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Suitability Of Physical Oceanographic Conditions To Ministerial Decree No. 64/Kepmen-Kp/2020 On The Establishment Of Gili Ketapang Marine Protected Area

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Abstrak— Zoning planning for Marine Protected Areas (MPAs) in small island regions requires alignment with physical oceanographic conditions to ensure effective and sustainable marine spatial management. However, seasonal oceanographic dynamics are often not fully aligned with statically defined zoning schemes. This study aims to evaluate the alignment of physical oceanographic conditions with the zoning of the Marine Protected Area in the waters of Gili Ketapang based on the Decree of the Minister of Marine Affairs and Fisheries No. 64 of 2020. The research methods included analysis of tidal, ocean current, wave, and seasonal wind data obtained from oceanographic measurements and modeling, followed by descriptive and spatial analysis. The results of the study indicate that the waters of Gili Ketapang exhibit a dominant mixed semidiurnal tidal type with a Formzahl (F) value of 1.3. Ocean current speeds range from 0.01 to 0.37 m/s, while significant wave heights fall within the range of 0.15 to 1.47 m. Optimal current and wave conditions never occur simultaneously within a single season, resulting in the Aquaculture Subzone in the southeastern part of the island having the highest level of unsuitability. In contrast, the Tourism Subzone in the western part, as well as the Core Zone and Rehabilitation Subzone, are relatively more suitable due to more stable and sheltered hydrodynamic conditions. These findings highlight the need for a seasonal adaptive management approach in the management of the KKP in the waters of Gili Ketapang.

Keywords—*marine conservation area, physical oceanography, zoning suitability, tides, waves, small islands.*.

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I. INTRODUCTION

Gili Ketapang is a small island village located in the waters of the Madura Strait, about 8 km north of Probolinggo City, Indonesia. Administratively, Gili Ketapang is part of Sumberasih District, Probolinggo Regency, East Java. The majority of the island's residents are from Madura, with fishing as their primary livelihood [1]. Small-scale fishing, including the use of payang fishing gear, is a mainstay of the local economy and supports the socioeconomic resilience of coastal households [2]. Consequently, the condition of the surrounding marine ecosystem has a direct and significant impact on the social and economic stability of the Gili Ketapang community.

The local community's high dependence on marine resources has led to intensive exploitation of fishery resources in the waters around Gili Ketapang. Without adequate management, this intensity increases the vulnerability of the coastal ecosystem to environmental degradation. Rachman [2] emphasizes that the sustainability and economic viability of fisheries-based livelihoods in Gili Ketapang are closely linked to environmental conditions, particularly the availability of fish stocks and the stability of coastal and marine ecosystems. These characteristics highlight the urgent need for a conservation-based management approach capable of balancing resource utilization with long-term ecosystem conservation

In response to increasing pressure on coastal and marine ecosystems, the Indonesian government has designated Marine Protected Areas (MPAs) as a strategic tool for ecosystem-based management. One such initiative is the designation of the Gili Ketapang Marine Conservation Area through Minister of Marine Affairs and Fisheries Decree No. 64/KEPMEN-KP/2020 on the Gili Ketapang Conservation Area and its surrounding waters. This area is classified as a Marine Tourism Park, covering approximately 476.78 hectares and encompassing ecologically important habitats, including coral reefs, seagrass beds, and productive fishing grounds [3]. This ecosystem not only supports biodiversity but also provides vital ecosystem services for fisheries, tourism, and coastal protection.

On a broader scale, the waters of East Java are part of the Coral Triangle, which is globally recognized as a center of marine biodiversity with the world's highest diversity of coral reef species and reef fish. Burke [4] reports that the Coral Triangle possesses extraordinary ecological value while simultaneously facing increasing anthropogenic pressures, including overfishing, habitat degradation, and the impacts of climate change. Within this regional context, marine conservation areas such as

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Gili Ketapang play a strategic role in protecting biodiversity, maintaining ecosystem resilience, and supporting sustainable coastal livelihoods.

However, the effectiveness of marine protected areas is not solely determined by the establishment of regulations or legal frameworks. Rather, successful implementation is greatly influenced by the alignment between management zoning and local environmental conditions, particularly physical oceanographic characteristics. Small islands are highly sensitive to oceanographic dynamics due to their limited land area, shallow coastal waters, and direct exposure to marine processes. According to Wyrtki [5], the waters of Southeast Asia are characterized by strong seasonal variability driven by the monsoon wind system, which significantly influences ocean circulation, wave generation, and coastal hydrodynamics.

In Indonesian waters, oceanographic variability is further shaped by complex regional circulation patterns and the interaction between local and large-scale processes. Atmadipoera [6] highlights that the Indonesian seas exhibit significant spatial and temporal variability, particularly in relation to seasonal wind patterns and regional current systems. These dynamics directly influence physical parameters such as current speed, wave height, and tidal characteristics, which in turn affect the suitability of coastal waters for various human activities.

Wave conditions are one of the most critical oceanographic parameters affecting the use of coastal and marine areas. Studies by Wurjanto [7], [8] indicate that wave characteristics in Indonesian waters exhibit a strong seasonal pattern, with significant wave heights increasing during specific monsoon periods. Such conditions can restrict marine activities, including fishing operations, aquaculture, and marine tourism, particularly in semi-enclosed waters such as the Madura Strait.

Selain gelombang, dinamika pasang surut memainkan In addition to waves, tidal dynamics play a fundamental role in shaping coastal processes and water level variability. Indonesian waters are largely characterized by mixed tidal regimes, either predominantly semidiurnal or predominantly diurnal [9], [10]. Tidal characteristics influence effective water depth, sediment transport, and the accessibility of coastal zones, making tidal analysis highly relevant for evaluating the suitability of conservation zoning. Furthermore, previous studies have shown that some coastal areas in East Java, including the Probolinggo region, experience tidal amplification that can significantly affect local hydrodynamic conditions [11].

