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Sustainability THEORY, PRACTICE AND POLICY

Optimization of Fish Aggregating Device (FAD) Distribution Using a Geospatial Approach Based at Pasar Lama Fish Landing Site, Kaur Regency

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ABSTRACT

Kaur Regency is a coastal area in Bengkulu Province with capture fisheries activities dominated by tuna commodities. The use of fish aggregating devices (FADs) by fishermen at the Pasar Lama Fish Landing Site is the main tool for collecting fish. However, increasing the number of FADs without proper management has the potential to cause conflicts in the use of marine space and the degradation of aquatic ecosystems. This study aims to analyze the spatial distribution of FADs and determine the ideal number of FADs based on geospatial and spatial statistical approaches. Data were collected through interviews, participatory mapping, and GPS tracking of fishermen, then analyzed using ArcGIS through the stages of analyzing the distance between FADs (pairwise distance), buffers, overlays with conservation areas and shipping lanes, and scoring based on three criteria: distance between FADs ≥10 nautical miles, outside the conservation area, and the shipping lane. The results showed that all 38 existing FAD points did not meet the distance criteria of ≥10 nautical miles, with 75% of the distance being between 5–10 nautical miles and 2% <1 nautical miles. Scoring also showed that there were no optimal points, and several FADs were in conservation areas. Based on the total distribution area of 9,695.21 km² and the ideal zone area per fish aggregating device of 813.78 km² (calculated based on the 10-nautical-mile minimum distance radius), the ideal number of fish aggregating devices is 12 points. This study emphasizes the importance of Education and supervision of FADs management to support the sustainability of fisheries and the protection of marine ecosystems fairly and sustainably. The findings also offer a spatially driven approach to inform evidence-based policy and support the digital transformation of FADs monitoring systems in coastal fisheries management.

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Introduction

Kaur Regency is one of the areas in Bengkulu Province that has fishing activities, with the main fishery commodity being tuna. Pasar Lama Fish Landing site is one of the main locations for collecting, buying, and selling fishermen's catches in Kaur Regency (Zamdial et al., 2021). Fish aggregating devices are part of the supporting equipment for fishermen, especially those operating at the Pasar Lama Fish Landing site in Kaur Regency in fishing activities, with the main function of collecting fish at a certain location. The study location was chosen because most fishermen used fish aggregating devices, and the waters were adjacent to conservation areas and shipping lanes based on marine spatial planning regulations in Bengkulu Province.

The distribution of fish aggregating devices needs to be studied further to prevent unsustainable practices in capture fisheries activities, including conflicts in the use of sea space between capture and non-capture zones, such as conservation and shipping lanes (Atmaja & Nugroho, 2012; Imzilen et al., 2022; Maufroy et al., 2015; Purnama et al., 2016) and the decline in aquatic ecosystems (Selatan et al., 2019). The use of fish aggregating devices, which continues to experience a significant increase, has the potential to cause socio-economic conflicts among fishermen (Guyader et al., 2018; Pittman et al., 2020; Wudianto et al., 2019). Based on this, the optimal management of fish aggregating devices needs to be a special concern to support sustainable fishery governance and the protection of marine resources.

The geospatial approach through geographic information system (GIS) and spatial statistics is one approach that can identify the problem of fish aggregating device distribution with numerical and visual analysis processes in the form of maps. GIS enables spatial analysis features, such as buffers and overlays, to extract new information from geographic data (Huda et al., 2024; Rahayu et al., 2022; Saefudin & Susandi, 2020). GIS is an effective tool for supporting space-based decision-making (Rahayu et al., 2022; Setiawan, 2016). GIS can simultaneously visualize the relationship between spatial objects in the form of points, lines, and areas, such as analyzing the relationship between fish aggregating device point distribution, conservation areas, and shipping lanes to provide information for space-based decision-making. Spatial statistics can calculate numerical information reflected from spatial data to determine the distance between fish aggregating device points and analyze the ideal number of devices.

To realize sustainable marine resource management, the formulation of effective marine spatial planning policies requires comprehensive supporting data—presented not only in numerical and descriptive form but also visually as maps—to facilitate the understanding of stakeholders at the local and regional levels (Arafat & Kusumarani, 2024; Priyanta, 2021). The presentation of data in the form of geospatial information can provide a view of the distribution of fish aggregating devices based on location, making it more contextual and applicable in the field. Therefore, this method is considered the most appropriate to answer the research objectives to analyze the optimization of fish aggregating device locations and support the realization of marine resource governance by implementing fair and sustainable principles.

