Coastal erosion on the north coast of Java: adaptation strategies and coastal management

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Abstract. Coastal erosion remains a problem for the socio-economic development of the coastal zone in the north coast of Java. This study aims to determine the coastal characteristics, shoreline changes, and adaptation strategies of the north coast of Java through satellite study and on-ground observations. The analysis covers two decadal periods of satellite data starting from 1998 to 2018. The coastal characteristic of the north coast of Java is typified by sandy, muddy, and gravelly coast. At particular coasts have been extensively modified becoming coastal structure buildings. The shoreline changes are characterized by sectors alternating between erosion and accretion, although in general indicating the erosion processes. The conversion of mangrove ecosystems into fish ponds along with an increase of coastal constructions such as groins, jetties, and seawalls may have strong influences on the coastal erosion at the particular coastal environments. Since traditional hard defense methods used so far have had more damaging than protective effects, there is a need now for the use of soft prevention alternatives and for providing new guidelines for coastal management. A set of permeable breakwater measures, in conjunction with sediment managing schemes, are proposed for the sustainable development of the coastal zone.

1. Introduction
Coastlines are among the most rapidly changing and dynamic landscape features. A combination of sea waves and currents erosions, sediment depositions, activities of living organisms such as coral, crustal movements, and sea-level variations due to climate changes is the factor governing coastline formation [1, 2, 3, 4]. The north coast of Java stretching from Serang Banten to Situbondo East Java is dominated by alluvial deposits composed of gravel, sand, and mud [5]. These deposits are loose materials which are experienced ongoing natural compaction until now. Consequently, the majority of the north coast of Java is having low resistance to the coastal erosion processes [6].

The north coast of Java has strategic values for the development of economic activities located alongshore. The majority of the coast is low relief with abundant water resources both surface and groundwater reserves making this ideal for urban development. In fact, this area has been utilized as an industrial area, center of government offices, seaports, marine tourism, fisheries, agriculture, settlements, mining, public services including roads, school, hospital, market, etc. Consequently, this massive land use and uncontrolled natural resources extraction have contributed to environmental degradation such as coastal erosion, pollution, rob, inundation, and land subsidence, not to mention social conflicts. This process is magnified by the existing conditions of a warming climate that have resulted in constant inundation and an increased risk of flooding during extreme wave events.

The issue of environmental degradation on the north coast of Java including adaptation and mitigation against it has recently generated a lot of concern from the general public, decision-makers, environmental practitioners, as well as scientists. Measures have immediately been taken to rehabilitate degraded areas, especially population centers, economic activities, and natural resources using hard structures including seawall, sea dike, groin, revetment, and/or hybrid protection such as submerged...
breakwaters and hybrid engineering. Unfortunately, these measures were poorly designed and hurriedly constructed in order to reduce the erosion process impact generating an “express” coastal defense structure that was not fit for purpose. As a consequence, these "coastal erosion solutions" are constructed on a sporadic (action-reaction) basis and a partial-solution approach.

Studies related to coastal environmental degradation on the north coast of Java have previously been conducted discussing primarily on coastal erosion [7, 8, 9, 10], coastal inundation [11, 12], shoreline changes [5, 13], land subsidence [14, 15, 16], and sea-level rise due to climate change [17]. However, no adaptation strategies and coastal management have been proposed. This paper assesses the coastal erosion management strategies used along the north coast of Java by analyzing the coastal characteristics, shoreline changes, and effectiveness of coastal protection structures. Thus, the overall objectives of this paper include 1). Identification of coastal characteristics consisting of geology, geomorphology, and coastal processes, 2). Analysis of shoreline changes related to erosion-accrretion processes, 3). Assessment of effectiveness of coastal protection structures, and 4). Recommendation of adaptation strategies and coastal management. The study is also projected to be suitable and applicable to many other coastal management and research purposes in the future.

