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Max Rudolf Muskananfola
Department of Aquatic Resources, Faculty of Fisheries and Marine Science, Universitas Diponegoro, Semarang, 50275, Indonesia, maxmuskananfola@yahoo.com

Sigit Febrianto
Department of Aquatic Resources, Faculty of Fisheries and Marine Science, Universitas Diponegoro, Semarang, 50275, Indonesia, sigitfebrianto40@lecturer.undip.ac.id

Diah Ayuningrum
Department of Aquatic Resources, Faculty of Fisheries and Marine Science, Universitas Diponegoro, Semarang, 50275, Indonesia, diahayuningrum21@lecturer.undip.ac.id

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Hydrodynamic Characteristics and Sediment Distribution Patterns in Wulan Delta Estuary, Demak, Indonesia

Max Rudolf Muskananfola*, Sigit Febrianto, and Diah Ayuningrum

Department of Aquatic Resources, Faculty of Fisheries and Marine Science, Universitas Diponegoro, Semarang 50275, Indonesia

E-mail: maxmuskananfola@lecturer.undip.ac.id

Abstract

The Wulan Delta, located in Wedung, Demak, was formed due to the sedimentation process of the Wulan and Serang rivers. Sediment transport starts from rivers to the sea; the process carries nutrients and various chemicals derived from agricultural, industrial, or household activities. This study aims to analyze the characteristics of hydrodynamics, suspended sediment, and bottom sediments in the Wulan Delta waters, Demak. Field data were collected in transitional season two (October) 2022. The obtained data were then analyzed in the laboratory at the Faculty of Fisheries and Marine Science. Results showed that the speed of the surface current in the study area ranged from 0 to 0.1 m/s in spring tide conditions with a surface current pattern coming from the direction of Semarang toward Jepara and 0–0.18 m/s in neap tide conditions with a current pattern coming from the direction of Jepara toward Semarang. The Wulan Delta has a sedimentary characteristic dominated by fine silt, which is as much as 82%–98%, with a deposition characteristic dominated by wave energy that causes successful sediment sorting with a sorting index of −2.25 to 2 and strongly asymmetrical to a small size with a skewness curve value of two.

Keywords: bedload sediment, hydrodynamics, satellite images, suspended sediment, Wulan Delta

1. Introduction

The Wulan Delta and its surrounding watershed in Demak Regency, Indonesia, are important coastal areas for fish nurseries and fishing. However, these areas are currently facing environmental threats, such as erosion and sedimentation, due to natural and human factors. Demak Regency has no potential for major natural disasters related to topography and geology, such as hurricanes, floods, and erosion. The occurrence of erosion in the coastal areas of Demak is due to human activities (such as logging mangrove forests and conversion of mangrove forests into ponds), natural causes (wave exposure and changes in current patterns), and land subsidence in the western region of Demak [1], [2]. The configuration of coastal land current induces deflection and wave diffraction and causes erosion [3], [4, 5]. Expansions of rice fields, mangrove forests, and shrimp ponds are eroded, lost, and turned into the sea [6]. This condition is coupled with waste input from surrounding cities, such as Semarang, which have experienced erosion and increased erosion rates in the Demak Regency. With exception of the Wulan Delta, this erosion occurs in almost all areas of Kendal, Semarang, and Demak.

The Wulan Delta holds water inputs from the Serang and Lusi Rivers and is divided into the following two streams: the old and new Wulan Rivers, which are areas formed due to the increase in land area. These changes occurred due to the creation of flood management channels, land clearing for agriculture and settlements, and coastal reclamation, thereby inducing an increase in sediment supply, especially in the Wulan Delta. The increase in the area of the Wulan Delta is suspected to be due to the high sedimentation rate. This condition began around 2002 and continued to increase up to 2010 to the present [7, 6].

Delta is an area of sediment accumulation where the material comes from river and sea deposits [8], which causes changes in the coastline [5]. Sediment can be induced by hydro or human activities, resulting in changes in hydro-oceanographic conditions. Furthermore, [9−12] stated that changes in coastlines depend on topography, rocks, and oceanographic properties and the presence of anthropogenic factors. The occurrence of sedimentation will cause erosion in other areas. The deposition process that occurs due to the flow of rivers to coastal areas is attributed to erosion [13, 14].

