Coastal Inundation and Land Subsidence in North Coast of West Java: A New Hazard?

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Abstract. The North Coasts of West Java are increasingly affected by human activities. The area has been utilized as settlement areas, industrial estates, and associated infrastructures including roads, school, hospital, market, etc. Consequently, this massive landuse and uncontrolled natural resources extraction have contributed to environmental degradation such as coastal erosion, accretion, pollution, inundation, and land subsidence. To date, we have so far very few field measurement data of land subsidence to support its importance. However, satellite image and on-ground observations used to determine spatio-temporal changes in the shoreline and area of inundation indicated the existence of land subsidence. Groundtruth data on selected areas also indicated the indicators of land subsidence such as damages of infrastructures including houses, roads, and sea dikes. The most noticeable shoreline changes in the North Coast of West Java are situated in Muara Gembong Bekasi and Legon Kulon Subang constituting maximum rates of shoreline retreat up to 200 and 150 m/year respectively for the last two decades (from 2000 to 2020). Whilst, the total areas of inundation in Muara Gembong and Legon Kulon based on recent satellite studies are 10.2 km² and 7.4 km² respectively. Coastal inundation might be linked to the combination of long-term behavior of oceanographic variables such as wave and sea level, in coincidence with hydrological changes due to river works (i.e. dam constructions and channellings) and an increase of settlement areas, fish ponds, groundwater extraction, etc. A set of preliminary engineering measures, in conjunction with sediment managing schemes, is proposed for the sustainable development of the coastal zone.

1. Introduction

The issue of environmental degradation in the North Coast of Java including adaptation and mitigation against it has recently generated a lot of concern from many stakeholders especially government and mandated institutions such as Ministry of Public Works and Housing as a leading sector in infrastructure constructions. This coastal region has extensively been developed as settlement areas, industrial estates, seaports, marine tourism, fisheries, agriculture, mining, public services including roads, schools, hospitals, markets, etc [1]. The ongoing urbanization and population growth in the North Coast of Java, in particular in coastal megacities such as in Jakarta, Semarang, Surabaya, and numerous other coastal cities have contributed to environmental degradation including coastal erosion, accretion, pollution, inundation,
and land subsidence [1]. This process is exacerbated by the existing conditions of a warming climate that has resulted in constant inundation and increased of flood risk during extreme wave events [2, 3, 4].

Land subsidence is a phenomenon that may raise a disaster risk particularly in a coastal region but is frequently slowly detected and therefore less paid attention. There is abundant evidence that land subsidence and coastal inundation are responsible for negative impacts on urban coasts, affecting economic activities and sustainable development [5, 6, 7, 8, 9]. Land subsidence increases coastal flood vulnerability in both frequency and duration, causing major economic impacts in the form of infrastructure damage and high maintenance costs on transportation networks, hydraulic infrastructures, sewage systems, buildings, and foundations. The total damage in Jakarta solely is estimated at millions of dollars annually [10].

In general, most areas of the North Coast of Java have the potency for land subsidence at high to very high levels ranging from 1 cm/year to 20 cm/year [5]. In fact, currently, the capital city of Jakarta is one of very high level of land subsidence rates in the world averaging about 15 cm/year [8, 11]. Ironically, this slow-onset disaster and associated deterioration effects have not received much attention. Based on recent document, it is recorded that around 112 regencies/cities throughout Indonesia are experiencing land subsidence and coastal inundation [10]. Around 16 of the 112 cities are currently being monitored and from the 16 cities being monitored, only about 5 cities are currently being risk-mapped. Of the 5 cities that have been risk-mapped, 4 areas have been carried out for mitigation and adaptation efforts including Jakarta, Pekalongan, Semarang, and Demak. This means that there are still around 108 regions throughout Indonesia that have not yet been carried out for mitigation and adaptation efforts [10]. The North Coast of West Java stretching from Bekasi to Cirebon is, by comparison, having limited monitoring data, risk-mapping, and adaptation as well as mitigation measures.