2. Material and Method

2.1. Study area

The geology of the north coast of Java is formed by alluvial river deposits and lahars from the volcanoes in the hinterland consisting of gravel, sand, silt, and clay (Figure 1). These materials are generally not well-consolidated and extensively spread almost the whole coastal plain of Java [5, 6]. These deposits are limited on the most western tip of the coast by the Gede Mountain (± 595 m high) and in Central Java by Muria Mountain (± 1,602 m high). The coastal morphology has generally low relief contours (<25m) and relatively flat with some river systems drain off into the Java Sea. The big river systems such as Ciujung and Cisadane in Banten, Citarum, Cipunagara, Cimanuk, and Cisanggarung in West Java, Pemali, Comal, and Wulan in Central Java, Bengawan Solo and Brantas in East Java tend to form a bird’s-foot delta around the estuary leaving the bays with relatively small rivers far behind [4]. The delta formation is a land augmentation due to shallow sea bottom and relatively small waves, tides, and currents on the north coast of Java [5].

The oceanography of the Java Sea is significantly influenced by the monsoonal drift prevailing easterly flow of surface current during the northwest monsoon from November to March. The pattern is reversed and the surface waters of the Java Sea are westerly flow during the southeast monsoon from May to September. This monsoonal reversal of surface currents is responsible for major changes in the sea surface salinities, ranging from 31 PSU (practical salinity unit) during the northwest monsoon to 35 PSU during the southeast monsoon [18, 19]. The bathymetry of the region is relatively shallow, rarely exceeding 60 m deep. The 5 m isobath lies generally about 2 km offshore, but in some places, especially around the delta environments, it can be more than 5 km. The average tidal range here is 1 m along the coast with diurnal tide type [5].

2.2. Coastal characteristic mapping

Coastal characteristic was investigated following methodology described by Dollan [1] which is practical for the coastal zone analysis because of the essentially linear (alongshore) nature of the coasts by which information such as geology (rock resistance), relief (morphology), and coastal processes are included. The surveys were conducted in 3 (three) consecutive years starting from 2018 to 2020 and representing whole province of the north coast of Java. Identification of sediment types were characterised by a visual assessment with an aid of magnifying lens. Groundtruth locations were photographed with a built in camera-global positioning system (GPS) unit. The coastal characteristic units are named based primarily on their form and fabric (constituents) such as “rocky”, “sandy” or “muddy” and secondarily described by the genetic or morphodynamic descriptors such as “cliff”, “beach”, “shore platform”, etc. The identification of distribution and type of coastal protection and
infrastructures such as groin, jetties, seawall, sea dike, etc was investigated online through google earth imageries which were then ground-truthed in the field in coincidence with coastal characteristics mapping. All coastal protection and infrastructures were counted within a zone extending from the shoreline to a landward distance of 100 m.

**Figure 1.** Map of study area showing geological setting, tidal pattern, and windrose diagram of average windspeed in Banten-DKI Jakarta, West Java, Central Java, and East Java.

2.3. **Satellite image processing**
Study was based on Landsat TM/ETM+ image covering whole region of the north coast of Java which is available for these following years: 1998, 2008, and 2018. The images were corrected geometrically to the universal transverse mercator (UTM) coordinate system and world geodetic system (WGS) 84 reference datum. The three visible bands of Landsat TM/ETM+ i.e. band 1 (0.45 – 0.52 µm), band 2 (0.52 – 0.60 µm) and band 3 (0.63 – 0.69 µm) as well as band 4 (0.76 – 0.90 µm) which is useful in differentiation of land from water, used in land-masking workflow. Groundtruth checking of the current status of coastal characteristic was assigned to the corresponding Landsat 30 x 30 m pixels. Multi-temporal Landsat TM/ETM+ images were analysed to assess shoreline changes following the DSAS modeling procedure described below.

2.4. **DSAS modeling**
The Digital Shoreline Analysis System (DSAS) extension from ArcGIS toolkit [20] was employed to calculate the shoreline change rate, with the use of regression indexes (Linear Regression Rate, LRR). The LRR method is particularly appropriate for analyzing shoreline changes and is considered as the best approach for the estimation of long-term coastal scalable tendencies [21]. A baseline was created offshore and transects perpendicular to the shoreline generated at 10 m intervals. Once the coastline vectors have been merged, they can be utilised by the DSAS extension in order to assess the rate of
change and total movement of the coastline over time. The net shoreline movement represents the total
distance between the oldest and youngest rates described in this paper represent the distance of shoreline
movement divided by the time elapsed between the oldest and the most recent shoreline. The dataset
analysed in this study only for the 2 (two) recent decadal periods (1998-2018).