Various types of research, such as the expansion of the Wulan Delta [15], crab distribution [16], gastropods and organic matter [17, 6], mangrove forest management [7], and the impact of human activities in the Wulan Delta Estuary [6], have been conducted in the Wulan Delta.

Given the continued development of the Wulan Delta and the importance of monitoring and identifying the impact of sedimentation in an environment, understanding and analyzing the distribution patterns of suspended and seabed sediments in the Wulan Delta area is essential for managing the area and its resources.

This study aimed to analyze the hydrodynamic characteristics of the Wulan Delta area, focusing on surface currents, bottom sediments, and total suspended solids, to understand the sediment distribution patterns in the area and provide scientific information for the management of coastal resources. The findings of this study can inform the development of effective management strategies for the Wulan Delta area, which is beneficial to the environment and the local communities that depend on its resources.

2. Materials and Methods

Study site. The study was conducted in Wulan Delta, Demak Regency, Central Java (Figure 1). The Wulan Delta is one big delta in Demak Northern Java, Indonesia, between latitude 6°43’30”S and 6°46’30”S and longitude 110°32’0”E to 110°36’0”E, covering an area of 31.75 km^2. From a hydrodynamic viewpoint, the coastal area of Demak can be classified into two parts: the eastern and western parts, wherein the eastern part (Wulan Delta) has relatively low energy (minimal wave actions), whereas the western part (Sayung area) has comparatively high energy (additional wave actions), particularly during west monsoon sessions [18]. Tidal characteristics recorded in the Demak area show the tidal range of neap and spring at 0.1 and 1.1 m, respectively [19]. The tide types are mixed semidiurnal, and two high and two low tides of different heights occur daily. More than 70% of the coastal sediment materials are mostly dominated by silt and clay fractions; the remaining materials comprise the mall sand fraction. These hydrodynamic characteristics are crucial in sedimentation in the area.

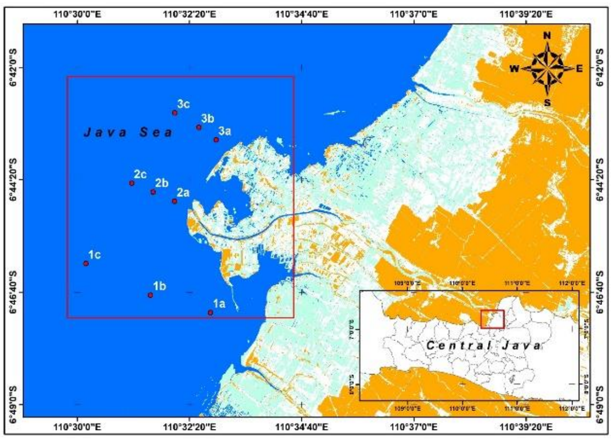

Figure 1. Research Location at Wulan Delta Demak

Sampling strategy. The research location is spread on the two branches of the Wulan River (the old and new Wulan River) and a large river flow (the Wedung River) (Figure 1). This strategy is expected to represent the true condition of the area and obtain data on the contribution of large river flows to the sedimentation process in the Wulan Delta. The sampling point was determined on the basis of differences in depth and special characteristics spread across the lower reaches of the old Wulan River, the new Wulan River, and the Wedung River. The research materials comprise samples of suspended sedimentary water and bottom sediment and Sentinel two satellite images. The collected sediment data included bottom sediments and total suspended solids (TSS).

All field data were collected *in situ* (on the spot). Some data were obtained from the data collection results in the field, such as suspended sediment and bed sediment samples, as well as depth and ocean current [20].

Sediment analysis method. Sediment samples were collected using *the Van Veen Grab* tool [21, 22]. Sediment samples were collected at nine points at three line stations perpendicular to the coastline (Figure 1). The points coordinates are as follows: points 1A 6º47’5.27”S; 110º32’45.95”E to points 3C 6º42’56.60”S; 110º32’01.61”E. The obtained samples were then put in plastic bags and bottles labeled for each point per station. Furthermore, sediment samples were transported to the laboratory to analyze sediment grains [23, 24]. Granulometric sediment analysis was performed with statistical approaches, such as mean, sorting, kurtosis, and skewness [25, 26].

