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ABSTRACT

Sayung is a coastal area located in the northern coast of Central Java Province, Indonesia. This area is severely damaged and experienced shoreline changes due to massive erosion and tidal flooding. This study aims to analyse the shoreline changes in Sayung coast during 24 years period from 1994 to 2018. Shoreline data were obtained by extracting multi-temporal satellite imagery of Landsat 5, 7, and Sentinel 2A. Coastline data for the year 1994, 2000, 2005, 2011 and 2018 were analysed using an overlay technique with the assistance of Geographic Information System (GIS) with ArcGIS software. Statistical analyses were conducted using the Digital Shoreline Analysis System (DSAS) to calculate erosion and accretion rates. The results show that the average end point rates (EPR) was −25 m/yr and net shoreline movement (NSM) was −592 m recorded. For five years measurement period: 1994–2000, the EPR value was −7 m/yr, the NSM value was −39 m; 2000–2005 the EPR value was −15 m/yr and the NSM value was −77 m. For 2005–2011 the EPR value was −20 m/yr, and the NSM value was −123 m, and 2011–2018 the EPR value was −41 m/yr, and the NSM value was −290 m. Severe erosions were found in Sriwulan, Bedono, and Timbulsoko. Slight accretion occurs in Surodadi which were caused by varying characteristics of waves, and storms surge, tidal currents, bathymetry forms, and mangroves cover.

1. Introduction

Globally, there are about 45% to 60% of the world's population settling in coastal zones (Syvitski et al., 2005; Church et al., 2006; Jonah et al., 2016; Boye et al., 2018) which are the most densely populated regions. Easy access to ocean transportation, food security, and aesthetical view may become the primary factors. A similar condition was found in Sayung coastal region, which has become the most degraded coast due to erosion and flooding (Marfai, 2011). These regions are highly dynamic and continuously vulnerable due to natural and artificial disturbances by humans (Bird, 2008; Jayakumar and Malarvannan, 2016), with changes continually occurring at different time and space scales (Eman et al., 2015). Natural disturbances are caused by tsunamis, storms surge, waves, currents, tides, erosion, accretion, and flooding, whilst human disturbances include construction of breakwaters, groins, jetties, domestic and industrial effluents, and recreational activities. Both natural and human factors have led to erosion and accretion causing shoreline changes both within short and long-term periods (Leatherman et al., 2003; Saranathan et al., 2011; Mahapatra et al., 2014; Poormima et al., 2015).

Consequently, shoreline changes play a critical role in deteriorating surrounding environment and loss in enviro-socio-economic aspects: destruction of natural and artificial coastal defence, loss of residential areas, damages of infrastructures, etc. Therefore, coastal regions are experiencing a global severe erosion and flooding. This phenomenon has occurred in coastal regions of Sayung where severe and extensive erosion and flooding have destroyed villages, fish ponds, and the economy of local communities.

With around 17,500 islands with 108,000 km of coastline, Indonesia is the third-longest coastline country in the world (Dahuri et al., 2001; Pushidrosal TNI AL, 2018). Most of the capitals and big cities are located in coastal regions. Coastal waters of Sayung have potential fisheries catching and fish ponds ("*tambak*") cultivation as well as a nursery ground for marine organisms. However, increasing mangroves and land conversion (into fish ponds) in late 1980's have caused the area to become vulnerable to, coastal erosion due to waves and storms actions (Achiari et al., 2015; Hapke et al., 2006; van Wessenbeeck et al., 2015; Elliff and Silva, 2017). The coastal vulnerability can be quantified through the changing in shoreline position and morphology, as well as the occurrence of erosion and accretion (Dean and Dalrymple, 2002; Appeaning Addo et al., 2008).

A shoreline can be defined as the borderline between land and a body of water (Kumaravel et al., 2013). Shorelines are

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Fig. 1. Map of research location at Sayung Coast Demak (Red box represent study area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

very highly dynamic regions with continuous sediment transport forming new morphological forms and characteristics (Jayakumar and Malarvannan, 2016). Sayung shoreline has experienced physical degradation, i.e., severe erosion due to wave actions, tidal flooding, and deforestation of mangrove forests for fishponds purposes (Marfai, 2011). Fast deforestation leads to damages of mangrove and lack of nutrients from mangrove leaves and branches decomposition by microorganisms. The depletion of mangroves area, physical structures, and composition of mangroves are some of the prominent impacts noticed along the shoreline (Thoai et al., 2019). The degrading condition has forced the local people from two villages in Bedono, Sayung were relocated to other places.