3. Result and Discussion

3.1. Coastal characteristics
In general, the coastal characteristics of the north coast of Java are classified into 4 (four) types, including
sandy coast, muddy coast (i.e. mangrove, tidal mud flats, salt marshes), gravelly coast, and coastal
protection and infrastructures (e.g. seawall, jetties, seaports, seadike, groin, rock armors, etc). The
coastal characteristics are described in detail as follows (Figure 2):

Figure 2. Map of coastal characteristics showing distribution of sandy beach, muddy beach, gravelly
beach, and coastal protection and infrastructures on the north coast of Java.

3.1.1. Sandy coast. Sandy coasts are widespread on the north coast of Java particularly in Karawang,
Subang, Indramayu, Tegal, Pekalongan, Batang, Rembang, Tuban, and Gresik (Figure 2). The geometric
forms of the coasts are elongated sandy beaches with extensive coastal plain landward. Geologically,
sandy beaches consist of unconsolidated fine to medium sand, gray to blackish gray, and in particular
coasts contain coral and shell fragments. This coastal type has low resistance to wave erosion and ocean
currents. The beach slope is gently sloping seaward forming an angle between 2° and 4°. The coastal
plains have generally low relief contours (<25m) and relatively flat in which agriculture, fish ponds, salt
ponds, public facilities, settlements, and industrial areas are developed. The dominant coastal process is
erosion by both waves and longshore currents. The river systems draining off into this coastal type have
low energy so that at high tide, sea water enters the river channels far into the land.
3.1.2. Muddy coast. Muddy coasts including mangroves, mudflats, and salt marshes are associated with the highly active river and are extensively occurred on the north coast of Java particularly in Serang, Tangerang, North Jakarta, Bekasi, Subang, Cirebon, Brebes, Semarang, Demak, and Pati (Figure 2). This coastal characteristic comprises unconsolidated sediments that have accumulated for the last 5,000 years and is therefore of Holocene age [22, 23]. The muddy coasts are exposed in the intertidal zone at low tide up to ± 2 km seaward forming tidal mudflats morphology. The dominant coastal process is accretion or sedimentation through active rivers that drain off into the Java Sea. The high energy of river flow and mud content causes high accretion rates in big river systems forming a birdsfoot-type delta such as at Ciujung-Cidurian, Cisadane, Muara Gembong, Citarum, Cipunagara, Muara Curug, Cimanuk, Cisanggarung, Kali Comal, Kali Wulan, Bengawan Solo, Brantas, etc. Mangrove ecosystems, mainly Avicennia marina and Rhizophora apiculata, occur on mud substrates as narrow basins in the tidal reaches of rivers and streams discharging directly onto the north coast of Java. Muddy coast, together with landforms adjoining the tidal reaches of inland water is vulnerable to river flooding and marine inundation, separately and coincidentally. The frequency and duration of both processes, as well as their extreme events, are important factors that must be considered in coastal planning and management.

3.1.3. Gravelly coast. The gravelly coasts are found in a small part of the north coast of Java particularly in Serang, Batang, Jepara, Rembang, and Tuban (Figure 2). The coasts are usually composed of sand and rock fragments from near-shore rock abrasion. Geologically, the rock types are Quaternary volcanic rocks such as in Serang, Jepara, and Rembang, claystone in Batang, and limestone in Tuban and Lamongan. This coastal type has moderate to high resistance against the abrasion processes depending on the hardness of the rock. The dominant coastal process is abrasion by both waves and ocean currents.

3.1.4. Coastal protection and infrastructures. The coastal protection and infrastructures on the north coast of Java consist of jetties, seawalls, seadikes, revetments, groins, seaports, etc. These structures are mainly scattered in Serang, Tangerang, North Jakarta, Subang, Indramayu, Cirebon, Tegal, Pemalang, Pekalongan, Semarang, Jepara, Rembang, Tuban, and Surabaya (Figure 2). Concerning coastal protection structures, there are 2 (two) different categories: those which harden the shoreline to make it more resistant to erosion (seawalls, seadikes, revetments, etc) and those which stabilize the shoreline while altering the coastal processes (groins, jetties, breakwaters). These structures were mostly constructed during the last 30 years when the necessity to protect the coast raised driven by the growing coastal zone population and political-economic pressures.