Sediment analysis measures and classifies grain and sediment sizes [27, 28]. In addition to the distribution and classification of sediment grains, the interpretation of distribution, transport mechanisms, and sediment deposition is performed. The spread, transport mechanism, and deposition of sediments are obtained using empirical mean calculations, separation coefficients, and deposits, respectively. The collected and analyzed data are then simulated using hydrodynamic model software and overlaid with ArcGIS.

Hydrodynamic model. Currents generated by tides and winds blowing over the sea were simulated using hydrodynamic models. Ocean waves also affect ocean currents near the coast. However, the effect of currents generated by waves is considered small during model operation. The circulation of currents in shallow coastal waters can be assumed to be a perfectly mixed (homogeneous) flow of water from sea level to the bottom of the waters, and the influence of wind surfaces is assumed to reach the seafloor [27, 29, 30]. Therefore, the model equation used is an equation integrated into depth. Seawater is considered a compressive fluid in this model. The hydrodynamic model comprises the following.

a) Continuity equation. The discharge is entered in this equation. The continuity equation [31, 32] is expressed as follows:

$$\frac{\partial \xi}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = Q_s, \quad (1)$$

where:

ξ : elevation of sea level to average water level (m)
U : transport toward the x-axis ($m^2 s^{-1}$)
V : transport toward the y-axis ($m^2 s^{-1}$)
Q_s : discharge ($m^2 s^{-1}$)
x, y : coordinates increase in size to the east and north (m).

b) Equation of momentum conservation and the influence of wind and tides will be observed. The equation of momentum conservation of [26, 27] is expressed as follows:

$$\frac{\partial U}{\partial_t} + \frac{U\partial U}{H\partial_x} + \frac{V\partial U}{H\partial y} + gH\frac{\partial \xi}{\partial_x} + rU\frac{\sqrt{U^2+V^2}}{H^2} + A_h\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) = \lambda W_x\sqrt{W_x^2 + W_y^2}, \quad (2)$$

$$\frac{\partial U}{\partial_t} + \frac{U\partial V}{H\partial x} + \frac{V\partial V}{H\partial y} + gH\frac{\partial \xi}{\partial_y} + rV\frac{\sqrt{U^2+V^2}}{H^2} + A_h\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) = \lambda W_y\sqrt{W_x^2 + W_y^2}, \quad (3)$$

where:

$$U = \frac{1}{h+\xi}\int_{-h}^{\xi} u\, dz, \quad (4)$$

$$V = \frac{1}{h+\xi}\int_{-h}^{\xi} v\, dz\ , \quad (5)$$

u, v : current velocity of directions x and y (ms^{-1})
t : time (second)
g : acceleration of earth's gravity (ms^{-2})
H : actual depth = $h + \xi$ (m)
h : reference depth (m)
r : basic friction coefficients
A_h : horizontal eddy friction Coefficients ($m^2 s^{-1}$)
λ : wind friction coefficients
W_x, W_y : x and y wind speed (ms^{-1})

The hydrodynamic model is completed using a two-step semi-implicit method, in which variables are calculated in a row of space cells at each time step. This method was chosen because the selection of the simulation time step does not depend on the stability criteria of Friedrich Lewy Courant as in the explicit method. Therefore, the computer memory is saved and the simulation becomes economical. The data used in this model are situation and bathymetric maps, tidal data, average winds speed, and physical conditions around the research site (i.e., coastal buildings, inlet discharges, and outlets).

3. Results and Discussion

Surface current pattern characteristics. The results of the current model are shown in spring and neap tide conditions from high to low tide. The analysis results using the hydrodynamic model showed the following: the speed of the surface current in the study area ranged from 0 to 0.1 m/s in spring under tide conditions with a current pattern coming from the direction of Semarang toward Jepara and 0–0.18 m/s in neap tide conditions with a current pattern coming from the direction of Jepara toward Semarang. A picture of the current patterns formed in the study area during sampling is shown in Figures 2 and 3. During spring tide, surface currents move from the southwest (Semarang) to the northeast (Jepara); during the neap tide, surface currents move from the northeast (Jepara) toward the southwest (Semarang). The speed of currents at the waters shows similar characteristics during spring and neap tide, where low current speeds (up to 0.02 m/s) occur at coastal waters and increases up to 0.14 m/s at deep waters. These results agree with [27, 18, 30, 5], which indicate that low current speed at shallow coastal waters is due to the effects of bottom frictions and roughness length characteristics of the seabed. These conditions allow settlement of sediment particles in the water column to the seabed, resulting in an increase in accretion and deposition to form a delta [8, 14]. A delta forms due to the rapid deposition of river sediment at a river mouth in a steady or decreasing sea level condition and comprises subaerial and subaqueous portions. River deltas are highly populated regions in coastal zones due to their capability to support large human populations because of their highly fertile soil and productive fisheries, such as the Wulan Delta in Demak.

