Spatial modeling of whale shark protection using the marxan method in Saleh Bay, West Nusa Tenggara

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Abstract. Saleh Bay is a recurring aggregation area for whale sharks (*Rhincodon typus*). This study applied the Marxan decision-support tool to identify spatial conservation priorities based on whale shark sighting records and selected environmental and anthropogenic proxies, without explicitly modeling habitat suitability or preference. The inputs included sea surface temperature, chlorophyll-a concentration, whale shark occurrences, fishing net distribution, and indicators of human activities. Three zoning scenarios, with increasing conservation targets, were evaluated. The scenario with the highest target identified a core priority area of 102,831.29 ha (50.13% of the study area), exceeding that of the lower-target scenarios. The resulting priority zones reflect the spatial patterns of whale shark aggregation and associated environmental conditions under the current observation data. These findings are intended to inform marine spatial planning by providing a precautionary basis for conservation decision making while accommodating existing coastal uses.

Keywords: Whale Shark, Marxan, Spatial Modelling, Conservation

1 Introduction

Saleh Bay is a water body located in eastern Indonesia, precisely between the Sumbawa Regency and Dompu Regency, West Nusa Tenggara Province [1]. Saleh Bay is a semi-enclosed water area connected to the Flores Sea [2]. This water area has diverse coastal and marine natural resources, which could become a new source of economy for future

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development in the West Nusa Tenggara Province [3]. West Nusa Tenggara has great potential for marine tourism with beautiful beaches, coral reef ecosystems, and abundant biodiversity. Tourists, both domestic and international, are attracted to various marine tourism activities such as enjoying biodiversity, diving, and snorkeling. The locations for diving and snorkeling activities are greatly influenced by the beauty of the underwater ecosystem, including stunning coral reefs and the presence of fish, marine mammals, and other marine animals. One of the famous marine tourism activities in West Nusa Tenggara is interacting with whale sharks (*Rhincodon typus*) [4].

Whale sharks (*Rhincodon typus*) are the largest species of shark in the world [5], and are often found in tropical to subtropical waters with temperatures of 25–31°C, such as the waters of Mozambique, Madagascar, the Maldives, Western Australia, the Philippines, Indonesia, and Taiwan [6]. This rare animal is a planktivorous fish that feeds on plankton, including zooplankton and phytoplankton, small shrimp, crab larvae, and small fish [7], as well as algae floating in the water [8]. Whale sharks are important for the development of ecotourism because they are docile and nonaggressive when interacting and appearing on the surface [9]. Since 1999, whale sharks have been included in the Red List of the International Union for Conservation of Nature (IUCN) as endangered, with an estimated population decline of 40-92% [10]. Megafauna, which are considered to have a significant positive impact on local communities because they are often used as tourist attractions [11], whale sharks are classified as rare animals whose survival must be protected through conservation strategies. Saleh Bay, West Nusa Tenggara, Indonesia, has been identified as a critical habitat for the whale shark (*Rhincodon typus*), which requires urgent attention from a spatial conservation perspective. Recent scientific evidence has confirmed the presence of neonatal whale sharks in Saleh Bay, indicating that this semi-enclosed bay may function as a pupping and early nursery area, a habitat type that is extremely rare and poorly documented. This finding substantially elevates the conservation value of Saleh Bay and strengthens the justification for spatially explicit protection measures focused on the critical life-history stages of whale sharks [12].

The implementation of these conservation strategies is supported by many software tools such as Reserve Selection and Connectivity (RESCON), Zonation, and Marxan. Marxan has been used in more than 180 countries to design conservation areas both on land and at sea [13]. Marxan is a conservation software that can find locations and design protected areas (conservation areas) that comprehensively cover the biodiversity in each area [14]. Marxan was used to identify potential conservation areas with the most efficient targets and costs [15]. The input used in Marxan is a planning unit filled with the target and cost features. The two target feature data are data that support the existence of whale sharks, whereas the cost feature data are data in the form of other activities that are suspected of threatening the existence of whale shark species [16]. In this study, the target and cost features were defined based on their functional roles in influencing the presence and vulnerability of whale sharks. Certain anthropogenic features, particularly lift-net fisheries, act as double-edged factors: they function as attractors of whale shark emergence due to increased prey availability while simultaneously posing potential risks through intensive human interaction and spatial disturbance. Therefore, these features are positioned as target features in the spatial analysis to represent interaction hotspots that support whale shark occurrence, while their associated risks are explicitly considered in the interpretation of conservation priorities rather than being treated solely as cost features. Marxan has two outputs as a result of the analysis: the best selected area and solution area. The best selected area provides only one option, namely, selected for conservation or not selected for conservation, while the solution area is an accumulation of the frequency of selection of each planning unit [17]. This study aimed to identify whale shark protection zones using the Marxan method in the Saleh Bay area in West Nusa Tenggara, Indonesia.

2 Method

2.1 Location and data

The study area covers the entire water of Saleh Bay, West Nusa Tenggara, Indonesia. The research location map is shown in **Fig. 1**. The research period was April 7-17, 2025.

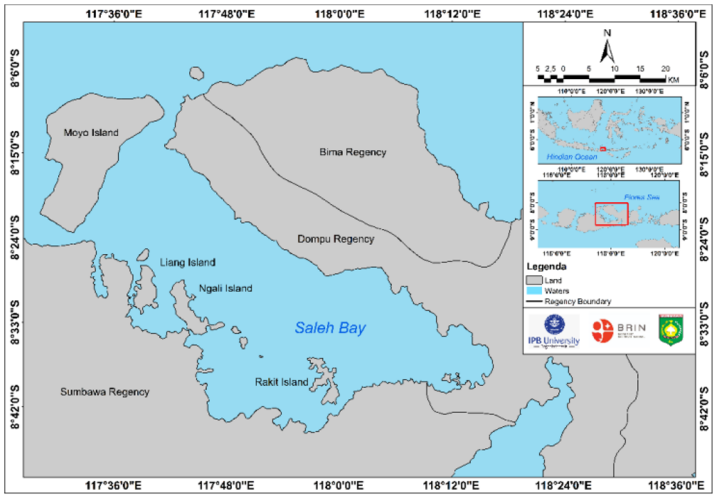

Fig. 1. Map of the research location in Saleh Bay, West Nusa Tenggara

During the observation and data collection phase in the field, various tools were used to support the smooth and accurate data collection process. Each tool has its own function for field data collection. The tools used during field data collection activities and their functions are listed in **Table 1**.

Table 1. Field research tools in Saleh Bay, West Nusa Tenggara

Name	Function
Global Positioning System (GPS) 64S	Marking the location of data collection
Research location map	Participatory location marker

Several software tools were used in the data-processing stage. This software supported the analysis of the obtained data. The data-processing tools are presented in **Table 2**.

Table 2. Research data processing tools

Name	Function
Quantum GIS 1.8.0	Import Marxan scenario processing results
Qmarxan	Data processing plugins
Zonae Cogito	Marxan scenario simulation
R 4.3 (*Add-on for Zonae Cogito*)	Marxan scenario simulation
C-Plan (*Add-on to Zonae Cogito*)	Marxan Scenario Simulation
SeaDAS	*Cropping* Aqua-MODIS images
ArcMap 10.8	Data processing results visualization
Microsoft Excel 2019	Filtering and organizing data
Microsoft Word 2019	Paper writing

The data used consisted of primary, secondary, and imaging data. This research material is required as *input* for Marxan. The data were obtained from various sources, as listed in **Table 3**.

Table 3. Type and source of data used

Type of Data	Source	Time
Conservation Area	https://www.konservasi-id.org/	2025
Aqua-MODIS imagery (Temperature and Chlorophyll-a)	https://oceancolor.gsfc.nasa.gov/	April 2025
Location of Whale Shark Sightings	Field observations and participatory mapping	April 2025
Location of Bagan	Field observations and participatory mapping	2022 - 2025
Port	Field observations and participatory mapping	2025
Settlements	Field observation and participatory mapping	2025
Shipping routes	Field observation and participatory mapping	2025
Coral Reef	https://allencoralatlas.org/atlas/	2025

The research procedure began by collecting all the data used to identify whale shark conservation areas. Temperature and chlorophyll data were obtained from Aqua-MODIS image processing by *spline* interpolation. According to [18], one of the most important components of analysis using Marxan is the determination of the study area boundary, known as *the Area of Interest* (AOI). The AOI was then converted into *a planning unit* (PU) in the form of a polygon that covered the entire study area. These polygons can be triangular, square, or hexagonal in shape. Among the three, hexagons are considered more efficient because they resemble circles, thus having a smaller edge-length ratio and being able to cover the area more optimally [19]. All processed data and other data *are* then *input* into Marxan software as conservation features (covering conservation areas, temperature, chlorophyll-a, whale shark sightings, fishing grounds, and coral reefs), and cost features (covering ports, settlements, and shipping lanes).