Groins are the most common engineering practice for protecting the coast against erosion along the north coast of Java. These structures are constructed to influence shoreline sediment transport as a result of longshore currents. Generally, groin structures were made from concrete tetrapods, while others have been made from concrete rests, geotextile bags, and rocks. Seawalls and revetments are another common protection method applied on the north coast of Java. These structures were mostly designed vertical and mainly constructed to prevent a collapse of houses or buildings located on the coast and to stop the destruction of threatened coastal roads. Given the protection measures on the north coast of Java were made under a “hard” concept, over the last 5 (five) years, a “softer” approach called “Hybrid Engineering” later called HE” has been introduced and constructed on the north coast of Java mainly in Central Java (Table 1).
Table 1. Distribution of coastal protection and infrastructures on the north coast of Java

| Province      | Groins | Jetty access channels | Port’s jetty | Sea-walls | Length of seawall (km) | Land reclamation | Sea-ports | Length of HE (km) |
|---------------|--------|-----------------------|--------------|-----------|------------------------|------------------|-----------|------------------|
| Banten        | 9      | 5                     | 102          | 21        | 6.17                   | 4                | 5         | -                |
| DKI Jakarta   | 0      | 1                     | 40           | 13        | 10.17                  | 7                | 4         | -                |
| West Java     | 85     | 41                    | 44           | 26        | 31.88                  | 4                | 2         | 4.76             |
| Central Java  | 289    | 48                    | 109          | 51        | 34.57                  | 14               | 9         | 15.885           |
| East Java     | 404    | 5                     | 91           | 76        | 33.76                  | 24               | 18        | 1.2              |

3.2. Shoreline changes

The results of the shoreline change analysis indicate some areas have been subject to a significant accretion and erosion during the last 2 (two) recent decades from 1998 to 2018. The most significant rate of change has been observed at the coast around Demak Central Java and Bekasi West Java. Demak experienced the highest rate of erosion with up to 279.1 m/year eroding coastline up to ± 5 km between 1998 and 2018. Whilst, Bekasi experienced the highest rate of accretion up to 154 m/year indicated by the formation of 3 (three) delta i.e. Citarum, Muara Gembong, and Kali Bekasi (Figure 3). Based on data from the Ministry of Marine Affairs and Fisheries [24], the coastal erosion has induced the loss of land on the north coast of Java including Banten (± 648 ha), DKI Jakarta (± 48 ha), West Java (± 2,953 ha), Central Java (± 5,519 ha), and East Java (3,710 ha). The length of the eroded coastline reached ± 52 km, 7 km, 180 km, 261 km, and 246 km respectively (Table 2). The coastal erosion has also degraded mangrove ecosystems almost 205,775 ha along the north coast of Java and generated marine inundation, especially during the tidal floods.

The most striking shoreline changes on the north coast of Banten are around Ciujung-Cidurian and Cisadane delta with maximum accretion rates up to 112 m/year and 70 m/year respectively. In addition, the formation of tombolo morphology at Kasemen Serang suggests an intensive accretion process in this area which is generally formed coincident with a fixed sediment cell boundary. The significant shoreline changes also occurred in Bojonegara Serang induced by the massive development of coastal infrastructures. However, several coasts in Banten also experienced slight erosion with maximum rates up to 20 m/year at Pontang Serang and up to 10 m/year at Kosambi, Tangerang (Figure 3).

The North Jakarta coast is relatively stable or there has been no significant change in the amount of accretion and erosion rates, except for the massive development of port infrastructures and rock groins for the last two decades (Figure 3). The coast is currently subject to reclamation activities and associated infrastructures which may have resulted in coastal accretion.