Methodology

This research is located at the Pasar Lama Fish Landing Site, Kaur Regency, Bengkulu. This research uses quantitative descriptive through spatial statistical methods and uses primary data as data sources. Primary data were obtained from eight fishermen through interviews, participatory mapping, and GPS tracking to collect information on the spatial distribution and types of fish aggregating devices (FADs) used. A snowball sampling technique was applied to select fishermen and ensure consistency and reliability in the information regarding the coordinates and types of FADs used.

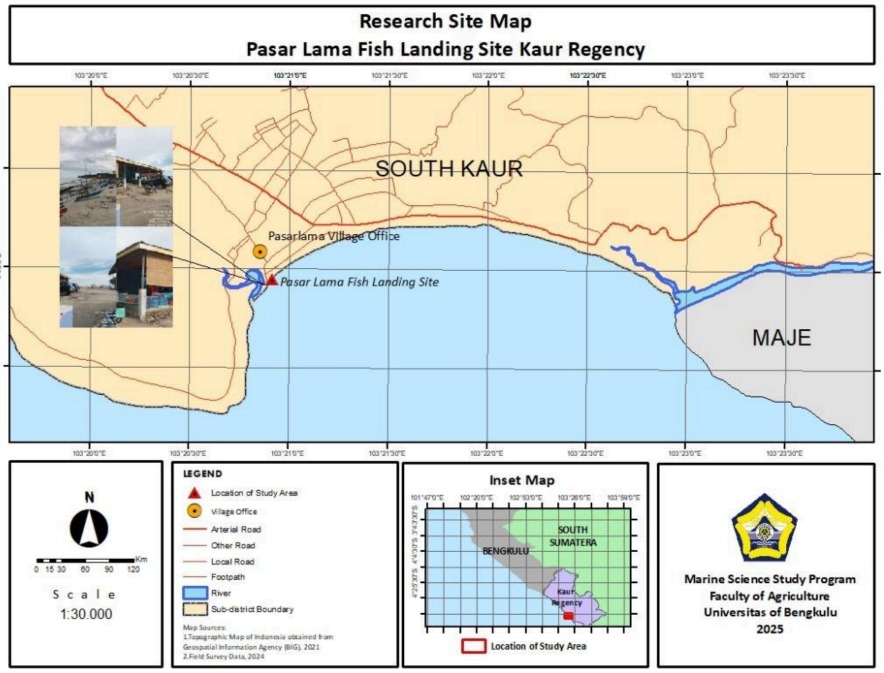

Figure 1. Research Site Map

The spatial distribution location data of fish aggregating devices were analyzed using ArcGIS software. The first step was to use Pairwise Distance Analysis to determine whether the distance between fish aggregating devices complied with the minimum distance requirement of 10 nautical miles based on the regulation of the Minister of Marine Affairs and Fisheries Regulation No. 18 of 2021. This analysis used ArcGIS software through the point distance tool to determine the spatial distribution of the distance between fish aggregating devices, especially if <10 nautical miles or considered too close. The results of the analysis can display fish aggregating device points that are considered not in accordance with applicable regulations and are presented visually through a map. The point distance formula is as follows (ESRI, 2023):

$$PD_{ij} = \sqrt{(X_i - X_j)^2 - (Y_i - Y_j)^2}$$

Information:

$PD_{ij} = distance\ between\ points\ i\ and\ j$

$X_i, Y_i = X\ and\ Y\ coordinates\ of\ point\ i$

$X_i, Y_i = X\ and\ Y\ coordinates\ of\ point\ j$

The second step was to conduct a buffer analysis at each fish aggregating device point. This process aims to strengthen the spatial presentation on the map, where the quantitative distance between fish aggregating devices was previously calculated from the results of the point distance analysis, especially at fish aggregating device points that have a distance of <10 nautical miles. In this process, spatial data preparation is also carried out in the form of conservation areas and shipping lanes based on Regional Spatial Planning Regulation (RTRW) No. 3 of Bengkulu Province for 2023-2043. These data, together with data on the distance between fish aggregating devices, are the main indicators for the analysis of the optimization of the distribution of fish aggregating devices for fishermen at the Pasar Lama Fish Landing Site in Kaur Regency.

The third step involved conducting an overlay analysis of each fish aggregating device point with the conservation area and shipping lane shapefile data. The overlay analysis uses the clip or intersects tool to see the distribution of fish aggregating device points, whether they are inside or outside the conservation area and shipping lane. The overlay results obtained were continued with a scoring analysis with 3 (three) main criteria, namely:

1. Distance between fish aggregating devices is more than 10 nautical miles (X1) = 1, otherwise 0.
2. Located outside the marine conservation area (X2) = 1, otherwise 0.
3. Located outside the shipping lane (X3) = 1, otherwise 0.