There have been only a few studies on shoreline changes of Indonesia coastal areas that allow researchers to have a more comprehensive understanding of the characteristics and behaviours of the shorelines. Previous studies are relatively limited to some areas of the coast, especially in Java, i.e., Coast of Gresik East Java (Fuad and Fais, 2017); Tuban District East Java (Joesidawati and Suntoyo, 2017); and Pondok-Bali West Java (Achiari et al., 2015). Apart from the limited coverage of these investigations, most analyses were carried out using Landsat images, which were quite general. Hence, there has been insufficient detail information retrieved concerning the shoreline change behaviours in Indonesia. Consequently, the patterns of shoreline changes of the Sayung coast need to be further investigated annually using higher-resolution satellites. Landsat 5, 7 and Sentinel 2A Images (the latter is a new satellite with high resolution 10 × 10 m) was used to explain the seasonal characteristics of the shoreline and its morphodynamic processes. The present aims to carry out an in-depth analysis of the Spatio-temporal shoreline change in Sayung for 24 years. Also, its contributing factors (i.e., waves, tides, and currents) using Digital Shoreline Analysis System (DSAS) with end point rate and net shoreline change in the coastal region. The adoption of the DSAS method based on its capability that enables the calculation of shoreline change rate statistics from multiple historical shoreline positions. The findings will contribute to the future integrated coastal management and rehabilitation of the Sayung coastal region.

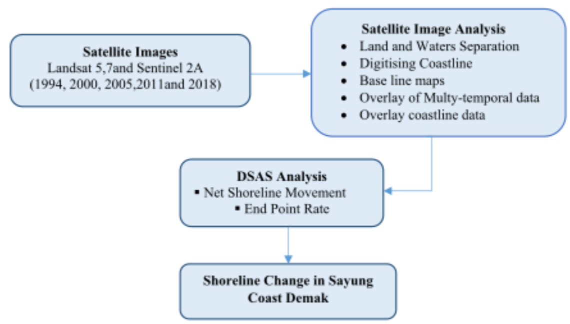

Fig. 2. Flowchart of the research.

2. Methods

2.1. Study area

The coast of Sayung lies within latitudes 6°54′0″ south and longitudes 110°30′0″ east (Fig. 1), which is about 8.84 to 11.8 km long. The shore length variation is due to erosion and or accretion. Hydrodynamically, the coastal area of Demak can be divided into two parts. The eastern part has lower energy (fewer wave actions), and the western part (Sayung area) has higher energy (more wave actions) during west monsoon sessions. The higher energy level is due to waves deflected by Semarang harbour pier leading to the concentration of higher waves energy in the western part (Hartoko, 2010). Consequently, Sayung coastal area experiences massive erosion and tidal flooding, and the eastern part has less erosion. Sayung sub-district consists of four villages: Sriwulan, Bedono, Timbulsloko, and Surodadi. Sixty per cent of the population work as fishermen and fishpond cultivator (Asiyah et al., 2015). The topography is generally low lying with elevation less than 2% and height 0–5 m above sea level (Subardjo, 2004).