The most noticeable shoreline changes on the north coast of West Java are situated in the delta environments including Muara Gembong, Citarum, Cipunagara, Muara Curug, Cimanuk, and Cisanggarung. The maximum accretion rates of the delta for the last two decades are 150, 45, 90, 25, 50, and 60 m/year respectively. The coastal erosion also significantly occurred around the Muara Gembong Bekasi, Pamanukan Subang, and Sindang Indramayu with maximum rates up to 150, 52, and 61 m/year respectively (Figure 3).

The most obvious shoreline changes on the north coast of Central Java occurred, including, in estimated order of erosion: Sayung Demak, Wanasari Brebes, Suradadi Tegal, Kaliwungu Kendal, and Tugu Semarang with maximum rates up to 279, 114, 60, 44 m/year and 40 m/year respectively. Whilst, the coastal accretions took place in the delta environments including Kali Comal Pemalang, Kali Bodri Kendal, and Kali Wulan Demak with maximum rates up to 70, 55, and 50 m/year respectively (Figure 3).

The most significant coastal accretion on the north coast of East Java from Tuban to Gresik occurred at the coast of Jenu Tuban and Paciran Lamongan with respective maximum rates up to 58 and 29 m/year. Whilst, the coastal erosion occurred at the Ujung Pangkah Gresik with a maximum rate up to 15 m/year (Figure 3).
Table 2. Total area of eroded coastline and degraded mangrove on the north coast of Java.

| Province     | Eroded area (ha) | Eroded coastline (km) | Degraded mangrove (ha) |
|--------------|------------------|-----------------------|------------------------|
| Banten       | 647.85           | 52.01                 | 2,282                  |
| DKI Jakarta  | 48.34            | 6.69                  | 414                    |
| West Java    | 2,953.17         | 179.45                | 10,507                 |
| Central Java | 5,518.91         | 261.27                | 124,870                |
| East Java    | 3,710.5          | 245.99                | 67,702                 |

Figure 3. Map of shoreline changes on the north coast of Java showing significant rates of shoreline changes at some particular areas.

3.3. Adaptation strategies and coastal management

The erosion affecting the north coast of Java is influenced by both human actions and natural forcing such as waves, tides, and meteorological events [5]. The rapid development of settlements due to demographic pressures generating the rapid expansion of economic activities and associated infrastructures such as coastal roads, seaports, and protection installations which in turn affect the stability of the coast [4].

The massive mangrove deforestation since the 1980s reduced the coastal resistance against the wave’s actions causing rapid retreat of the coast [4]. This happened almost along the north coast of Java.
mainly in Central Java (see Table 2). Other activities include illicit sand mining by the local population. This is also one of the main causes of shoreline recession because it impacts not only the overall coastal sediment budget but also deprive coastal segments downdrift of sand in systems that are strongly dominated by longshore drift [25]. The coastal erosion driven by sand mining mainly occurred in Serang Banten and Indramayu West Java [4, 26]. In addition, the change in a river mouth due to the making of new irrigation canals also resulted in erosion around the old river mouth and accretion around the new river mouth [5]. The most noticeable instances for the coastal erosion driven by the change of river mouth are Ciujung and Cidurian River in Serang Banten and Cimanuk River in Indramayu West Java [4, 27, 22]. Furthermore, the dams constructions will also have a dramatic effect on coastal stability due to potentially affect the coastal sediment budget [25]. It can be clearly seen after the Jatiluhur DAM construction, the accretion of Citarum River in its Muara Gembong estuary dramatically decreased in the period from 1950-1975 [4, 28]. All these natural and human-induced processes are the primary factors contributing to high erosion rates due to sedimentary imbalance.

The worrying situation of coastal erosion on the north coast of Java has driven various measures to eliminate coastal erosion and related impacts and to restore degraded areas, especially in the dense population areas and centers of economic activities including their infrastructures. Coastal protections including groins, seawalls, jetties, sea dike, rock armors, submerged breakwaters, etc have been extensively constructed on the north coast of Java (see Table 1). Unfortunately, most of these hard defense structures were constructed on a sporadic (action-reaction) basis or post-disaster basis, entailing those initiatives are usually triggered by emergencies, not by prevention [29, 30]. Thus, instead of solving the problem, these interventions only yielded a “short-time” impact but generated some adverse effects [31, 32, 33] such as 1) accelerated bottom erosion in front of the hard structures and downdrift scouring, 2) disturbance of sediment supply and beach reduction, 3) restricted public access, 4) potential risks for bathers, and 5) aesthetic visual effects on the seaside landscape.

