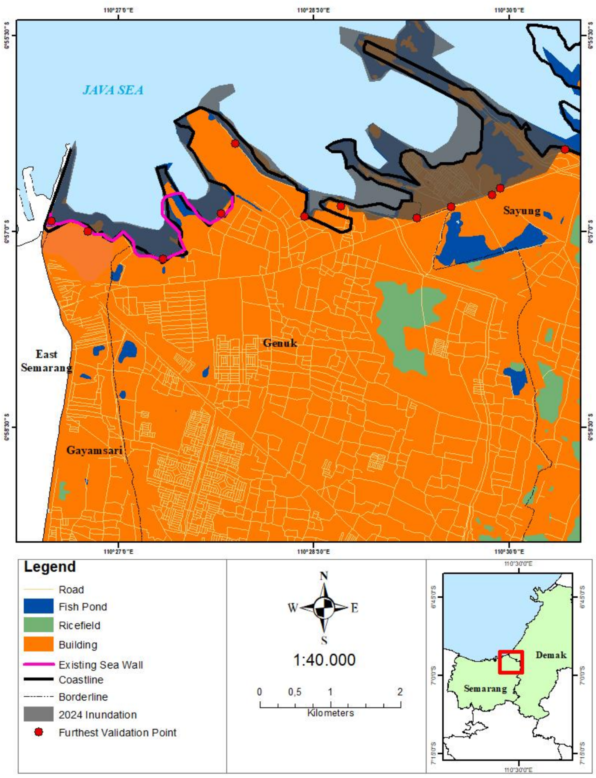

Figure 6. Furthest Tidal Flood Points in Semarang – Demak in 2024

Table 3. Validation of Tidal Flood Points in Semarang – Demak

No	Longitude	Latitude	District	Land Use	Distance from Shoreline (cm)
1	110,441498	-6,948674	Gayamsari	Aquaculture	0
2	110,488210	-6,948278	Gayamsari	Residential	0
3	110,446159	-6,950063	Genuk	Aquaculture	0
4	110,455779	-6,953534	Genuk	Aquaculture	0
5	110,463218	-6,947782	Genuk	Aquaculture	0.00005
6	110,465003	-6,938757	Genuk	Aquaculture	0
7	110,473830	-6,948079	Genuk	Aquaculture	0.00005
8	110,478491	-6,946790	Genuk	Aquaculture	0.00025
9	110.492613	-6.946908	Genuk	Aquaculture & Residential	0.0003
10	110,498922	-6,944509	Sayung	Road	0.0006
11	110.497881	-6.945317	Sayung	Road	0.0005
12	110,507153	-6,939550	Sayung	Road	0

Note: Based on the validation results, all points are accurate except for points 11 and 12.

Modeling for the year 2054 indicates that the integration of the toll road and sea wall, with a height of 7 meters, effectively protects the districts of Gayamsari to Sayung **(Figure 7)**. By 2054, areas protected by the toll road and sea wall integration are expected to be free from tidal flooding, even though land subsidence and rising sea levels will continue. However, despite the protection provided by the toll road and sea wall integration, 19 hectares of aquaculture land with a flood height of 185 cm will still be affected by tidal flooding, as the infrastructure does not cover this area. The prediction model demonstrates that the Semarang-Demak toll road-sea wall integration is highly effective, reducing tidal flooding by 96.37%.

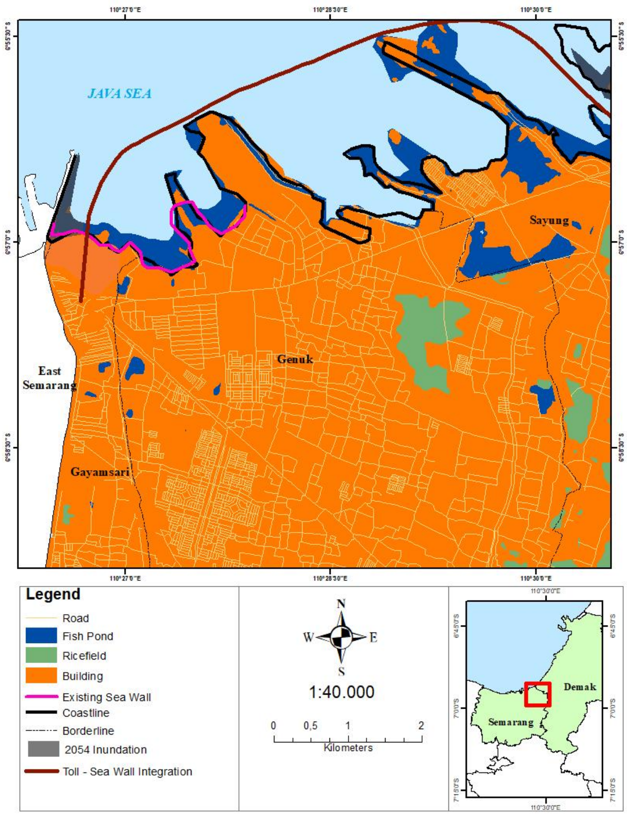

Figure 7. Predicted Tidal Flood Inundation Area in Semarang - Demak in 2054

Table 4. Predicted Total Tidal Flood Inundation Area in Semarang - Demak for 2054