2.2 Data analysis

2.2.1 Image data processing

SPL data and chlorophyll-a concentration processing using Aqua MODIS Level-3 imagery. The data consisted of averaged geophysical *grid* parameters. *Grid* or *rectified* data are combinations of time and region. The algorithm used in SPL image extraction processing is the *Algorithm Theoretical Basic Document Modis* 25 (ATBD-MOD-25) algorithm with coefficients in **Table 4** [20].

$$\text{Modis SST} = c_1 + c_2 \times T_{31} + c_3 \times T_{31\,32} + c_4 \times (sec(\theta) - 1) \times T_{31\,32} \quad (1)$$

Note:
T_{31} = brightness temperature of channel 31
$T_{31\,32}$ = Brightness temperature difference (channel 32–channel 31)
θ = satellite *zenith* angle
c_1, c_2, c_3, c_4 = constants.

The constants used in the SPL algorithm to determine the BT difference between channels

31 and 32 are listed in **Table 4**.

Table 3. MODIS band 31 and 32 coefficients SPL algorithm

Coefficient	ΔT ≤ 0.7	ΔT ≥ 0.7
c_1	1.22855	1.69252
c_2	0.95765	0.95584
c_3	0.11821	0.08737
c_4	1.77463	1.19958

The algorithm used to determine the chlorophyll-a concentration in Aqua MODIS images is based on the empirical relationship *between* the blue *reflectance* band (443-488 nm) and green band (551 nm) of Aqua MODIS images [21]. Calculation of chlorophyll-a concentration using Aqua MODIS imagery with the ATBD-19 algorithm [22]

$$C_a = 10^{a0+a1R+a2R^2+a3R^3+a3R^4} \quad (2)$$

$$R = \left[log_{10} \frac{Rrs_{443} > Rrs_{488}}{Rrs_{551}}\right] \quad (3)$$

Explanation:
C_a = Chlorophyll-a concentration (mg/m^3)
R = Reflectance ratio
Rrs = *remote sensing reflectance*

Aqua MODIS Data Extraction consists of chlorophyll-a and SPL concentration data obtained from Aqua MODIS level 3 satellite imagery in the form of compressed digital data in *NonConformance* (NC) format. Data processing was continued using *SeaWIFS Data Analysis System* (SeaDAS) *software* for *cropping* according to the predetermined location. The extracted and *cropped* image data were stored in *Text Tab Delimited* (txt) format and then filtered using Microsoft Excel 2019 *software*. Data filtering aims to eliminate the cloud cover and land intensity values. The filtered data were processed using ArcMap 10.8 software for interpolation and layouting of chlorophyll-a and SST distribution maps. Interpolation uses the *spline* method to visualize SST and chlorophyll-a distribution. Sea surface temperature (SST) and chlorophyll-a data were obtained from the Aqua MODIS products with a native spatial resolution of 4 km. Spline interpolation in ArcGIS was applied to improve map visualization and facilitate the interpretation of broad spatial patterns. The interpolated layers were not used as inputs for Marxan or for quantitative spatial analysis. All analyses were performed using the original resolution datasets after quality assurance masking, including cloud removal and the exclusion of non-marine pixels.

2.2.2 Spline interpolation method

The *Spline* method estimates values using mathematical functions that minimize the total curvature of the surface. The equation used in the *Spline* method is based on the surface interpolation formula [23].

$$s(x, y) = T(x, y) + \sum_{j=i}^{N} \lambda j R(r_j) \quad (4)$$

Explanation:
s(x, y) = Spline function value at the coordinate point (x, y)
T(x, y) = surface value
N = Number of data points used in the interpolation

j = i = summation starting from index i
$R(r_j)$ = distance between data points and interpolated points
λj = Coefficient found in the linear equation system

2.2.3 Marxan processing

Marxan works through an algorithm called *simulated annealing*, which was developed to obtain optimal results in a short time by optimizing its algorithm [19]. In general, the algorithm in Marxan operates under the following four conditions [13]:

$$Total\ Cost = \sum_{i=1}^{n} Cost + (BLM \times \sum Boundary) + \sum_{i=1}^{n}(SPF \times Penalty) \quad (5)$$

Explanation:
$Cost$ = Combination of socioeconomic values in each *planning unit* in the selected solution
BLM = Values set by the user and related to the level of connectivity between *planning units*. The higher the *boundary length* value, the denser the solution area.
$Boundary$ = Selected area boundary
SPF A user-defined value related to the importance of the higher the SPF assigned to a feature, the more Marxan will give more priority to that feature target.
$Penalty$ = Penalty value assigned if the biodiversity protection target is not achieved
i = *Shapefile* unit id
n = Last shapefile unit id

Marxan is a flexible software that can be adapted for conservation planning. In its analysis process, Marxan uses various algorithms, one of which is *the Boundary Length Modifier* (BLM), which regulates the length of the boundaries between planning units. A low BLM value results in scattered planning units, whereas a high BLM value encourages the formation of groups of adjacent areas [24].

According to [25], *the Species Penalty Factor* (SPF) is used in Marxan to impose penalties if the conservation target for a species is not achieved. The higher the SPF value assigned, the greater the penalty imposed if the species habitat is not protected according to the specified target. The use of SPF aims to make Marxan more focused on meeting priority species conservation targets during the planning process. In the present study, an SPF value of 100 was assigned to all species, indicating the importance of appropriate conservation space allocation to ensure optimal habitat protection. The SPF value for bird species was set at 100% to ensure that conservation goals were the main focus, and to reduce the risk of conservation targets not being met.

3 Result and discussion

3.1 Existing conservation areas in Saleh Bay, West Nusa Tenggara

Saleh Bay has two conservation areas established by the Decree of the Minister of Marine Affairs and Fisheries (Kepmen KP), as shown in **Fig. 2**. Based on the Ministry of Marine Affairs and Fisheries Decree No. 20 of 2020 [26], the conservation area in the region of Liang Island, Ngali Island, and surrounding waters in West Nusa Tenggara Province has a total area

of 32,644.43 ha, consisting of a core zone with an area of 1,405.54 ha, a utilization zone covering 1,428.82 ha, a sustainable fisheries zone covering 757.92 ha, and other zones covering 757.92 ha. Based on the Ministry of Marine Affairs and Fisheries Decree No. 105 of 2023 [27], the conservation area in the Lipan Island and Rakit Island region of West Nusa Tenggara Province has a total area of 26,670.80 ha, consisting of Area 1 and Area 2. Area 1 is located in the waters around Lipan Island and has an area of 14,522.01 ha, consisting of a core zone with an area of 320.70 ha and a limited-use zone with an area of 14,201.28 ha. Area 2 is located in the waters around Rakit Island with an area of 12,148.79 ha, consisting of a core zone with an area of 12,148.79 ha, a limited use zone with an area of 11,419.89 ha, and another zone used for rehabilitation with an area of 58.11 ha.