Given this complexity, oceanographic assessments must be conducted as a fundamental step prior to the implementation of development or conservation activities in small island environments. The establishment of marine conservation zones must take into account local physical environmental conditions, rather than being based solely on the size of the water area. Recent review studies indicate that the number and types of zones in marine spatial planning are influenced by conservation targets, habitat distribution, and the oceanographic conditions that govern aquatic ecosystem dynamics. This approach aligns with the concept of marine spatial planning, which emphasizes the integration of environmental conditions in the establishment of conservation zones [12]. Furthermore, sustainable conservation management must integrate social dimensions and community participation to ensure long-term success and acceptance among local stakeholders [13].

Although marine protected areas have been widely promoted as an ecosystem-based management tool, their effectiveness largely depends on how well zoning schemes align with local physical oceanographic conditions. On small islands characterized by dynamic hydrodynamic environments, mismatches between zoning designations and environmental suitability can lead to conflicts over the use of marine space and undermine ecological and socio-economic sustainability. Therefore, evaluating the suitability of conservation zoning based on comprehensive physical oceanographic parameters is a crucial step toward adaptive, evidence-based marine management.

Based on these considerations, this study aims to address this gap by analyzing the suitability of physical oceanographic conditions for the zoning of the Gili Ketapang Marine Protected Area. By utilizing long-term oceanographic data covering tides, currents, waves, and winds across the four monsoon seasons, this study evaluates the alignment between the physical dynamics of the waters and the established zoning functions. The novelty of this study lies in its regulation-based evaluative approach, which directly links physical oceanographic parameters to the zoning of conservation areas established through official policies, rather than merely assessing environmental conditions in isolation. The results of this study are expected to provide a scientific basis for more adaptive, season-based, and relevant management of marine conservation areas in small island regions

II. METHOD

This study employs a secondary data analysis approach to evaluate the suitability of physical oceanographic conditions in relation to the zoning of Gili Ketapang Marine Protected Area (Figure 1).

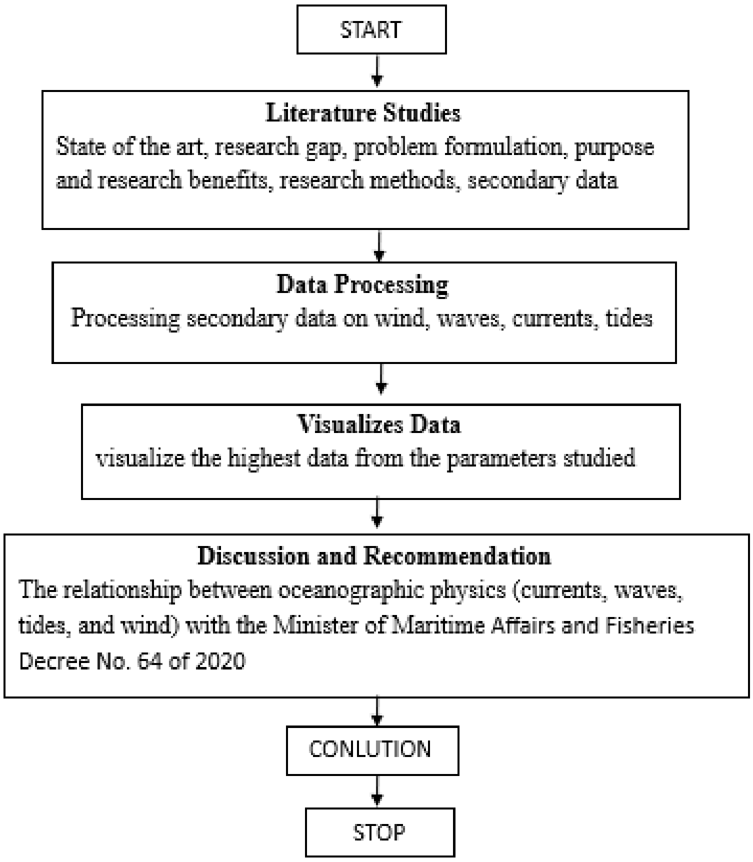

Figure 1 Stages of the research method

The first phase of this literature review aims to obtain secondary data on the oceanographic parameters used in this study, which is located in Gili Ketapang, Probolinggo Regency, East Java. The research location is situated at coordinates between 7°40'30”–7°41'00” South Latitude and 113°14'30”–113°16'00” East Longitude, within the waters of the Madura Strait. The methods used in this study include a literature review and the analysis of secondary data on oceanographic parameters—specifically tides, wind, ocean currents, and sea waves—from 2015 to 2025, divided into four seasons: the west monsoon (December–March), transitional dry season 1 (April and May), the east monsoon season (June–September), and the transitional dry season (October and November). The secondary data were sourced from Srgi BIG (National Geospatial Information Agency) (https://srgi.big.go.id/), Copernicus Marine (https://data.marine.copernicus.eu/), and Copernicus Climatology (https://cds.climate.copernicus.eu/). Coral reef coverage data was obtained from Allen Coral (https://www.allencoralatlas.org/atlas/) and depth data was obtained from MapSea. Data processing was performed by identifying the highest values over a ten-year period. Each parameter (current and wave) was then visualized in ArcMap. Wind data processing was performed by determining the direction of the wind and visualized using WRPLOT. Tidal data is processed using the Admiralty method to determine the type of tide.

