

Spatio-Temporal pattern of coastal flooding due to microclimate change and mangrove deforestation in Semarang and Demak Coastal Area

Widjonarko^{1,2*}, Hartuti Purnaweni³, and Maryono²

¹Doctoral Program of Environmental Science Diponegoro University, Indonesia

²Department of Urban and Regional Planning, Diponegoro University, Indonesia

³Department of Public Administration, Diponegoro University, Indonesia

Abstract. The coastal area of Semarang-Demak has a high intensity of economic activity, indicated by the presence of industry, housing, and other socio-economic activities. On the one hand, the coastal area of Semarang-Demak is faced with increasing pressure due to climate change, and environmental degradation (mangrove deforestation). The climate change and mangrove deforestation have made the coastal flooding wider. This study is aimed to reveal the relationship between climate change, environmental degradation, and its impact to coastal flooding in Semarang Demak. This study used remote sensing methods using Landsat data from the years 1988-2023. The results showed the strong relationship between climate change, mangrove deforestation, and coastal flooding. And they have a significant impact on increasing the area of flooding on the Semarang-Demak coast. The modeling using regression statistics resulted the regression equation $Y = -8966.7 + 290.8X_1 + 5.06X_2$, where Y is the area of flooding on the Semarang Demak coast, X_1 is mangrove forest damage, and X_2 is microclimate change, with a determination coefficient of 74%. Based on this model, the opportunity for an increase in the area of flooding will be even greater if no efforts are made to overcome mangrove damage, and also microclimate change.

1 Introduction

Coastal areas are the main center of economic, social, and cultural activities in various countries in the world. Coastal areas, although spatially only a small fragment of the earth's surface, however they are the main concentration of industrial activities, population concentrations with various kinds of social, economic, and cultural activities. [1,2]. On the other hand, coastal areas are the most sensitive areas to external environmental changes, and various studies show that coastal areas are the areas most easily exposed to climate change, global warming, and rising sea levels. This event has caused an increase in the threat of natural disasters in coastal areas. Climate change is characterized by an increase in sea surface temperatures of up to 0.2°C in recent decades [3],[4],[5]. Climate change greatly affects the existence of organisms in marine habitats [6],[7]. Increasing sea surface temperatures result in increased sea salt levels, oxidation

* Corresponding author: widjonarko@live.undip.ac.id

and deoxygenation of sea water, and threaten the existence of organisms living in the water. [8],[9]. Climate change and global warming also contribute to rising sea levels. The trend of global sea level rise of up to 2.6 mm per year has a significant impact on coastal areas [10],[11]. The impact of sea level rise has increased the risk of coastal flooding, as shown by studies by Taherkhani et al and Osland et al in coastal areas of the Americas [12,13]. If coastal flooding becomes more widespread and intense and the salinity of coastal water increases, it will threaten biodiversity in coastal areas, one of which is the threat of damage to mangrove habitats [14],[15],[16]. In addition, increasing coastal flooding will also put pressure on the social, economic and cultural lives of the people living there [7,17],[18].

Indonesia as an archipelagic country is experiencing pressure on coastal areas due to climate change, global warming, and rising sea levels. Pressure on coastal areas in Indonesia is exacerbated by anthropogenic factors, such as the mangrove deforestation for ponds, agriculture, and other economic activities in coastal areas [19,20]. Another pressure on coastal areas in Indonesia is exacerbated by excessive groundwater extraction that is triggering land subsidence. The northern coast of Java, where Indonesia's economic activity and population are concentrated, is the area most affected by climate change, global warming and rising sea levels, and is exacerbated by land subsidence. Research by Chaussard et al in 2013 [21], Sidiq et al in 2021 [22], and Susilo et al in 2023 [23], provide empirical evidence of the real threat of the phenomenon of rising sea levels and land subsidence to urban areas on the north coast of Java Island.