It is understandable that the purpose of coastal protection installations including seawalls, jetties, groins, breakwaters, etc is to stabilize the altering shoreline. However, these hard structures themselves will not be useful unless they are complemented with a sand bypass system [31]. Since coastal erosion is mainly related to human-induced sedimentary imbalance [31]. These circumstances are well observed in almost 80% of cases along the north coast of Java [4, 9, 10, 34]. Groins catch sediments transported alongshore, creating a significant sediment deficit downdrift side e.g. in Karawang West Java, Tegal Central Java, Probolinggo and Situbondo East Java. Seawalls reflect incoming waves, generating coastal erosion and hampering energy dissipation with a later increase in turbulence and cross-shore erosion e.g. in Serang Banten, Indramayu West Java, Pekalongan Central Java, Tuban and Lamongan East Java. Breakwaters drract incoming waves, concentrating wave energy in specific places with subsequent coastal erosion e.g. in Indramayu West Java, Semarang, Jepara, and Rembang Central Java.

Given the appropriateness of hard protection structures, it is clear that along the north coast of Java, the current coastal erosion management strategy is too weak and requires change. The short-term perspective conditioned by economic-driven manifested in an action-reaction basis or a cost-benefit analysis approach is not working, making it clear that coastal management of the north coast of Java must be focused on identifying coastal problems together with mitigation strategies from a regional and long-term perspective. A comprehensive approach that integrates the infrastructures of upstream-downstream and downstream-downstream is proposed for the sustainable development of the coastal zone. This will include a watershed-based and sediment cell-based coastal zone management [35, 36].

The coastal management strategies from IPCC CZMS [37] that include 4 (four) generic options including protect, accommodate, planned retreat and do-nothing could be an option for adaptation strategies on the north coast of Java. For instance, the protect option could be implemented by optimizing permeable breakwater measures, cheap, environmentally friendly, and locally available and considering the different coast types and their related processes. Whilst, the accommodating option is applied by changing the house construction method and improving awareness and preparedness. The planned retreat option seems an inevitable solution for fast eroding areas and probably the most appropriate solution for human settlements such as in Muara Gembong Bekasi, Sayung Demak, and Pekalongan.
We know that there is also subsidence in these areas, but we have so far no data to support its importance. In addition, the do-nothing option could be a solution for areas of low economic value that are threatened by erosive processes, such as small rural houses and/or unoccupied coastal land.

From a governance point of view, it must be clear and regulated which institution is responsible for addressing coastal erosion and especially their management. Ministry of Public Works and Public (MPWP) Housing as a leading sector in infrastructure construction needs to collaborate with the Ministry of Marine Affairs and Fisheries (MMAF) under the coordination of the Coordinating Ministry for Maritime and Investment Affairs (CMMIA). In addition, coordination between central government i.e. MMAF, Ministry of Land and Spatial Planning/National Land Agency (MLSP/NLA), Ministry of Environment and Forestry (MEF), and local government (Province and/or Regency) must be enhanced in terms of licenses for building or construction in the coastal zone as well as environmental impact assessment.

4. Conclusion
Coastal erosion is the main problem on the north coast of Java in addition to inundation, flooding, and land subsidence. Sediment imbalances associated with massive deforestation of mangrove, emplacement of coastal protection and infrastructures, illicit sand mining, and dam construction are the main factors contributing to the high rates of erosion on the north coast of Java. Since traditional hard defense methods used so far have had more damaging than protective effects, there is a need now for the use of soft prevention alternatives and for providing new guidelines for coastal management. A comprehensive approach that integrates the infrastructures of upstream-downstream and downstream-upstream is proposed for the sustainable development of the coastal zone. This will include a watershed-based and sediment cell-based coastal zone management. It is important that a new coastal management strategy be introduced that takes into account current conditions of principal human occupation and coastal erosion processes.

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