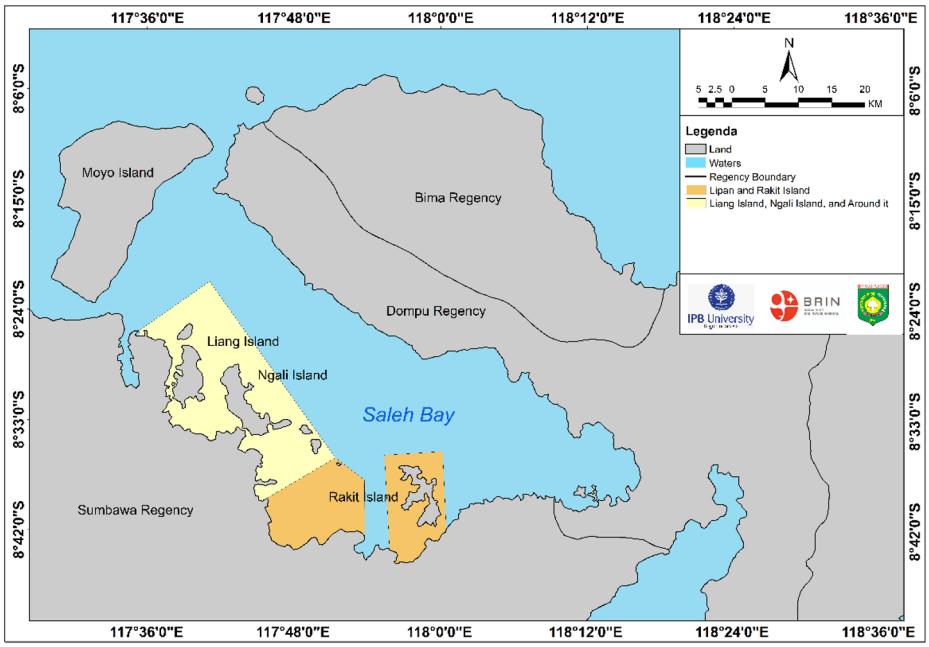

Fig. 2. Map of the conservation area established in Saleh Bay, West Nusa Tenggara.

3.2 Distribution of chlorophyll-a in Saleh Bay, West Nusa Tenggara

Chlorophyll-a, a photosynthetic pigment found in phytoplankton, is commonly used as an indicator of phytoplankton biomass and water productivity [28]. High chlorophyll-a concentrations in the coastal area of Saleh Bay indicate increased primary productivity, which is directly related to the availability of food for whale sharks [29]. Analysis of chlorophyll-a concentrations in the study area, shown in **Fig. 3**, obtained from Aqua-MODIS imagery in April 2025, showed that chlorophyll-a values range from 0.17 to 1.50 mg/m³. According to [9], the chlorophyll-a concentration shows a positive correlation with the appearance of whale sharks (R. *typus)*, indicating the availability of food in the water column. This is in line with the research by [30], which showed that in the northern Gulf of Mexico, chlorophyll-a is an environmental parameter that affects the distribution of whale sharks because of its strong relationship with prey abundance.

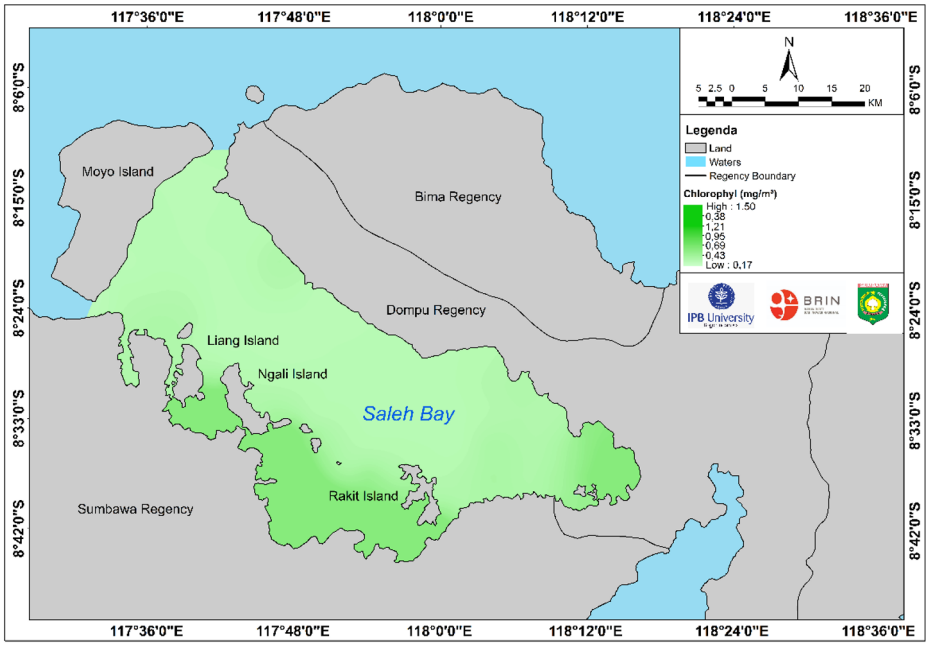

Fig. 3. Chlorophyll distribution map in April 2025 in Saleh Bay, West Nusa Tenggara.

3.3 Sea surface temperature distribution in Saleh Bay, Nusa Tenggara

Whale sharks (*Rhincodon typus*) are highly mobile marine megafauna capable of performing deep vertical dives and experiencing a wide range of temperatures throughout the water column. Therefore, their distribution was not constrained by narrow thermal tolerances. However, numerous studies have shown that whale sharks are frequently associated with specific sea surface temperature (SST) ranges during surface-oriented behaviors such as feeding and aggregation, particularly in productive tropical and subtropical waters [31]. In this context, SST is considered an important environmental parameter that influences surface activity patterns and habitat use rather than a strict physiological limitation on species occurrence. [32] stated that the optimal temperature for whale sharks in a region generally ranges from 28 to 30°C, especially in the morning, when whale sharks are active in feeding at the surface. Based on the results of research by [33], it is indicated that the frequency of whale shark appearance increases significantly when the sea surface temperature (SST) exceeds 30.5°C, which shows that this temperature is close to the optimal threshold for the biological activities and feeding behavior of this species. The sea surface temperature shown in Figure 4, based on Aqua-MODIS satellite image analysis in April 2025, indicates that the temperature in the waters of Saleh Bay ranges from 26.97°C to 32.11°C. Based on this, it can be said that Saleh Bay is a suitable habitat for whale sharks. Sea water temperature not only has a direct effect on thermal comfort for whale sharks but also has a broader ecological impact, especially in relation to the distribution of plankton and zooplankton, which are major components of the whale shark food chain [34]. In Saleh Bay, satellite-derived data indicate a temporal association between sea surface temperature (SST) and chlorophyll-a concentrations in April, suggesting conditions that may support elevated primary productivity. Although higher temperatures do not universally result in increased phytoplankton growth, the observed SST and chlorophyll-a patterns in Saleh Bay coincide

with periods of increased zooplankton availability and whale shark surface feeding activity. Therefore, SST in this study was interpreted as an environmental indicator associated with productive conditions, rather than as a direct driver of whale shark aggregation.

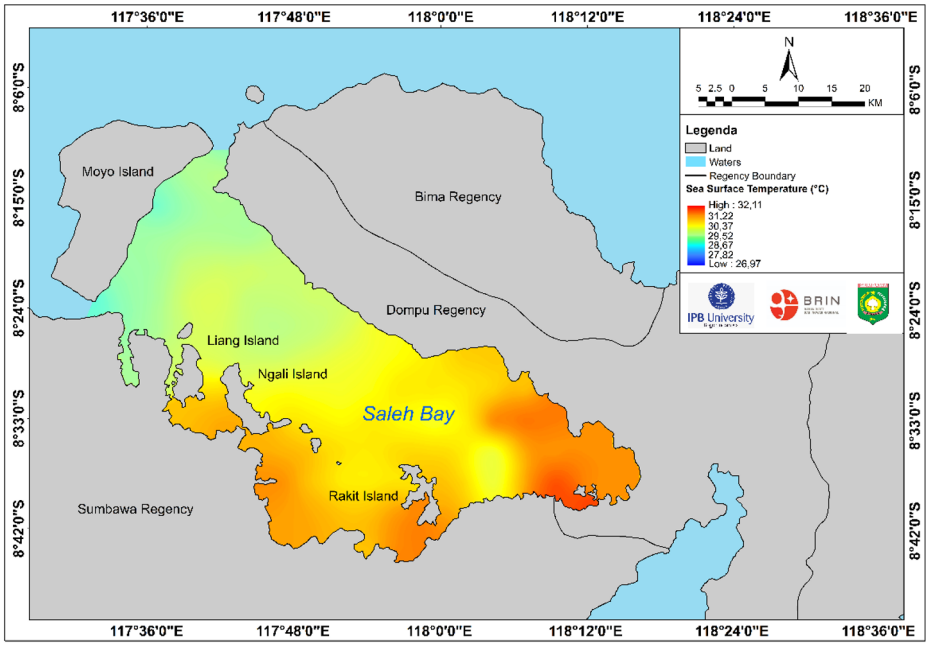

Fig. 4. Map of sea surface temperature distribution in April 2025 in Saleh Bay, West Nusa Tenggara.