This paper assesses the coastal inundation and land subsidence along the North Coast of West Java with focusing on the most significant and noticeable shoreline changes including in Muara Gembong Bekasi and Legon Kulon Subang. Thus, the overall objectives of this paper include 1). Identification of shoreline changes using digital shoreline analysis system modeling, 2). Identification of coastal characteristics using satellite and thematic map studies supported by on-ground observations, 3). Identification of inundation areas using spatio-temporal satellite images analysis, 4). Assessment of land subsidence indicators based on ground observations, and 5). Formulation of adaptation and mitigation strategies.

2. Material and Method

2.1. Study area

The geology of the North Coast of West 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 West Java stretching from Bekasi on the west to Cirebon on the east [12, 13, 14, 15]. The coastal landform is generally low-lying coast (<10 m) with relatively flat topography spanning up to ± 30 km inland in the north of Karawang and only about 4 km inland in the north of Cirebon based on the shuttle radar topography mission (SRTM) data. The river systems drain off into the Java Sea with several big river systems such as Citarum, Cipunagara, Cimanuk, and Cisanggarung tend to form a bird’s-foot delta around the estuary leaving the bays with relatively small rivers far behind [16]. 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 [17].

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. Waves and currents produced by easterly wind are generally stronger than those generated by westerly winds. The wind blows from west-northwest to the east with a maximum speed of 5-6 m/s during the west monsoon, while during the east monsoon, a dry wind shifts from east-southeast to the
west with a maximum speed of 3-4 m/s. This monsoonal reversal of surface currents is responsible for major changes in the sea surface salinities, ranging from 31 during the northwest monsoon to 35 during the southeast monsoon [18, 19]. The bathymetry of the region is relatively shallow, rarely exceeding 60 m deep. The 5 m depth 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 [17].

2.2. Satellite image processing
Study was based on Landsat TM/ETM+ and Landsat 8 OLI multispectral satellite images covering the whole region of the North Coast of West Java which is available for the following years: 2000, 2010, and 2020. The images were downloaded at no cost from the United State Geological Survey (USGS) Earth Resources Observation and Science Data Centre (www.earthexplorer.usgs: accessed in 2021). The images then 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 the three visible bands of Landsat 8 i.e. band 2 (0.45 – 0.52 μm), band 3 (0.52 – 0.60 μm) and band 4 (0.63 – 0.69 μm), were analyzed to extract shoreline data following method NDVI-based and manual digitization. The shorelines were then analyzed following the Digital Shoreline Analysis System (DSAS) modeling procedure described below.

![Map of study area](image)

Figure 1. Map of study area showing a) low-lying coast of North Coast of West Java, b) geological setting, c) windrose diagram of average windspeed, and d) tidal pattern in North Coast of West Java

2.3. DSAS modeling
The Digital Shoreline Analysis System (DSAS) extension from ArcGIS toolkit was employed to calculate the shoreline change rates, with the use of regression indexes [20]. The Linear Regression Rate (LRR) method is particularly appropriate for analyzing shoreline changes and is considered the best approach for the estimation of long-term coastal scalable tendencies [21]. A baseline was created onshore and transects
perpendicular to the buffered line inland generated at 10 m intervals. Once the coastline vectors have been merged, they can be utilized 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 analyzed in this study only for the 2 (two) recent decadal periods (2000-2020).

2.4. Coastal characteristic and inundation mapping
Coastal characteristic was investigated following methodology described by Dollan [22] which is practical for the coastal zone analysis because of the essentially linear (alongshore) nature of the coasts by which information such as geology, relief (morphology), and coastal processes are included. The coastal characteristic units are named based primarily on their form and constituents such as “rocky”, “sandy” or “muddy”, etc. The changes in the area of coastal inundation were investigated online through google earth imageries which can be multi-temporarily displayed. The delineations of the inundation area from each image for the following years: 2008, 2011, 2013, 2015, 2015 (Muara Gembong, Bekasi) and 2010, 2012, 2014, 2016, 2018, 2020 (Legon Kulon, Subang) were manually digitized on-screen and saved into tiff format.

2.5. Ground observation
On-ground observation and data collection include: mapping of coastal characteristic and inundation on selected areas using a drone-photogrammetry technique, taking photographs and marking locations using a built-in camera global positioning system (GPS) unit, interviewing and observing residents on adaptation behaviors to cope with the coastal flooding, identifying land subsidence by observing the infrastructure conditions (houses, roads, bridges, dikes) and water management-related effects (changing gradient of streams, canals, and drains, increased saltwater intrusion), and collecting information through local authorities.