III. RESULT DAN DISCUTION

A. Zoning of the Gili Ketapang Marine Protected Area

Persuant to Decree of the Minister Affairs and Fisheries No. 64/KEPMEN-KP/2020, he Gili Ketapang Marine Conservation Area is divided into four main zones, namely: (1) a Core Zone covering 15.16 ha, which serves as a strict ecosystem protection area; (2) The Utilization Zone, consisting of a Tourism Sub-Zone covering 25.63 ha for marine tourism activities; (3) The Sustainable Fisheries Zone covering 421.93 ha, which is divided into an Aquaculture Sub-Zone covering 23.5 ha on the southeastern side of the island and a Fishing Sub-Zone covering 398.43 ha; and (4) Other Zones consisting of a Rehabilitation Sub-Zone covering 14.06 ha (ast Java Provincial DKP, 2023; Probolinggo Regency Fisheries Office, 2023) (Figure 2)

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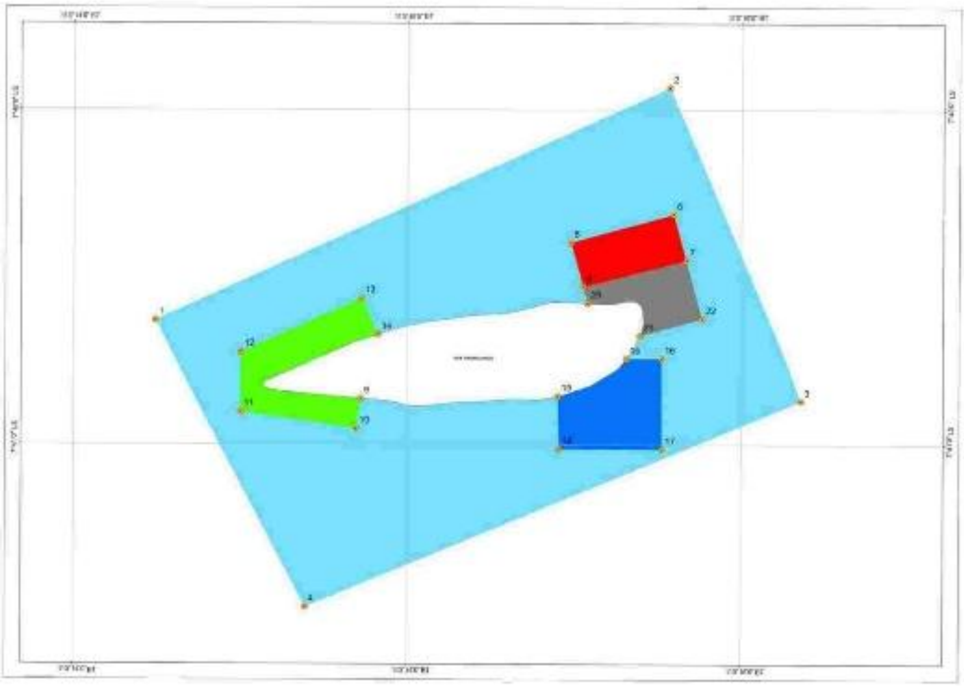


Figure 2. Zoning map of Gili Ketapang (source: Ministerial Decree No. 64 of 2020)

B. Distribution and Bathymetry of Coral Reefs

The image below shows the distribution of Allen Coral reefs overlaid on depth data obtained from PUSHIDROSAL navigation charts.

Coral reefs surround the island at varying depths. In this zone, coral reefs are found at depths ranging from 2 m to more than 10 m. In the rehabilitation subzone, coral reefs are found at depths ranging from 5 m to 10 m. In the aquaculture subzone, coral reefs are found at depths ranging from 5 m to more than 10 m.

In the tourism subzone, coral reefs are found at depths ranging from 1 m to 10 m. Furthermore, in the northern commercial fishing zone, coral reefs are found at depths ranging from 1 m to 5 m, while in the southern commercial fishing subzone, coral reefs are found at depths ranging from 5 m to 10 m (Figure 3).