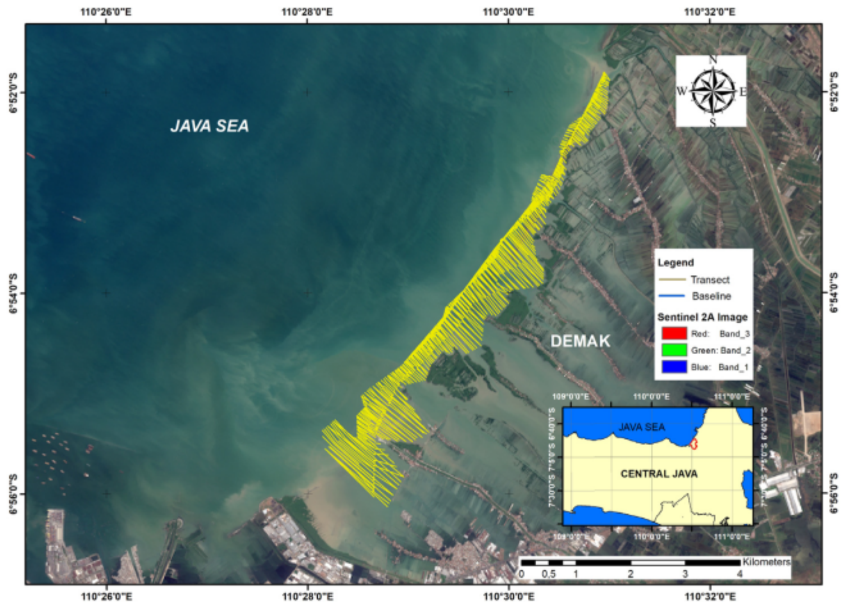

Fig. 3. DSAS analysis applied along Sayung coast with time series shoreline change and transect lines interval 50 m apart.

Oceanographic climate shows a significant wave height of about 25 cm to 30 cm and a significant wave period between 3 s to 4 s (Hawati et al., 2017; Brand et al., 2018). The dominant wave approaches the coastline from east and sea-level rise is about 8 mm/yr (Utami et al., 2017). Tidal characteristics recorded in Sayung area show that the tidal range of neap and spring tide is 0.1 m and 1.1 m, respectively (Dishidros, 2017). Type of tides is mixed semidiurnal, where two high tides and two low tides of different heights occur daily. Silt and clay fractions dominate more than 70% of the coastal sediment materials, and the remaining is sand fractions (Muskananfola et al., 2017). Scarce mangrove trees cover some portions of the shore to dense mangrove forests, which functions as coastal protection (Mazda et al., 1997; Zhang et al., 2012).

2.2. Data collection and analysis

The flowchart of the research is presented in Fig. 2, showing the step by step process from the data source, images analysis, DSAS analysis, and shoreline change. Data were obtained from RBI maps, and satellite images (1994, 2000, 2005, 2011, 2018) from Landsat 5, 7 and Sentinel 2A. The image dataset was georeferenced to WGS 1984, 49S for the study area, and the shoreline features were then obtained by digitising on-screen, overlaying, and integrating into a GIS format. High Water Line (HWL), which is the most commonly used shoreline indicator, was used to extract the positions of the shoreline (Boak and Turner, 2005). Visually, shoreline position is more comfortable to identify in the field by a distinct wet or dry line (Pajak and Leatherman, 2002). Frequently, this is the only existing indicator in the field, particularly at coasts protected by seawalls or other artificial structures (Del Rio and Gracia, 2013). Satellite image analysis covered the process of separating water and land, screen digitising on coastline and baseline, and overlay of coastline data, and transformation of transect lines into quantitative spatial data using cell-based calculation. A procedure of satellite images data selection was conducted. Only data taken during low tides (at 10.30 am) were used in this study to obtain data with the same water levels and to avoid unnecessary data corrections for tidal water levels.

Table 1
Average end point rate and net shoreline movement of Sayung beach.

Period	End point rate (m/yr)	Net shoreline movement (m)
1994–2018	−25	−592
1994–2000	−7	−39
2000–2005	−15	−77
2005–2011	−20	−123
2011–2018	−41	−290

DSAS analysis was performed on the Net Shoreline Movement (NSM) and End Point Rate (EPR) to calculate shoreline change that occurred during the investigation. The EPR is calculated by dividing the distance (in metres) between two shorelines by the number of years between the dates of the two shorelines (Dolan et al., 1991; Genz et al., 2007; Thieler et al., 2009).

$$EPR = \frac{\boldsymbol{D}_1 - \boldsymbol{D}_2}{\boldsymbol{t}_1 - \boldsymbol{t}_0}$$

where:
D_1 and D_2: the distance between the shoreline and baselines.
t_0 and t_1: the dates of the two shoreline positions.
The net shoreline movement reports a distance value, not a rate. The NSM is associated with the dates of only two shorelines and reports the distance between the earliest and the latest shorelines for each transect

$$\mathbf{NSM} = \mathbf{D}_{t2} - \mathbf{D}_{t1}$$

where:
D_{t2}: Distance of earliest shorelines for each transect
D_{t1}: Distance of latest shorelines for each transect
These methods were adopted to generate the statistics of Net Shoreline Movement (NSM) and End Point Rate (EPR) to illustrate the shoreline change in the study area. With a transect line distance interval of 50 m applied along with the 8.84 to 11.8 km of the coast of Sayung (Fig. 3).

