Hydro-oceanographic characteristics and sedimentation in the waters of Kemujan Island, Karimunjawa, Indonesia

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Abstract. Kemujan Island is one of the tourist destinations located in the Karimunjawa Islands in the Java Sea. This island's beach sands and aquatic resources have not yet been fully studied. Its coastal conditions are strongly influenced by hydro-oceanographic factors such as waves, currents and tides that can affect biotic and abiotic ecosystems, including bottom sediments' characteristics and movements. This study aimed to analyse the oceanographic factors and sediment movement in the waters of Kemujan Island, Karimunjawa. The research was carried out in two stages: sediment sampling and oceanographic data measurement in the field, and sediment sample analysis conducted at the laboratory. The methods used in this research are quantitative. Based on the sediment texture distribution analysis, the sediment type in the waters of Kemujan Island is dominated by medium to fine sand with grain sizes ranging between 0.5-0.125 mm. The surface current speed ranged from 0.04 to 0.25 m s^{-1}, the bed shear stress ranged from 0.0606 to 0.0151 N m^{-2} and the shear velocity ranged from 0.7658 to 0.3829 cm s^{-1}. The oceanographic factor that affects the transportation of sediments is the current and weak current conditions affect the ability of the sediment particles to settle. Based on the results of the calculation of bed shear stress and shear velocity, the shear stress at the seabed is related to the speed of the water current. The shear stress exerted on the seabed sediment is not adequate to move sediment grains dominated by fine to medium sands in the waters of Kemujan Island, Karimunjawa.
Key Words: hydro-oceanography, sedimentation, Karimunjawa waters.

Introduction. The Kemujan Island is one of the islands at the end of the Karimunjawa Archipelago. The island has facilities and infrastructure, including a sea harbour and a pier, the Dewodaru Airport, and the Diesel Power Plant (PLTD), serving 24-hours a day to establish power connections for Karimun and Kemujan island. The economic potential of this island largely depend on the marine fisheries, seaweed cultivation or fishing and marine tourism (BTNKJ 2016; Sulardiono et al 2018). The concept of ecotourism on Kemujan Island is aligned with the strategies of environmental conservation and with the empowerment of local communities (Muniah 2016).

Karimunjawa waters are open seas located in northern Java. Information on the hydro-oceanographic characteristics of this water is crucial and needed. This information is essential in planning coastal protection buildings, ports, sea transportation, coastal movement, sedimentation, erosion and accretion (Kurniawan & Pradana 2016; Lanuru & Yusuf 2018; Mawardi 2016; Muskananfola et al 2020b). Hydro-oceanographic conditions (currents, waves and tides) directly affect the distribution of materials in coastal areas (Azizi et al 2017; Gusman et al 2013; Lindawati et al 2018). Karimunjawa waters are shallow sea waters so that the influence of small winds can cause waves at the sea level (Purbani et al 2019). In the period of northwest winds, the wave height can reach 0.5-1.58 m, with surface current speeds reaching 8-25 cm s^{-1} (BNTKJ 2004).

In coastal areas, sediments are dynamic and can experience erosion, transportation and deposition at spatial and temporal scales (Qhomariyah & Yuwono 2016; Setiady et al 2015). The sedimentation process is strongly influenced by various hydro-oceanographic factors, namely currents, waves and tides, and characteristics of sediment grains (Ali et al 2017; Muskananfola et al 2020b; Nugroho & Basit 2014; Nugroho & Putra 2019). In addition, sedimentation in coastal areas results from accumulated sediment from land and is transported by rivers, wind, biological activities and atmospheric inputs (Dyer 1986; Gemilang et al 2018; Muskananfola et al 2020a; Siregar et al 2014).

Various studies have been conducted in the waters of Karimunjawa and Kemujan Island, concerning the benthic organisms, sand dollars distribution and abundance (Suryanti et al 2016), mangroves ecosystem (Hapsari et al 2020), seagrass and fish larvae (Erzad et al 2020), and coral reef ecosystem (Afifa et al 2020). At the same time, the study of the sedimentation and sediment movement is still minimal, for instance regarding the distribution of sediments in artificial coral reefs (Gamellia et al 2019) or the influence of sedimentary organic content on coral diversity (Nugroho et al 2018). Therefore, this study aimed to analyse the characteristics of hydro-oceanography and its effect on the stability and dynamics of bottom sediments in the waters of Kemujan Island, Karimunjawa. The results of this study are expected to provide valuable scientific information to policymakers and the surrounding community in order to maintain and manage fishery resources in Karimunjawa National Park and its surrounding waters.

