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Tidal Characteristics in the Southern Waters of Java - Indonesia

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ABSTRACT
Detailed information regarding tidal characteristics in Indonesian waters is not yet available evenly, including in the southern waters of Java. Tides are one of the most essential hydro-oceanographic parameters in water dynamics. Therefore, this study aims to analyze the characteristics of the tides in the southern waters of Java, starting from Banten Regency in West Java to Malang Regency in East Java. Tidal data with measurement intervals every one hour were collected from December 23, 2022, to January 20, 2023, from ten tide stations with details: 1 station each in Banten and Central Java, three stations each in West Java and East Java, as well as two stations in Yogyakarta. Data from each station is then processed using the Admiralty method to obtain tidal harmonic constant and Formzahl values. Based on the tidal harmonic constants' amplitude and the Formzahl values (F), the tidal type in the southern waters of Java is a mixed tide prevailing semi-diurnal (F ranged from 0.64 - 1.34). The tidal range in the southern waters of Java ranges from 178 - 332 cm. In more detail, Banten and Pelabuhan Ratu waters are classified as micro tides (the tidal range is 178 and 182 cm, respectively). At the same time, the rest are categorized as meso tides (tide range between 200 - 400 cm).

INTRODUCTION

Indonesia is an archipelagic country with abundant potential for natural landscapes and resources in coastal areas (Riggs et al. 2021; Amaruzaman et al. 2022; Alwi and Mutaqin 2022; Isnain and Mutaqin 2023). The coastal area is an essential area for the life and livelihood of humans and other living things, including the southern coastal area of Java Island (Reichel et al., 2009; Mutaqin, 2017; Fitrianggraeni, 2019; Alwi and Mutaqin, 2022; Isnain and Mutaqin, 2023). As an archipelagic country with a shoreline of more than 90,000 km (Pushidrosal, 2018; BIG, 2021; BPS, 2021), information related to hydro-oceanographic parameters is essential. This information can be used in many ways, such as planning coastal areas, managing marine and coastal resources, as well as mitigating coastal disasters (Hamuna et al., 2018; Fitriana et al., 2019; Adalya and Mutaqin, 2022; Isnain and Mutaqin, 2023).

Tides are essential hydro-oceanographic parameters to be studied in detail (Pamungkas, 2018; Hamuna et al., 2018; Fitriana et al., 2019). Tides are one of the essential parameters in water dynamics, influencing coastal areas (Wei et al., 2016; Pamungkas., 2018; Finkl and Makowski, 2019). Tides can be defined as the phenomenon of the periodic rise and fall of sea level caused by the action of the gravitational force of celestial bodies, namely the attractive force between the earth, the moon, and the sun (Finkl and Makowski, 2019). Tides are the energy that works on the beach and occurs daily (Hamuna et al., 2018; Fitriana et al., 2019). This is very useful for people who live on the coast, especially those who work as fishermen (NOAA, 2022). Fishermen can use the tides to find the right time to go to sea to provide maximum sea yields (NOAA 2022).

The tides have several types, namely single daily type (diurnal), double daily type (semi-diurnal), and mixed (Finkl and Makowski, 2019; Lee and Chang, 2019). The single daily type of tide is the type that has one high tide and one lowest low tide. The double daily type of tide is the type that has the highest tide twice and the lowest tide twice (Finkl and Makowski, 2019; Lee and Chang, 2019). Meanwhile, if there is a combination of the two types of tides, it is called a mixed-type tide and leans towards one of the two types (Finkl and Makowski, 2019; Lee and Chang, 2019).

In Indonesia, there are differences in tidal characteristics between regions (Pamungkas, 2018; Hamuna et al., 2018; Fitriana et al., 2019). In addition, Indonesia's tidal system is quite complex due to differences in seabed topography, monsoon systems, dynamics of coastline morphology, and the interaction of tidal wave propagation from the Pacific Ocean, Indian Ocean, and South China Sea (Wei et al., 2016).