Scoring can be conducted using the following formula:

$$S = X_1 + X_2 + X_3$$

Information:
S = Total score of fish aggregating device location
X1, X2, X3 = Score for each criterion
Basis for scoring:
If S = 3, then the fish aggregating device location is optimal.
If S < 3, then the fish-aggregating device location is not optimal.

In the fourth step, after obtaining the results of the scoring of the FAD location by obtaining optimal or non-optimal status at each FAD point, an analysis of the ideal number of FADs was carried out based on the main indicator of the distance between FADs ≥ 10 nautical miles. This analysis requires the area of FAD distribution and the area of the zone per FAD unit. The area of FAD distribution was calculated using ArcGIS through the buffer method with an area of 10 miles at each FAD point, and continued with the dissolving method to combine all buffer results into one and avoid overlapping in ArcGIS. The data results from the dissolving method were summed into a total area, which was the area of all FADs. The area of the zone per FAD uses the calculation of the area of a circle as follows:

$$A = \pi r^2$$

Information:
$\pi = 3,1416$

$r = minimum\ distance \geq 10\ nautical\ miles\ (16,093.4\ meters)$

After obtaining the distribution and zone areas per fish aggregating device, the two areas were compared to obtain the ideal number of fish aggregating devices.

Result and Discussion

Result

The results of the study showed that fishermen at the Pasar Lama Fish Landing Site in Kaur Regency had 38 fish aggregating devices (FADs) spread across the waters of Kaur, Manna, Krui, and Enggano Islands. The types of FADs in Kaur Waters have a fixed-type classification. These FADs consist of parts such as buoys, attractor ropes, attractors and weights. The buoys have a size of 200 liters in the form of 1 blong. The attractor rope has 12 m on each rope connection made of 12 mm nylon, which is made into three pairs and connected six times. The attractor was in the form of banana leaf stems tied with an attractor rope. The FAD weights used 60 × 100 cm blocks totaling eight with the function of balancing the FADs so that they did not move or shift. FAD weights can differ to adjust to the conditions of the area, such as those found in Bone and Jeneporto Regencies, which use mountain stones or limestone (Hikmah et al., 2016; Nurwahidin & Setianto, 2019).

The management of the distribution of urgent fish aggregating device points focuses on optimizing their locations to achieve the goal of sustainable use of marine space. Three important indicators were selected in this study to analyze the optimization of fish aggregating device point locations. First, the distance between fish aggregating device points should be considered to ensure sustainable use of space so that fishery resources can be managed in the future. Second, the area of conservation areas needs to be considered so that they do not become locations for fish aggregating device points to protect aquatic ecosystems. Third, the suitability of shipping routes to avoid conflict in the use of marine space, especially in the field of general shipping, docks, and ship traffic areas. Sustainable marine resource management is reflected in a series of efforts to achieve a balance between economic utilization and protection of marine ecosystems (Fonner et al., 2020; Priyanta, 2021; Ward et al., 2022).

Table 1. Categorized Pairwise Distances Between FAD Locations

Category	*Numbers of Point Pairs*	*Percentage*
< 1 nautical mile	*2*	*2%*
1-3 nautical miles	*8*	*8%*
3-5 nautical miles	*14*	*15%*
5 - ≤10 nautical miles	*72*	*75%*
≥ 10 nautical miles	*0*	*0%*
Total	*96*	*100%*

The calculation results using Pairwise Distance Analysis showed that most of the distances between fish aggregating devices were included in the category of 5–≤ 10 nautical miles, with a percentage of 75%. Meanwhile, the distance between fish aggregating devices was 3-5 nautical miles in 15% of the responses. The distance between fish aggregating devices between 1-3 nautical miles is 8%, and 2% have a very close distance of fish aggregating devices, namely <1 nautical mile. The analysis of the distance between fish aggregating devices identified that all fish aggregating device points have a distance of ≤ 10 nautical miles, meaning that they do not meet the requirements based on the rules of the Minister of Marine Affairs and Fisheries Regulation No. 18 of 2021. The results of the analysis showed that the closest distance between fish aggregating devices was 0.96 nautical miles, and the furthest distance was 9.84 nautical miles.

The scoring results in this study indicate that there are no fish aggregating device points that have an optimal category, namely fish aggregating devices that meet all criteria, including a distance between fish aggregating devices ≥ 10 nautical miles, not entering a conservation area, and not being on a shipping lane. This is because all fish-aggregating device points do not meet the criteria for the distance between fish-aggregating devices, and there are fish-aggregating device locations that are in a conservation area, while all fish-aggregating device points are not on a shipping lane.