Material and Method

Study area. The research was conducted in the waters of Kemujan Island, Karimunjawa (Figure 1). Karimunjawa Islands are located in the north of Java Island, which is included in the territory of Jepara Regency, Central Java. The archipelago consists of 27 islands situated in the position of 5'40"-5'57" South Latitude (S) and 110'4"-110'40" East Longitude (E). The Karimunjawa National Park has an area of 111,625 ha, where the lowland tropical rainforest ecosystem covers 1,285.50 ha, while the mangrove forest ecosystem occupies 222.20 ha and the rest is as a Natural Conservation Area (KPA) of 110,117.30 ha (BTNJK 2019).

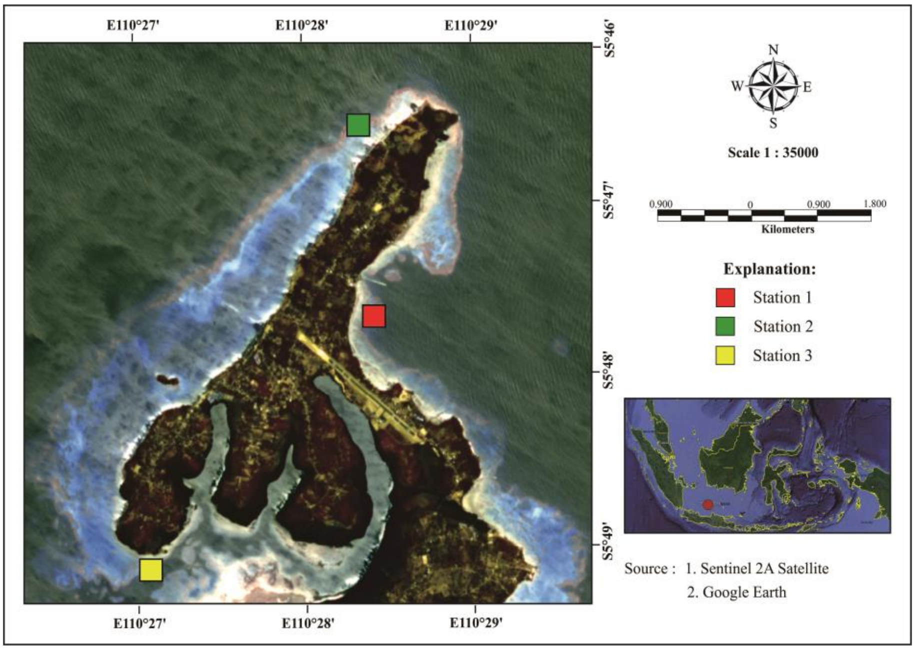

Figure 1. Research location at Kemujan Island, Karimunjawa.

The location of the sampling station is, for the station 1: 5°47'26.74" S 110°28'33.92" E; for the station 2: 5°46'28.30" S 110°28'37.29" E and for the station 3: 5°49'0.34" S 110°27'15.27" E (Erzad et al 2020). The research area is divided into three stations. Station 1 is east of Kemujan Island, adjacent to the Port of Legon Bajak, where ships can anchor and sail. Station 2 is located on Laendra Beach, a white sandy beach located at approximately $\pm$22 km to the north from the centre of Karimunjawa square and adjacent to Batu Pengantin Beach. While, station 3 is located in the waters of Ujung Pandean, south of Kemujan Island, which have mangrove forest ecosystems. According to the research conducted by Hapsari et al (2020), Kemujan Island has a vast ecosystem with mangrove species, including *Avicennia alba*, *Avicennia marina*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Sonneratia alba*, *Bruguiera gymnorrhiza*, *Ceriops tagal* and *Xylocarpus granatum*.