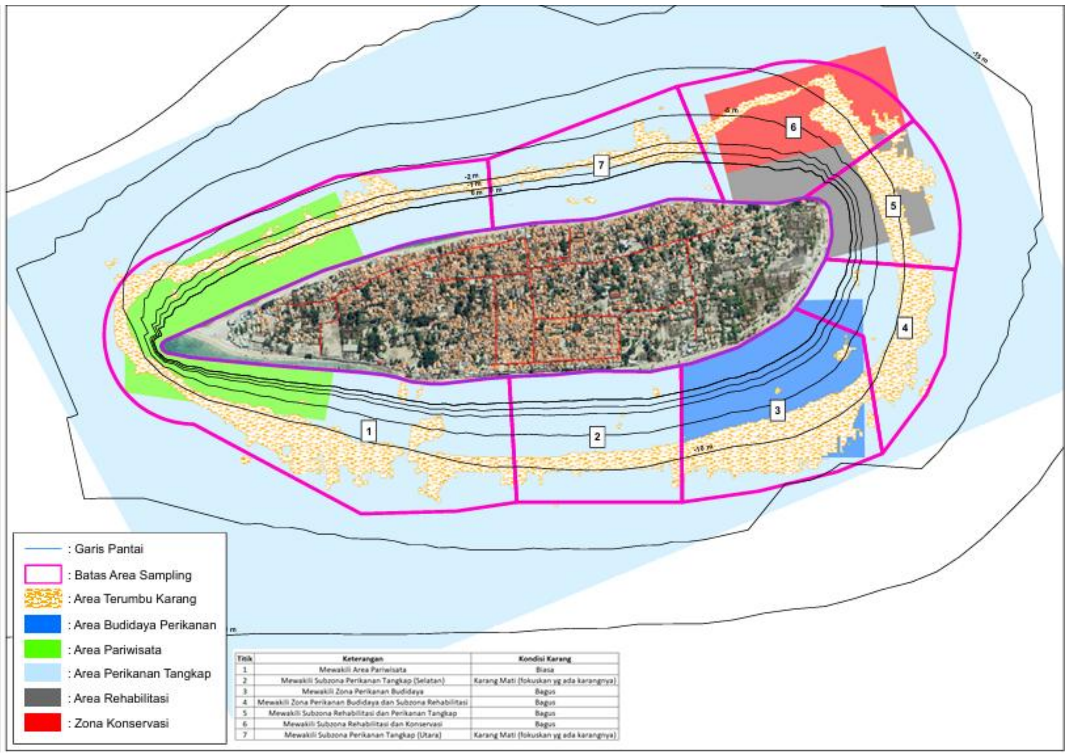


Figure 3. Overlay map showing the distribution of coral reefs by depth

C. *Tidal Characteristic*

The waters around Gili Ketapang have a mixed tide pattern with a dominant semidiurnal tide (Mixed Tide Prevailing Semidiurnal) with a magnitude of 1.3. This is because mixed tides (dual-dominant) and mixed tides with a dominant semidiurnal tide occur twice a day, but sometimes occur only once a day with varying heights and times.

The hightes tide in 2025 will accur on December 5, 2025, at 4:00 p.m, and lowest tide will accur on the same day at 11:00 p.m. On that day, the tides at Gili Ketapang will reach their highest and lowest points of the year, with an average sea level of 2.6 m. (Figure 4)

TABLE 1 SUMMARY OF TIDE LEVELS

Season	West	Transtational 1	East	Transtationals 2
H maks (m)	1.029	3.605	3.601	3.593
H min (m)	3,65	1.095	1.069	1.196

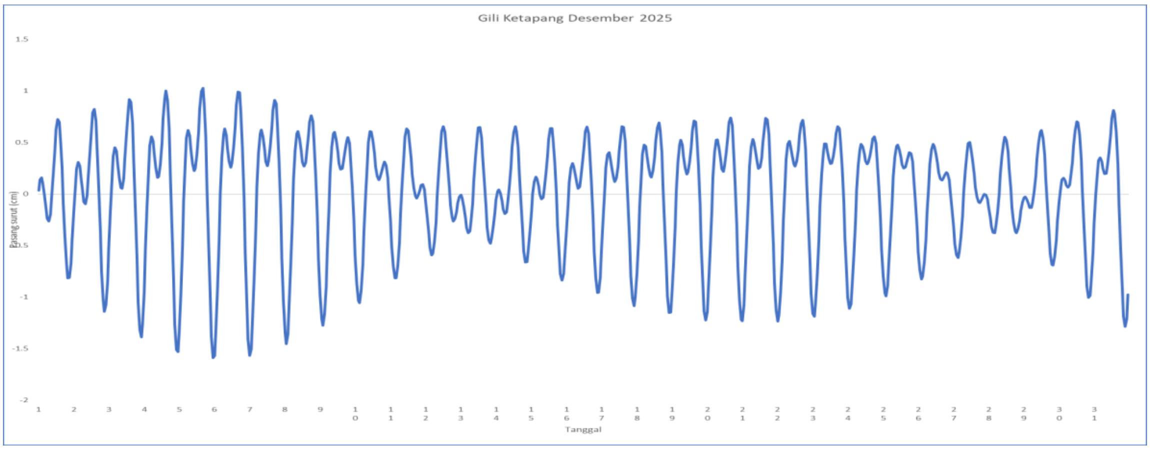


Figure 4 Tidal profile in the waters of Gili Ketapang

Semi-diurnal mixed tides are a common feature of the waters of central and western Indonesia, influenced by the interaction of tidal waves from the Indian and Pacific Oceans [10], and are frequently found in semi-enclosed areas such as the Madura Strait. These results are consistent with Hasanudin [11], who stated that the coastal morphology, water depth, and configuration of the Madura Strait amplify tidal amplitudes along the Probolinggo coast, including Gili Ketapang. Furthermore, water geometry and seabed topography also influence tidal phase and amplitude variations; in narrow and shallow waters, amplitudes tend to increase due to wave interaction with the shoreline [15].

These conditions affect variations in effective water depth and zone accessibility, particularly in the Aquaculture Subzone and the Rehabilitation Subzone. Sea-level fluctuations have the potential to impact aquaculture activities, sedimentation, and the effectiveness of conservation area management. Therefore, tidal characteristics need to be considered in the evaluation of zoning suitability based on Ministerial Decree No. 64 of 2020.

D. *Ocean Currents Characteristics*

Current speeds in the waters around Gili Ketapang vary seasonally, ranging from 0.26 to 0.31 m/s. During the West Monsoon (December–March), currents reach 0.26–0.31 m/s, primarily flowing eastward. The direction and peak current velocity during the West Monsoon are presented in Figure 5.

The first transitional monsoon (April–May) has current speeds of 0.12–0.17 m/s, primarily toward the northeast and east. The current direction and maximum velocity during the first transition season are shown in Figure 6.

The East Monsoon (June-September) shows the lowest currents, at 0.11-0.20 m/s, primarily toward the southeast and south. Figure 7 illustrates the direction and peak current velocity during the East Monsoon.

Meanwhile, during the second transitional monsoon (October – Novemver), current speeds range from 0,12-0.19 m/s, primarily toward the east . The direction and peak current velocity during the second transition season are presented in Figure 8.