The coastal cities in the north of Java Island that are most affected by sea level rise and land subsidence are Jakarta, Semarang, and Demak. The coastal area of Semarang Demak is the area with the highest level of threat due to sea level rise and land subsidence. Various studies conducted in the last fifteen years by Abidin et al., Yastika et al., Yuwono et al., and Hakim et al. show empirical evidence of land subsidence in the coastal area of Semarang Demak [24–26],[27]. Sarah et al.'s research also shows that land subsidence in the coastal areas of Semarang Demak is not only triggered by anthropogenic factors but also by natural factors, especially geological factors [28]. The geological conditions of the Semarang Demak coastal area are dominated by soft soil formations that are easily compacted when there is pressure from buildings above the ground surface [24],[29]. Anthropogenic factors that cause land subsidence on the coast of Semarang Demak are uncontrolled and excessive groundwater extraction, the presence of industrial buildings, and settlements with high building intensity [30,31].

The increase in sea level and land subsidence on the coast of Semarang Demak has resulted in the increasing spread of inundation towards the mainland. This condition also causes widespread coastal erosion in the coastal areas of Semarang Demak, which in fact no longer has a reliable natural coastal protection system due to the destruction of mangrove forests that were displaced by fish farming activities in the early 1980s. Mangrove plants in conditions of sufficient thickness have the ability to inhibit the flow of water from the sea towards the mainland, so that they will be able to inhibit the threat of flooding in coastal areas [32,33], [34]. Research by Arbyakto and Kardyanto in 2002, Marfai et al in 2008, and Sanjaka et al in 2013 provided empirical evidence on the implications of land subsidence and sea level rise on the spread of tidal flooding in the coastal areas of Semarang Demak [35–37]. In line with Marfai and Sanjaka, Irawan et al. in their research found that coastal flooding in the coastal areas of Semarang will become more widespread due to land subsidence. From previous research it can be seen that environmental damage affects the widespread of coastal flooding in the coastal areas of Semarang Demak. [38]. However, most studies focus on measuring the phenomena of climate change impacts, land subsidence, mangrove deforestation, and tidal flood phenomena, and none have examined the relationship and influence of these phenomena on coastal flooding. The research questions that arise due to the limitations of previous research are: is there a relationship between climate change and mangrove deforestation on tidal flooding? and How big is the influence of climate change and mangrove deforestation on tidal flooding? To answer

the research questions, this study aims to measure the influence of climate change and mangrove deforestation on tidal flooding in the coastal areas of Semarang-Demak quantitatively, using GIS and statistical methods.

2 Methodology

2.1 Research's Location

This research was conducted in the coastal area of Semarang Demak which stretches from Genuk District-Wedung District. The selection of the location was based on considerations of the uniqueness of the location, where the Genuk-Sayung area is a location with a high level of mangrove damage, while the Bonang-Wedung area is an area with a lower level of mangrove damage, and a lower level of inundation due to climate change. A clearer picture of the research location can be seen in Figure 1.

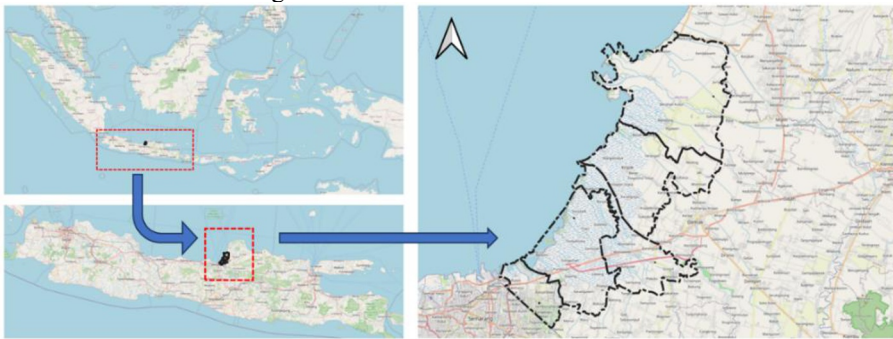


Fig. 1. Research's Location

2.2 Data and Analysis Methods

The data used in this study are secondary data by using temporal satellite imagery of Landsat 5 and 7 in the last 35 years (1988-2023). The use of Landsat satellite imagery for research related to spatiotemporal changes in coastal areas has been widely carried out, including the use of satellite imagery to detect changes in the area of mangrove forests [39,40], [41]. The use of Landsat data has also been widely used to detect the impact of climate change on coastal areas to identify the sea surface air temperatures, the extent of inundation in coastal areas, and the physical condition of waters in coastal areas [42–44]. Surface temperature detection uses thermal sensor data, and then converted into air temperature indicators. While the potential for coastal flooding is identified using the Normalized Difference Water Index (NDWI) method. The NDWI value is obtained by comparing the difference in visible green wave, near infrared, or short wave infrared values [45–47]. Visible green wavelengths maximize the reflectance of water surfaces, while near infrared wavelengths maximize the reflectance of land or vegetation. The mathematical formula of NDWI can be denoted as follows:

$$NDWI = \frac{(Green - SWIR)}{(Green + SWIR)} \quad (1)$$

Using the NDWI formula, the inundated coastal area can be easily identify, the positif number of NDWI represent the water surface.