3.4 Location of whale shark appearances in Saleh Bay, West Nusa Tenggara

The location of whale shark sightings is an important indicator of the environmental conditions that support the survival of this species, including high plankton availability, optimal sea surface temperatures, and low levels of anthropogenic disturbance [35]. According to [36], whale sharks in Indonesian waters are found in several areas, including Sabang, Padang, Ujung Kulon, Kepulauan Seribu, Probolinggo, East Kalimantan, Bali, Nusa Tenggara, Gorontalo, Central Sulawesi, Maluku, and Papua. **Fig. 5** shows 87 sightings of whale sharks in the Saleh Bay area in April 2025 obtained from field observations and participatory mapping. Based on the monitoring results of [37], who are members of Konservasi Indonesia, who actively monitored the whale shark population in Saleh Bay and have successfully identified more than 100 different individuals in the region from 2017 to 2023, an average of 38 different whale sharks were detected each year. During this period, the highest number of individuals observed in one year was 66, whereas the lowest number was 21. The peak season for whale shark appearance in Saleh Bay is very short, lasting only one month per year in April. This duration is comparable to the peak season in Shib Habil, Red Sea, Yemen, which also lasts only one month, while in Ningaloo Reef, Australia, it lasts four months, and in Baa Atoll, Maldives, it reaches six months. The peak season refers to the period of time in a year when the frequency of whale shark sightings reaches its highest point, both in terms of the number of individuals and consistency of observations. The difference in the duration of the peak season between locations is influenced by various environmental factors, such as food availability, water temperature, ocean currents, and human activity [38].

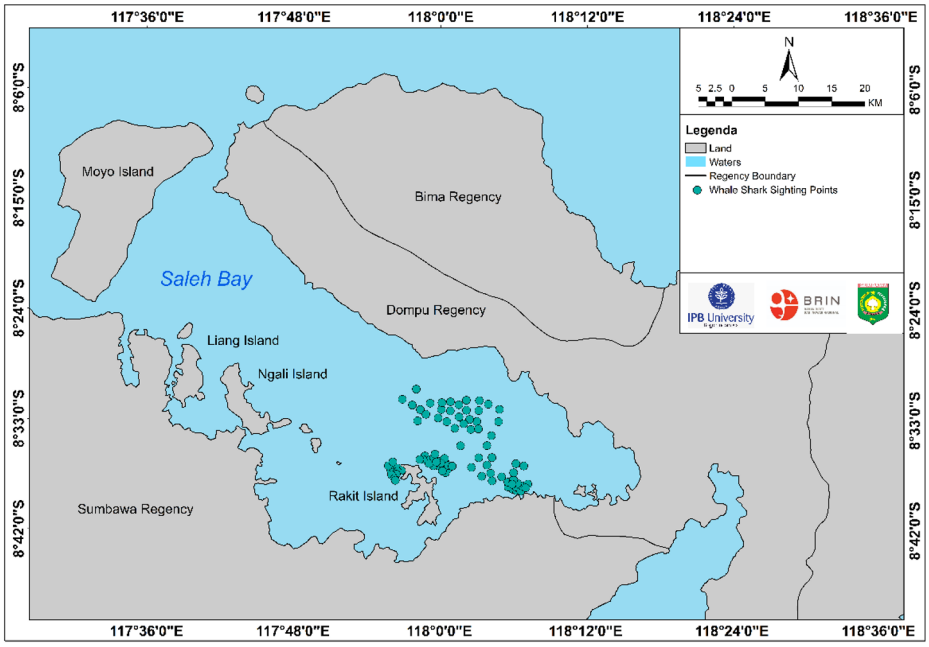

Fig. 5. Map showing the location of whale shark sightings in April 2025 in Saleh Bay, West Nusa Tenggara.

3.5 Location of fishing nets in Saleh Bay, West Nusa Tenggara

The fishing platform locations shown in **Fig. 6** were identified based on field observations and participatory mapping, with 133 fishing platform locations in Saleh Bay between 2022 and 2025. Based on observations and interviews with bagan fishermen using the questions listed above, it was found that whale sharks tend to appear on the sea surface when fishermen begin to pull in their nets, whether they contain small fish or shrimp. This activity appears to be the main trigger for the feeding behavior of whale sharks, which are attracted to small fish trapped in the nets. In addition, it is known that whale sharks can stay around the bagan for quite a long time, up to more than an hour, when there is interaction between humans and whale sharks, for example, through feeding activities by fishermen. Based on the observations of [39], it is known that whale sharks in the waters of Cendrawasih Bay rise to the surface of the sea to search for fish in fishing nets by swimming slowly around the nets and, in a vertical position, sucking in nets containing small fish. This behavior is generally observed in the morning for approximately 15-30 minutes without any human interaction and with a large stock of fish available in the bagan nets. [40] stated that the appearance of whale sharks in the waters of Kwatisore, Papua is strongly related to the number of anchovies caught using bagan. The greater the volume of anchovies stored in the storage container, the faster the whale shark approaches the bagan area and tends to stay in that location for a longer period.

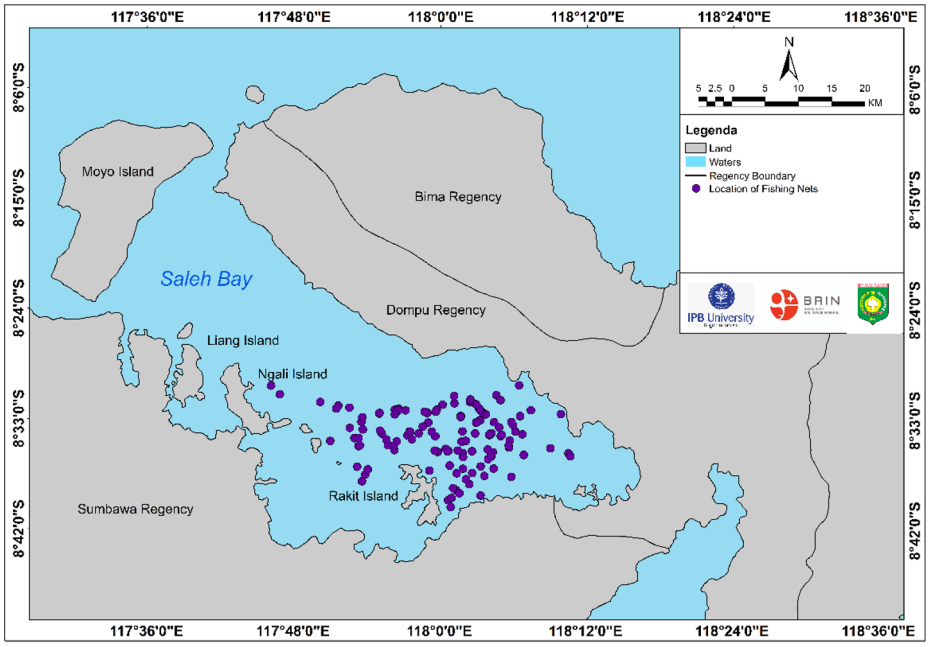

Fig. 6. Map of bagan locations from 2022 to 2025 in Saleh Bay, West Nusa Tenggara

3.6 Coral reef distribution in Saleh Bay, West Nusa Tenggara

Coral reefs in Saleh Bay play an important role in supporting the existence of whale sharks, especially as habitats that indirectly provide food for this species. Whale sharks are planktivores that consume zooplankton, phytoplankton, and small fish, and their populations tend to be high in areas with healthy coral ecosystems. Coral reefs in Saleh Bay were included as target features in the Marxan analysis to represent ecologically important habitats that support marine biodiversity and ecosystem functioning, rather than as direct drivers of whale sharks (*Rhincodon typus*). Coral reef ecosystems play a fundamental role in sustaining complex food webs by supporting high biological productivity and diverse trophic interactions, which indirectly contribute to prey availability at higher trophic levels [7]. The spatial distribution of coral reefs around Liang Island, Ngali Island, and Rakit Island highlights areas of high ecological value that are essential for maintaining the ecosystem integrity in Saleh Bay [41]. Within the framework of spatial conservation planning, coral reefs were selected as conservation targets to ensure that priority areas encompassed representative and functionally important ecosystems, consistent with ecosystem-based management principles. Protecting these habitats contributes to the resilience and persistence of marine ecosystems and indirectly supports whale shark conservation by maintaining productive and stable ecological conditions rather than by assuming a direct causal relationship with whale shark feeding or aggregation [7]. The spatial distribution of the coral reefs is shown in **Fig. 7**.