One area that needs to do an in-depth analysis of tidal characteristics is the southern waters of Java. The southern waters of Java are known for their various potential fishery resources, coastal tourism, and disaster potential (Sarwanto et al., 2016; Fitrianggraeni, 2019; Mutaqin et al., 2021; Alwi and Mutaqin, 2022; Isnain and Mutaqin, 2023). Until now, there are at least eleven fishing ports in southern Java, namely the Pelabuhan Ratu Archipelago Fishing Port, Jayanti Fish Landing Port (PPI), Cikidang Pangandaran Fishing Port, Tanjung Intan-Cilacap Port, Tanjung Adikarto Port, Gesing Port, Coastal Fishing Port. Tamperan, Prigi Archipelago Fishing Port, Tambakrejo Fishery Port, Sendang Biru Harbor, and Grajagan Harbor (Figure 1).

Adequate data and information on tidal characteristics will assist the government and the community in planning and developing coastal areas (Syahputra and Nugraha, 2016; Hamuna et al., 2018; Fitriana et al., 2019). Regarding tide monitoring, Presidential Regulation Number 93 of 2019, concerning Strengthening and Development of Earthquake Information Systems and Tsunami Early Warning, states that the Geospatial Information Agency (BIG) is tasked with carrying out the construction and operation of equipment for earthquake observation and tsunami, including carrying out maintenance of the equipment. The equipment is a Continuous Global Positioning System, a Continuously Observation Reference Station (CORS), and a Tide Gauge (Government of Indonesia, 2019).

Figure 1. An example of a fishing port in southern Java (Source: Data analysis, 2023)

The real-time tidal station owned by BIG is a system of equipment that records the phenomenon of the movement of sea level rise and fall at any time continuously and is monitored online from a data center that can be used for various purposes continuously and in real-time (BIG, 2022). Until 2022, at least 238 national tidal stations throughout Indonesia will be managed by BIG (BIG 2022). Of course, these facilities can be used for both practical and scientific purposes, one of which is to determine the characteristics of the tides in the region.

This study aims to analyze the characteristics of the tides in the southern waters of Java, starting from Banten Regency in West Java to Malang Regency in East Java. Information on tidal characteristics in an area can be further utilized to assist in port engineering activities, water navigation, disaster mitigation, as well as planning and management of coastal areas (Syahputra and Nugraha, 2016; Hamuna et al., 2018; Fitriana et al., 2019; BIG 2022).

RESEARCH METHODS

This research was conducted in the southern waters of Java, starting from Banten Regency in West Java to Malang Regency in East Java. Tidal measurement data were obtained from ten tide stations managed by BIG, namely Binuangeun - Banten (BINU), Pelabuhan Ratu - West Java (PRTU), Pameungpeuk - West Java (PMPK) stations, Pangandaran - West Java (PGDR), Cilacap - Central Java (CCAP), Glagah - Yogyakarta (GLGH), Sadeng - Yogyakarta (SADG), Pacitan - East Java (PCTN), Prigi - East Java (PRGI), and Sendang Biru - East Java (SBRU). The distribution of tidal stations about the research location can be seen in Figure 2 and Table 1. Tide measurement data obtained from the ten tidal stations are seawater fluctuations resulting from measurements for 29 days, from December 23, 2022, to January 20, 2023, with data intervals every 1 hour.

Determining the type of tides can be known of them through the results of the Admiralty method analysis (Glen, 2015; Tapilatu et al., 2022; Adalya and Mutaqin, 2022; Hoseini and Soltanpour, 2022). The Admiralty method is a simplified graphical method for obtaining tidal curve predictions to provide estimates generated with full predictions using far more data (Glen, 2015; Tapilatu et al., 2022).

The Admiralty method is used to find the harmonic components of the tides. The Admiralty method can calculate the highest high tide or Highest High-Water Level (HHWL) and lowest low tide or Lowest Low Water Level (LLWL) (Glen 2015; Tapilatu et al. 2022). The advantage of this method is that it can be used in various water conditions and requires input for a short observation period (Glen, 2015; Tapilatu et al., 2022; Adalya and Mutaqin, 2022; Hoseini and Soltanpour, 2022). Therefore, the Admiralty method is widely used in research on tides.

