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Spatial Analysis of Potential Fishing Zones (PFZ) for Tuna in Parangtritis Waters Based on Sea Surface Temperature, Chlorophyll-a, and Bathymetry

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Abstract

Parangtritis possesses significant fisheries potential, particularly for tuna; however, this potential remains underutilized due to poorly managed information on fishing grounds. This study aims to identify Potential Fishing Zones (PFZ) for tuna in Parangtritis waters based on oceanographic parameters, namely sea surface temperature (SST), chlorophyll-a concentration, and bathymetry. The analysis utilizes MODIS Aqua satellite imagery (July 2021–June 2022) and GEBCO bathymetric data, processed spatiotemporally using Geographic Information Systems (GIS). The results indicate that PFZ were detected only in August, September, and October 2021, as well as April 2022, with a total of 55 identified points. The highest distribution occurred in September 2021, coinciding with chlorophyll-a concentrations reaching 25.378 mg/m³ and SSTs falling within the optimal range of 25.17–25.95°C, conditions that enhance primary productivity and support the base of the tuna food web. The PFZ points were generally located more than 3.5 nautical miles offshore at depths of approximately 100 meters. These findings reveal an ecological relationship among SST, chlorophyll-a, and bathymetry in shaping the habitat preferences of tropical tuna. This approach demonstrates the effectiveness of remote sensing and GIS-based oceanographic data in predicting tuna habitats, supporting small- to medium-scale fisheries, and integrating modern technology with local ecological knowledge.

Keywords : PFZ, tuna fish, sea surface temperature, chlorophyll-a, satellite imagery, remote sensing

1. INTRODUCTION

Coastal regions around the world are not only ecologically rich but also offer substantial economic potential, especially through sustainable fisheries. In Indonesia, the southern coastal region of Java, notably Parangtritis in Bantul Regency, Yogyakarta, is widely recognized for its tourism appeal. However, recent insights suggest that this area also holds significant promise for the fisheries sector, particularly in large pelagic species like tuna and skipjack, whose stocks are still underutilized and potentially sustainable [1]. The integration of fisheries and tourism has been emphasized as a strategic opportunity to enhance local economic growth, provided it is managed collaboratively and sustainably [2]. Development models that merge marine resource utilization with tourism such as community-led coastal enterprises, have proven effective in other Indonesian regions like North Sumatra [3]. This dual-sector synergy aligns with Indonesia's broader blue economy strategy and presents a geographically and economically viable pathway for regional development [4].

Despite the potential, field interviews with local fishers indicate that tuna fishing in Parangtritis remains constrained by traditional methods relying on intuition and historical fishing patterns. These conventional approaches often fail to incorporate dynamic oceanographic variables such as sea surface temperature (SST) and chlorophyll-a concentration, which significantly influence tuna distribution. As a result, fishing efficiency is reduced, while fuel costs and resource waste increase [5]. The integration of satellite-based remote sensing data and Geographic Information Systems (GIS) has been shown to enhance real-time identification of Potential Fishing Zones (PFZ), especially for pelagic species such as tuna [6]. These technologies can significantly improve catch success rates and minimize unnecessary search efforts. For example, SST and chlorophyll-a concentrations have demonstrated predictive capabilities for fishing grounds with up to 73.6% accuracy, underscoring the critical role of oceanographic variables in effective fishery planning [6].

A strategic and scientifically grounded approach to improving tuna fisheries involves mapping PFZ using environmental parameters derived from remote sensing. Studies have established SST, chlorophyll-a, and bathymetry as primary indicators of tuna distribution [7]. In tropical Indonesian waters, high tuna concentrations are typically associated with SST ranging from 26°C to 31°C and chlorophyll-a levels between 0.1 to 2.6 mg/m³ [8], [9]. The use of satellite-derived environmental data enhances operational accuracy and reduces fishing time, contributing to more sustainable practices [7]. Fishing grounds are traditionally identified using visual cues such as seabird activity, sea foam, or ripples, yet these are often inconsistent. Modern approaches leveraging SST, chlorophyll-a, and bathymetric data offer more

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precise and consistent alternatives [9], [10]. For instance, skipjack and yellowfin tuna are typically found in areas with SST between 29–31°C and chlorophyll-a concentrations between 0.14–0.44 mg/m³ [5], [7].