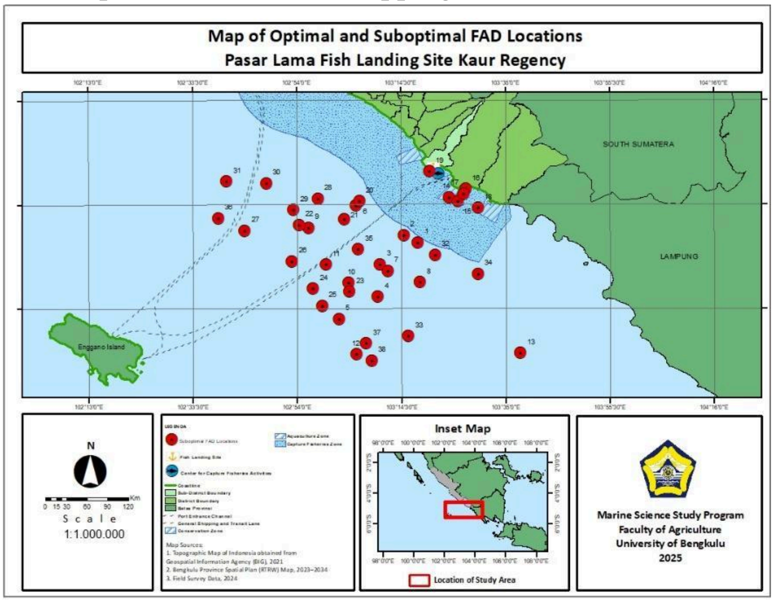

Figure 2. Map of Optimal and Suboptimal FAD Locations

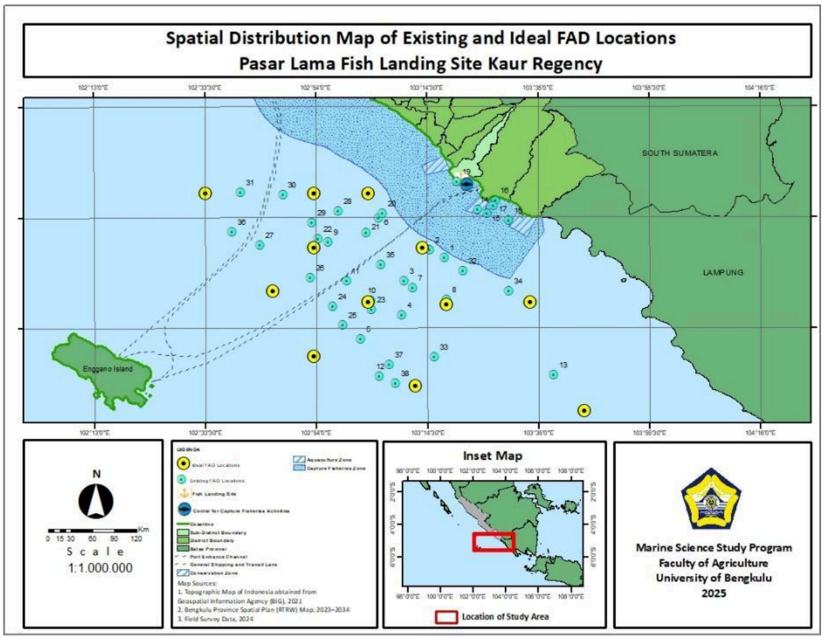

Figure 3. Spatial Distribution Map of Existing and Ideal FAD Locations

This study conducted calculations based on the existing conditions of the distribution of fish aggregating device locations to calculate the ideal number of fish aggregating devices that should be used by fishermen at the Pasar Lama Fish Landing Site, Kaur Regency. The area of the fish aggregating device distribution from the calculation results was 9695.21 km^2, and the area of the zone per fish aggregating device with the rule of distance between fish aggregating devices ≥ 10 nautical miles was 813.78 km^2. Therefore, based on this information, by comparing the area of distribution and the area of the zone per fish aggregating device, the ideal number of fish aggregating devices should be 11.91 or 12 fish aggregating devices.

This study, which attempts to calculate the ideal number of fish aggregating device placements in the waters of Kaur Regency, is expected to provide input for relevant stakeholders in formulating capture fisheries management policies based on the principles of justice and sustainability.

Discussion

The spatial analysis revealed that none of the 38 existing fish aggregating devices (FADs) met the legal distance requirement of ≥10 nautical miles, and the ideal number of FADs based on the total distribution area is only 12. This significant gap between the current practice and regulatory standards reflects underlying issues in awareness and decision-making among local fishermen. Based on the results of observations and interviews, one of the causes is due to the community's ignorance regarding the regulation. Likewise, related to the way fishermen determine the location of relatively uniform fish aggregating devices (FADs), such as looking at the characteristics of the waters because there are flocks of birds, watercolor, water ripples and prioritizing experience and instinct so that the spatial pattern of fish aggregating devices (FADs) is close to each other.