To measure the relationship between climate change, mangrove deforestation, and coastal flooding, statistical methods are employed. Statistical methods, especially correlation and regression methods, have been widely applied in many researchs related to the impacts of

climate change [48–50]. A brief description of the data and methods used in this study can be seen in Figure 2.

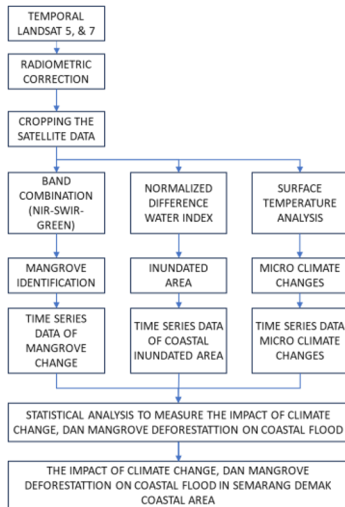


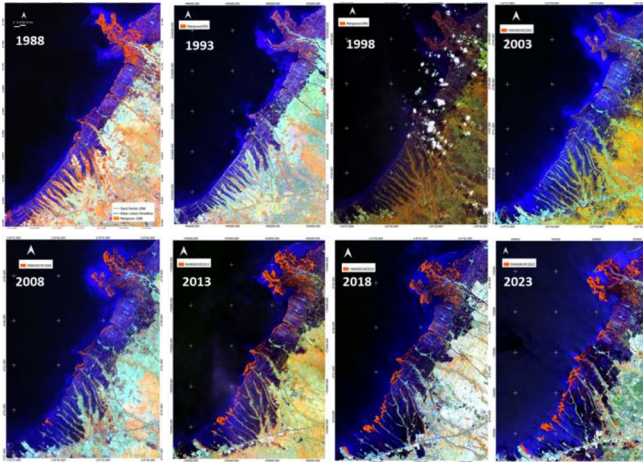
Fig. 2. The Research Workflow

3 Results and Discussion

3.1 Spatio Temporal Patterns of Mangrove Forest Change

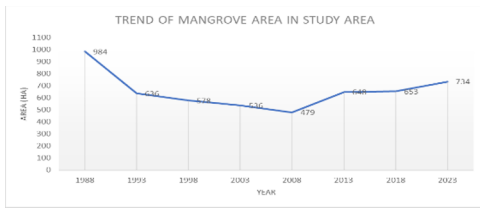
Mangrove classification using the support vector machine (SVM) algorithm shows that the area of mangrove forests has decreased significantly in the period 1988-2023. The area of mangrove forests in 1988 was 984 Ha, and decreased to 479 Ha in 2008. Wedung District has the largest mangrove forest, which is 632 Ha (64.2% of the total area of mangrove forests) and the thickness of vegetation ranges from 200 meters to 450 meters. Meanwhile, in Genuk, Sayung, Bonang Districts, it has the narrowest mangrove forest with a mangrove forest shape in the form of a line pattern surrounding the pond with a forest thickness of 40 meters to 60 meters which functions to protect the pond from the impact of sea waves. However, along with the conversion of land into ponds, the area of mangrove forests in the area is only 362 Ha left in 2023.