Total suspended solids. The Total Suspended Solids (TSS) obtained at the time of the study ranged from 134 mg/L to 266 mg/L in spring tide conditions, where the lowest and highest concentrations were obtained at points 2C and 3A, respectively (Figure 4). TSS concentrations in neap tide conditions ranged from 221 mg/L to 301 mg/L; the lowest and highest concentrations were found at points 3C and 1A, respectively (Figure 5). The highest concentration in point 1A is due to the sediment supply from the Wedung River, which is a large river on the west of the Wulan Delta; point 3A contributes the lowest concentration because it is located at the small river mouth. These suspended sediment concentrations show that maximum turbidity occurred in the coastal waters of the Wulan Delta, as stated by Dyer [27]. Fluvial sediment discharge to coastal ocean regions is essential in delta erosion and accretion processes.

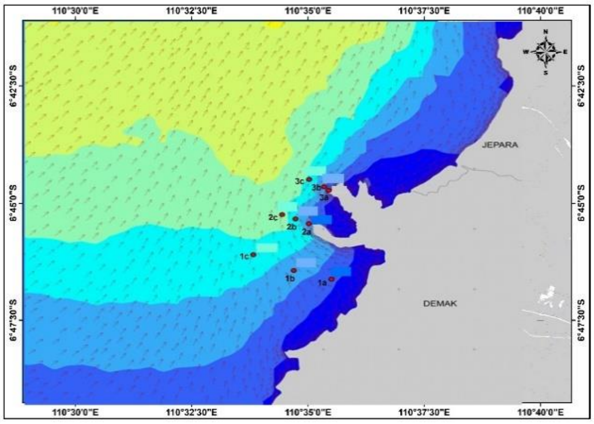

Figure 2. Current Pattern during Spring Tide at the Waters of Wulan Delta Demak

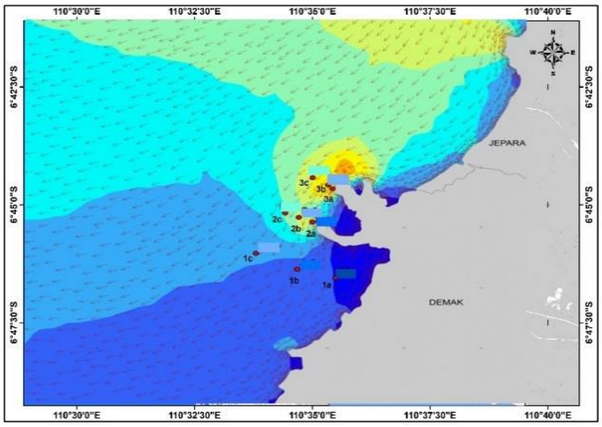

Figure 3. Current Pattern during Neap Tide at the Waters of Wulan Delta Demak

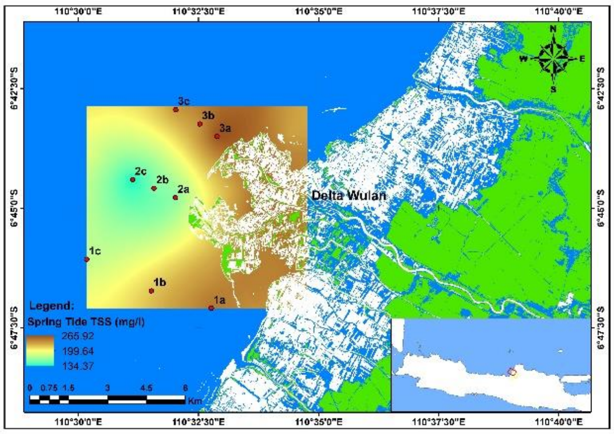

Figure 4. Total Suspended Solids Distribution Patterns at Spring Tide

Seabed sediment grain size and granulometry. The analysis results of bottom sediment grains using the analysis pipette are presented in Figure 6. The results of the empirical mean analysis showed that the study site was dominated by fine mud, which ranged from 82% to 98%, followed by clay. The separator coefficient shows that the sediment distribution at the study site is included in the excellent to poorly sorted criteria, wherein the separator coefficient with the excellent criterion is highly dominant. Korea *et al*. [24] stated that granulometry with poorly sorted category is due to the random accumulation of particle sizes. This condition is induced by the transport of sediments by current, while sediments with well- or moderately sorted granulometry indicate that waves strongly influence sediment transport in the area.