This condition is also found in fishermen in Pelabuhanratu who have not complied with regulations regarding the distance of fish aggregating devices (FADs), even though they continue to implement informal rules in the form of social ethics (Depari et al., 2022). Effective placement of fish aggregating devices is still a note, such as research in Bone Bolangi waters, which found that the fish aggregating device deployment technique was inefficient (Asruddin & Nasriani, 2018).

This research provides novelty in utilizing spatial analysis through geographic information systems and spatial statistics to assess the level of effectiveness of existing fish aggregating devices (FADs) distribution while estimating the ideal number of FADs that should be based on applicable regulations. The approach in this study can be an initial foothold to realize data-based FAD governance (evidence-based policy) and encourage the transformation of digital-based FAD monitoring and observation systems in the future.

The results of this study indicate the need for supervision of the location of fish aggregating devices, as well as education for fishermen regarding the benefits and objectives of the regulation. Education aims to maintain fishermen's compliance with regulations and foster a caring attitude toward the long-term function of sustainable fish-aggregating device management. Fishermen at the Pasar Lama Fish Landing Site, Kaur Regency, are worried that they will face a situation of decreasing catches and fighting over fishing areas that risk causing conflict between fishermen if the practice of placing fish aggregating devices is left as it is currently.

Research related to the distribution of fish aggregating devices can provide broader research developments, especially related to the topic of measuring fishery carrying capacity, which is closely related to the aspects of availability and needs. Analysis related to fish aggregating devices can contribute to these two aspects, namely the aspect of availability, by estimating the potential of fish resources based on the distribution of existing fish-aggregating devices. The aspect of needs is to describe the potential exploitation of fish resource utilization based on the activities of fishermen at each fish aggregating device point.

The minimum distance requirement of 10 miles between fish aggregating devices is also interesting for further discussion. The question that arises is whether the distance imposed by the regulation is ideal and applied uniformly across all regions. What about the fishermen in the Kaur Regency? Future research requires multidisciplinary involvement in studying this with a comprehensive approach to understanding the dynamics of social, economic, and biophysical aspects, as well as multisector stakeholder involvement, to enrich recommendations for contextual and adaptive policy formulations.

Conclusion

This study shows that the management of fish aggregating devices (FADs) by fishermen at the Pasar Lama Fish Landing Site in Kaur Regency has not fully met the principles of sustainable marine spatial management. Based on the results of the pairwise distance analysis, all 38 FAD points spread across the waters of Kaur, Manna, Krui, and Enggano Island Regencies have a distance between points of ≤10 nautical miles, which does not meet the minimum distance requirements between FADs according to the Ministerial Regulation of KP No. 18 of 2021. In addition, none of the FAD points based on the scoring results met all the criteria (distance, conservation area, and shipping lane), indicating their status as suboptimal FAD locations.

The calculation of the ideal number of fish aggregating devices based on the area of distribution and minimum distance rules shows that only 12 fish aggregating devices are needed, which is much less than the current number. This indicates excessive use of space and the potential for excessive pressure on fish resources in the future. This discrepancy is influenced by the lack of knowledge of regulations among fishermen, as well as traditional methods for determining the location of fish aggregating devices that are not based on ecological or legal considerations. Therefore, strengthening supervision, ongoing education, and policy adjustments based on data and local contexts are needed.

Given that this study evaluates compliance with the existing regulation—a regulation that itself may not be fully adaptive to local ecological and socio-economic contexts—future research becomes crucial to review the technical provision of the minimum distance between FADs. This study also emphasizes the importance of developing further research to measure fisheries carrying capacity based on both the potential and the exploitation pressure around fish aggregating devices (FADs). Such research should adopt a multidisciplinary approach that integrates biophysical, social, and economic aspects to ensure more context-sensitive and adaptive policy recommendations.

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Competing Interests

The author(s) declare no competing interests.

Data Availability

The datasets generated during and/or analysed during the current study are not publicly available due ethics related to protecting the privacy and confidentiality of research participants but are available from the corresponding author on reasonable request.

AI Use Declaration

The authors did not use AI tools at any stage of the research process, including data collection and analysis. All research activities were conducted independently by the authors without AI assistance for language editing, structural refinement, and phrasing improvements. All research activities and writing were conducted independently by the authors, who are fully responsible for the content and any errors.

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