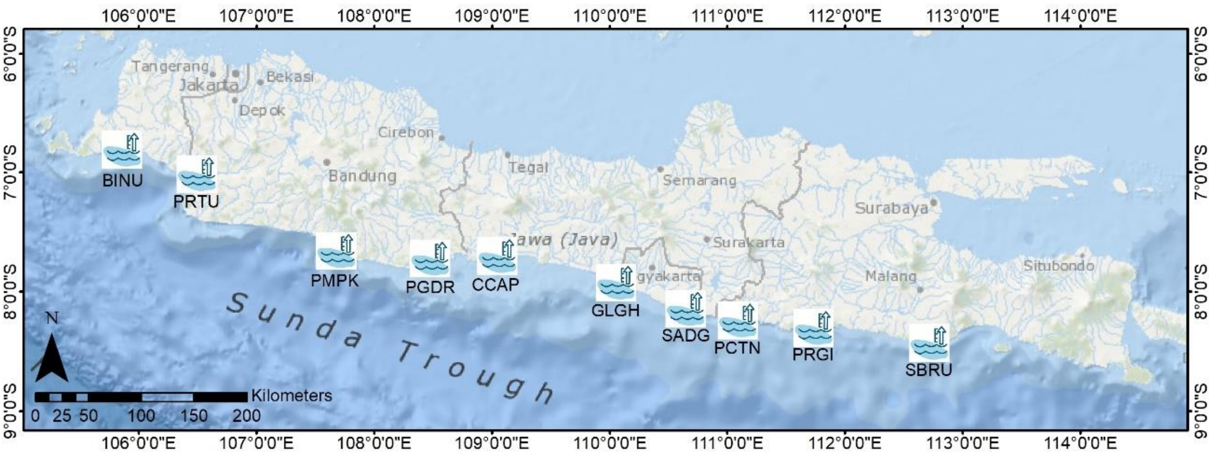

Figure 2. The location of the tidal station used in the study (Source: Data analysis, 2023)

Table 1. Tidal Station Information Used in the Study

No	Station name	Station code	Coordinates		Province
			Latitude	Longitude	
1	Binuangeun	BINU	06° 50 07.72	105° 53 46.67	Banten
2	Pelabuhan Ratu	PRTU	06° 59 16.47	106° 32 34.07	West Java
3	Pameungpeuk	PMPK	07° 39 41.50	107° 40 57.35	
4	Pangandaran	PGDR	07° 44 53.91	108° 30 05.04	
5	Cilacap	CCAP	07° 44 29.03	108° 59 47.39	Central Java
6	Glagah	GLGH	07° 54 59.50	110° 04 54.48	Yogyakarta
7	Sadeng	SADG	08° 11 25.72	110° 47 57.48	
8	Pacitan	PCTN	08° 13 38.09	111° 04 26.76	East Java
9	Prigi	PRGI	08° 17 12.65	111° 43 39.00	
10	Sendang Biru	SBRU	08° 26 03.15	112° 41 00.95	

(Source: Data analysis, 2023).

The data obtained from each station was then processed using the Admiralty method to obtain the amplitude values of the tidal harmonic constants (Table 2), including the Formzahl values (Tapilatu et al., 2022; Adalya and Mutaqin, 2022). Calculation of the Formzahl value for determining the type of tide (Table 3) is obtained by comparing the amplitude (wave height) of the leading single tide elements with the main double tide elements using the formula in Equation 1 (Tapilatu et al., 2022). The results of the calculation of the formula will determine the type of tide at the study location.

$$\text{Formzahl value (F): } \frac{(O1+K1)}{(M2+S2)} \text{ .... Eq. (1)}$$

Table 2. Tidal Harmonic Constants' Amplitude Values

Code	Information
M_2	Harmonic constants that are affected by the position of the moon
S_2	Harmonic constants that are affected by the position of the sun
N_2	Harmonic constants that are affected by changes in the distance of the moon
K_2	Harmonic constants that are affected by changes in sun distance
O_1	Harmonic constants affected by the moon's declination
P_1	Harmonic constants affected by solar declination
K_1	Harmonic constants affected by the declination of the sun and moon
M_4	Harmonic constants affected by the double influence of M2
MS_4	Harmonic constants that are affected by the interaction between M2 and S2

(Source: Glen, 2015).