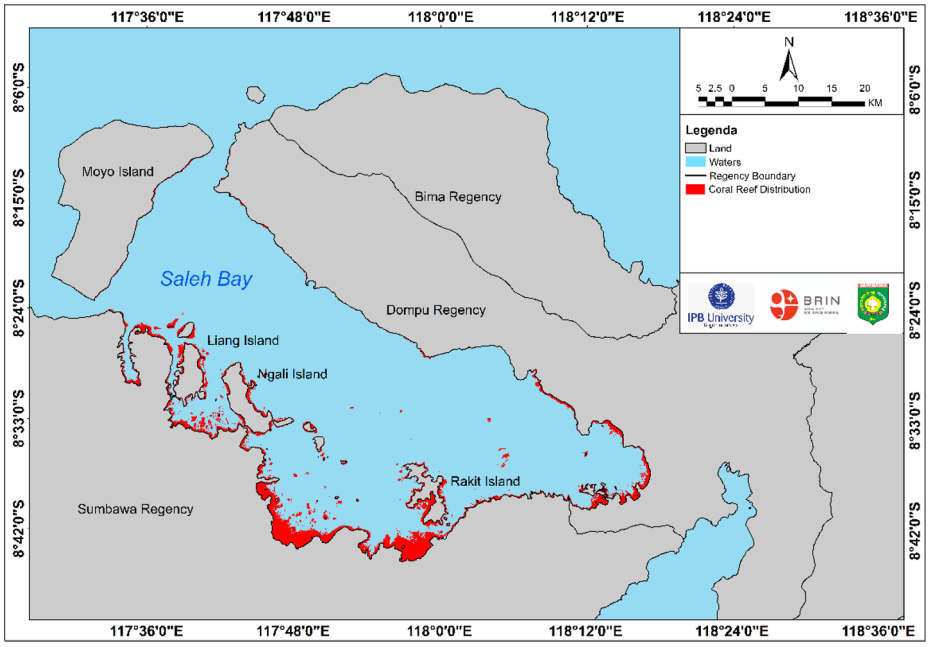

Fig. 7. Coral reef distribution map in Saleh Bay, West Nusa Tenggara.

3.7 Location of the Port in Saleh Bay, West Nusa Tenggara

Fig. 8 shows the locations of the eight ports in Saleh Bay. One of the main activities in coastal areas is port activity, which serves as a means of supporting transportation and other activities [42]. Ports play an important and strategic role in all their activities for industrial and trade growth and are a business segment that can contribute to national development and has a socio-economic impact that is felt significantly by fishermen and is able to attract the attention of the upstream sector [43]. However, their existence also has the potential to negatively impact the marine ecosystem, namely, a decline in the quality of the environment around ports caused by a number of factors such as liquid waste, garbage, air pollution, and other domestic waste. Changes in seawater quality can be observed from changes in water color, increased turbidity, and increased pollution. Sometimes, we also see many dead fish floating on the sea surface and a lot of trash scattered across the sea [44]. These polluted water conditions can disrupt the comfort of the marine ecosystem and cause species such as whale sharks to avoid the area around the port because it is no longer considered a suitable habitat. The water pollution caused by port activities can have a serious impact on the balance of marine ecosystems. This pollution not only affects small organisms, such as plankton and small fish, but also puts ecological pressure on larger species, such as whale sharks. Whale sharks tend to avoid water that has degraded in quality, such as increased turbidity, presence of solid waste, smell of fuel, and other organic waste. This is in line with research by [45] on environmental pollution, including poor waste and sewage management, which has a negative impact on water quality and the distribution pattern of whale sharks in Botubarani Village. The decline in water quality indirectly affects the presence of whale sharks in the area.

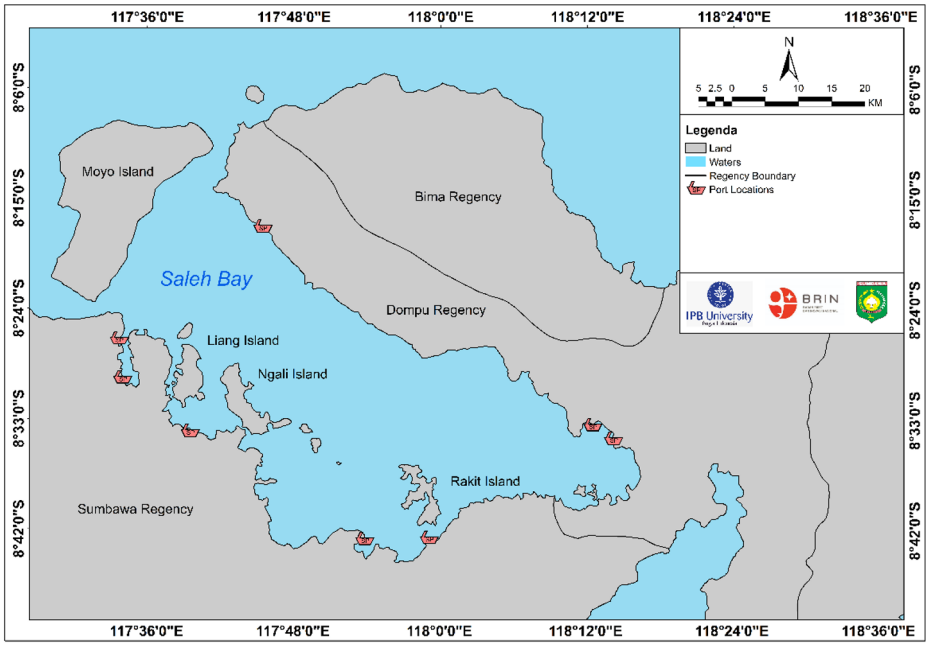

Fig. 8. Map of the location of the port of in Saleh Bay, West Nusa Tenggara

3.8 Settlement locations in Saleh Bay, West Nusa Tenggara

Fig. 9 shows 20 settlement locations in the coastal area of Saleh Bay. Settlements around the waters of Saleh Bay play an important role in coastal environmental dynamics. The main causes are rivers that flow into the sea, waste carried by rivers, including chemicals used as natural fertilizers in agriculture, and waste from livestock and humans, one of the most commonly found detergents. Eutrophication occurs when water becomes too fertile, causing an explosion in the number of algae and phytoplankton competing for light for photosynthesis. Because there are too many, algae and phytoplankton at the bottom will die en masse, and there will be competition for O2 consumption because there are too many organisms in that place. Respiratory waste produces a large amount of CO2, causing the water to become anoxic, leading to the mass death of aquatic animals [46]. A dominant problem for coastal areas, beaches, and the sea is pollution, which causes a decline in the quality and quantity of coastal and marine resources. A decline in water quality will reduce the utility, yield, productivity, carrying capacity, and capacity of water resources, ultimately reducing the wealth of natural resources [47]. According to [48], any change in the ecosystem is vulnerable to anthropogenic activities that can endanger the habitats of fish and other aquatic organisms.