3. Result and Discussion

3.1. Shoreline changes
Shoreline change analysis indicates some areas have been subject to a significant accretion and erosion during the last 2 (two) recent decades from 2000 to 2020 (Figure 2). The most noticeable accreted shoreline on the North Coast of West Java is situated in the estuary environments such as in: Muara Kali Bekasi, Ciasem Subang, and Cimanuk Indramayu with accretion rates are up to 150 m/year, 70 m/year, and 180 m/year respectively. Whilst, the most significant rates of coastal erosion have been observed at Muara Gembong Bekasi and Legon Kulon Subang. Muara Gembong experienced the highest rate of erosion with up to 225 m/year, while Legon Kulon experienced erosion with a maximum rate of up to 175 m/year. Overall, the length of the accreted coastline along the North Coast of West Java is 172.8 km, while the eroded coastline reaches ± 159.8 km. The coastal erosion has also degraded mangrove ecosystems almost 10,507 ha and generated coastal inundation, especially during the high tides.
3.2. Coastal characteristic

Coastal characteristic of the North Coast of West Java is classified into 2 (two) types, including sandy coast and muddy coast (i.e. Mangrove, tidal mud flats, salt marshes). The coastal characteristics comprise unconsolidated sediments that have accumulated for the last 5,000 years and are therefore of Holocene age [23]. The details of the coastal characteristics are described in the Figure 3.
3.2.1. Sandy coast
Sandy coast is widespread on the North Coast of West Java particularly in Karawang and Indramayu (Figure 3). The geometric forms of the coasts are elongated sandy beaches with extensive sandy coastal plain landward. Geologically, sandy beaches consist of unconsolidated fine to coarse 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 up to 4 degrees. The coastal plains have generally low relief contours (<10 m) and relatively flat in which agriculture, fish ponds, salt ponds, settlements, and industrial areas are developed. The dominant coastal process is erosion by both waves and longshore currents.

3.2.2. Muddy coast
Muddy coast including mangroves, mudflats, and salt marshes is associated with the highly active river and is extensively occurred on the North Coast of West Java particularly in Bekasi, Subang, and Cirebon (Figure 3). The muddy coast is, in a particular area, exposed in the intertidal zone at low tide up to ± 1 km seaward forming tidal mudflats morphology. The dominant coastal process is fluviatile deposits through active rivers that flow 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 Citarum, Cipunagara, Cimanuk, and Cisanggarung (Figure 3). Mangrove ecosystems, mainly Avicennia marina and Rhizophora apiculata, occur on mud substrates as narrow swamp basins in the tidal reaches of rivers and streams discharging directly onto the North Coast of West Java. Muddy coast is vulnerable to river flooding and marine inundation, separately and coincidentally.

3.3. Coastal inundation and land subsidence
Spatio-temporal changes in the area of inundation supported by on-ground observations confirmed the existence of coastal inundation in both Muara Gembong Bekasi and Legon Kulon Subang. However, we
have so far very limited data on land subsidence rates using accurate measuring techniques such as optic leveling and GPS survey. The determination of land subsidence rates using Interferometric Synthetic Aperture Radar (INSAR) satellite imagery is now still underway. However, ground observations on selected areas such as in Muara Gembong Bekasi and Legon Kulon Subang indicated some major impacts of land subsidence including loss the functionality of structure (buildings and foundations), subsided infrastructures (roads, bridges, coastal dikes), and disruption of water management-related effects (changing gradient of sewerage and drainage and increased saltwater intrusion). The most noticeable impact of ongoing subsidence observed in both areas is increased area of coastal inundation which described in detail as follows (Figure 4).

Figure 4. Photos of some major impacts of coastal inundation and land subsidence in Muara Gembong Bekasi (Photo a) and Legon Kulon Subang (Photo b, c, and d) taken by both drone and pocket camera

The coastal inundation in Muara Gembong Bekasi has induced the loss of land about ± 1,076 ha mostly fish pond areas. In 2001, the inundation did not exhibit yet until it flooded the coastal area about 791 ha in 2010. Whilst, In 2013, the inundation area experienced a slight reduction due to measures taken by local authorities to about 686 ha before it significantly increased in 2019 with about 1,076 ha impacted areas (Figure 5). The study was not able to establish the exact timing when the coastal initially inundated due to lack of data being covered between 2001-2010.
In Legon Kulon Subang, the initial coastal inundation occurred in 2005 based on information from local authorities. This was confirmed by the satellite image data in 2006 with a total area of inundation of about 147 ha. There was a rapid increase in 2013 where the area of inundation reached about 522 ha. In 2019, the area of inundation showed a gradual increase to about 735 ha (Figure 6).