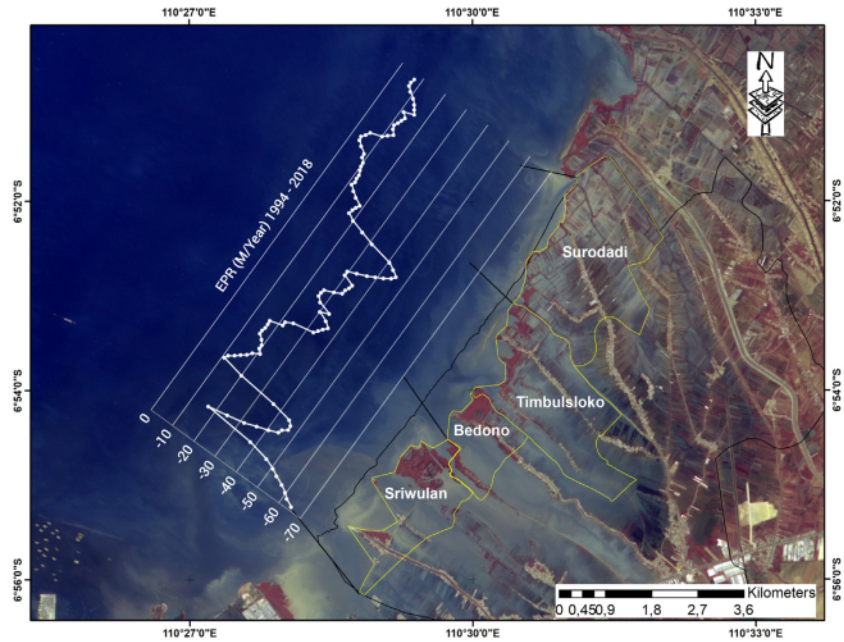

Fig. 4. Erosion rates (m/yr) along the coastline of Sayung during the year 1994–2018 period.

Table 2
The highest and lowest values of erosion rates and accretion rates in Sayung beach.

Period	End point rate erosion (m/yr)		End point rate accretion (m/yr)	
	Highest values	Lowest values	Highest values	Lowest values
1994–2018	−65	−4	0	0
1994–2000	−108	−1	34	2
2000–2005	−222	−1	21	6
2005–2011	−95	−2	6	2
2011–2018	−129	−7	0	0

3. Results

3.1. Summary of shoreline changes: 1994–2018

The results of the application of DSAS analysis on the rates of shoreline changes calculated at 50 m transect distance across the coast of Sayung are presented in Fig. 3. Furthermore, the summary of the analysis results of the shoreline change as the average value of end point rate (EPR) and net shoreline movement (NSM) between 1994 and 2018 are shown in Table 1. Overall, this indicates that erosion and shoreline movement rates increased continually during the 1994–2018 with end point rate −25 m/yr and net shoreline movement −592 m. It was observed in each period that there was continuous erosion, and a remarkable increase in end point rate and net shoreline dynamic occurred within 2011–2018.

3.2. Erosion and accretion rates

The erosion and accretion that occurred in the study area are shown in Table 2. Overall during the whole period, 1994–2018, the erosion rate was −65 (highest value) and −4 (lowest value) with an average −25 m/yr. Here it is noted that there was no accretion recorded during the study; the erosion rates were far higher causing small rate accretion unrecorded. It is indicated that during the 2000–2005 observational periods, the range of end point rate erosion fluctuates with the highest value −222 m/yr and the lowest value −1 m/yr. End point rate accretion highest value was 34 m/yr, and the lowest was 2 m/yr, which occurred from 1994 to 2000.

