

ANALYSIS OF *DUNES* PRESSURE AND VULNERABILITY IN TOURISM BEACH IN PANGANDARAN REGENCY, WEST JAVA

Analisis Tekanan dan Kerentanan *Dunes* di Pantai Wisata Kabupaten Pangandaran
Jawa Barat

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ABSTRACT

Dunes play an important role in protecting coastlines from erosion and storm waves, as well as providing habitats for flora and fauna. However, increased human activity in tourist beach areas can put pressure on dunes, affecting their ecological functions, coastal resilience to storms, and increasing their vulnerability. This study aims to analyze the level of vulnerability and pressure on dunes in tourist beach areas of Pangandaran Regency, West Java, as a basis for sustainable coastal area management. The research was conducted directly at four tourist beaches, namely Batu Hiu Beach, Karang Nini Beach, Pananjung Beach, and Pasir Putih Beach, using the Dune Vulnerability Assessment scoring, which has been modified according to local conditions. The assessment includes physical parameters in the form of beach conditions and human parameters in the form of usage pressure. Vulnerability index are calculated using a Euclidean algorithm approach based on the distance of human parameter indices (M) and physical parameters (F) from ideal conditions $E = \sqrt{(M - 1)^2 + (F - 1)^2}$ where E represents the vulnerability index. The values of M and F are obtained from the total scores of each parameter group divided by the number of parameters assessed. The study results show that the dunes at Karang Nini Beach and Pasir Putih Beach have a low level of vulnerability, with the main influence coming from the physical parameters of beach conditions. Meanwhile, the dunes at Batu Hiu Beach and Pananjung Beach have a moderate level of vulnerability, with the dominant influence from human parameters. The high pressure at these two locations is related to human access and activities around the dune areas. From the results of the study, appropriate handling is needed to reduce the vulnerability index both from physical parameters, beach conditions, and human parameters.

Keywords: Dunes Vulnerability, Pangandaran, Tourism Beach

ABSTRAK

Dunes berperan penting dalam melindungi garis pantai dari erosi dan gelombang badai serta menyediakan habitat bagi flora dan fauna. Namun, peningkatan aktivitas manusia di kawasan pantai wisata dapat memberikan tekanan terhadap *dunes*, memengaruhi fungsi ekologis, ketahanan pesisir terhadap badai, dan meningkatkan kerentanannya. Penelitian ini bertujuan menganalisis tingkat kerentanan dan tekanan pada *dunes* di kawasan pantai wisata Kabupaten Pangandaran, Jawa Barat, sebagai dasar pengelolaan kawasan pesisir yang berkelanjutan. Penelitian dilakukan secara langsung pada empat pantai wisata, yaitu Pantai Batu Hiu, Pantai Karang Nini, Pantai Pananjung, dan Pantai Pasir Putih, menggunakan skoring *Dune Vulnerability Assessment* dan telah dimodifikasi sesuai kondisi lokal. Penilaian mencakup parameter fisik berupa kondisi pantai dan parameter manusia berupa tekanan penggunaan. Nilai kerentanan dihitung menggunakan pendekatan algoritma Euclidean berdasarkan jarak indeks parameter manusia (M) dan parameter fisik (F) terhadap kondisi ideal, dengan $E = \sqrt{(M - 1)^2 + (F - 1)^2}$ di mana E merupakan indeks kerentanan. Nilai M dan F diperoleh dari total skor masing-masing kelompok parameter yang dibagi berdasarkan jumlah parameter yang dinilai. Hasil penelitian menunjukkan bahwa *dunes* Pantai Karang Nini dan Pantai Pasir Putih memiliki tingkat kerentanan rendah, dengan pengaruh utama berasal dari parameter fisik kondisi pantai. Sementara itu, *dunes* Pantai Batu Hiu dan Pantai Pananjung memiliki tingkat kerentanan sedang dengan pengaruh dominan dari parameter manusia. Tingginya tekanan pada kedua lokasi tersebut berkaitan dengan akses dan aktivitas manusia di sekitar kawasan *dunes*. Dari hasil penelitian diperlukan penanganan yang tepat untuk menurunkan nilai indeks kerentanan baik dari parameter fisik kondisi pantai, maupun parameter manusia.