The decreasing area of mangroves, and the increasing area of ponds on the Semarang-Demak coastal area, in line with the previous research which stated that anthropogenic factors are a major threat to the existence of mangrove forests in coastal areas [20]. This condition is exacerbated by rising sea levels which have damaged mangrove plants. This situation has encouraged local governments and NGOs to restore mangrove forests, and has succeeded in increasing the area of mangrove forests to 648 Ha in 2013, and to 734 Ha in 2023, and the Semarang Demak sea wall which is currently under construction has not yet put significant pressure on the mangrove forest area around the embankment. A clearer picture of the pattern of changes in mangrove forests at the research location can be seen in Figures 3 and 4



Source: Landsat 5, 7, dan 8, processed in 2024

Fig. 3. Spatio Temporal Pattern of Mangrove Forest In Semarang Demak Coastal Area 1988-2023



Source: Landsat 5, 7, dan 8, processed in 2024

Fig. 4 The Trend of Mangrove Area in Semarang Demak Coastal Area 1988-2023

3.2 Spatial Temporal Patterns of Coastal Flooding

The results of inundation identification using the NDWI method show that there has been an increase in the area of inundation in the coastal areas of Semarang Demak City, especially in the research location. In 1988, the area of inundation due to coastal flooding was 3929 Ha, and increased to 6856 Ha in 2023 or an average increase around 84 Ha per year. Sayung District and Bonang District, Demak Regency are the area has highest increase of inundated area. A clearer picture of the spatial pattern of changes in inundation based on NDWI values from 1988 to 2023 can be seen in Figure 5 and Figure 6.

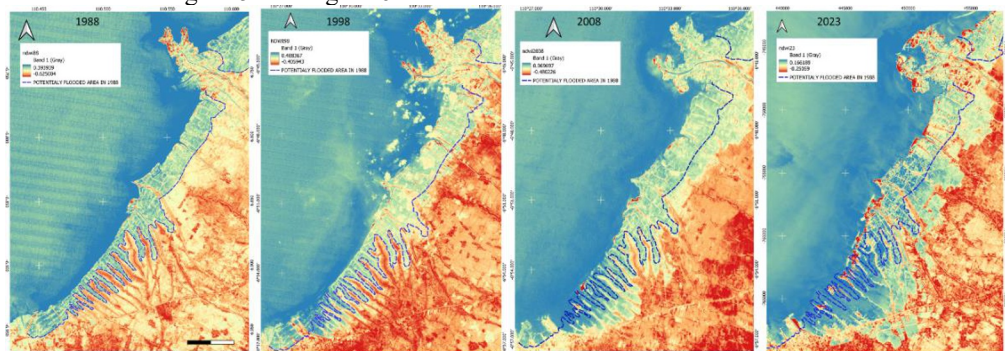


Fig. 5. The Spatio Temporal Inundated Area Based on NDWI Value (1988-2023)

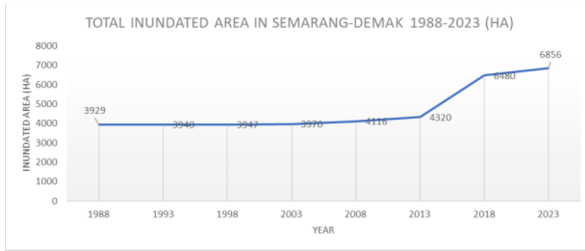
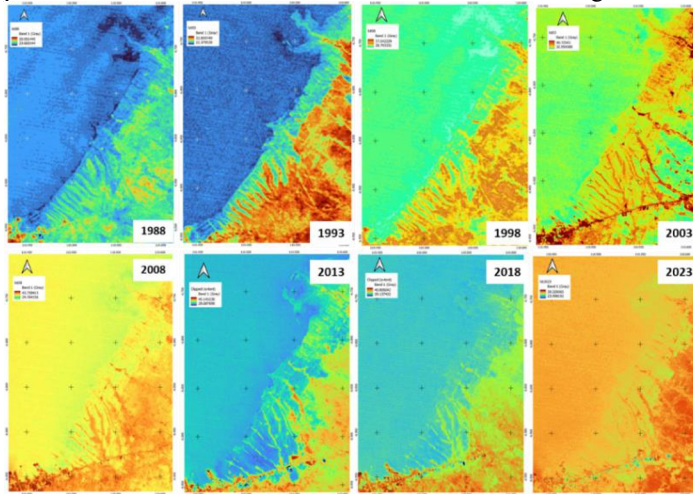


Fig. 6. Trend of Inundated Area in Semarang Demak Coastal Area

3.3 Microclimate Spatial Temporal Patterns

In the last three decades, there has been a change in the microclimate in the coastal areas of Semarang-Demak. The pattern of microclimate change is characterized by a tendency for increasing land surface temperatures and sea surface temperatures. Land surface temperatures have increased by 8.6°C in the last 35 years (1988-2023), or an average increase of 0.24°C per year. The highest temperature was reached in 2013-2018 with an average land surface temperature of 38°C . Sea surface temperatures have also increased by 8.8°C in the last 35 years. Increased surface temperatures have the potential to increase evaporation and can strengthen the greenhouse gas effect on the atmosphere [51,52], [53]. Figure 7 shows the spatiotemporal patterns of microclimate in the coastal area of Semarang-Demak.



