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INUNDATION PREDICTION AS THE EFFECT OF RISING MEAN SEA LEVEL AND HIGH ASTRONOMICAL TIDE IN NORTH JAKARTA BASED ON 2013-2021 TIDAL DATA

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Coastal, Inundation, Sea Level Rise, Tidal

ABSTRACT
Future sea level rise in North Jakarta is one of the potential hazards that threaten the safety of coastal communities and infrastructure. Prediction of sea level rise is needed to reduce the vulnerability of the people living on the coast. This study was conducted to estimate the height of sea level rise in 2045 using linear regression analysis of hourly tidal data for 2013-2021 coupled with the highest astronomical tide value from the results of tidal harmonic analysis in 2021 using the t_tide application in matlab. The water elevation was then projected on the Digital Elevation Model to obtain the inundation area in 2045. The result of this study is an inundation area of 56 km^2 in North Jakarta in 2045 due to an increase in total sea level of 117 cm at high tide.

INTRODUCTION
Coastal environments are highly volatile and are affected by natural factors such as climate change and human activities and at the same time, the sector plays a significant role in national economic growth (Veettil et al., 2020). Approximately 20% of the global population will be exposed to 100-year coastal flooding if the global mean sea level is increased by 0.15 m without further population shift and adaptation (Intergovernmental Panel on Climate Change (IPCC), 2023). Cities in coastal Indonesia face the danger of sea level rise. Surabaya, Semarang, and Jakarta are large, densely populated coastal cities that are also centers of economic activity in Indonesia. In the long-term, sea-level rise may lead to an increase in the frequency and intensity of flooding in coastal settlements (Clemente et al., 2022).

Sea level dynamics can be influenced by various factors including climatic and seasonal weather-driven and non-climatic and geological-driven (Triana & Wahyudi, 2020). Some of the factors are local tidal characteristics (Anzidei et al., 2023), weather changes such as rainfall (Park et al., 2018), changes in ocean currents (Soerjawo & Maryanto, 2018), changes in coastal topology (Parker et al., 2007), temperature (Tresnawati et al., 2024).

Sea level rise can be calculated globally and locally (Intergovernmental Panel on Climate Change (IPCC), 2023). Local mean sea level in an area can be observed from tidal stations located on the coast (Irawan et al., 2021). Tidal stations are generally permanent, making it easier to analyze the average sea level rise for a certain period (Parker et al., 2007). The trend of sea level rise is obtained using linear regression (Anggraeni Damayanti, 2016)(Amalina et al., 2019)(Bappenas, 2018).

Some studies that predict sea level rise in coastal Indonesia include (Dewi, 2020) with an increase of 2.26 cm/year in Lamongan City, and on Saparua Island with an increase of 2.89 cm (Djunarsjah et al., 2021). Indonesia also has a RAN-API Review document on Ocean Climate Projections issued by Bappenas which can be a guideline in the implementation of mitigation and adaptation to sea level rise. The document states that the relative water level rise in Pantura Java could reach 10 cm/year (Bappenas, 2018). However, coastal communities do not only face potential hazards due to sea level rise. Before the mean sea level rise, they faced inundation hazards due to tides (Rahman et al., 2021)(Dahl et al., 2017), and extreme waves either from storms or climate change (Vitousek et al., 2017). Extreme wave heights in Pantura Java can reach 1 m to more than 1.5 m, increasing the risk of flooding in coastal zones at low elevations between 0 m - 3 m (Bappenas, 2018). There is uncertainty in predictions of sea level rise, so a vertical range is needed to incorporate the risk factors of extreme tides and waves (Hunter, 2012).

The height of the tide experienced in a coastal area depends on tidal characteristics. Tidal characteristics can be predicted because they are related to the interaction and motions between the Earth the Moon and the Sun at a certain period (Parker et al., 2007). Each of these motions or constituents is a mathematical value describing the effect. Analysis of tidal characteristics can be done by analyzing the harmonic constituents/components (Julianto et al., 2021). Harmonic constituents that can be identified include the Highest Astronomical Tide (HAT), Mean High Water Level (MHWL), Mean Sea Level (MSL), etc.

High sea level rise and tidal waves can cause inundation in coastal areas. Inundation projections and the impacts that will occur can be analyzed spatially using a Digital Elevation Model (DEM) (Lasmana et al., 2013) (Bagheri et al., 2021). The data on potential inundation that occurs due to sea level rise and tidal waves is important because this can be very useful to know which locations in coastal areas are vulnerable to these hazards and can be a part of the consideration in making mitigation and adaptation programs to maintain the safety of people living in coastal areas, especially North Jakarta.