Erosion patterns occurring during 1994–2018 in the study area is presented in Fig. 4. Overall, this indicates that erosion patterns varied spatially and temporally along the shoreline. However, it was clearly shown that the highest erosion occurred in Sriwulan, Bedono, and Timbulsloko, and the lowest erosion occurred in Surodadi. Fig. 5 shows the erosion and accretion rates from 1994 to 2000. The highest erosion dominantly occurred in Sriwulan and low erosion in Bedono and Timbulsloko. Low accretion also occurred in Sriwulan and Surodadi. Fig. 6 shows erosion and accretion rates (m/yr) along the shoreline of Sayung during the year 2000–2005. A relatively flat trend of erosion along the Sayung coast, where only a small area with high erosion was recorded in Sriwulan and Timbulsloko, whilst low accretion occurred in Surodadi. Fig. 7 shows erosion rates (m/yr) along the shoreline of Sayung during the year 2005–2011 period. It indicates that the highest erosion occurred in Timbulsloko, medium erosion occurred in Surodadi, and low accretion occurred in Sriwulan and Surodadi. Fig. 8 shows erosion rates (m/yr) along the shoreline of Sayung during the year 2011–2018 period. It indicates that erosion patterns fluctuated during this period with varying degrees. The highest erosion recorded in Sriwulan, medium erosion in Timbulsloko, and low erosion occurred in Bedono and Surodadi.

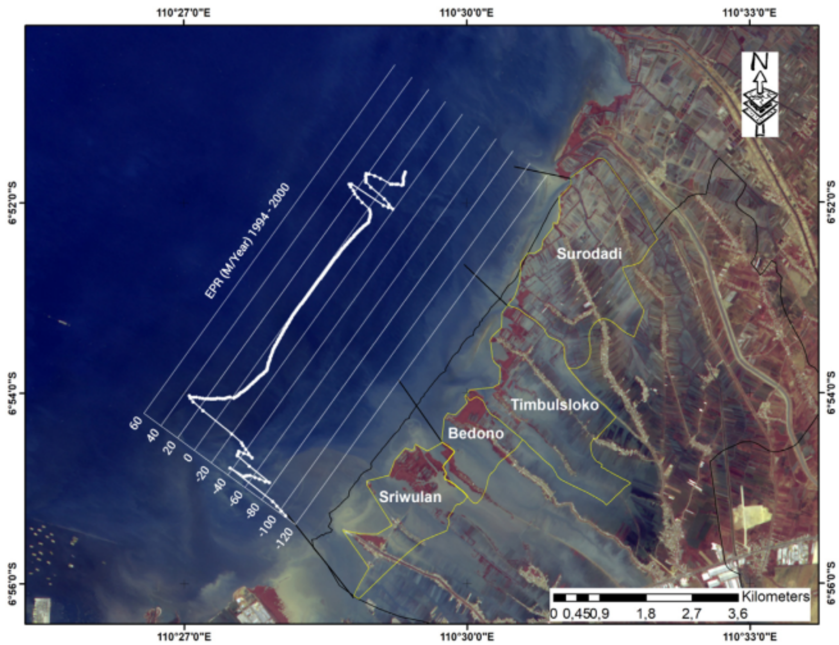

Fig. 5. Erosion and accretion rates (m/yr) along the shoreline of Sayung during the year 1994–2000 period.

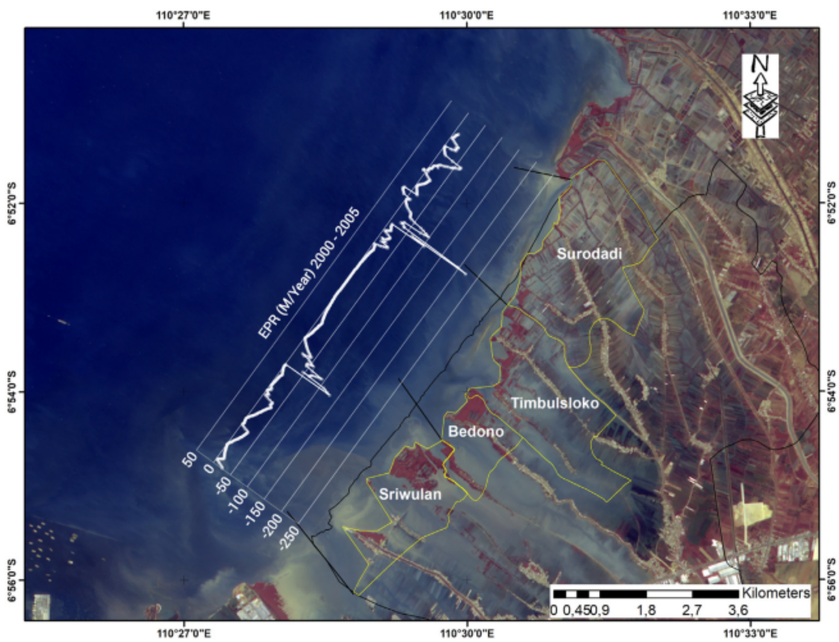

Fig. 6. Erosion rates (m/yr) along the shoreline of Sayung during the year 2000–2005 period.