Source: Thermal Infrared Data of Landsat 5, and 7, Processed, 2024

Fig. 7 Microclimate Change Patterns on the Coast of Semarang Demak 1988-2023

3.4 The Impact of Microclimate Change and Mangroves on Coastal Flooding

The results of the analysis show that microclimate changes (MC), and mangrove deforestation (MD) have a strong correlation to the increase in the area of inundation in the coastal area of Semarang- Demak, with a correlation value of 0.65 (correlation value of MC to inundation area), -0.59 (correlation value between MD to inundation area). The correlation value shows that MC and MD have an effect on the increase in the area of inundation on the coast of Semarang-Demak, and this is in line with previous studies which state that the existence of mangrove forests naturally has the ability to protect the coast from the threat of flooding due to sea tides, if it has adequate forest thickness [32–34,54]. MC has a positive correlation value and indicates

that increasing air temperature will cause coastal flooding more widespread. Increasing air temperature will trigger higher evaporation, and will cause higher rainfall intensity. If rainfall intensity increases, and nature's ability to absorb water decreases due to changes in land cover, it will increase surface runoff, and cause inundation. This is in line with previous research by Panthou et al in 2014 and Tabari in 2020 [55,56].

The regression analysis show that MC (X1) and MD (X2) as independent variables have a significant contribution to coastal flooding (Y) as the dependent variable. These independent variables contribute 74% to the coastal flood regression model in the Semarang-Demak Coastal Area, and the remaining 26% is influenced by other factors that have not been studied in this study. Other factors that may affect the widespread of inundation on the Semarang-Demak coast are the existence of industrial areas that still take groundwater uncontrollably, and changes in land cover in the water catchment area that cause greater water runoff. These factors are interesting to study further, in order to provide a more comprehensive picture of the problem of inundation on the Semarang-Demak coastal area. The statistical model of the influence of microclimate changes and changes in mangrove forests on the area of inundation in the Semarang-Demak coastal area can be denoted in the following regression equation:
$$Y = -8966,7 + 290,8X_1 + 5,06X_2.$$

This model explains that coastal inundation will increase by around 290.8 Ha if the mangrove forest is reduced by 1 Ha, and the microclimate variables do not change. If there is a change in the microclimate by one degree Celsius, and the area of mangrove forest does not change, then the area of water inundation will increase by 5.06 Ha. This model is in line with research that has been conducted which proves that climate change and mangrove forest damage have a significant impact on water inundation in coastal areas [32–34,54], [56–58].

4 Conclusion

From the analysis it can be concluded that increasing microclimate and deforestation of mangrove forests will cause coastal flooding to become more widespread. Increasing air temperature as an indicator of microclimate change has the potential to increase the area of inundation due to increased evaporation that make rainfall intensity is higher, and increased runoff discharge in coastal areas. Likewise, deforestation of mangrove forests will cause coastal flooding to become more widespread due to the decline in mangrove ecosystem services as coastal protectors from tidal waves.

Based on the research results, to reduce the area of inundation in the coastal areas of Semarang-Demak, efforts to improve the microclimate (reducing the increase in local air temperature), and improving the mangrove ecosystem with sufficient thickness and mangrove reforestation can be effective instruments to reduce the potential for inundation in the coastal areas of Semarang Demak. Mangrove forest restoration and reforestation not only require support from local governments, but also from all stakeholders. Not only to restore or reforest, but also to reduce the rate of deforestation of mangrove forests. However, efforts to repair or reforest mangroves require special conditions, namely the availability of sufficient planting media (mud) and of course it takes a long time to provide, so if it requires faster efforts to overcome coastal problems, then of course it must involve the right technology that needs to be studied through further research.

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