Kata Kunci: Kerentanan *Dunes*, Pangandaran, Pantai Wisata

INTRODUCTION

As a tropical nation, Indonesia possesses numerous white-sand beaches bathed in sunlight throughout the year, which serve as a major tourism draw; consequently, many of Indonesia's coastal regions have been developed with the primary objective of attracting visitors (Hasibuan et al., 2019). According to data from the Ministry of Tourism, Indonesia's tourism industry continues to grow in terms of both visitor numbers and foreign exchange earnings. Following coal, oil, and palm oil, the tourism industry ranks among the top four contributors of foreign exchange to the country (Fauzi et al., 2019). Given its geographical setting—dominated by coastline, with the Pangandaran Regency coastline stretching for 91 km—the area has established itself as a prominent marine tourism destination (Pangandaran Tourism and Culture Office, 2018). Coastal tourism in Pangandaran Regency is considered both economically and ecologically significant within West Java Province and has been designated at the national level as a tourism destination. As a National Tourism Strategic Area—defined as a region with a primary function in tourism or one capable of fostering national tourism with significant impact—Pangandaran stands out as a premier tourist attraction in West Java Province (Rizal et al., 2021).

As noted by Tegar and Gurning (2018), "coastal tourism" is defined as activities taking place in coastal areas, encompassing beach-based tourism and recreational pursuits such as swimming, sunbathing, beach walking, and stays at resorts. Infrastructure and facilities for coastal tourism are also located on land, typically in close proximity to the shoreline. A similar perspective is offered by Hall (2001), who defines coastal tourism as any tourism or recreational activity occurring within the coastal zone and adjacent offshore waters. This includes the development of coastal tourism—such as accommodations, restaurants, food-related industries, and secondary residences—as well as coastal infrastructure, including retail

outlets, marinas or specialized harbors with moorings and facilities for cruise ships or small vessels, and providers of recreational activities. Coastal or beach tourism is a major contributor to environmental damage through the depletion of resources; it is also a primary driver of global dune degradation, resulting from the construction of tourism facilities, recreational pressure, and the intensification of tourism-related activities (Kurniawan *et al.*, 2016; Gao *et al.*, 2020). As areas highly sensitive to both natural and anthropogenic factors, any disruption to coastal natural systems can adversely affect the long-term stability of these dynamic ecosystems (Armenio *et al.*, 2021; Cicin-Sain and Knecht, 1998, in Hall, 2001).

While beaches may be relatively more resilient to the pressures of human activity, coastal zones and dunes are significantly more vulnerable (Brown and McLachlan, 2006). Dunes—which play a vital role in protecting shorelines from erosion, provide essential habitats for unique flora and fauna, and offer recreational opportunities for visitors—are increasingly threatened by human interventions such as tourism, road construction, agriculture, and livestock grazing; these are the primary causes of dune degradation (Barbier *et al.*, 2011; Sapkale, 2014; Martínez *et al.*, 2021). The popularity of such tourist destinations renders them more susceptible to heightened risks stemming from human activity (Purvis *et al.*, 2015). Pressures from mass tourism—including infrastructure development and the exploitation of resources—pose an ever-growing threat to dune ecosystems (Gao *et al.*, 2020). Coastal and dune tourism share a highly complex relationship, as this type of recreation attracts visitors while simultaneously exposing coastal and dune areas to potential hazards resulting from human activity (Martínez *et al.*, 2021). Consequently, the issues of mass tourism and the vulnerability of tourist destinations must be addressed to ensure sustainable tourism development (Wisha *et al.*, 2021).

The high level of activity in the coastal environment of Pangandaran Regency has led to a decline in environmental quality, manifesting as pollution and changes in coastal morphology (Rizal *et al.*, 2021). Sandy coastal systems—including beaches and dunes, which hold significant ecological and economic value for tourism—are highly susceptible to erosion (Cinelli *et al.*, 2021). As a transitional zone between land and sea, coastal areas are subject to considerable pressure from various activities and phenomena occurring both inland and at sea, including those related to tourism (Hastuti, 2012). It is well recognized that recreational tourism activities can have negative impacts on coastal ecosystems. Olale *et al.* (2020) note that tourism activities have caused adverse effects, such as the degradation of marine and coastal environments. The degradation of dunes is driven by the expansion of coastal tourism and the development of associated facilities near these fragile ecosystems. The construction of infrastructure—such as hotels, resorts, and recreational facilities—frequently results in habitat destruction and the alteration of the natural dune landscape (Gao *et al.*, 2020). Furthermore, the influx of tourists into these areas leads to increased foot traffic, which can disrupt vegetation and contribute to dune erosion (Farris *et al.*, 2013). Another issue arising from the intensification of tourism-related recreation is the leveling of coastal dunes to accommodate tourism infrastructure, alongside the damage to vegetation caused by human trampling (Jones *et al.*, 2008).