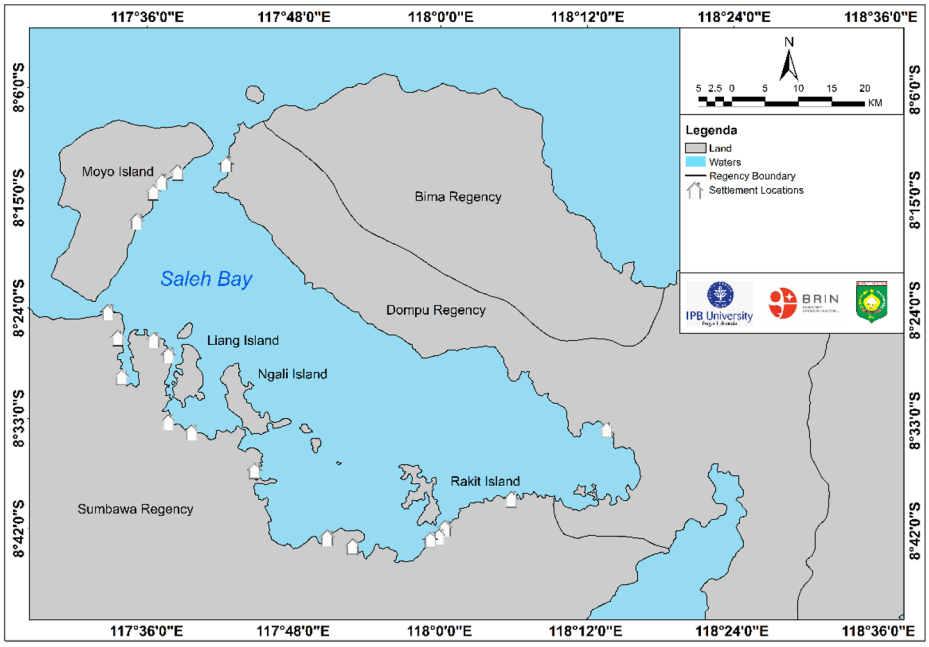

Fig. 9. Map of the location of the settlement in Saleh Bay, West Nusa Tenggara

3.9 Fishermen's boat routes in Saleh Bay, West Nusa Tenggara

Based on the results of participatory mapping, the fishing vessel routes shown in **Fig. 10** were identified, revealing ten fishing vessel routes in Saleh Bay. [38] analyzed the overlap between shipping lanes and the global spatial distribution of whale sharks. The study concluded that 92.4% of the global whale shark range overlapped with shipping lanes, indicating a high potential for collisions. Evidence was found for whale shark deaths due to ship collisions, which are generally undetected (*cryptic mortality)*. Such deaths have likely been systematically underestimated by whale shark population statistics. According to [49], changes in shipping lanes also have the potential to disrupt the survival of whale sharks, which can be injured when struck by passing ships. Whale sharks near ships typically defend themselves by changing their behavior, altering their swimming direction, and exhibiting other changes. Based on research by [50], during monitoring, several individuals were found to have injuries caused by fishing hooks used by fishermen in whale shark interaction zones and ship hulls. Decline in whale shark populations and collisions with ships in recent decades in other countries in the Indo-Pacific [51].

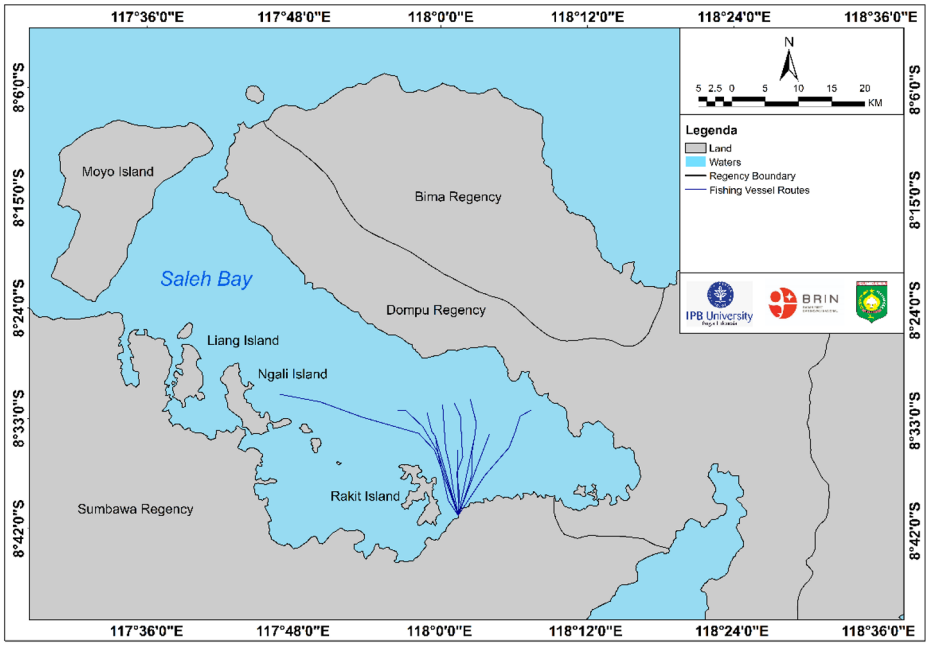

Fig. 10. Map of fishing vessel routes in Saleh Bay, West Nusa Tenggara

3.10 Formation of AOI and *planning unit*

According to [18], one of the most important components of analysis using Marxan is the determination of the boundaries of the study area, known as the Area of Interest (AOI). The AOI was then converted into a planning unit (PU) in the form of a polygon that covered the entire study area. Polygons can be triangular, square, or hexagonal. Of these three, hexagons are considered more efficient because they resemble circles, thus having a smaller edge length ratio and being able to cover the area more optimally [19]. Each PU has an edge length of 500 m. With this size, the area of one PU is 649,500 square meters or equivalent to 64.95 hectares. The Area of Interest (AOI) has a total area of 205,121.45 hectares, which is then divided into 3,480 planning units, slightly more than the theoretical calculation because some PUs are partially cut off or intersecting with the AOI boundaries. Each formed PU has conservation and cost features.

3.11 Determination of scenarios

3.11.1 Target features

According to Ministerial Regulation No. 31 of 2020 [52] concerning the management of conservation areas, the designation of whale shark conservation areas falls under the category of sanctuaries for the protection, preservation, and utilization of biodiversity and/or fish resources. The requirements are that the area must have one type of fish that is distinctive, unique, rare, endemic, and/or endangered in its habitat, which requires protection and conservation efforts to ensure its natural development; has a habitat area of the target species that supports the sustainability of the target species' life cycle; is a place where a certain type of fish that needs to be protected and conserved lives and breeds; and the surrounding

environmental conditions support sustainable fishery development efforts. In this study, these regulatory provisions were used as a policy framework to contextualize conservation planning rather than as a quantitative basis for determining spatial targets. Given that comprehensive habitat mapping for whale sharks beyond occurrence or sighting data remains limited, the 70% core zone criterion is not directly applied in spatial analysis. Instead, conservation priorities are identified using ecological indicators and spatial patterns of species–environment interactions, with regulatory thresholds serving as long-term reference points for future management once robust habitat delineation becomes available. Therefore, in this study, the three scenarios are listed in **Table 5**.

Table 5. Target features for conservation area planning analysis

No	Target Features	Scenario		
		A	B	C
1	Whale Shark Sighting Point	50	60	70
2	Location of the Chart	50	60	70
3	Sea Surface Temperature	20	25	30
4	Chlorophyll	30	35	40
5	Existing Conservation Areas	40	45	50
6	Coral Reef Distribution	30	35	40

Scenario A set a conservation target of 50% for whale shark sightings, which is the regulatory minimum. The 50% conservation target for fishing grounds is directly related to whale shark sightings. A conservation target of 20% for sea surface temperature is based on the importance of optimal temperatures for the comfort and existence of plankton. The conservation target of 30% chlorophyll was based on the indication of areas with abundant food sources. The existing conservation area target is set at 30% because, although the area has good water conditions and is ecologically supportive, based on observational data, there are no whale shark sightings in the area, so it is not a primary focus in the conservation of this species. The coral reef distribution target is 30%, because coral reefs serve as important habitats for various marine biota that support the ecosystem, even though they are not directly related to the presence of whale sharks.

Scenario B sets a target of 60% for whale shark sightings to strengthen the long-term protection of the main habitat of the species. A conservation target of 60% for fishing grounds was chosen, because this area is important for the movement and migration of whale sharks. A conservation target of 25% for sea surface temperature was considered because the optimal temperature is a determining factor for the abundance of plankton, which is their main food source. A chlorophyll conservation target of 35% aims to ensure that food availability is maintained in the conservation area. The existing conservation area target was increased to 45% because even though there are no whale shark sightings, this area is considered to have ecological potential for supporting aquatic ecosystem functions. A coral reef distribution target of 35% was set to protect coral habitats that support primary productivity and the food chain in these waters.

Scenario C set a conservation target of 70% for whale shark sightings to provide full protection for their main habitat. A conservation target of 70% for fishing grounds aims to optimize the protection of areas frequently visited by whale sharks for feeding and migration. A conservation target of 30% for sea surface temperature was set to maintain the optimal environmental conditions for plankton survival. A 40% chlorophyll conservation target was set to ensure food abundance throughout the conservation area. The existing conservation area target has increased to 50% because this area remains an important habitat reserve for other marine biota and for maintaining ecosystem stability. A coral reef distribution target of

40% aims to ensure the maximum sustainability of the coral reef ecosystem as an important habitat and food source for various marine species.