Figure 5. Map of changes of coastal inundation areas in Muara Gembong Bekasi between April 2001 and May 2019

Figure 6. Map of changes of coastal inundation areas in Legon Kulon Subang between July 2001 and August 2019
3.4. Adaptation strategies and coastal management

The coastal inundation affecting the coast of Muara Gembong Bekasi and Legon Kulon Subang is closely linked to the combination of long-term behavior of oceanographic variables such as extreme waves (short term) and rising sea levels (long-term) due to climate change [3, 5, 24]. Based on IPCC scenarios, current global mean absolute sea-level rise is around 3 mm/year and is projected to a range of 3-10 mm/year until 2100 [2, 25]. However, the current observed subsidence rates in coastal cities in the North Coast of Java such as in Jakarta, Subang, Pekalongan, Semarang, and Demak are in the range of 1-20 cm/year [6,26]. The latter may increase in the near future if measures are not taken and will exacerbate the coastal flooding and other widespread impacts of land subsidence.

Land Subsidence can have natural as well as anthropogenic causes. The natural causes include tectonics, glacial isostatic adjustment, and natural sediment compaction [27, 28]. Whilst, subsidence from anthropogenic causes occurs as a result of compression of shallow layers (0-20 m) by rapid development of settlements due to demographic pressures [8, 9]. This is related to the physical characteristics of alluvial sediments (alternating layers of sand, silt, and clay), making low-lying coastal and delta areas in the North Coast of West Java very prone to land subsidence [6,26]. The configuration of the Quaternary geology of Muara Gembong Bekasi and Legon Kulon Subang confirmed that the sediments are mangrove swamp deposits and shallow marine deposits comprising silty clay and clay as main components of up to 10 m deep [29, 30]. All these natural and human-induced processes are primary factors contributing to high subsidence rates in the North Coast of Java.

The hydrological changes due to river works such as dam constructions in the upstream and channeling of new irrigation canals will also have a dramatic effect on coastal stability due to potentially affect the coastal sediment budget delivered by the river [1, 17]. In pristine low-lying coast and delta environments, the naturally occurring subsidence is compensated by the sediment delivered by the river [11]. However, nowadays, many river systems deliver much less sediment to the estuary, because sediment is trapped by the upstream dams or is transported to the new river mouth [31, 32]. With limited sediment supply, natural subsidence remains inadequately compensated. Hence the coastal plains start to subside. This is noticeable in Muara Gembong and Legon Kulon.

In deeper layers, subsidence is caused by the extraction of resources such as oil, gas, and groundwater [33, 34, 35, 36, 37]. The excessive groundwater extraction due to rapid urbanization and population growth is a major cause of severe land subsidence in most large cities in the North Coast of Java including Jakarta, Pekalongan, Semarang, and Demak [5, 6, 8, 9, 11, 26]. The rapid development of settlements, industrial estates, and associated infrastructures required huge amounts of water for domestic, urban services, and industrial water supply. Consequently, this often leads to over-exploitation of groundwater resources, especially when surface waters are seriously polluted. In Muara Gembong and Legon Kulon, the groundwater extraction, based on information from local authorities and communities, is mostly in the deeper layer (> 60 m). This may also lead to high subsidence rates in the near future if groundwater overpumping in these areas is uncontrolled.

The worrying situation of the coastal inundation in the North Coast of Java has driven various measures to restore the degraded areas, especially in the dense population areas and centers of economic activities including their infrastructures. Land subsidence has worsened the situation with the increased flooding and other widespread detrimental impacts including loss of the functionality of structures like buildings, roads, and indirect damage such as changes in relative water levels both groundwater and surface water.