The sustainability and competitiveness of marine tourism destinations depend on the conservation of natural resources; yet, at the same time, tourism activities exert pressure on these very resources, particularly along the coast (Santos-Lacueva *et al.*, 2017). Therefore, research is needed to analyze the vulnerability of and pressures on coastal dunes, based on both the physical conditions of the coast and the pressures resulting from anthropogenic activities—particularly tourism. It is necessary to assess various physical and human-related parameters to determine which factors exert the most significant influence on the coastal tourism areas in Pangandaran Regency, West Java.

RESEARCH METHODS

This research was conducted on June 19–20, 2024, in the coastal area of Pangandaran Regency, West Java. The Area of Interest (AOI) encompassed four research stations: Karang Nini Beach, Pananjung Beach, Batu Hiu Beach, and Pasir Putih Beach. Data collection was carried out through direct field surveys, with one observation point established at each beach, resulting in a total of four observation points. These points were selected using a purposive sampling method—chosen intentionally based on site characteristics that allowed for the observation and assessment of all or most of the parameters included in the Dune Vulnerability Assessment scoring checklist. Observations at Karang Nini Beach and Pananjung Beach took place on the afternoon of June 19, 2024, while observations at Batu Hiu Beach and Pasir Putih Beach were conducted during the day on June 20, 2024. The assessment of dune vulnerability followed the Dune Vulnerability Assessment method developed by Davies *et al.* (1995), which was modified to suit the specific characteristics of the study area. In the original method, the assessment utilizes a checklist covering several parameter groups: site and dune morphology, beach conditions, surface characteristics of the area 200 meters seaward of the dunes, usage pressure, and protection measures. Each parameter is assessed individually based on observed field conditions, and the resulting scores are then used to calculate a vulnerability index. In this study, the parameter groups were simplified into two primary categories—physical parameters and human-related parameters—as presented in Tables 1 and 2. Physical parameters are represented by beach conditions, while human-related parameters are represented by usage pressure. This modification was necessary because some parameters from the original method were either absent or not well-suited to the characteristics of the study sites. Davies *et al.* (1995) noted that such vulnerability assessment checklists are not universal and can be adapted to reflect regional conditions. Each parameter was assigned a score based on the actual conditions observed at each research station. The range and number of score categories may vary across parameters, depending on the characteristics of the indicators being assessed—an approach consistent with the checklist developed by Davies *et al.* (1995). Consequently, the fact that some parameters may have three, four, or five rating categories is simply a feature of the scoring structure and does not imply any difference in weighting between the parameters. Equal weighting is applied because this study lacks a sufficient empirical basis to justify assigning different weights to specific parameters.

The horizontal width of the intertidal zone is calculated by dividing the vertical height of the intertidal zone (determined via clinometer angle measurements) by the tangent of the beach slope angle, with the actual ground distance measured using a measuring wheel. Secondary data used to analyze shoreline changes consist of Landsat satellite imagery—specifically, Landsat Collection 2 Level-2 Surface Reflectance products for Path/Row 121/065. The first dataset comprises Landsat 8 imagery acquired on December 15, 2016, while the second consists of Landsat 9 imagery acquired on June 20, 2024. Both datasets have a spatial resolution of 30 meters and serve as comparative data to assess shoreline changes at the study site. The use of Level-2 Surface Reflectance products ensures that the data have undergone preliminary processing (Ulfa & Taliding, 2026). Image processing involved selecting the appropriate spectral bands, followed by digitization in ArcGIS software using the Normalized Difference Water Index (NDWI) and the Digital Shoreline Analysis System (DSAS) applied to the Landsat 8 (2016) and Landsat 9 (2024) imagery. The resulting shoreline change data are then used to assign scores for the "Sand Supply Input" parameter within the assessment of beach conditions.

Table 1. Beach Condition Parameters

No.	Parameter	Score				
		1	2	3	4	5

1	Width of the intertidal zone (km)	> 0.5	> 0.2	> 0.1	> 0.05	< 0.05
2	Sand supply input	Forward		Stationary		Backward
3	% Gravel covers the surface	0	< 5	> 5	> 25	> 50
4	Dune conditions	Overgrown with tall trees	Overgrown with small trees/weeds	No vegetation	Dunes repurposed	There are no dunes
5.	A gap in the sea surface	None		Some		Many
6	Width of the gap at the sea surface	< 2		2-10		> 10
7	Macroalgae in the upper intertidal zone	Many		Some		None