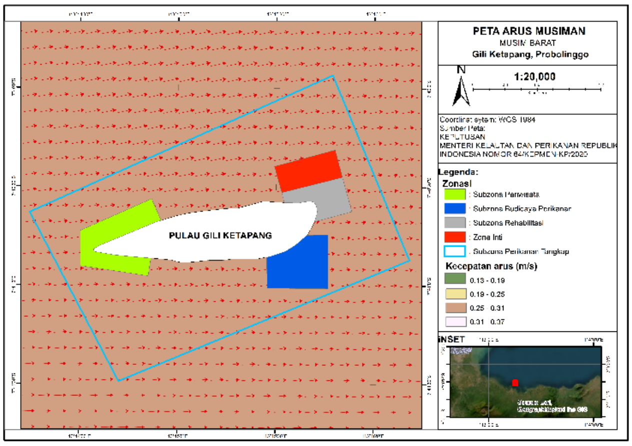


Figure 5 Illustrates the direction and peak current velocity during the West Monsoon

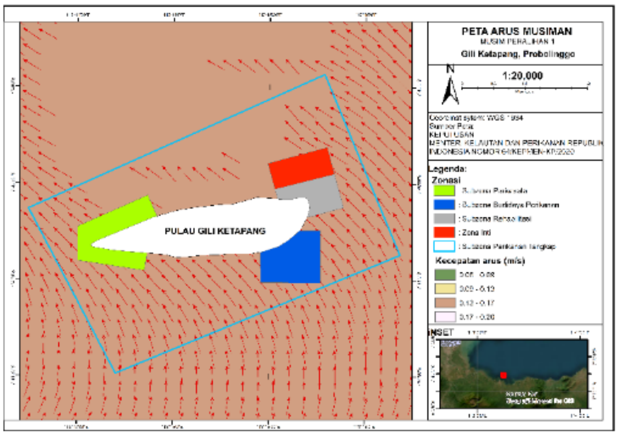


Figure 6 Illustrates the direction and peak current velocity during the First Transition Season

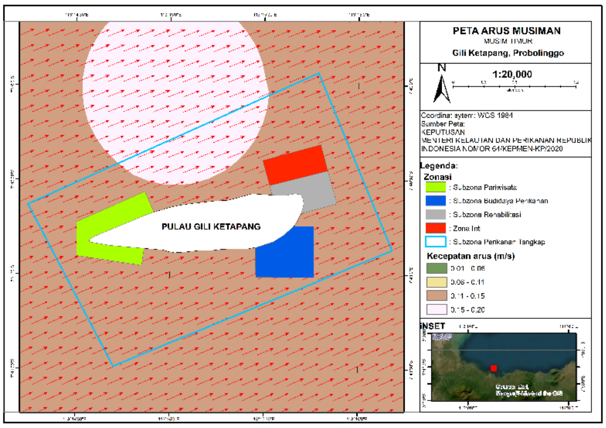


Figure 7 Illustrates the direction and peak current velocity during the East Monsoon

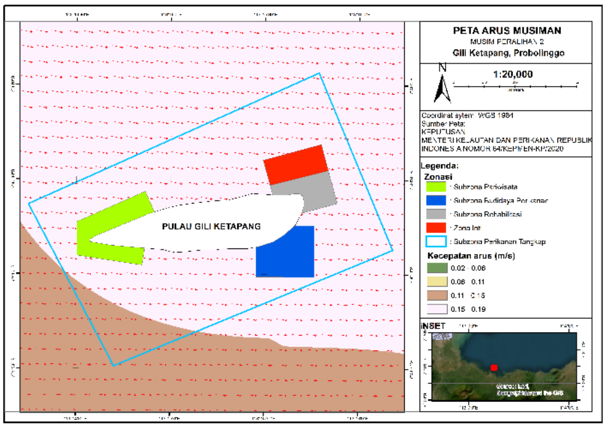


Figure 8 Illustrates the direction and peak current velocity during the Second Transition Season

Current conditions are inconsistent throughout the year, and during other seasons, currents tend to be low, even falling below the optimal threshold for aquaculture activities. Data on ocean circulation and current dynamics are key components in the design and evaluation of marine protected areas, as currents influence patterns of biological connectivity and population sustainability. In general, current velocity is a key physical parameter that determines the success of marine aquaculture because it plays a role in nutrient supply, the removal of metabolic waste, and the stability of aquaculture structures [15].

Ocean current patterns are a key parameter in determining the suitability of conservation zones, as they play a role in controlling sediment resuspension, nutrient distribution, and the spread of pollutants. A study by Petrosillo [16] indicates that areas with weak to moderate currents are more suitable for protection zones due to their sediment stability and lower hydrodynamic stress. These conditions align with the principles of marine conservation zoning in Ministerial Decree No. 64 of 2020, which stipulates that core zones and rehabilitation zones require minimal physical oceanographic disturbance to maintain coastal ecosystem functions.

In general, current velocity is a key physical parameter that determines the success of marine aquaculture because it plays a role in nutrient supply, the removal of metabolic waste, and the stability of aquaculture structures. Determined that the optimal current velocity range for seaweed aquaculture is 20–40 cm/s (0.20–0.40 m/s). The same range was also used by Mustafa [17] in evaluating the suitability of fish farming using floating net pens (FNP).

According to Ariputro [18], the currents at the Gili Ketapang fish cage farm fall into the "suitable" category during the West Monsoon season, with values ranging from 0.26 to 0.31 m/s. Meanwhile, the Transition 1, Transition 2, and East Monsoon seasons fall into the "fairly suitable" category, with current speeds ranging from 0.11 to 0.20 m/s.

According to Tantowi and Ilham [19], the tourism zone is suitable and highly suitable for snorkeling and diving throughout all seasons, as the current speed in the waters of Gili Ketapang within the tourism zone ranges from 0.11 to 0.2 m/s during all seasons—namely the west, transition 1, east, and transition 2 seasons.