METHOD RESEARCH

This study examines the impact of sea level rise on the North Jakarta area which has an area of 139.56 Km^2. Sea level rise projections were obtained through tidal data from the Sunda Kelapa Jakarta Tidal Station from the Geospatial Information Agency consisting of 76,760 data from January 1, 2013, to December 31, 2021. Of the 9 years of data, there are some days where no tidal data is available, but the 2015 data is the most complete because it includes data every hour for one year. The location of the SKLP Tidal Station is at coordinates -6°7'30.72" and 108°48'36".

Harmonic analysis took place with the t_tide application, which can perform nodal correction that is accurate when using data for one year (Pawlowicz et al., 2002). T_tide was performed in matlab using 2021 tidal data to obtain the predicted value of the model at the highest tide condition. The results of the tidal harmonic component analysis are the amplitude and phase values of the tidal harmonic components, such as M2, K1, O1, M4, MS4, S2, N2, K2, and P1. The plan water level elevation can be calculated based on the values of harmonic constituents as follows:

- Mean Sea Level (MSL) = Zo
- Highest Astronomical Tide (HAT) = Zo + (all constituents)

The highest astronomical tide value from the t_tide model is used to estimate the highest tide conditions that have the potential to cause inundation that endangers coastal areas. The projected value of mean sea level in 2045 and the highest tide conditions are projected on a Digital Elevation Model (DEM) map to obtain an inundation map. Based on the inundation map, the affected area will be obtained.

RESULT AND DISCUSSION

Figure 1 shows the sea level from the Sunda Kelapa Tidal Station (SKLP) observations for 2013-2021.