Table 3. Tidal Type Based on Formzahl (F) Value

Formzahl Value	Tidal Type
F≤0.25	Semi-diurnal tides
0.25<F≤1.5	Mixed tide prevailing semi-diurnal
1.5<F≤3.0	Mixed tide prevailing diurnal
F>3.0	Diurnal tides

(Source: Hamuna et al., 2018).

Based on the values of the tidal harmonic components that have been obtained previously, the next step is to calculate the significant sea level elevation values and also the tidal ranges for each station. The significant sea level elevation values referred to are: a) highest high-water level (HHWL), b) mean high water level (MHWL), c) mean sea level (MSL), d) mean low water level (MLWL), and e) lowest low water level (LLWL). The tidal range variable is calculated from the difference between the highest and lowest tidal values. The highest tide value is indicated by the Highest Astronomical Tide (HAT), while the lowest ebb is indicated by the Lowest Astronomical Tide (LAT). The results of tidal ranges can be classified into three classes, namely micro (<2 meters), meso (2-4 meters), and macro (>4 meters) (Appelquist et al., 2016).

RESULTS AND DISCUSSION

Tidal types

Based on tidal data for 29 days for each tidal station, the tidal harmonic constants' amplitude values are obtained, presented in Table 4. Furthermore, by comparing the amplitude (wave height) of the leading single tidal elements with the main double tidal elements using the formula in Equation 1 (Tapilatu et al. 2022), the Formzahl values (F) for each tidal station can also be obtained (Table 4).

Table 4. Values of Tidal Harmonic Constants' Amplitude and Formzahl in Each Tidal Station

Tidal station	Amplitude (A) & phase (g)	Tidal harmonic constants' amplitude values										Formzahl Values
		S_0	M_2	S_2	N_2	K_1	O_1	M_4	MS_4	K_2	P_1	
BINU	A (cm)	51	34	9	6	37	11	0	1	3	15	1.13
	g (°)	0	271	70	167	39	171	239	323	70	39	
PRTU	A (cm)	198	31	9	6	41	12	0	1	3	16	1.34
	g (°)	0	263	69	201	47	167	235	360	69	47	
PMPK	A (cm)	106	37	12	7	40	15	0	0	4	16	1.11
	g (°)	0	327	86	255	45	228	186	89	86	45	
PGDR	A (cm)	692	40	14	8	41	14	1	1	4	16	1.03
	g (°)	0	336	90	275	45	232	257	48	90	45	
CCAP	A (cm)	174	46	14	2	42	14	1	1	5	17	0.94
	g (°)	0	358	109	254	55	241	89	172	109	55	
GLGH	A (cm)	9	37	12	6	32	12	1	1	4	13	0.90
	g (°)	0	301	103	205	62	196	206	45	103	62	
SADG	A (cm)	157	50	18	9	43	16	1	0	6	17	0.86
	g (°)	0	347	100	291	44	229	196	171	100	44	
PCTN	A (cm)	82	29	11	10	30	14	2	3	3	12	1.12
	g (°)	0	309	63	312	29	192	349	132	63	29	
PRGI	A (cm)	183	54	18	11	30	16	1	1	6	12	0.64
	g (°)	0	357	102	295	61	185	239	21	102	61	
SBRU	A (cm)	156	65	21	12	46	17	1	1	7	18	0.73
	g (°)	0	283	108	183	52	155	113	26	108	52	

(Source: Data analysis, 2023)

Based on the Formzahl values in Table 4, information is obtained from ten tidal stations in southern Java, and the Formzahl values range from 0.64 to 1.34. The lowest Formzahl value was found at the Prigi station, located at the wharf of the Indonesian fishing port in Prigi (Trenggalek, East Java). Meanwhile, the highest Formzahl score is at Pelabuhan Ratu station, near the fish auction site in Pelabuhan Ratu (Sukabumi, West Java). Even though the values look pretty varied, they are classified into one class only, namely the mixed tide prevailing semi-diurnal. This type of tide means two high tides and two low tides in one day, but the height and period differ (Finkl and Makowski, 2019; Lee and Chang, 2019; Tapilatu et al., 2022). More detail can be seen clearly in the tidal chart presented in Figure 3.