3.3. Shoreline change

Table 3 shows the results of shoreline change, which occurred in the study area during the period of the study. It is indicated that shoreline change due to erosion increased steadily during the 24 years study period. Overall, during 1994–2018 net shoreline movement erosion −1558 m (highest value) and −90 m (lowest value), average −592 m; there was no shoreline movement accretion recorded during this total period.

The highest net shoreline movement erosion during 2000–2005 was −1108 m (highest value) and −4 m (lowest value) with an average −77 m. The highest net shoreline movement accretion was 205 m (highest value) and 12 m (lowest value), with an average 105 m occurring in 1994–2000.

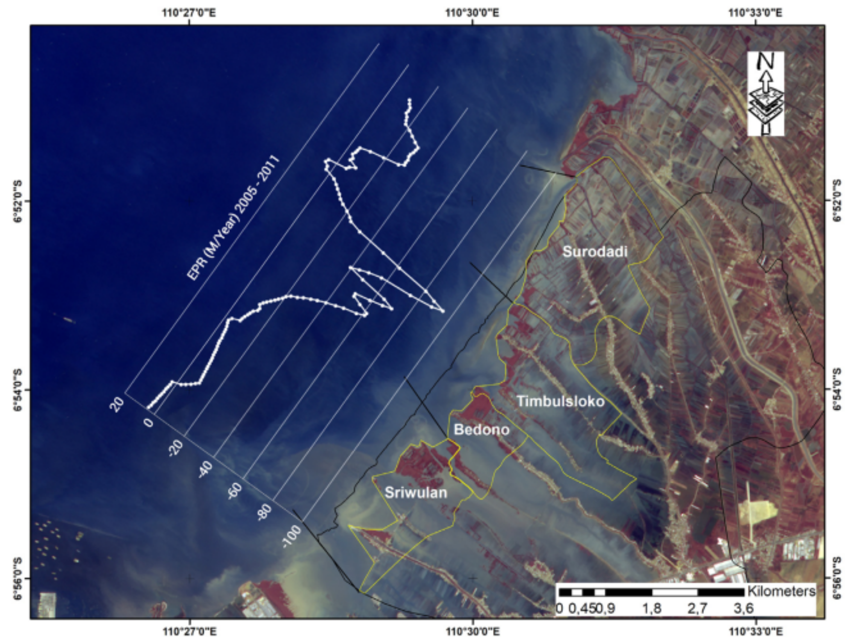

Fig. 7. Erosion rates (m/yr) along the shoreline of Sayung during the year 2005–2011 period.

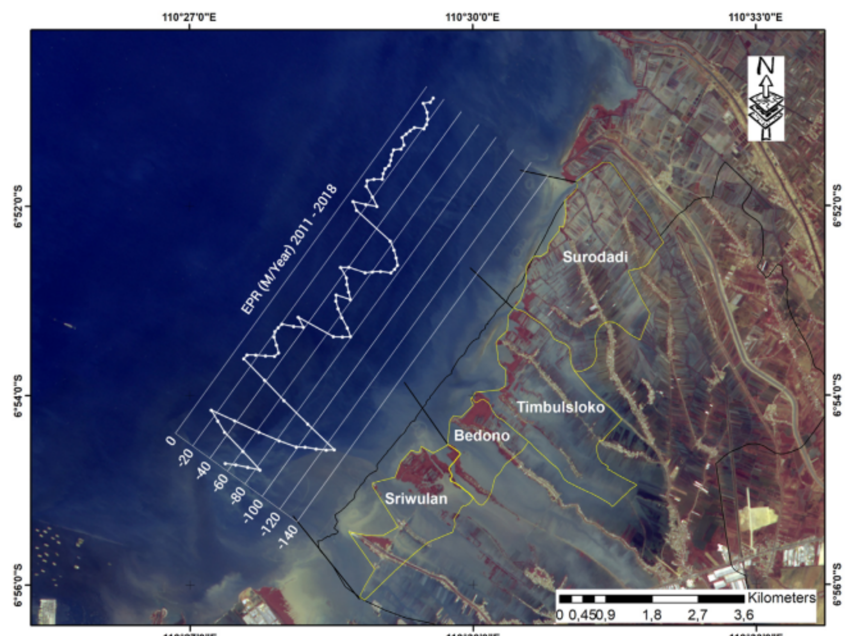

Fig. 8. Erosion rates (m/yr) along the shoreline of Sayung during the year 2011–2018 period.