Source: Davies *et al.*, 1995

Table 2. Operational Pressure Parameters

No.	Parameter	Score				
		1	2	3	4	5
1	Visitor pressure	Constrained by space and time		Time-limited		Not limited
2	Road access	On foot	Motorcycle access		Car access	Bus access
3	Driving on the dunes	None at all		ATVs and motorcycles		Everything is there
4	Horseback riding	None		< 5 animals		> 5 animals
5	Parking area	Not visible		Only motorcycle parking is visible		Car parking is visible
6	Facility	No facilities	1 Facility	2 Facility	3 Facility	>3 Facility
7	Home residents	<10		10-30		>30
8	Commercial area	None	Service provider	Street vendors	Traditional port	Heavy industry/port
9	Livestock grazing	None		Cattle/sheep		Both

Source: Davies *et al.*, 1995

After the scoring results are obtained, they are then calculated using the Euclidean algorithm approach and plotted into a Euclidean graph, and classified based on the vulnerability level classification in Table 3. (Taofiqurohman *et al.*, 2018).

$$E = \sqrt{(M - 1)^2 + (F - 1)^2} ; M = m/n ; F = f/n.$$

Note:

E = vulnerability index;
 M = human parameter;
 F = physical parameter;
 M = total score for all coastal condition parameters;
 F = total score for all usage pressure parameters;
 n = number of parameters assessed.

Table 3. Euclidean Vulnerability Classification

Value	Very Low	Low	Medium	High	Very High
E	0 – 1,13	1,14 – 2,25	2,26 – 3,38	3,39 – 4,51	4,52 – 5,65

Source: Taofiqurohman *et al.*, 2018

RESULT

Table 4. Results of Coastal Condition Parameter Assessment

No.	Parameter	Assessment Results			
		Batu Hiu Beach	Karang Nini Beach	Pananjung Beach	Pasir Putih Beach
1	Width of the intertidal zone (km)	0,0265 (score 5)	0,0687 (score 4)	0,0158 (score 5)	0,0244 (score 5)
2	Sand supply input	Tetap (score 3)	Tetap (score 3)	Tetap (score 3)	Tetap (score 3)
3	% Gravel covers the surface	0% (score 1)	0% (score 1)	0% (score 1)	0% (score 1)
4	Dune conditions	Repurposed (score 4)	None (score 5)	Repurposed (score 4)	None (score 5)
5.	A gap in the sea surface	None (score 1)	None (score 1)	None (score 1)	None (score 1)
6	Width of the gap at the sea surface	None (score 1)	None (score 1)	None (score 1)	None (score 1)
7	Macroalgae in the upper intertidal zone	None (score 5)	None (score 5)	None (score 5)	None (score 5)
F	Component Value (Total Score/7)	2.857142857	2.857142857	2.857142857	3

Table 5. Results of the Assessment of Usage Pressure Parameters

No.	Parameter	Assessment Results			
		Batu Hiu Beach	Karang Nini Beach	Pananjung Beach	Pasir Putih Beach
1	Visitor pressure	Not limited (score 5)	Not limited (score 5)	Not limited (score 5)	Time-limited (score 3)
2	Road access	Bus access (score 5)	Walking (score 1)	Bus access (score 5)	Walking (score 1)
3	Driving on the dunes	None (score 1)	None (score 1)	None (score 1)	None (score 1)
4	Horseback riding	None (score 1)	None (score 1)	None (score 1)	None (score 1)

5.	Parking area	Visible car parking (score 5)	Not visible (score 1)	Visible car parking (score 5)	Not visible (score 1)
6	Facility	>3 facilities (score 5)	None (score 1)	1 Facilities (score 2)	None (score 1)
7	Home residents	10 – 30 (Score 3)	None (score 1)	10 – 30 (Score 3)	None (score 1)
8	Commercial area	Street vendors (score 3)	None (score 1)	Traditional port (score 4)	Service provider (score 2)
9	Livestock grazing	None (score 1)	None (score 1)	None (score 1)	None (score 1)
M	Component Value	3.222222222	1.444444444	3	1.333333333
(Total Score/9)					