Oceanographically, Karimunjawa waters, such as Indonesian sea waters, generally experience two main seasons: the western season and the eastern season and two transition seasons, the first transition season and the second transition season (Muskananfola et al 2021; Wyrtki 1961). In the western and eastern seasons, seas are rougher, with higher waves than in the transition seasons. Karimunjawa waters are included in the transition waters and have a wave energy value directly proportional to the height value of the wave. According to the research conducted by (Gunawan et al 2017), the results of field data processing in Karimunjawa Waters showed a maximum wave height of 1.22 m with a period of 7.30 sec, and a minimum wave height of 0.09 m, with a period of 4.30 sec. Karimunjawa waters have a single mixed daily tidal type with a minimum current speed of 0.004 m s^{-1}, while the maximum current speed is 0.954 m s^{-1} (Ismunarti et al 2016). Furthermore, according to a research conducted by Gamellia et al (2019), the bottom sediment type in Karimunjawa waters is dominated by sand, with the following composition: 98.48% sand, 1.14% silt and 0.38% silt.

Tidal observation method. A field data campaign (tides, currents measurements and sediments collection) was conducted in October 2019, a period categorized as transition season two (Muskananfola et al 2021; Wyrtki 1961). Tide and current measurements were carried out at station 3, while sediment samples were taken from all three stations. Tidal data retrieval is done by reading data on a pole scale submerged in seawater every hour for one day (24 hours). The determination of observation stations is carried out in open areas, not affected by human activities. The tidal pole should be long enough to allow the measurements of the highest tidal level and the minimum receding water at the lowest tidal levels. The tidal bar is perpendicular and in an unchanged (fixed) position (Lisnawati et al 2013).

Currents measurements. Measurement of the currents velocity over one tidal cycle was carried out at 100 cm above the sea bed, using one current meter: mechanical standard flowmeters series 2030. The current meter was dropped from a boat that was connected with a cable. The current velocity was recorded every hour during one tidal cycle from 07.00 am to 5.00 pm (WIT) (Muskananfola et al 2017). By applying the 'Quadratic Stress Law' (Sternberg 1972) to the obtained data, bed shear stress (τ_0) and friction velocity (U_*) can be quantified. It has been proved experimentally (Sternberg 1966) that in a turbulent flow environment the boundary shear stress is proportional to the fluid density and the square of the mean velocity:

$$\tau_0 \sim \rho {U_z}^2$$

Or, after introducing a proportionality coefficient:

$$\tau_0 = C_D \rho {U_z}^2$$

Where:

C_D - the drag coefficient representing the mean velocity near the seabed to the force exerted by the fluid per unit area of the bed.

If the velocity is measured at a standard distance from the bed (generally 100 cm, in the oceanographic research), then the equation can be written (Sternberg 1972):

$$\tau_0 = C_{100} \rho {U_{100}}^2$$

or, in terms of the friction velocity:

$$U_* = C_{100}{}^{1/2} U_{100}$$

Investigations in the laboratory (Nikuradse 1933) and the sea (Sternberg 1968) have shown that the drag coefficient assumes a constant value related to the bed configuration for hydrodynamically rough flows. Hence, given an expected value of U_{100} the boundary shear stress can be obtained from a single measurement of mean velocity within the boundary layer.

The results of Sternberg's study (1972) indicate that for naturally sorted sand sediment textures, an estimate of boundary shear stress (τ_0) from measurements U_{100} is best to obtain from the following equation:

$$\tau_0 = (3 \times 10^{-3}) \rho U_{100}{}^2$$

or, in terms of friction velocity:

$$U_* = 5.47 \times 10^{-2} U_{100}$$

The data obtained in the present study is applied to equations to calculate the shear stress exerted on the seabed and the shear velocity of the flow. By knowing the shear stress operating on the seabed, subsequently, it is possible to predict sediment movements and distribution in marine and coastal environments (Korwa et al 2013; Saputra et al 2013; Wisha et al 2017).

Sediments samples collection and analysis. Sediment samples were taken at three stations. Each station is laid in three quadrants perpendicular to the coastline with a distance between points of 30 m using roll meters perpendicular to the sea (Aini et al 2016). Three transect quadrants measuring 5 x 5 m are placed zigzag, with the distance between quadrants of 20 m. The sediment collection in each quadrant is carried out by collecting five samples from five different points (centre and four corners) and then combined for further analysis in the laboratory (Meynita et al 2016). In this way, the sample taken can represent each part of the quadrant. Sediment collection is conducted using sand pegs on the surface of the bottom sediment. Samples that have been taken are then put in plastic bags and labeled for each point per station. Furthermore, sediment samples are taken to the laboratory to measure sediment grains (Buchanan 1984; Hartati et al 2017).