The analysis showed that the study area belonged to the strong asymmetrical to small size category with a value of 2.

The aforementioned granulometric analysis shows that waves strongly influence sediment transport in the Wulan Delta area, which also undergoes a deposition process [24]. This finding reveals that the Wulan Delta experienced sediment deposition, which increased the land area due to the deposition phenomenon.

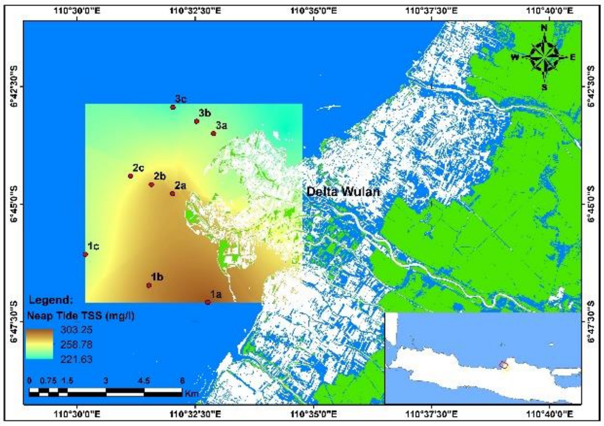

Figure 5. Total Suspended Solids Distribution Patterns at Neap Tide

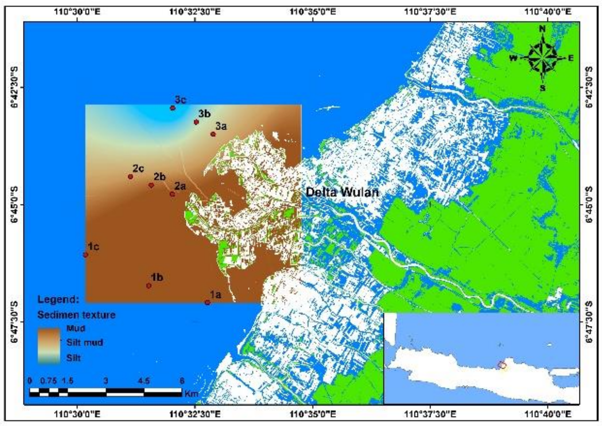

Figure 6. Bottom Sediment Texture Distribution Patterns at Wulan Delta

Impacts of coastal erosion and sedimentation. The Wulan Delta has sediment characteristics dominated by fine mud originating from the mainland through the Wulan River, which is deposited by low wave energy [6]. A coastline is a complex series of interlinked physical systems involving offshore and onshore processes. Coastal erosion is one of these physical processes, which wears away and disturbs solid elements of the shoreline and sediment, generally by natural forces, such as waves and tidal and littoral currents. Coastal sediments and those arising from inland erosion and transported seaward by rivers are redistributed along the coast, providing material for dunes, beaches, marshes, and reefs. Coastal erosion usually results from natural and human-induced factors operating on different scales. Erosion is defined as the encroachment of land by the sea after an average over a sufficiently long period to eliminate the impacts of weather, storm events, and local sediment dynamics [11]. Coastal erosion results in different effects, such as loss of land with economic value (i.e., beaches) or decrease in ecological value, and the collapse of properties situated on the coastal area affecting the welfare of local communities. Meanwhile, coastal sedimentation may increase land area and lead to siltation of shipping lanes and fishing ports.

4. Conclusions

Hydrodynamic analysis indicated that surface currents flow from Semarang to Jepara during spring tide; this flow pattern was reversed during the neap tide, where surface currents flow from Jepara to Semarang. Current speed increases from shallow coastal waters toward the deep open sea. The characteristics of bottom sediments in the waters of the Wulan Delta are dominated by fine silt with deposition features dominated by low wave height, causing the sediments to be very well sorted and strongly asymmetrical to small sizes.

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