4. Discussion

4.1. Erosion and accretion evidence

In the present study, negative values for shoreline changes indicate that the shoreline moved landwards (erosion); whilst positive values (+) represent shoreline shifting seawards (accretion). These two phenomena can be analysed and discussed spatially and temporally. Overall, Figs. 4–8 of the current study show that Sayung coastal region has experienced severe erosion and flooding along Sriwulan, Bedono, and Timbulsloko, with low accretion along Surodadi. The findings are in line with the

Table 3
The highest and lowest values distance shoreline movement in Sayung beach.

Period	Net shoreline movement erosion (m)		Net shoreline movement accretion (m)	
	Highest values	Lowest values	Highest values	Lowest values
1994–2018	−1558	−90	0	0
1994–2000	−646	−7	205	12
2000–2005	−1108	−4	106	31
2005–2011	−567	−13	34	15
2011–2018	−907	−47	0	0

results of Marfai (2011), Saranathan et al. (2011), Mahapatra et al. (2014), Poormima et al. (2015), Jayakumar and Malarvannan (2016) and Boye et al. (2018) that coastal region is frequently susceptible to erosion, accretion, and tidal inundation. The present study also reveals new evidence that, spatially, the north-eastern section of the study area has experienced lower erosion rates in comparison to the south-western section. The north-eastern section covers Surodadi and the east part of Timbulsloko, and the south-western section covers Sriwulan, Bedono, west of Timbulsloko. This variation might be due to the variation in wave energy, morphological characteristics and bathymetry, water depth, and mangrove cover and density along the coast of the study area. This evidence is in line with the findings of Bird (2008), Mazda et al. (1997) and Zhang et al. (2012). The wave height reached 2 m during the wet season; tidal currents speed reached 0.5 ms^{-1}. Bathymetry forms and mangroves have functions to protect coastal regions from erosion. Mangroves are the last fence protector of shoreline changes due to erosion and accretion. In coastal zones, the energy of incoming waves is attenuated by coral reefs at the forefront, by seaweeds at the intertidal coast, and by mangroves at intertidal towards coastline (Elliff and Silva, 2017; Thoai et al., 2019).

The bathymetry characteristics also contribute to the condition as the water depth in the south-western part of Sayung (Sriwulan, Bedono) is deeper (more than 2 m) than in the north-eastern part (less than 2 m) (Timbulsloko and Surodadi) (Muskananfola et al., 2017). The higher water depth allows waves to run further landwards and hit the coastline of Sriwulan and Bedono, causing erosion. This phenomenon mainly occurred periodically during the wet season leading to severe erosion and land loss in the Sayung coastal area. Moreover, the development of jetties/wave breakers of Semarang harbour causes more concentration of waves energy reaching Sayung coast and high erosion during wet/rainy season (Hartoko, 2010).

This study reveals and confirms that the Sayung region is experiencing a significant coastal erosion problem. Based on the findings of previous studies i.e. Sayung topography (Subardjo, 2004); wave characteristics (Hawati et al., 2017); sea-level rise (Utami et al., 2017); erosion and transport rates of sediments (Muskananfola et al., 2017); it is assumed that wave actions reached 2 m, tidal currents speed 0.5 ms^{-1}, and that river flows and decreased sediment loads input from the surrounding rivers are the possible causes for the increasing erosion of shoreline in Sayung. It is suggested that, to some extent, sea-level rise and land subsidence may have contributed to the present condition. Land subsidence at the neighbouring Genuk regency was 8 cm y^{-1}. These two variables are out of scope of this study; therefore, they need to be investigated in further studies. Leatherman et al. (2003) supports this argument that sea-level rise causes beach erosion and accelerates shoreline retreat in the following ways, i.e.: (1) waves will break closer to the shore with higher energy, (2) wave refraction will decrease, and longshore sediment transport capacity will increase, and (3) waves and currents will act further up the beach causing re-adjustment and re-shaping of beach profile. There are many hard and soft structures built for coastal protections at different parts of Sayung coastal waters indicating the erosion severity, which alarms public awareness and attention. The inhabitants in two villages in the most degraded areas in Bedono have been relocated to other places due to severe erosion and tidal flooding that impacted the areas (Asiyah et al., 2015).