Granulometric sediment analysis is conducted with statistical approaches such as mean, sorting, kurtosis and skewness (Kamarz et al 2015). The formula used to calculate these variables (Blott & Pye 2001) is as follows:

a. Empirical average/mean

$$\bar{x} = \frac{\Sigma f mm}{100}$$

b. Sorting

$$\sigma a = \sqrt{\frac{\Sigma f (mm - \bar{x}a)2}{100}}$$

c. Skewness

$$Ska = \frac{\Sigma f (mm - \bar{x}a)3}{100 \sigma a3}$$

d. Kurtosis (Folk & Ward 1957)

$$Ka = \frac{\Sigma f (mm - \bar{x}a)4}{100 \sigma a4}$$

Where:
$\bar{x}$ - the empirical average;
f - frequency;
m_m - the mid-point for each class (mm);
σa - the value of sorting;
Sk_a - the value of mismatch;
K_a - the value of kurtosis.

Results

Oceanographic characteristics

Tidal characteristic. The oceanography parameters observed in situ in this study are related to the tidal characteristics. Results from observations of tidal data in the field showed an average water level value of 80.08 cm height. The highest tide occurred at 07.00 WIT, which is 100 cm in height, and the lowest receding tide occurred at 18.00 WIT, with 60 cm in height. The results of tidal observations are presented in Figure 2.

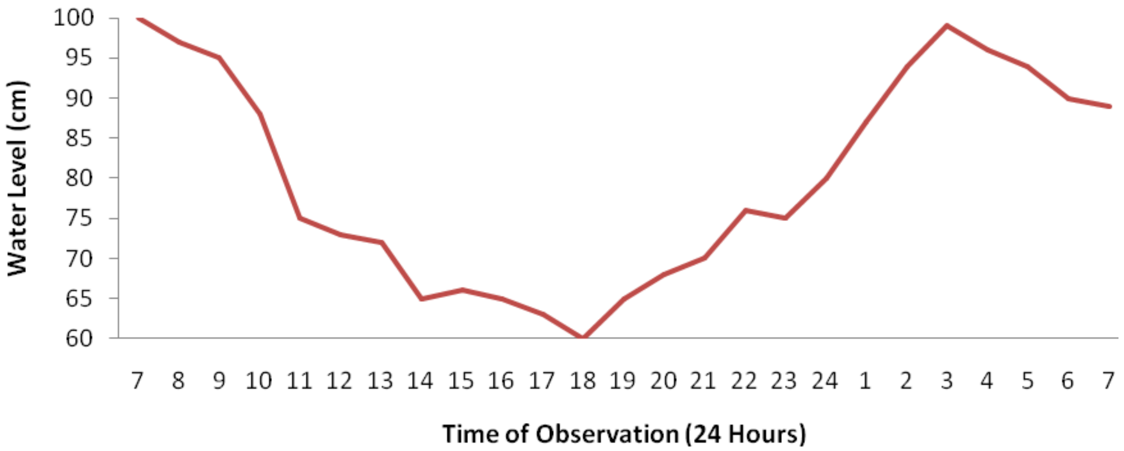

Figure 2. Tidal graph observed for 24 hours in the waters of Kemujan Island.

Current speed. Based on the results of current measurements that have been conducted, the overall current speed in the waters of Kemujan Island, at the sampling location, is quite small. The current speed is measured two times, namely the measurement of the current on the surface and the current in the water column, at the height of 100 cm above the substrate, to determine bed shear stress and shear velocity. The results of surface current measurement (Table 1) at station 1 range from 0.08 to 0.10 m s^{-1}; at station 2 it ranges from 0.04 to 0.05 m s^{-1} and at station 3 it ranges from 0.20 to 0.25 m s^{-1}, while the current speed at a depth of 100 cm above the seafloor ranges from 0.07 to 0.14 m s^{-1} (Table 2).