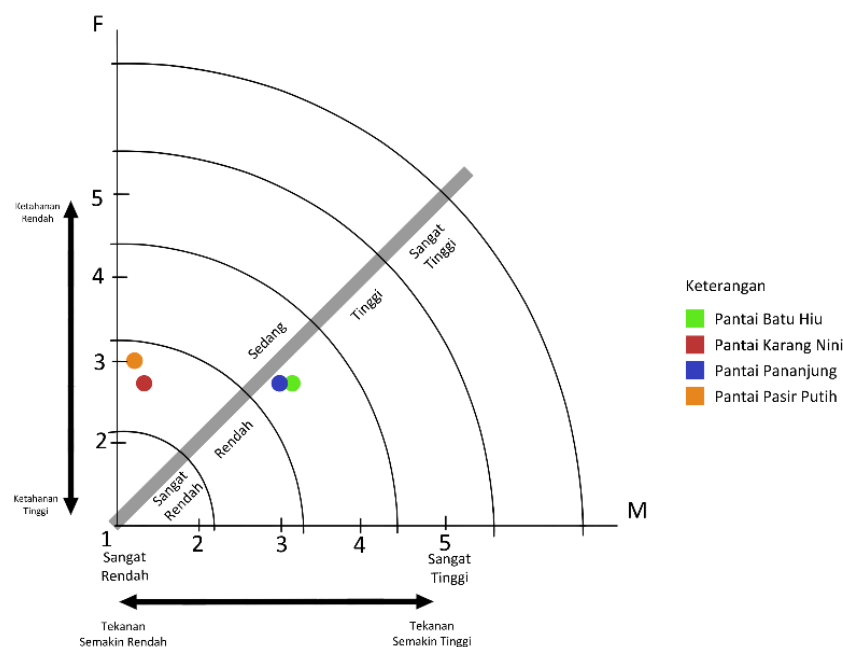


Figure 1. Plotting of Scoring Results for Physical Parameters and the Fourth Human Parameter

Table 6. Vulnerability Classification of the Four Beaches

Beach	Vulnerability Index Value	Classification
Batu Hiu Beach	2,90	Medium
Karang Nini Beach	1,91	Low
Pananjung Beach	2,73	Medium
Pasir Putih Beach	2,03	Low

DISCUSSION

Coastal Pressure Analysis

Based on the field scoring results, the intertidal zone width at Karang Nini Beach—measuring 0.0687 km—received a score of 4. Meanwhile, Batu Hiu Beach, Pananjung Beach, and Pasir Putih Beach—with intertidal zone widths of 0.0265 km, 0.0158 km, and 0.0244 km, respectively—each received a score of 5. These scores indicate that all four beaches have narrow intertidal zones. According to research by Crapoulet *et al.* (2017), the width of the

intertidal zone is linked to beach morphology; a narrow intertidal zone can lead to reduced sediment availability, affecting how dunes respond to major storms and rendering them more susceptible to erosion.

Regarding the sand supply input parameter, the study utilized shoreline change data derived from satellite imagery captured on December 15, 2016, and June 20, 2024. Digitization results indicate that the shorelines at all four locations experienced a slight shift toward accretion—or seaward advancement. Nevertheless, the sand supply input parameter was assigned a score of 3, indicating a "stable" condition. This score takes into account that the observed shifts in shoreline position may not be solely attributable to sedimentation processes; they could also be influenced by differences in sea level conditions at the time the imagery was acquired. The imagery from December 15, 2016, was captured during a relatively high tide, whereas the imagery from June 20, 2024, was captured under different tidal conditions. Such variations in sea level can alter the identified boundary between land and water in each image. Consequently, the measured changes in shoreline position do not exclusively reflect changes resulting from sedimentation, as they may be influenced by various other factors. Setyoningrum *et al.* (2023) explains that wind, waves, currents, as well as the type and composition of coastal materials, can influence sedimentation processes, water movement, and coastal morphology. Variations in land subsidence rates across different locations can also affect shifts in the coastline position, with subsidence rates generally being higher in areas closer to the shore. Consequently, relatively minor changes in the coastline—as observed through digitization—are not interpreted as direct evidence of an increased sediment supply; therefore, the sand supply input parameter is treated as a constant. According to Mohamad *et al.* (2019), accurate mapping requires an assessment of water level variations across different tidal phases—a point echoed by Ma *et al.* (2024), who emphasize the necessity of synchronizing image acquisition times with tidal levels to ensure precise mapping.

The percentage of gravel covering the surface of all four beaches is 0%, corresponding to a score of 1. A lower percentage of gravel cover on the dune surface is considered better. This is because surface gravel not only affects tidal flow resistance—as tides move in and out of an area—but also reduces sediment mobility, which is essential for stabilizing dunes and enhancing their function as protective barriers that lower vulnerability to erosion (Williams *et al.*, 2006; Bonte *et al.*, 2021).

Regarding the condition of the dunes, Pananjung Beach and Batu Hiu Beach both received a score of 4; at Pananjung Beach, the dunes have been replaced by large rocks and concrete walls, while at Batu Hiu Beach, they have been replaced by stalls or kiosks. Meanwhile, no dunes are present at all at Karang Nini Beach or Pasir Putih Beach. All four beaches received poor scores, as the absence or conversion of dunes leads to negative environmental impacts; dunes play a critical role in protecting the coastline from erosion and storm surges, which otherwise pose risks to both the environment and infrastructure (Houser, 2009).