Conservation targets in each scenario were set using a heuristic approach, which is a method of determining targets based on previous experience, commonly used practices, and references from the literature that have been proven effective in conservation planning and have become a common method for developing conservation scenarios using tools such as Marxan. In this approach, features that are considered very important or have a high level of scarcity, such as habitats of threatened species, are usually given greater protection targets, such as 50–100%. In addition, target setting also uses gradual increases in value to facilitate the analysis of the effectiveness of various levels of protection between the scenarios tested [53]. For example, sea surface temperature (SST) and chlorophyll concentration are used as supporting habitat indicators because they both play important roles in determining the availability of plankton and zooplankton as the main food source for whale sharks [31, 34].

3.11.2 Cost feature

Cost features are activities that are thought to threaten the existence of whale sharks [16]. In all scenarios used, the weight values for the cost features remain consistent. The weighting of the cost features in **Table 6** aims to influence the priority of location selection in the final spatial results. The greater the weight given to an area, the less likely it is that an area will be selected as a region with the highest level of protection [24]. A weight of three was assigned to ports and settlements so that planning units containing these features would be excluded from the analysis process because of the high level of pollution that results in a decline in the quality and quantity of coastal and marine resources, causing whale sharks to move away from the waters of Saleh Bay. A weight of 1 is assigned to fishing boat routes so that planning units containing these features will still be considered by Marxan, with a rating of 1 for fishing boat routes to avoid collisions between boats and whale sharks.

Table 4. Cost features for conservation area planning analysis

No	Cost Feature	Weight
1	Port	3
2	Settlement	3
3	Fishermen's Boat Channel	1

3.12 Target protection area

Marxan analysis produces two main types of output: the best solution and the summed solution (ssoln). In this study, the output is the result of the summed solution. The summed solution or solution area is the result of the accumulation of the frequency of selection of each planning unit over thousands of iterations run by Marxan. The values in the summed solution indicate how often a planning unit is selected from the solutions generated during the optimization process. The summed solution helps to identify priority conservation areas that are consistently selected as part of the optimal solution. Areas with high values in the summed solution are considered to have high conservation values and are important for protection [54]. The number of planning units selected based on the class range is listed in **Table 7**.

Table 7. Number of planning units based on *summed solution*

Summed Solution	Number of Planning Units		
	Scenario A	Scenario B	Scenario C
0 – 333	1064	926	797
334 – 666	1587	1174	868
667 – 1000	829	1380	1815
Total	3480	3480	3480

The conservation recommendation map for scenario A in **Fig. 11** shows that most planning units fall into the moderate frequency category (334–666), with the highest number of units being 1587. This indicates that in scenario A, the areas selected as conservation priorities are not dominated by locations that are consistently selected in all iterations of the Marxan modeling. The planning units in Scenario A are spread across various locations, reflecting a more flexible conservation approach in determining priority areas. There are only 829 planning units with a high frequency (667–1000), which means that only a small portion of the study area is consistently selected as a conservation priority location throughout the iteration process. Based on this, it can be said that Scenario A is designed with high spatial efficiency in mind, so that land or water space use can still be optimized for activities other than conservation, such as fishing or marine transportation. In the conservation recommendation map for scenario B shown in Figure 12, it can be seen that the frequency distribution of planning units shows an increase in scenario B. The number of units in the high-frequency category was 1,380, or approximately 39.7% of the total planning units.

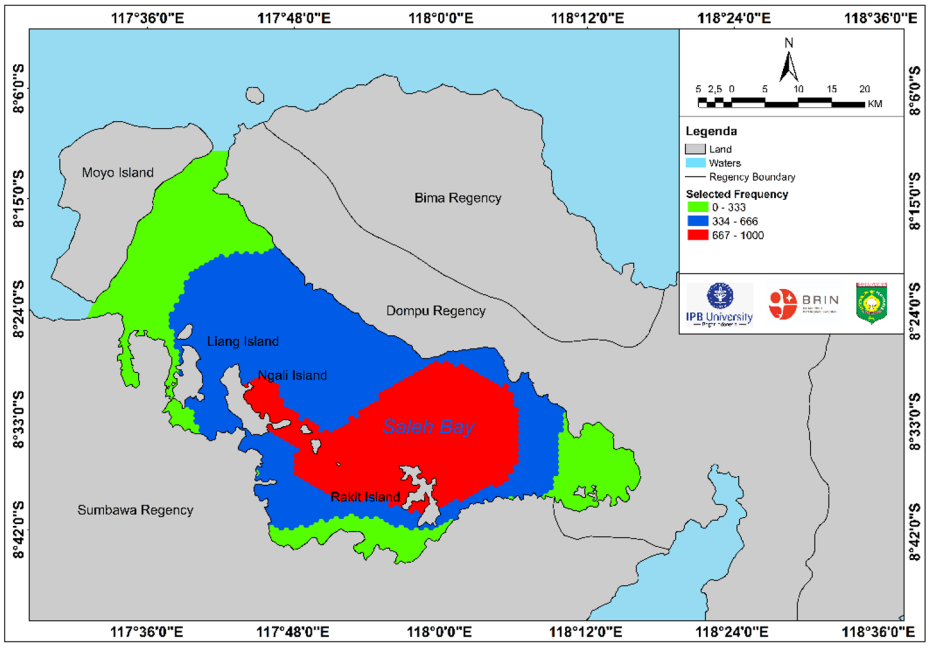

Fig. 11. Map of whale shark protection recommendations for scenario A in Saleh Bay, West Nusa Tenggara

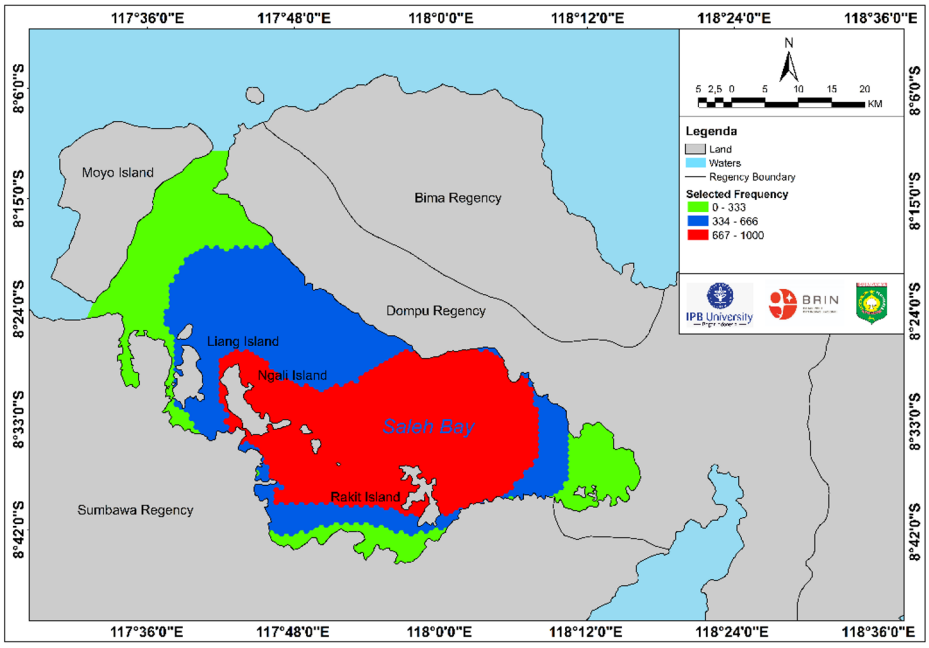

Fig. 12. Map of whale shark protection recommendations for scenario B in Saleh Bay, West Nusa Tenggara

This figure is much higher than that of Scenario A, indicating that in Scenario B, more areas are consistently selected as priority conservation areas in each Marxan iteration. In addition, the number of units in the medium-frequency category remained significant, at 1174 units. This pattern indicates that Scenario B is a compromise between spatial flexibility and ecological protection needs. With an increase in the number of consistent priority areas, it is hoped that target conservation features, such as whale shark emergence points, bagan locations, sea surface temperature, chlorophyll, existing conservation areas, and coral reef distribution, can be better preserved than in Scenario A. However, Scenario B still maintains some flexibility in space allocation, so that the potential for conflicts between the use of space and other activities in the water can be minimized.