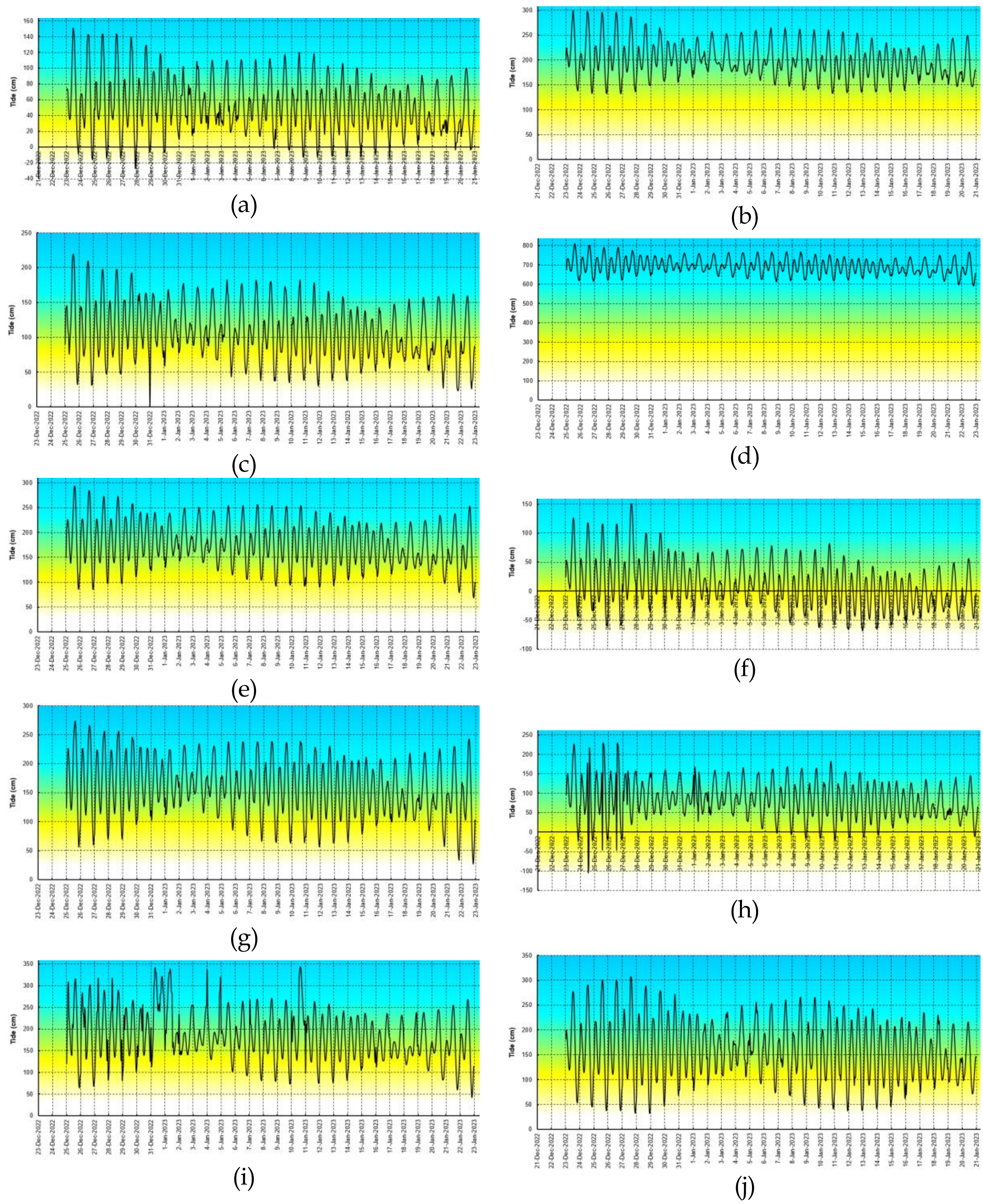

Figure 3. Tidal chart for 29 days in a) Binuangeun (BINU), b) Pelabuhan Ratu (PRTU), c) Pameungpeuk (PMPK), d) Pangandaran (PGDR), e) Cilacap (CCAP), f) Glagah (GLGH), g) Sadeng (SADG), h) Pacitan (PCTN), i) Prigi (PRGI), and j) Sendang Biru (SBRU) (Source: Data analysis, 2023)