All four beaches received a score of 1 for both the "seaward-facing gap" and "width of seaward-facing gap" parameters, as there are no gaps present along the beach fronts. This indicates an excellent condition for these two parameters, as gaps—which represent disruptions in natural barriers like seaward-facing dunes—can allow water to flow through and potentially cause erosion in the coastal environment. Williams *et al.* (2015) note that the presence of such gaps can cause sediment deposits from the back-barrier area to be transported out to sea, thereby affecting the overall coastal morphology. These gaps can be formed by erosion or extreme weather events. Human activities include coastal reclamation, sand extraction, urbanization, and other anthropogenic interventions.

Based on field assessments, no macroalgae were found in the upper beach zone at any of the four study sites; consequently, each site received a score of 5. The presence of macroalgae

in the upper beach zone can enhance dune stability. Provost *et al.* (2022) state that macroalgae contribute to increased dune biomass, sand-trapping capacity, and overall dune resilience. Furthermore, macroalgae can help mitigate the impacts of storms and erosion on dunes (Vergiev, 2019). However, as noted by Ghazali *et al.* (2024), the presence of macroalgae on a beach can fluctuate due to environmental factors, such as wave action. Therefore, the observations in this study reflect the status of macroalgae at the time of the survey—June 19–20, 2024—and cannot be generalized to represent their presence throughout the entire year.

Regarding the "visitor pressure" parameter, Batu Hiu Beach, Karang Nini Beach, and Pananjung Beach each received a score of 5, as there are no time restrictions for visitors, nor are there any restricted zones at these locations. In contrast, Pasir Putih Beach received a score of 3; while there are no restricted zones, access is time-limited. This is because the Pangandaran Nature Reserve—one of the routes to reach the beach—is only open until 5:00 PM, while the alternative route, which requires a boat, is only available until 6:00 PM. A poor score in this category indicates that uncontrolled visitor access to the beach can have negative consequences for the dunes. Human activities associated with unrestricted beach access—such as camping and various recreational pursuits—can contribute to dune degradation and hinder both the development of dunes and the availability of sediment within them, thereby impacting the overall health of the dune ecosystem (Thompson & Schacher, 2008; Bella *et al.*, 2024). Furthermore, a lack of restrictions on beach access leads to increased trampling intensity and greater disturbance to dune vegetation (Santoro *et al.*, 2012).

Two of the four beaches received scores of 1 and 5, respectively, for the parameters of road access and parking facilities. Karang Nini Beach and Pasir Putih Beach scored 1; they are located at a considerable distance from both the main road and parking areas—to the extent that parking facilities are not even visible—and can only be reached on foot. In contrast, Batu Hiu Beach and Pananjung Beach, which are situated along the roadside, received a score of 5; they are accessible to motor vehicles, including four-wheeled vehicles such as cars and buses, which can park directly behind these beaches. Ease of access to coastal areas can increase the potential for human activity within the dune zone, particularly through visitor mobility, recreational pursuits, and the use of parking facilities. In this study, road access and parking availability serve as indicators of "use pressure," as they reflect the level of ease with which people can reach the coastal area. From the perspective of tourism demand, the importance of accessibility to coastal resources—beaches in particular—highlights how a beach and its attractive features can drive demand for a given destination (Wang *et al.*, 2024). Nevertheless, vehicle access to a coastal area does not necessarily imply that vehicles are entering the dune zone itself. Therefore, the pressure indicated by these parameters relates to the proximity and ease of access to the dune area. As noted by Listiowati *et al.* (2020), the ease of reaching a tourist site—whether on foot or by vehicle—can influence the site's overall appeal. However, the potential for mass tourism resulting from improved accessibility can create challenges for conservation efforts and the management of visitor behavior (Kamal *et al.*, 2023). Consequently, Batu Hiu Beach and Pananjung Beach, which offer vehicle access and parking facilities in closer proximity to the coastal area, exhibit a higher level of use pressure compared to Karang Nini Beach and Pasir Putih Beach. At all four beaches, there is no driving on the dunes nor horseback riding, resulting in a score of 1, which indicates an excellent rating. This is because the use of vehicles in dune areas can damage vegetation by creating deep ruts in the sand, leading to sand compaction and erosion—all of which contribute to the destabilization of the dunes (Hogan & Brown, 2021; Orchard *et al.*, 2022). Meanwhile, the weight of a horse combined with the small surface area of its hooves in contact with the ground carries a high potential for environmental damage (Landsberg *et al.*, 2001). Activities associated with horseback riding, such as grazing and trampling, can lead to an increase in bare ground, a

reduction in dune height, and the loss or decline of vegetation cover (Phillips & Newsome, 2001).