Scenario C in **Fig. 13** shows the most distinct distribution pattern of the three scenarios. The number of units in the high-frequency category increased significantly to 1,815, or approximately 52.1% of the total planning units. This means that more than half of the planning area was consistently selected as a conservation priority in all Marxan iterations. In addition, the number of units in the low-frequency category (0–333) decreased to 797, which is the lowest number among the three scenarios. This pattern shows that Scenario C applies a strict conservation approach and tends to focus on the full protection of all the ecological components that have been designated as conservation target features. With its broader coverage, Scenario C can provide comprehensive protection not only for the main habitat of whale sharks, but also for supporting features such as chlorophyll, sea surface temperature, coral reefs, and existing conservation areas. However, this strategy also significantly reduces spatial flexibility, potentially increasing pressure or conflict with other interests in the waters, such as fishing, marine tourism, and sea transportation.

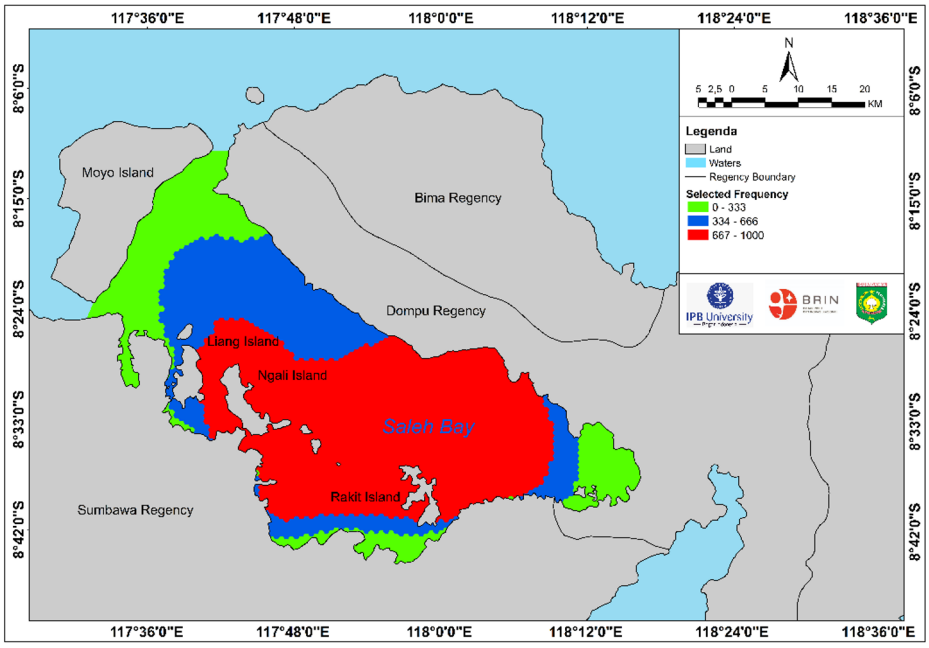

Fig. 13. Map of whale shark protection recommendations for Scenario C in Saleh Bay, West Nusa Tenggara

Overall, the selected frequency results from each scenario provide an overview of the level of importance of an area in supporting the achievement of conservation targets. The higher the conservation target set, the more planning units that are consistently selected in each iteration, which is reflected in the increasing number of units with high frequencies. Scenario A prioritizes efficiency with a minimum regulatory approach, making it suitable for realistic conservation policies with limited scope. Scenario B offers a more balanced approach that combines long-term protection and space-efficiency considerations. Meanwhile, Scenario C demonstrates comprehensive protection efforts for important species and habitats, but owing to its broad scope, its implementation needs to consider potential challenges in the field, whether social, economic, or marine spatial management.

3.13 Scenario results in conservation area studies

In conservation area management, zoning is the division of space into different functions, boundaries, and utilization rules. Each zone was designated to support conservation objectives while allowing sustainable resource use. These zones have specific characteristics such as activities that are permitted, restricted, or prohibited. Zoning can be based on natural features, such as coastlines, or ecological considerations, such as important habitats or species distribution [55]. According to the Regulation of the Minister of Marine Affairs and Fisheries No. 31 of 2020 [52], marine conservation areas are divided into three main zones: core, utilization, and other zones. The core zone serves as an area with full protection of the target biota and ecological processes, where human activities are severely restricted or even prohibited. The utilization zone is designated for sustainable fishing and tourism activities with appropriate supervision and management. The other zone covers conservation areas that are not included in the previous two zones, and its designation is adjusted to the needs or characteristics of the specific area.

In the area recommendation map, the core zone is represented by a frequency of 667–1000 times and is shown in red, indicating the highest priority for conservation. The utilization zone is depicted with a frequency of 334–666 times and is colored blue, representing areas with limited potential for use but still of ecological value. Meanwhile, other zones are illustrated with a frequency of 0–333 times and are colored green, indicating areas with the lowest conservation priority or that can be used for purposes other than primary conservation.

In scenario A (**Table 8**), the core zone covered an area of 48,775.49 ha, or approximately 30.57% of the total conservation area. The utilization zone covers an area of 93,598.33 ha or about 45.60%, while the other zones have an area of 62,747.63 ha or about 23.83%. The larger proportion of the utilization zone compared with the core zone indicates that this scenario emphasizes flexibility in land use and accommodates various utilization activities, but with the consequence of lower protection coverage for the core ecosystem compared with the other two scenarios.

In scenario B, the core zone increased in size to 81,335.26 ha, or approximately 39.66% of the total conservation area. The utilization zone is reduced to 69,176.85 ha, or approximately 33.73%, while other zones cover 54,609.34 ha, or approximately 26.61%. The increase in the percentage of the core zone in this scenario indicates an increase in the priority of protecting areas of high conservation value while still providing a significant portion for utilization and spatial flexibility.

Meanwhile, scenario C shows the most conservative trend, in which the core zone area increases dramatically to 106,947.85 ha or approximately 52.15% of the total conservation area. The utilization zone only covers 51,188.79 ha or about 24.94%, and the other zones cover 46,984.81 ha or about 22.91%. The dominance of the core zone in this scenario indicates a primary focus on protecting ecologically essential areas and important habitats, although it limits the space available for direct human use.

Table 5. Area of conservation zone zoning for each scenario

Scenario	Zoning	Area (ha)	Percentage of Total Area (%)
Scenario A	Core Zone	48,775.49	30.57
	Utilization Zone	93,598.33	45.60
	Other Zones	62,747.63	23.83
	Total per Area	205,121.45	100
Scenario B	Core Zone	81,335.26	39.66
	Utilization Zone	69,176.85	33.73
	Other Zones	54,609.34	26.61
	Total per Area	205,121.45	100
Scenario C	Core Zone	106,947.85	52.15
	Utilization Zone	51,188.79	24.94
	Other Zones	46,984.81	22.91
	Total per Area	205,121.45	100

The design of the selected conservation area must be communicated to stakeholders because although conservation areas have been linked to biological and ecological success, they often face local resistance due to internal restrictions. Lack of public support or acceptance can occur, especially if there is a perception that the benefits of marine conservation areas are not equally shared among stakeholders. Rejection can also take the form of non-compliance with conservation area regulations. If there is too much resistance, conservation planning and management efforts may fail. Therefore, the success of a conservation area often depends on the continued support of stakeholders [56].

4 Conclusion

Planning for whale shark conservation areas in Saleh Bay, West Nusa Tenggara, using the Marxan method, was conducted by incorporating conservation features (including existing conservation areas, sea surface temperature, chlorophyll-a, whale shark sighting locations, fishing platforms, and coral reefs) and cost features (including ports, settlements, and shipping lanes). The results of the three scenarios indicate that increasing conservation targets leads to a proportional increase in the size of the core zone. Scenario A produced a core zone area of 48,775.49 ha (30.57%), Scenario B resulted in 81,335.26 ha (39.66%), and Scenario C yielded 106,947.85 ha (52.15%). While Scenario C prioritizes a broader spatial coverage of areas associated with whale shark occurrence and relevant environmental proxies, it also implies greater spatial constraints for other activities, such as fishing and shipping.

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