Based on Figure 3, it can be seen that the tidal charts at Pangandaran and Glagah stations look different from other tidal stations. This is due to the Pangandaran tidal station being in the waters near the shore, namely in Batukaras Recreation Park, Pangandaran (BIG 2022) (Figure 4a). Hence, the location of the water level sensor is quite different. Unlike the Pangandaran station, the Glagah station is installed at the Kulon

Progo fish landing base (PPI) pier. The problem is that there has been siltation at the Serang River estuary (Puspa and Purwono, 2020). Hence, the recorded data has the potential to no longer be natural due to seawater being held back from entering and leaving the PPI Glagah dock area (Figure 4b).

(a)

(b)

Figure 4. Conditions of a) Pangandaran tidal station in Batukaras Recreation Park (Courtesy: BIG 2022); and b) problem in the Glagah tidal station location (Source: Data analysis, 2023)

Things that need to be considered in placing a tidal station include (Suprapto, 2016): a) the location must represent the characteristics of the tides in the surrounding area, b) hard soil and not muddy, c) it must be far from the river mouth to avoid the influence of the flow, sediment, and garbage that are carried to the sea, d) the waters are clean and clear and not disturbed by marine plants, e) easy to carry out monitoring and maintenance, and f) protected from surface wave activity.

Tidal characteristics in southern Java waters, which are categorized as mixed tide prevailing semi-diurnal, are supported by research from (Haryono and Narni, 2004; Setyawan and Pamungkas, 2017; Sasmito, 2020). The tides in the Cilacap and Prigi waters are classified as mixed tides prevailing semi-diurnal, each having a Formzahl value of 0.493 and 0.463 (Haryono and Narni, 2004). Tides in the Pelabuhan Ratu waters are also classed as mixed tides prevailing semi-diurnal based on measurements in January 2016 (Setyawan and Pamungkas, 2017). Sea Level Anomaly data from the Topex/Poseidon and Jason-1 altimetry satellites in Cilacap, Sadeng, and Prigi also show that the tidal type in the area falls into the category of mixed tides prevailing semi-diurnal with Formzahl values of 0.55, 0.47, 0.69, respectively (Sasmito, 2020).

Significant sea level elevation

Based on tidal harmonic constants' amplitude values for each tidal station, the significant sea level elevation parameters are obtained, presented in Table 5. Furthermore, by performing simple mathematical calculations using HAT and LAT data (Appelquist et al., 2016), the tidal ranges for each tidal station can also be obtained and then compared with the Indonesian Geospatial Reference System (SRGI) of the Indonesian Geospatial Agency (BIG, 2022) (Table 5). Results of tidal range data may be divided into three categories: micro (less than 200 cm), meso (200 - 400 cm), and macro (more than 400 cm) (Appelquist et al., 2016).

Based on the significant sea level elevation in each tidal station in Table 5, information is obtained from ten tidal stations in southern Java, and the tidal ranges from 178 to 332 cm. The lowest tidal range was found at the Binuangeun station, located at the harbor of the iron sand company in Binuangeun, Banten, i.e., 178 cm. This tidal range is classified as micro-tidal (Appelquist et al., 2016) and has almost the same value as SRGI of (BIG, 2022), i.e., 1.588 m ± 0.145. Meanwhile, the highest tidal range is at Pacitan station, situated at the Tamperan Fishing Port, East Java, i.e., 332 cm and categorized as meso tidal. Of the ten tidal stations, two stations are classified as micro-tidal, i.e., Binuangeun in Banten and Pelabuhan Ratu in West Java. The rest (eight stations) are categorized as meso tidal with ranges from 200 to 400 cm (Appelquist et al., 2016).