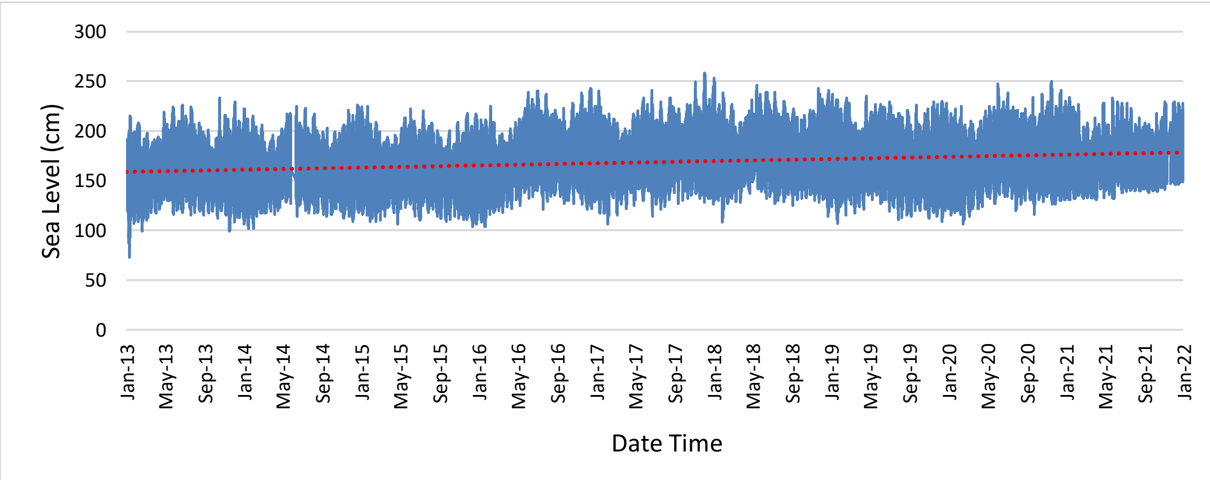


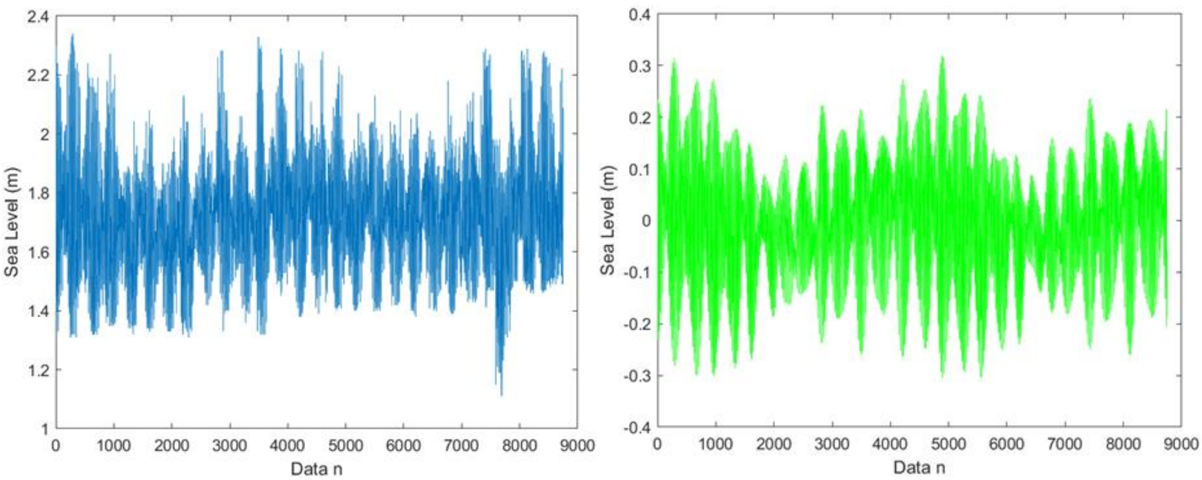
Figure 1. Sea Level at Sunda Kelapa Tidal Station Year 2013 - 2021
Source: Zahra, 2024

The following linear equations were generated from sea level measurements at Sunda Kelapa Tidal Station (SKLP) from 2013 to 2021:

$$Y = 0.0059X - 86.127$$

Based on the equation, the average sea level trend increases by 2.3 cm per year. As a result, the mean sea level in 2045 will rise to 55 cm compared to the mean sea level in 2021.

Analysis of tidal harmonic constants with the least square method using the t_tide application was completed using 2021 data at Sunda Kelapa Station resulting in a graph of observation and model data as shown in Figure 2.



(a) **(b)**

Figure 2. Tidal Harmonic Analysis Using t_tide. (a) Observation Data. (b) T_tide Model
Source: Zahra, 2024

Table 1 shows some harmonic constants as a result of the analysis so that the Highest Astronomical Tide (HAT) is obtained as follows. The table does not show all harmonic constants but only shows some important constants, but the calculation of HAT has considered all harmonic constants.

Table 1. Harmonic Constants

Tide	Frequency	Amplitude (m)	Phase (°)
Q1	0.0372185	0.0278	314.8
O1	0.0387307	0.0685	336.85
P1	0.0415526	0.0661	309.6
K1	0.0417807	0.0801	346.97
N2	0.0789992	0.0070	80.55
M2	0.0805114	0.0302	93.90
S2	0.0833333	0.0155	93.92
K2	0.0835615	0.0065	162.22
M4	0.1610228	0.0028	34.38
MS4	0.1638447	0.0003	171.09
Highest Astronomical Tide (HAT)		2.34 m	
Mean Sea Level (MSL)		1.72 m	
Root Mean Squared Error (RMSE)		0.171 m	

Source: Zahra, 2024

The highest astronomical tide is 62 cm above mean sea level. The scenario used in calculating the height of inundation that can occur in 2045 is the height of the mean sea level due to sea level rise plus the height of tidal waves, resulting in an inundation value of 117 cm. This inundation height was overlaid on the map and resulted in the inundation prediction shown in Figure 3. Red-colored areas indicate inundated areas.