These ocean current values make the area suitable for beach tourism (current speed ranges from 17 cm/s—highly suitable—to 34 cm/s—sufficiently suitable) or for diving and snorkeling (current speed ranges from 15 cm/s—highly suitable—to 30 cm/s—sufficiently suitable) [20].

The lowest current velocity was recorded on the 24th trip, with a current velocity of 8.24 cm/s and a catch of 3.7 kg, while the highest current velocity was recorded on the 6th trip, with a current velocity of 14.57 cm/s and a catch of 0.7 kg. The highest catch during the 30 fishing trips was recorded on the 25th trip at 7.5 kg with a current speed of 9.17 cm/s [21]. Based on this, fishing zones with year-round currents at speeds of 0.11–0.3 m/s are estimated to yield low catches, so currents at those speeds are considered unsuitable for fishing zones.

Based on current velocity classifications, the core and rehabilitation zones are categorized as having weak currents in every season. This is advantageous in these zones because, during the initial stages of transplantation, the new coral fragments are attached to the substrate. Currents that are too strong (> 0.5 m/s) risk sweeping away or dislodging the fragments before the corals have a chance to form natural bonds (basic calcification) with the new substrate.

Compared to these criteria, the results of this study indicate that the Gili Ketapang Aquaculture Subzone only meets the optimal current range during certain periods, particularly during the west monsoon season, whereas during the east monsoon and transition seasons, current speeds are mostly below the optimal threshold. These conditions indicate that, temporally, the aquaculture zone lacks sufficient hydrodynamic stability to support sustainable marine aquaculture activities.

Current values at Gili Ketapang, ranging from 0.11 to 0.32 m/s, can be compared with reference data from other tropical conservation zones. For example, measured currents in the Great Barrier Reef range from 0.006–0.57 m/s [22], indicating that current values in the study area fall within the range commonly found in protected and conserved reef habitats.

From a marine spatial planning perspective, the inconsistency in current speeds within the Gili Ketapang Aquaculture Subzone indicates that zoning has not yet fully integrated oceanographic physical parameters as primary limiting factors. The ideal approach to determining aquaculture sites should consider multi-parameter spatial analysis, as recommended, which emphasizes the importance of integrating oceanographic data into a GIS-based site selection framework [23], [24].

E. *Ocean Wave Characteristic*

Significant wave height (Hs) in the waters off Gili Ketapang shows seasonal variation, ranging from 0.28 to 1 m. During the West Monsoon (December–March), wave heights range from 0.9 to 1 m, with a dominant southwest direction. Figure 9 illustrates the peak current velocity during the West Monsoon. During first transition season (April–May), wave heights range from 0.28–0.41 m with a dominant westerly direction. Figure 10 illustrates the peak current velocity during first transition season.The East Monsoon (June–September) shows wave heights of 0.62–0.86 m with a dominant direction of 93.05° west. . Figure 11 illustrates the peak current velocity during East Monsoon. Meanwhile, second transition (October–November), wave heights range from 0.65–0.78 m with a dominant westerly direction. Figure 12 illustrates the peak current velocity during second transition season.

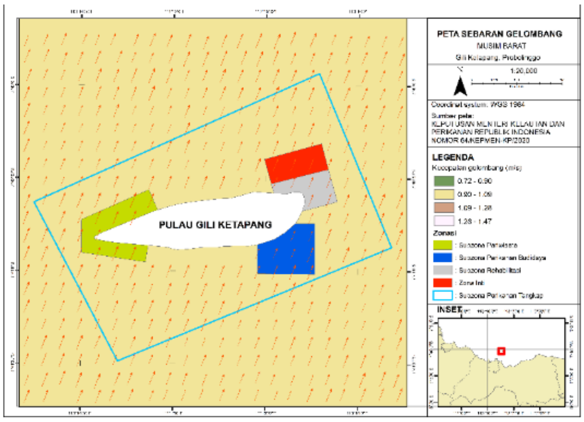


Figure 9. Peak current velocity during the West Monsoon

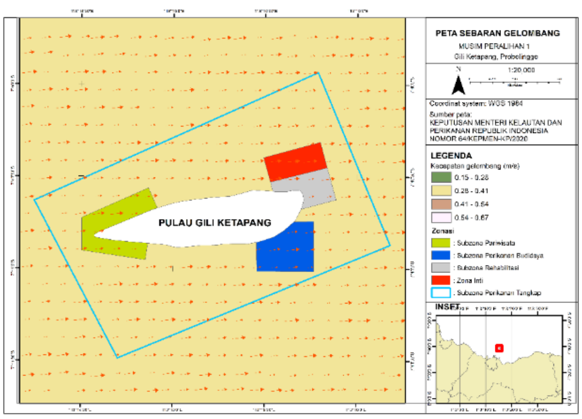
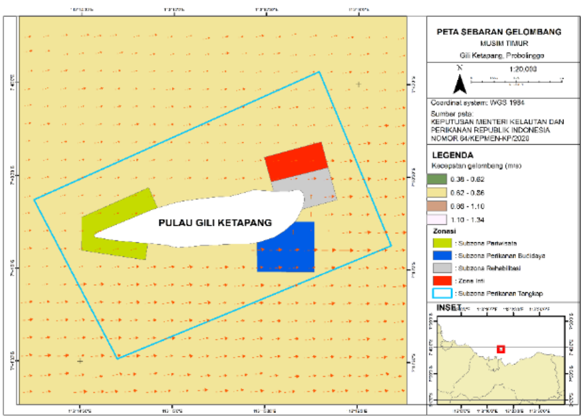