Table 5. Significant Sea Level Elevation in Each Tidal Station (cm)

Station Code	HHWL	MHWL	MSL	MLWL	LLWL	HAT	LAT	Tidal range	Tidal range class[a]	Tidal range SRGI[b]
BINU	160	133	51	-31	-59	151	-27	178	Micro	1.588 m ± 0.145
PRTU	310	282	198	114	86	300	118	182	Micro	1.615 m ± 0.196
PMPK	229	197	106	15	-18	219	0	219	Meso	1.840 m ± 0.167
PGDR	821	786	692	597	563	810	587	224	Meso	2.016 m ± 0.144
CCAP	312	276	174	72	37	293	58	235	Meso	2.067 m ± 0.160
GLGH	120	91	9	-73	-102	151	-69	219	Meso	1.073 m ± 0.242
SADG	306	266	157	48	8	273	24	249	Meso	2.404 m ± 0.169
PCTN	182	155	82	9	-18	229	-103	332	Meso	2.450 m ± 0.173
PRGI	318	282	183	84	49	343	37	307	Meso	3.003 m ± 0.146
SBRU	330	284	156	29	-17	307	32	275	Meso	2.732 m ± 0.172

(Source: Data analysis, 2023; a) Appelquist et al., 2016; b) BIG, 2022).

Binuangeun in Banten and Pelabuhan Ratu in West Java have micro-tidal characteristics and confront significant potential issues due to their dynamics. Micro-tidal inlet dynamics are challenging since their stability is influenced by tidal range and littoral drift (Senthilkumar et al., 2017). Generally, wave dynamics on micro-tidal coasts are the primary cause of morphological change and sediment transfer. Wave activities rapidly transform depositional shorelines on micro-tidal coasts to achieve a state of equilibrium. Also, the micro-tide range compresses the ecological zonations; hence, salt marshes and mangrove swamps are usually severely restricted on micro-tidal beaches. Meanwhile, meso tidal inlets are tide-dominated, more stable, and have a significant relationship with Pleistocene drainage systems (Galgano and Leatherman, 2005; Andrew and Cooper, 2005).

Glagah station has a vast difference between the tidal range from field measurements (219 cm or 2.19 meters) and the tidal range from the SRGI of BIG (2022), i.e., 1.073 m ± 0.242. This may be happened due to several reasons, such as unsuitable tidal station locations (Suprapto 2016) or geomorphological events from fluvial and marine processes in the form of sedimentation and siltation in the Serang River estuary (see Figure 4b) (Puspa and, Purwono 2020).

CONCLUSION

Based on the tidal harmonic constants' amplitude and the Formzahl values, which range from 0.64 to 1.34, the tidal type in the southern waters of Java is a mixed tide prevailing semi-diurnal ($0.25 < F \leq 1.5$). This type of tide means two high tides and two low tides in one day, but the height and period differ. The tidal range in the southern waters of Java ranges from 178 -

332 cm. Binuangeun Banten and Pelabuhan Ratu waters are classified as micro tides (178 and 182 cm, respectively), meaning wave dynamics are the primary cause of morphological change and sediment transfer in those areas. Wave activities rapidly transform depositional shorelines on Binuangeun (Banten) and Pelabuhan Ratu coasts to achieve a state of equilibrium. While the rest (Pameungpeuk, Pangandaran, Cilacap, Glagah, Sadeng, Pacitan, Prigi, and Sendang Biru) are categorized as meso tides with tidal ranges value of 219 - 332 cm, While the rest (Pameungpeuk, Pangandaran, Cilacap, Glagah, Sadeng, Pacitan, Prigi, and Sendang Biru) are categorized as meso tides with tidal ranges value of 219 - 332 cm, meaning those areas are tide-dominated coasts and more stable. Information on tidal characteristics in a given location may therefore be used to aid in port engineering, water navigation, disaster mitigation, and coastal planning and management.

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AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper: study conception and design, analysis, and interpretation of results, draft manuscript preparation: BWM, data collection: RLN. All authors reviewed the results and approved the final version of the manuscript.

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