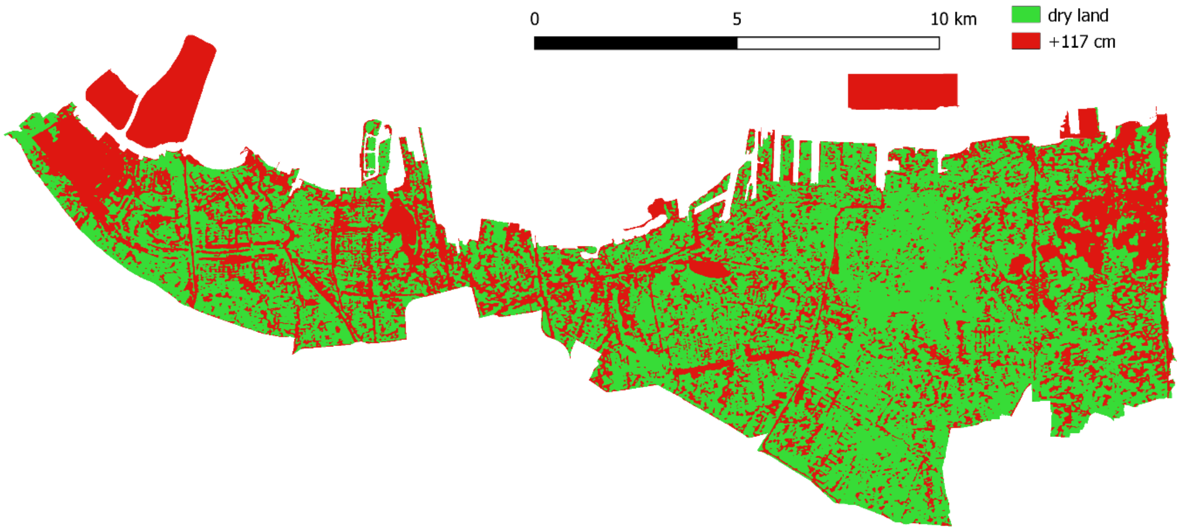


Figure 3. North Jakarta Inundation Map in 2045
Source: Zahra, 2024

The rising sea level indicated by tidal data is in line with previous research on sea level rise in Indonesian waters. According to Bappenas estimates from the RAN API Review Document-Scientific Basis Study of Ocean Climate Projections, sea level rise in the waters of Jakarta Bay is as follows: Sea Level Rise (absolute) = 0.7-1 cm per year; Relative Sea Level Rise = 10 cm per year; and Extreme Wave Height = 1-1.5 m.

Figure 4 shows how sea level changes in some cities, such as Jakarta, Surabaya and Semarang, based on isostatic sea level recorded by tidal stations. Isostatic sea level rise is the result of vertical land drift, including subsidence rates, and other factors. Therefore, directly recorded tide gauges cannot be used to estimate sea level rise regionally, as they can only be used at the local level (Bappenas, 2018). In Jakarta, based on tidal data from 1993-2015, which increased by 2.56 cm per year, this trend is consistent with the findings of this study based on tidal data from 2013-2021, which increased by 2.3 cm per year.

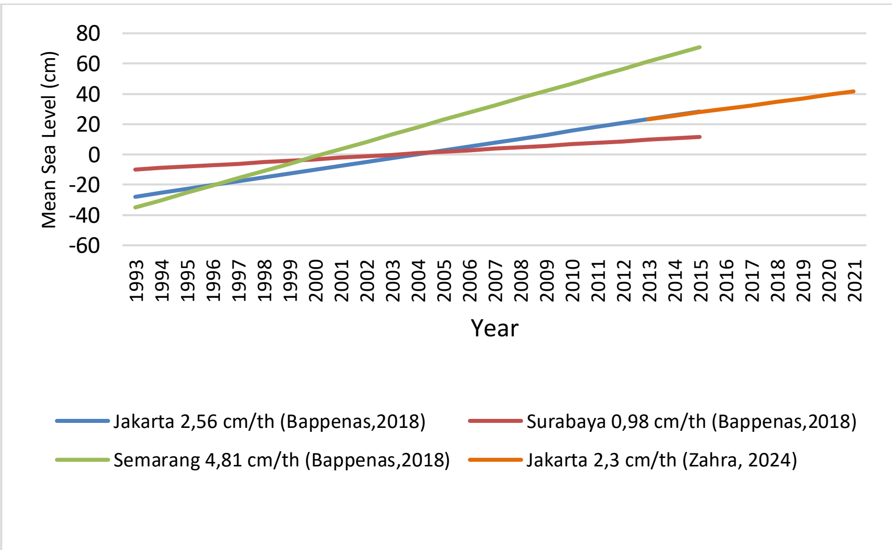


Figure 4. Ketinggian Muka Air Laut pada Stasiun Pasang Surut Sunda Kelapa Tahun 2013 - 2021
Source: Adapted from Bappenas, 2018

The hazards faced by communities living on the coast are not only inundation due to permanent mean sea level rise, but they can also be exposed to hazards from high tides. As the result of spatial analysis, the projected inundation in 2045 that could occur during the highest tides could inundate an area of 56 km^2 in North Jakarta.

CONCLUSION

In 2045, North Jakarta could experience a sea level rise as high as 55 cm. Based on harmonic analysis, the Highest Astronomical Tide that can occur in coastal North Jakarta is as high as 62 cm, so the total inundation height that can occur at the highest tide condition is 117 cm in 2045 compared to the mean sea level in 2021. Based on the inundation projection on the DEM map, the area inundated due to mean sea level rise is 56 km^2. This prediction is useful in preparing mitigation and adaptation activities to face the risk of inundation in the future so that the community can avoid large losses.

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