Due to their significant distance from the aforementioned facilities, Karang Nini Beach and Pasir Putih Beach received a score of 1, as no facilities were observed in the vicinity of the data collection sites. Pananjung Beach received a score of 2, as only one facility—a public restroom—was found near its data collection site. Conversely, Batu Hiu Beach—a popular destination located adjacent to a main road—received a score of 5, as it features more than three public facilities, including several bathrooms, public restrooms, and a *mushola* (small prayer room). Amenities—services that support tourism activities, such as toilets, places of worship, accommodations (hotels), restaurants, transportation, and other public facilities—are key components of tourism that influence tourists' decisions when choosing a destination (Listiowati *et al.*, 2020; Saputra *et al.*, 2023). However, the intensification of human activity—driven by increased recreational pursuits facilitated by the presence of such amenities near a beach—can have adverse consequences for the dunes. Trampling of dunes by visitors can lead to dune degradation and soil compaction—which alters substrate characteristics—as well as affecting the abundance and cover of existing vegetation (Carranza *et al.*, 2008; Purvis *et al.*, 2015; Del Vecchio *et al.*, 2022; Sarmati *et al.*, 2024). Furthermore, an increase in the intensity of recreational activities often necessitates the expansion of tourism-related infrastructure, which in turn imposes additional negative impacts on the dunes and the beach itself. As noted by Taïbi (2016), construction activities on dunes can exacerbate long-term coastal erosion, resulting in a loss of tourism appeal and compromising the stability of the dune system.

Located within a production forest area managed by the Forest Management Unit (KPH) and the Pangandaran Nature Reserve, Karang Nini Beach and Pasir Putih Beach have no residential dwellings in their vicinity; consequently, both beaches received a score of 1. In contrast, the other two beaches—Batu Hiu Beach and Pananjung Beach—received a score of 3, as there are between 10 and 30 residential houses near the data collection sites. The proximity of human settlements often leads to the development of beach-related activities, such as sports and recreation, as well as resource exploitation—for instance, sand mining—which can result in the alteration and degradation of dunes (Portz *et al.*, 2023). Human activities associated with residential development near tourist beaches, such as urbanization, can cause habitat loss, erosion, and increased vulnerability to coastal risks. Furthermore, rising population density in coastal areas drives a greater demand for housing, recreation, and infrastructure development, all of which contribute to dune degradation (Sapkale, 2014; Pinna *et al.*, 2022).

Regarding the commercial area parameter, Karang Nini Beach received a score of 1, as there are no commercial areas near the data collection site. Pasir Putih Beach received a score of 2, with the only commercial activity being the rental of life jackets and snorkeling gear. Batu Hiu Beach received a score of 3 due to the presence of numerous kiosks and street vendors along the shoreline, while Pananjung Beach received a score of 4, as it features a traditional harbor constructed from bamboo. The score of 2 for Pasir Putih Beach is considered favorable, as the rental of life jackets and snorkeling equipment does not involve permanent structures like the kiosks or stalls commonly found along other beaches. Meanwhile, the adverse impacts resulting from the proliferation of kiosks or street vendors around Batu Hiu Beach, as well as the presence of a traditional harbor at Pananjung Beach, are similar to the negative effects caused by an abundance of coastal facilities. Human intervention and infrastructure development in coastal areas—driven primarily by tourism—intensify the pressure on dune systems. Such activities not only lead to habitat loss but also disrupt the natural processes that maintain the stability and functionality of dune ecosystems (Teixeira *et al.*, 2016).

The absence of livestock grazing across all four beaches—assigned a score of 1—is a positive factor. Livestock grazing can negatively affect ecosystems by altering vegetation dynamics, the nesting habitats of key species, nutrient cycling processes, and overall

biodiversity. The lack of grazing ensures that the dunes remain free from the pressures caused by trampling. Bonte (2005) noted that trampling by livestock has been shown to negatively impact the nest density of digger wasps, which are dune-dwelling organisms that contribute to the ecosystem. Furthermore, the presence of livestock on dunes can alter vegetation patterns; overgrazing may lead to a permanent reduction in biodiversity, necessitating a cautious approach toward any potential reintroduction of livestock into dune environments (Middleton *et al.*, 2006).