Figure 10. Peak current velocity during the First Transition Season



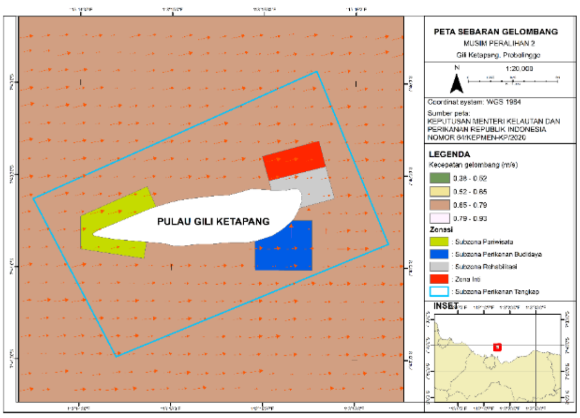


Figure 11. Peak current velocity during the East Monsoon

Wave characteristics in the waters off Gili Ketapang exhibit a strong seasonal pattern and are controlled by the Asian–Australian monsoon system. Significant wave height (Hs) ranges from 0.28 to 1.00 m, with the highest intensities occurring during the West Monsoon and East Monsoon seasons. This variability reflects the dominant role of monsoon winds in transferring energy to the sea surface, particularly in semi-enclosed waters such as the Madura Strait.

During the West Monsoon season (December–March), wave heights reach 0.9–1.0 m, with a dominant southwest direction. These conditions are influenced by westerly winds blowing from the Indian Ocean toward the Java Sea, generating waves with a relatively long fetch. Research by Wyrtki [5] and Atmadipoera [6] indicates that during this period, an increase in wave energy generally occurs in western Indonesia due to the strengthening of the southwest monsoon winds.

In contrast, during first Transition Season (April–May), wave heights decreased significantly to 0.28–0.41 m. The weakening and change in wind direction led to a reduction in energy transfer to the sea, resulting in relatively calmer sea conditions. This pattern is consistent with the findings of Wurjanto [8], who states that the transitional season is the period with the lowest wave conditions in Indonesian waters.

During the East Monsoon Season (June–September), wave heights rise again to 0.62–0.86 m, with a dominant direction from the east to the southeast. Strong easterly monsoon winds from the Australian continent increase wave energy, particularly on the open water side facing the dominant wind direction. These conditions cause the Aquaculture Sub-Zone on the southeastern side of Gili Ketapang to experience the highest wave exposure throughout the year. A similar phenomenon was reported by Siswanto & Nugraha [25] in the waters south of Java and by Fadholi [26] in the southern coastal regions of Indonesia.

During Transition Season 2 (October–November), wave heights ranged from 0.65 to 0.78 m, indicating a transition phase toward westerly conditions. Although wind intensity decreased compared to the East Monsoon season, wave energy remained relatively high due to residual energy from the previous monsoon system.

Overall, wave variations in the waters of Gili Ketapang indicate that seasonal factors are the primary controllers of hydrodynamic stability, which has direct implications for the suitability of conservation zoning. Wave heights above 0.5 m are known to limit marine aquaculture activities and increase the risk of damage to aquaculture structures as well as mechanical stress on cultured organisms [27].

Figure 12 Peak current velocity during the Second Transition Season

F. Wind Characteristics

Wind patterns in the waters off the coast of Gili Ketapang show seasonal variations influenced by the Asian-Australian monsoon system. During the West Monsoon, winds mostly blow from the west to the northwest at speeds ranging from 2.10 to 5.70 m/s (Figure 13). During first Transition Season, winds shift to the eastern sector with varying speeds.(Figure 14). The East Monsoon exhibits the highest intensity, dominated by winds from the east to southeast, with contributions from the south, at speeds ranging from 3.60–8.80 m/s (Figure 15) Meanwhile, during second transition season , winds remain dominated by easterly and southerly directions, with speeds decreasing to 2.10–5.70 m/s (Figure 16). In general, the East Season is the most energetic, while the transition seasons are relatively calmer.

Wind patterns in the waters off the coast of Gili Ketapang show distinct seasonal variations due to the influence of the Asian-Australian monsoon system, which governs changes in wind direction and intensity and affects ocean currents and waves [28], [29]. During the West Monsoon, winds predominantly blow from the west-northwest at speeds of 2.10–5.70 m/s, creating relatively uniform waves. Entering First Transition Season, wind direction shifts to the east with a more scattered distribution, resulting in more unstable wave conditions.

During the East Monsoon, winds generally blow from the east-southeast to the south at higher speeds of 3.60–8.80 m/s, increasing energy transfer to the sea surface and generating larger waves, especially in open waters. These conditions explain the high wave exposure on the southeast side of Gili Ketapang, which directly impacts the Aquaculture Subzone. Conversely, during Transition Season 2, wind intensity decreases (2.10–5.70 m/s) and its direction becomes more scattered, resulting in lower and less consistent waves.