Accretion is defined as the migration of shoreline seawards due to the deposition of sediment materials. Table 2 shows that overall, there was no accretion during the whole study period 1994–2018. Periodically, during the 5-year investigation, accretion rates are relatively low, ranging from 34 m/yr to 2 m/yr (1994–2000) and from 21 m/yr to 6 m/yr (2000–2005). From 2005 to 2011, accretion ranged from 6 m/yr to 2 m/yr, whilst from 2011 to 2018; there was no accretion recorded. These findings confirmed that there was low accretion occurring on several spots of Sayung coastal area. The calm waves condition during east/dry season (wave steepness $<$ 0.010) leads to accretion, and erosion occurs under higher wave energy (wave steepness $>$ 0.010) (Marfai, 2011; Brand et al., 2018). Calm waters allow fine sediment particles to settle onto the seabed whilst rough waters stir and agitate bottom sediments to be re-suspended into water column and washed out to open ocean (Leatherman et al., 2003; Muskananfola et al., 2017; Hapke et al., 2006) by faster tidal currents during low tides.

4.2. Shoreline changes

The varying patterns in the rates of shoreline change identified in this study (Table 3) indicate that the contributing factors and the associated response factors differ in magnitude along the coast of Sayung. Hydro-oceanographic characteristics (wave height reached 2 m, and tidal currents speed reached 0.5 ms^{-1} during west monsoon season) as the main contributing factors vary seasonally (between wet session and dry session); whilst the main responsive factors (bathymetry forms, mangrove forests density) vary spatially which lead to spatial variations in erosion and accretion rates (van Wessenbeeck et al., 2015; Eman et al., 2015; Jonah et al., 2016). Equal variability of the shoreline change, to some extent, implies that erosive forces are in the state of dynamic equilibrium with resistive forces. In which case, the driving and response factors of shoreline change could be considered valid at a regional scale only (Dean and Dalrymple, 2002; Appeaing Addo et al., 2008). Conversely, the shoreline change varies considerably (Fuad and Fais, 2017). This study suggests that site-specific characteristics have paramount importance in the formation of Sayung coastal areas. The characteristics could be described by the varying degrees of the erosive force and the corresponding resistance force working at the two different sections. The south-western section was dominated by deeper water, and the north-eastern section was dominated by shallower water with sand dunes along the coast. This finding is consistent with the findings of Hapke et al. (2006), Muskananfola et al. (2017) and Joesidawati and Suntoyo (2017); which attributed short-term variation in shoreline to seasonal variation of wave characteristics, shear stress working at the seabed and current speed along the coast.

5. Conclusions

The present study indicates that most of Sayung shoreline has suffered from severe erosion. The erosion rate ranging between −4 m to −65 m with average −25 m/yr and net shoreline movement erosion ranged between −90 m to − 1558 m with average −592 m. The annual shoreline recession trends in most parts of the study area with limited accretion indicate that the sediment is being carried away consistently from the Sayung coastal water system towards offshore.

The south-western section (Sriwulan and Bedono) is eroding much faster towards land than the north-eastern section (Timbulsloko and Surodadi). This spatial variability of shoreline change might be due to variation in the corresponding driving factors. Those factors are the different features of the coastal morphology covered by mangroves, bathymetry forms, and water depth.

It is recommended that immediate actions be taken, and that coastal communities be trained on the effects of erosion and coastline change on the environment, and the effects of human activities on coastline change. Further studies on land use patterns, sea-level rise and land subsidence taking place in the coastal area of Sayung are highly recommended for a better future comprehensive coastal management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Max Rudolf Muskananfola: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing-original draft, Writing-review & editing. **Supriharyono:** Formal analysis, Funding acquisition, Investigation, Validation. **Sigit Febrianto:** Data curation, Formal analysis, Investigation, Project administration, Software, Validation, Visualization, Writing-review & editing.

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