Table 1

Results of current speed measurements on the surface

Station	*Current speed (m s^{-1})*		
	Quadrant 1	*Quadrant 2*	*Quadrant 3*
1	0.10	0.08	0.09
2	0.05	0.05	0.04
3	0.20	0.20	0.25

Table 2

Results of current velocity measurement in the water column for 10 hours

Time	*Current speed (m s^{-1})*
07.00	0.14
08.00	0.13
09.00	0.13
10.00	0.11
11.00	0.10
12.00	0.09
13.00	0.08
14.00	0.07
15.00	0.07
16.00	0.07
17.00	0.07

Bed shear stress and shear velocity. Bed shear stress is known to show how intense is the force is working on the bottom of the ocean to cause movement or transport of sediments. In contrast, shear velocity determines the speed of the sediment is in its motion to settle. The shear stress on the seafloor becomes a parameter associated with the sediment movement from a place due to flowing currents. The maximum shear stress occurs at 07.00, which is 0.0606 N m^{-2}. In comparison, the minimum shear stress occurs in hours 14.00 to 17.00, which is 0.0151 N m^{-2}. The maximum value of shear velocity is 0.7658, and the minimum of shear velocity is 0.3829 cm s^{-1}. The measurements of bed shear stress and shear velocity are presented in Table 3.

Table 3

Results of bed shear stress calculation in the waters of Kemujan Island

Time (West Indonesian Time)	*Current speed (m s^{-1})*	*Bed shear stress* τ_0 *(N m^{-2})*	*Shear velocity* U^* *(cm s^{-1})*
07.00	0.14	0.0606	0.7658
08.00	0.13	0.0522	0.7111
09.00	0.13	0.0522	0.7111
10.00	0.11	0.0374	0.6017
11.00	0.10	0.0309	0.5470
12.00	0.09	0.0250	0.4923
13.00	0.08	0.0198	0.4376
14.00	0.07	0.0151	0.3829
15.00	0.07	0.0151	0.3829
16.00	0.07	0.0151	0.3829
17.00	0.07	0.0151	0.3829

The spatial changes in grain size parameters consist of 4 parameters, including mean, sorting, skewness and kurtosis. The average grain size is an index of grain measurements based on the fraction of each sample obtained, which can then be said to be a grain size representing the sampling point. Based on the analysis of grain size parameters, the average empirical value ranged from 7.98 to 15.87% of the fractional measurement results in each sampling point. Sediment sorting values at each sampling point range from excellent (very well sorted) to poorly sorted. The skewness value ranges from 0.96 to 1.720, which falls into the asymmetric category to very fine skewed. At the same time, the kurtosis value ranges from 0.995 to 2.26, which falls into the category of mesokurtic to very leptokurtic.

Sediments characteristics

Sediment grain size. The results of the analysis of sediment grains at the research site are presented in the form of graphs with grain diameters in millimetres (mm) and sediment weights in percentage (%) (Figure 3). The sediment samples that have been collected around the waters of Kemujan Island counted nine items from 3 retrieval stations. The percentage of sediment distributed at each sampling station was dominated by sand, with a gravel percentage of 17.74% and a grain size of 1-2 mm, 66.51% sand of a grain size ranging from 0.125-0.5 mm and 14.85% dust with a grain size ranging from 0.25-0.0032 mm.

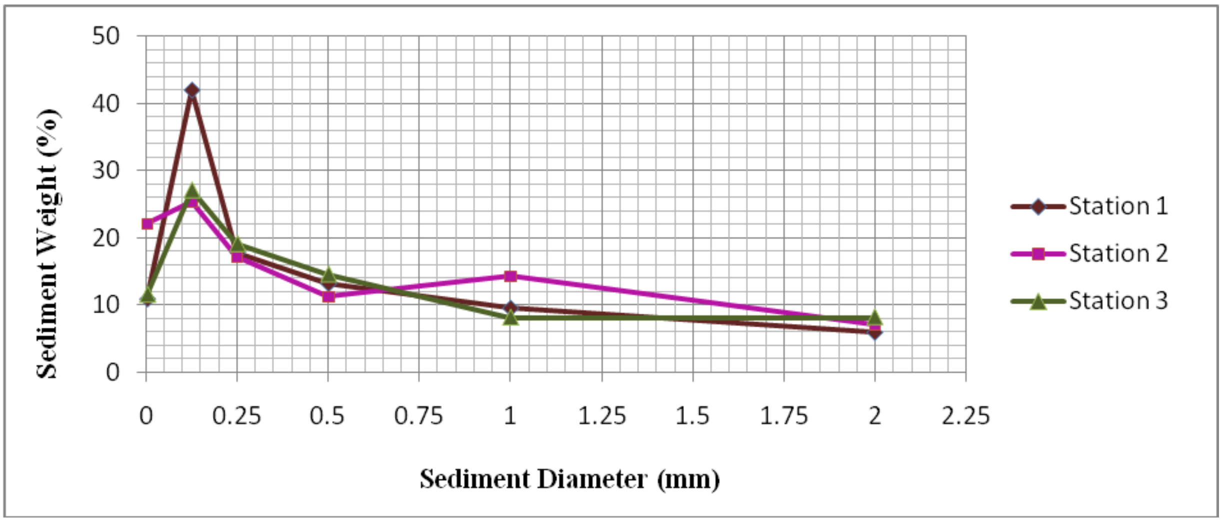

Figure 3. Diameter and percentage size of sediment grains.