Generally, the dominant wind direction shifts from west to east, with the most energetic conditions occurring during the East Monsoon and calmer conditions during the transition seasons. This aligns with Fadholi [26], who states that during the East Monsoon, winds move from Australia to Asia via the southern part of Java Island, and with Siswanto & Nugraha [25], who explain that southern Indonesia is more influenced by the East Monsoon due to differences in air pressure. These variations play a significant role in water mass exchange, the formation of surface currents, and ocean waves, and therefore need to be considered when evaluating the suitability of conservation area zoning

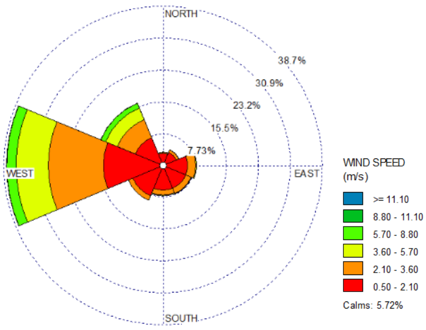


Figure 13 Wind rose diagram during the West Monsoon

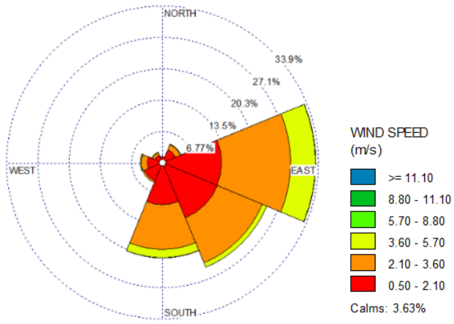


Figure 14 Wind rose diagram during the First Transition Season

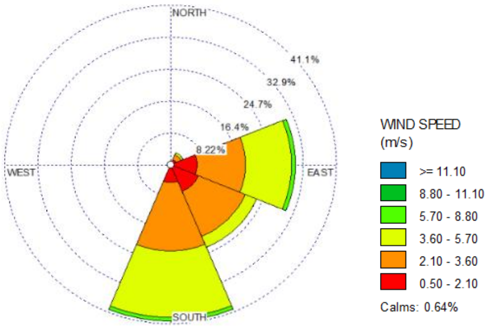


Figure 15 Wind rose diagram during the East Monsoon

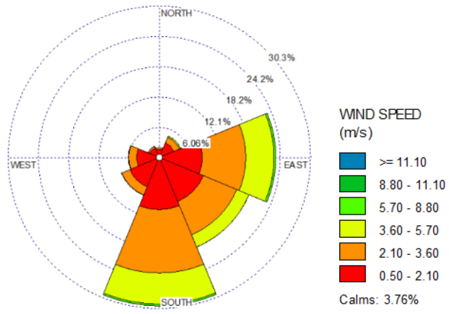


Figure 16 Wind rose diagram during the Second Transition Season

Discussion

The dynamics of ocean waves and surface currents are key components of coastal hydrodynamic systems that influence many oceanographic and biological processes, including the constraints on conservation zoning [30]. Ocean waves are primarily generated by winds blowing over the sea surface, so their characteristics are strongly influenced by seasonal wind patterns such as the Asia–Australia monsoon in the Indonesian region [31]. Wave modeling studies in Indonesian waters indicate that significant wave height (Hs) exhibits strong spatial–temporal variations linked to the monsoon cycle (SWAN model), with the highest waves tending to occur during specific periods throughout the year. This aligns with climatic variations that influence winds and ocean waves in an archipelagic nation like Indonesia.

Other field analyses in Indonesia's coastal regions also reveal significant interactions between waves and currents that modify coastal current patterns, such as rip currents that can accelerate the movement of water masses in specific directions [32]. These interactions not only influence sedimentation processes but also the redistribution of nutrients and organisms, which are directly linked to habitats and biological productivity.

High and seasonally variable wave and current parameters have direct implications for the suitability of zoning. Conservation zoning typically identifies areas with stable physical conditions that support sensitive ecosystems or planned activities such as aquaculture, tourism, or coral reef rehabilitation.

First, in zoning for marine aquaculture, high waves can cause mechanical stress on aquaculture structures and cultured organisms, as well as affect the stability of aquaculture installations due to increased wave and current energy [30]. Such conditions, if they occur seasonally or persistently, will reduce aquaculture efficiency and increase the risk of losing cultured stocks.

Second, from the perspective of marine tourism, relatively moderate yet constant wave dynamics provide the best access for activities such as snorkeling and diving in areas designated as marine tourism zones. Studies on coastal tourism suitability indicate that calm waters are one of the primary parameters for tourist comfort [31].

Third, in ecosystem rehabilitation subzones (e.g., coral reef or seagrass bed transplantation), waves and currents must remain within a range that does not damage the biotic fragments or transplanted structures. Excessively harsh hydrodynamic conditions can hinder the recovery process and the stabilization of new biotic structures.

Research findings indicate that no single seasonal period simultaneously meets the optimal criteria regarding wave height and current intensity for all planned conservation zones. These criteria are critical because conservation zoning is often static, whereas physical conditions such as waves and currents vary throughout seasonal cycles [31].

Therefore, the implementation of fixed conservation zoning must be complemented by an adaptive approach that accounts for seasonal variability and climate change scenarios that may alter future wind and wave patterns. This approach could include seasonal zoning or proactive planning that dynamically adjusts zoning boundaries and their use throughout the year based on real-time oceanographic parameters.

IV. CONCLUTION

This study shows that the physical oceanographic conditions of the waters around Gili Ketapang are highly dynamic on a seasonal basis and are not yet fully aligned with the Marine Protected Area (MPA) zoning scheme as stipulated in Minister of Marine Affairs and Fisheries Decree No. 64 of 2020. The dominant semi-diurnal mixed tide type (F = 1.3) causes fluctuations in effective depth that affect the accessibility and stability of marine space utilization. Current velocity and wave height never occur simultaneously under optimal conditions within a single season, with sea waves being the primary limiting factor, particularly in the Aquaculture Subzone on the southeastern side of the island, which exhibits the highest level of mismatch. Conversely, the Tourism Subzone on the western side, as well as the Core Zone and Rehabilitation Subzone, are relatively more suitable due to more sheltered and stable hydrodynamic conditions. These findings confirm that static conservation zoning is less adaptive to the oceanographic dynamics of small islands, necessitating a seasonal adaptive management approach to enhance management effectiveness and minimize ecological risks in the waters of Gili Ketapang.

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