Vulnerability Classification

Averaged results from the dune vulnerability assessment across four beaches reveal varying levels of vulnerability, influenced by both physical and human-related parameters. Plotting the data for Batu Hiu Beach and Pananjung Beach places them in the "moderate" vulnerability category, falling within the quadrant associated with human parameters; this indicates that human-related factors contribute more significantly to the dune vulnerability index at these locations. Conversely, Karang Nini Beach and Pasir Putih Beach fall into the "low" vulnerability category and are situated within the quadrant associated with physical parameters, suggesting that physical factors exert a greater influence on dune vulnerability at these sites. Furthermore, calculations of the dune vulnerability index—using a Euclidean algorithm approach—classify the dunes at Karang Nini Beach and Pasir Putih Beach as having low vulnerability, while those at Batu Hiu Beach and Pananjung Beach are classified as having moderate vulnerability. The low dune vulnerability at Pasir Putih Beach and Karang Nini Beach may be attributed to their distance from urban areas, which shields them from the pressures associated with urbanization. In contrast, Batu Hiu Beach and Pananjung Beach are located directly adjacent to a main road; consequently, their dunes are significantly more vulnerable due to their proximity to human activity and greater accessibility. Moreover, the Euclidean plot confirms the vulnerability index findings for Batu Hiu Beach and Pananjung Beach, placing them in the moderate vulnerability category within the human-parameter quadrant—a result driven by the fact that human-related factors have a greater impact than physical factors at these sites.

Dunes located near urbanized coastal areas are more vulnerable than those on remote beaches due to higher levels of human disturbance and activity, which can jeopardize the dunes and diminish their effectiveness in protecting the coastline. This aligns with the observations of Alcérreca-Huerta *et al.* (2020) and Brew *et al.* (2011), where infrastructure and development in urban settlements and recreational areas near the coast can increase the vulnerability of dunes and impair their capacity to act as buffers against storms and floods. Conversely, the dunes at Karang Nini Beach and Pasir Putih Beach fall into a low-vulnerability classification; being distant from urbanization, they remain largely undisturbed by human activity and are better able to fulfill their natural role in coastal erosion risk management as dynamic coastal defense lines (Mahmoud *et al.*, 2021).

Furthermore, it is not only human-related parameters that warrant attention. Even if the plotting of dune vulnerability—based on physical parameters or coastal conditions—falls into a "low" category, the physical state of the coast could still deteriorate, subsequently increasing the vulnerability of the dunes. This is because the physical condition of the coast—including beach width, natural features, and vegetation cover—directly influences the susceptibility of dunes to erosion. Research by Overbeck *et al.* (2017) indicates that changes in dune crest elevation are influenced by beach width; narrower beaches lead to increased vulnerability to dune erosion. Additionally, Provost *et al.* (2022) highlight the importance of natural elements, such as vegetation and macroalgae, in enhancing dune resilience by improving sand-trapping capacity and overall dune biomass. As noted by Passeri *et al.* (2021) and Durán and Moore (2013), the presence of vegetation influences both dune size and coastal vulnerability to storms;

vegetation cover bolsters dune resilience, whereas its reduction diminishes the dunes' ability to withstand erosive events. Moreover, as discussed by van Puijenbroek *et al.* (2017), coastal morphology, storm characteristics, and rainfall all play a role in the overall development and resilience of dunes.

CONCLUSION

The assessment and calculation of the vulnerability index, using a Euclidean algorithm-based approach, indicate that the dunes at Batu Hiu Beach and Pananjung Beach fall under the moderate vulnerability classification, while those at Karang Nini Beach and Pasir Putih Beach fall under the low vulnerability classification. Plotting these results on a Euclidean graph reveals that Batu Hiu Beach and Pananjung Beach lie within the "human parameters" quadrant, signifying that human-related factors contribute more significantly to their vulnerability index than physical factors. Conversely, Karang Nini Beach and Pasir Putih Beach fall within the "physical parameters" quadrant, indicating that physical factors make a greater contribution to their vulnerability index. These differences in vulnerability levels are linked to the intensity of usage pressure at each location. At Batu Hiu Beach and Pananjung Beach, road access and parking areas are situated closer to the coastal zone, resulting in higher values for the usage pressure parameter. In contrast, Karang Nini Beach and Pasir Putih Beach have relatively more restricted access, leading to lower values for the usage pressure parameter. Based on these findings, dune management should focus on reducing usage pressure—specifically by regulating access and human activities in the vicinity of the dune zones, organizing facilities and visitor pathways, and conducting periodic monitoring of the dunes' condition. Such management is particularly crucial for Batu Hiu Beach and Pananjung Beach, given their moderate vulnerability and the significant contribution of human-related factors to their vulnerability index.

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