No	District	Land Use	Area (Ha)	Total (Ha)
1	Gayamsari	Buildings	0	19
		Aquaculture	19	
2	Genuk	Buildings	0	0
		Aquaculture	0	
3	Sayung	Buildings	0	0
		Aquaculture	0	
	Total affected area (Ha)			19

The toll road and sea wall integration will require updating by 2059. In 35 years, tidal flooding is expected to return to the area due to high tides and low topography, resulting in flooding of up to 5023.41 hectares. In 2059, with land subsidence expected to reach 575 cm (5.75 m) and sea levels projected to rise to 193 cm, the seawall-toll elevation of 1.8 meters (180 cm) will be overtopped, leading to flooding **(Figure 8).** Gayamsari is still free from inundation because its land subsidence rate is lower than in Genuk and Sayung, keeping its ground level more stable. However, the northern part of Gayamsari is at a higher risk of flooding due to its proximity to coastal areas and tidal influences.

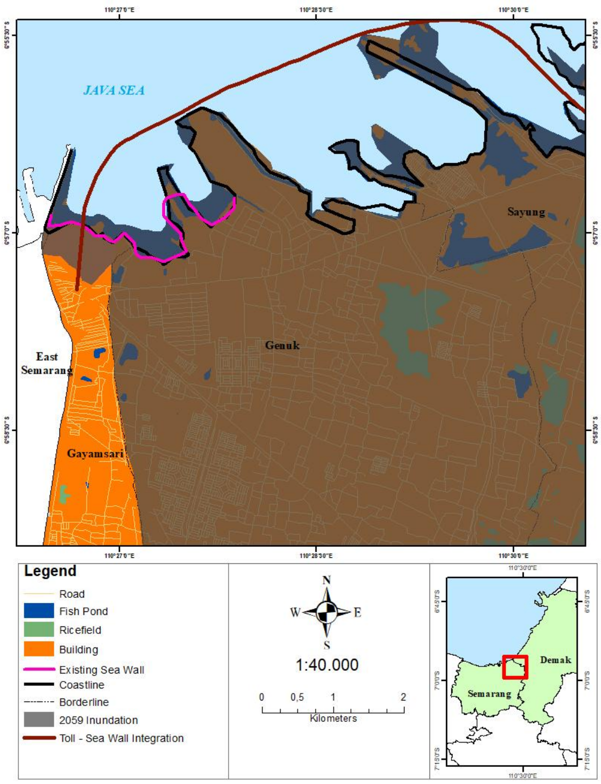

Figure 8. Predicted Tidal Flood Extent in Semarang-Demak in 2059

Sustained land subsidence will lead to increased seawater encroachment during high tides. This encroachment is considered tidal flooding (Syafitri and Rochani, 2021). Areas with low topography are particularly vulnerable, and the low-lying coastal areas of Semarang are expected to experience significant flooding. The Semarang coastline, which directly borders the Java Sea, will see water overflowing into residential areas during high tides.

The impacts of tidal flooding include the inundation of aquaculture lands, residential areas, industries, and rice fields, along with damage to infrastructure. Efforts to mitigate these effects include the construction of the Semarang-Demak toll-road-sea wall integration, stretching 26.95 km. This seawall has effectively reduced tidal flood extent by 96.37%. However, this 7-meter-high sea wall is designed to manage tidal flooding for only 30 years. It is hoped that the Semarang-Demak integration will also protect infrastructure and mangroves in the coastal area, ensuring sustainability.

4. Summary

Tidal flooding is influenced by land subsidence, with rates of 14.16 cm/year in Genuk, 15.5 cm/year in Gayamsari, and 17.8 cm/year in Sayung, combined with a sea level rise of 4.7 mm/year. The Semarang-Demak toll-road-sea wall integration is expected to be effective for the next 30 years, spanning from Kaligawe to Sayung at a height of 7 meters above MSL. Geospatial modeling indicates that the existing tidal flood extent in Semarang-Demak for 2024 is 523.67 ha, with the largest flood area in Sayung at 345.97 ha. By 2054, the integration will effectively protect the areas behind it, although 19 ha of unprotected aquaculture land will still be flooded. In 2059, overtopping is predicted, with tidal flood extent reaching 5032.41 ha, affecting Genuk, Gayamsari, and Sayung. While the Semarang-Demak toll-road-sea wall integration is highly effective in reducing tidal flooding by 96.37% in 2054, overtopping will necessitate upgrades by 2059.

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