Sediment granulometry analysis. The spatial changes in grain size parameters consist of four parameters: mean, sorting, skewness and kurtosis. The average grain size is an index of grain measurements based on the fraction of each sample obtained, which can be a grain size representing the sampling point—table of granulometric sediment analysis presented in Table 4.

Table 4

Results of sediment granulometric analysis calculations

Classification and analysis of sediment granulometry	*Data processing results*	*Criteria*
Mean	7.98-15.87	Fine sand
Sorting	0.009-1.2	Sediment sorting values at each sampling point are included in very well sorted to poorly sorted categories)
Skewness	0.96-1.72	Asymmetric to small sizes (very fine skewed)
Kurtosis	0.99-2.26	Mesokurtic to very leptokurtic

Discussion

Oceanographic characteristics. Current measurements are carried out on the water surface and in the water column at the height of 100 cm above the substrate. The average current speed in the water column at high tide to low tide is around 0.14 m s^{-1}, while the current speed at low tide is 0.07 m s^{-1}. Currents in the waters have different speeds according to the condition of the waters at the time of measurement. According to Mawardi (2016), the movement that occurs in the current is the resultant of various forces acting on the surface, water column and bottom of the water. Wind stress that works at sea level will push water on the surface to form surface currents. The surface current pattern follows the surface wind pattern. In addition, surface currents are also formed due to the influence of the moon attraction force on the earth, known as tidal currents. Tidal currents of seawater have an essential role in changing the textural characteristics of coastal sedimentary deposits (Muskananfola et al 2020b; Nugroho & Putra 2019). In addition, the influence of waves that spread is mainly generated by wind and affects the amount of sediment transport from sea to land (Azizi et al 2017; Purbani et al 2019).

The tidal data analysis shows that the water level decreases from the high tide at 7 am and reaches low tide at 6 pm, then gradually increases to reach high tide at 3 am. As the increase and decrease occur with different periods, the waters on Kemujan Island are categorized into the mixed diurnal tide. Lisnawati et al (2013) also stated that Parang Island, located in the Karimunjawa Islands, has a single daily dominant mixed tidal type. Tidal information could be used for navigational activities, development purposes and all activities carried out in the waters. Furthermore, according to Ali et al (2017), the single daily type of tides with low current speeds cannot cause significant changes of the current movement and capacity to transport bottom sediment. This finding suggests that the speed of currents can affect deposits of specific sizes. At the high tide, currents carry water from the sea to coastal waters, while at low tide, the current carries water from coastal waters to the high seas. Water circulation due to tidal currents can contain sedimentary material, therefore the tidal current patterns of the water will affect the sediment transport patterns (Kurniawan & Pradana 2016; Muskananfola et al 2020b).

Sediment characteristics. The usual size of sediment grains is strongly influenced by oceanographic processes around the sediments location. The results of the sediment grains' size calculation showed that the sediment contained in the waters of Kemujan Island Karimunjawa was dominated by medium sand to fine sand that had a grain size range of 0.5-0.125 mm. Differences in the size of sediment grains are related to the origin of the sediment sources (Dyer 1986; Gemilang et al 2018). The type of sediment obtained in the form of sand that have a white to browning body, fine-coarse and partly in the form of gravel indicates that the sediment source comes from the sea, which then undergoes the process of transportation until it finally gets deposited into the sediment. The sediments obtained are dominated by the shells of marine biota, foraminifera, grains and coral fragments. According to Setiady et al (2015), the transfer of coastal sediment can be caused by river currents, tidal currents, waves and winds. Sediment is transported from offshore to coastline by wave currents (mass transport) and parallel coastal currents (longshore current).