There is a need for an integrated approach in order to manage subsidence and related effects to develop appropriate strategies and measures that are effective and efficient in both the short (adaptation) and long term (mitigation). A set of preliminary engineering measures, in conjunction with sediment managing schemes, is proposed as adaptation strategies. Muara Gembong and Legon Kulon are categorized as low-lying coast and delta environments. The much less sediment supply delivered by the river due to dam constructions such as in Citarum and the change of river mouth from previously in the north to the east in Cipunagara are aspects contributing to the increased flooding and other widespread impacts of land subsidence.
In the short-term perspective, channeling or re-opening the river toward the degraded areas is one option available to obtain sediment supply as depicted in Muara Gembong Bekasi (Figure 7) and Legon Kulon Subang (Figure 8). This will become a ‘natural reclamation’ to compensate the natural sediment compaction that occurred in the degraded areas. Afterward, a traditional coastal structure composed of bamboo and geobag is installed ± 500-1,000 m from the current shoreline seaward functionated as a breakwater and/or sediment trap coming from the river/canal. Once sediment accumulated behind the structure, mangrove planting can be carried out to promote sedimentation processes and coastal progradation. However, it is necessary to do hydrodynamic numerical modeling to determine the sediment transport and budget prior to conducting the channeling. Thus, the adverse impacts of increased flooding and land subsidence can be addressed by the growth of the ‘new land’ (Figure 9).

Figure 7. Channeling the Citarum River or re-opening the old Citarum Creek toward the degraded areas is one alternative option to obtain sediment supply and to ‘reclaim’ the loss land

Figure 8. Channeling the Cipunagara River or re-opening the Old Cipunagara River toward Pondok Bali Coast is one alternative option to address the increased inundation and ongoing land subsidence
Figure 9. Installation of a traditional breakwater in the degraded areas will promote sedimentation processes and coastal progradation.

Moreover, from a regional and long-term perspective, a comprehensive and integrated approach framework to address land subsidence is proposed for more sustainable and resilient solution. There are some possible measures dealing with land subsidence that are closely linked to land and water management including [38]: 1) restriction of groundwater extraction for counteracting human-induced subsidence, 2) natural and artificial recharge of aquifers in the upstream for speeding up recovery as well as controlled aquifer storage and recovery, 3) development of alternative water supply instead of groundwater to meet the increasing urban water demand and alternative water supply for the industry as well as domestic users, 4) integrated floodwater management strategy, 5) improving governance and decision-making by enhancing technical, administrative, and institutional capabilities, 6) appropriate monitoring and database system, 7) integration of geotechnical aspects in planning and design of buildings and infrastructure.

4. Conclusion

Land subsidence is a slow-onset disaster that may increase inundation and other detrimental impacts particularly in a coastal region but is frequently slowly detected and less paid attention. Hence, the disaster has not received much proper attention especially from the government and communities at large until it causes significant economic losses and poses a nuisance to many people. The coastal inundation occurred in the North Coast of West Java particularly in Muara Gembong Bekasi and Legon Kulon Subang has induced the loss of coastal land up to ± 1,076 ha and ± 735 ha respectively since the last two decadal periods. This is closely linked to the combination of the long-term behavior of oceanographic variables such as extreme waves and rising sea levels in coincidence with the high subsidence rates along the North Coast of Java. Although, we have so far very few data of ongoing land subsidence rates in both Muara Gembong Bekasi and Legon Kulon Subang, on-ground observations have confirmed some indicators of land subsidence including subsided infrastructures and increased area of inundation. The land subsidence occurred in the low-lying coast and delta environment such as in Muara Gembong Bekasi and Legon Kulon Subang is not merely caused by the anthropogenic factors as previously postulated but is involved complex technical aspects including natural sediment compaction due to physical characteristics of alluvial deposits and less sediment supply from the river due to hydrological changes. A
comprehensive and integrated approach to manage subsidence is needed to develop appropriate strategies and measures from both the short and long-term perspectives. A set of preliminary engineering measures, in conjunction with sediment managing schemes, is proposed as an adaptive measure. Moreover, in the long-term perspective, some more sustainable and resilient measures are proposed to mitigate and largely stop the negative impact of land subsidence including urban groundwater management, urban flood risk management, and strategic spatial planning. The study is also projected to be suitable and applicable to many other coastal cities throughout Indonesia.

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