Parameters of sediment grain size (mean, sorting, skewness and kurtosis) are used to identify sediment movement processes (Blott & Pye 2001; Kamarz et al 2015; Korwa et al 2013). The results of the sediment granulometry analysis showed that the sorting at stations 1 and 2 were very well sorted. The current tends to be weak and stable at this location, so it does not produce significant sediment transport and sediment grains do not become randomly distributed. Well-sorted sediments indicate that the sedimentary fraction tends to be uniform (Dyer 1986). The sorting results at station 3 are poorly sorted because they have a distribution of more diverse sizes than other regions. This pattern follows the conditions in station 3, which has stronger currents due to wind factors that cause sediment grains to settle randomly mixed. According to (Wisha et al 2017), highly sorted sediments consist of particles with a minimal range of sizes, while mechanical forces have eliminated other particle sizes in the form of wave and current.

Sediment transport patterns consist of bedload and suspension transportation. Bedload transportation mechanism occurs in coarse fractions with traction current transportation in rolling, dragging and creeping (Dyer 1986; Muskananfola et al 2020b; Sternberg 1972). In contrast, the suspension load works to transport a smooth fraction (ranging from clay to very fine sand) in the form of a suspension lifted far enough in the flow before settling with a decreased current speed. The current is the oceanographic factor that plays a role in the distribution of sediments in water, especially of the suspended sediment (Muskananfola et al 2017). Muskananfola et al (2020b) stated that the speed of currents determines the transport of bottom sediments and particles of materials. Furthermore, the research conducted by Saputra et al (2013) considered that the most significant oceanographic factor thought to affect sediment distribution is the current along the coast, determined by the alignment of waves that break.

Sediment stability terms of current velocity and sediment grains size. Based on the results obtained, it is known that the currents at the location of sediment observation tend to be slow, but the wind is blowing quite strong. At the same time, the large size of sediment particles at the sampling site is dominated by coarse sand to fine sand. The slow current with low bed shear stress was inadequate to cause a motion of the coarse sediment grains, indicating that seabed sediments are in a stable condition (Dyer 1986; Muskananfola et al 2017, 2020b). According to Lanuru & Yusuf (2018), fine sedimentary grains are easily carried by currents, due to the small effect of the gravity on them, and tend to float in the water column so that they can be transported further out to sea and settle in deeper waters. Furthermore, according to Saputra et al (2013), currents have an essential role in the sediment transport; if the current speed is reduced, the current can no longer transport sediment. As a result, sediments with larger grain sizes will be deposited first and sediments with smaller grain sizes will be carried by currents in the form of suspended loads, far out to the sea. Particle displacement will result in erosion or sedimentation (Dyer 1986; Muskananfola et al 2017).

Fine sediment particles indicate a weak current strength (low hydrodynamic energy) to transport sediment and vice versa. In contrast, strong currents (high hydrodynamic energy) show grains of coarse sediment (Dyer 1986; Muskananfola et al 2020b). This finding is reinforced by Nugroho & Basit (2014), who stated that the current has properties that can select the size of the grains it carries in the sedimentation process. This process is influenced by the sediment grains and the currents speed in the waters. Furthermore, according to (Gamellia et al 2019), the process that most affects sedimentation in coastal areas and shallow waters is the supply of sediment from rivers, waves, tides, parallel coastal currents. Qhomariyah & Yuwono (2016) stated that the influence of tidal forces causes different sedimentation patterns in other places. Regions with double daily tides type and mixed inclined to double daily tides type undergo a more dynamic sediment transport process when compared to daily tidal types.

Conclusions. Kemujan Island, used as a research location, has a single daily mixed tide prevailing type with an average surface current speed of 0.12 m s^{-1} and an average current speed in the water column of 0.1 m s^{-1}. The dominating sediment types are medium sands with grain sizes ranging from 0.5 to 0.25 mm and fine sand grain size around 0.125 mm. The weak current conditions affect the sediment particles ability to settle. Smaller sediment particles are easier to move because the critical force required to move them is smaller. In addition, the difference in current velocity measured on the surface and in water column indicates that a decrease in the current velocity corresponds to an increasing depth, due to friction forces in each layer of depth and rough bottom conditions. The current speed at the study site affects sediments of a specific size; weak and constant currents speeds do not cause significant sediment movement and the sediment fractions found tend to be of a uniform size.

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Conflict of interest. The authors declare no conflict of interest.

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