The ecological significance of chlorophyll-a lies in its function as a proxy for primary productivity and phytoplankton biomass, which form the foundation of marine food webs. Waters with chlorophyll-a concentrations above 0.2 mg/m³ are generally nutrient-rich and support fish aggregation [11]. SST regulates fish metabolism and reproduction, directly affecting spatial distribution [12]. Bathymetry, reflecting ocean depth, is equally important in determining habitat suitability and migratory behavior, particularly for species with depth-dependent preferences. These three parameters are now reliably monitored via satellite-based systems, including MODIS for SST and chlorophyll-a, and GEBCO for global bathymetric models, all of which can be integrated into GIS platforms to support habitat assessment and fisheries management [13].

Tuna species such as Yellowfin (Thunnus albacares), Albacore (Thunnus alalunga), and Bigeye (Thunnus obesus) display distinct habitat preferences primarily governed by temperature and depth. Bigeye tuna possess advanced vertical mobility, often diving beyond 500 meters into colder, low-oxygen zones [14]. Conversely, Yellowfin and Albacore typically occupy shallower waters above the thermocline, preferring temperatures between 26–30°C and depths under 200 meters [15]. These ecological behaviors inform targeted fishing strategies, such as optimal timing and depth for gear deployment [16]. Yellowfin tuna, in particular, exhibit diel vertical migration, remaining near the surface at night and diving during the day, at depths of 80–100 meters where water temperatures range from 21–27°C. Bigeye tuna favor deeper layers around 150 meters with temperatures between 10–23°C, while Southern Bluefin tuna inhabit depths up to 200 meters, preferring 12–16°C [17]. Vertical temperature gradients and thermocline shifts play crucial roles in influencing juvenile tuna distribution and have thus become essential components in identifying ecologically sustainable PFZ [18].

In Parangtritis, local tuna fishing generally occurs at shallow depths around 30 meters, resulting in smaller-sized catches. Activities are often conducted from evening to early morning, in alignment with diel vertical migration behavior. These observations are corroborated by scientific studies linking tuna movement to thermal stratification and monsoonal shifts in Indonesian waters [19]. Therefore, integrating local ecological knowledge with oceanographic data and remote sensing technologies can significantly improve the precision and sustainability of tuna fishing practices in the region.

This study aims to address the need for spatially informed tuna fisheries management in Parangtritis waters by employing a spatial analysis approach using SST, chlorophyll-a, and bathymetry data to delineate PFZ. By utilizing remote sensing and GIS, the research enables objective mapping of tuna habitats, enhancing both the accuracy and efficiency of PFZ identification. Prior studies in southern Java and the Coral Triangle have demonstrated that SST and chlorophyll-a are critical predictors of tuna presence and fishing productivity [7], [20]. The integration of these parameters into spatial models supports more informed decision-making for sustainable tuna exploitation.

The findings of this research are expected to contribute to the development of more efficient, science-based tuna fisheries in Indonesia, particularly in underutilized yet promising coastal regions like Parangtritis. By replacing intuition-driven practices with data-driven spatial analysis, this study supports the broader goals of marine resource sustainability, economic optimization, and coastal community resilience.

2. RESEARCH METHODOLOGY

This study adopted a spatial analytical approach integrating geospatial technologies, satellite remote sensing, and participatory data collection to identify and delineate potential fishing zones for tuna in Parangtritis waters. The methodological framework was designed to capture the spatiotemporal variability of key oceanographic parameters influencing tuna distribution, namely sea surface temperature, chlorophyll-a concentration, and bathymetric depth. By combining quantitative data from Earth observation systems with qualitative insights from local fishers, this research aims to develop a scientifically robust and contextually grounded spatial model. The entire methodological process encompasses data acquisition, preprocessing, spatial analysis, validation, and cartographic representation, each of which is elaborated in the following subsections.

2.1 Study Area

This research was conducted in the coastal waters of Parangtritis, located in Parangtritis Village, Kretek Subdistrict, Bantul Regency, Special Region of Yogyakarta, Indonesia. The selected study area encompasses marine zones with depths reaching up to 475 meters, reflecting the typical vertical distribution range of tuna species within Indonesian seas. The geographical boundaries of this area were defined in accordance with the administrative and oceanographic characteristics of the region, which are illustrated in Figure 1. This specific location was selected due to its ecological relevance, proximity to artisanal fisheries, and data availability.

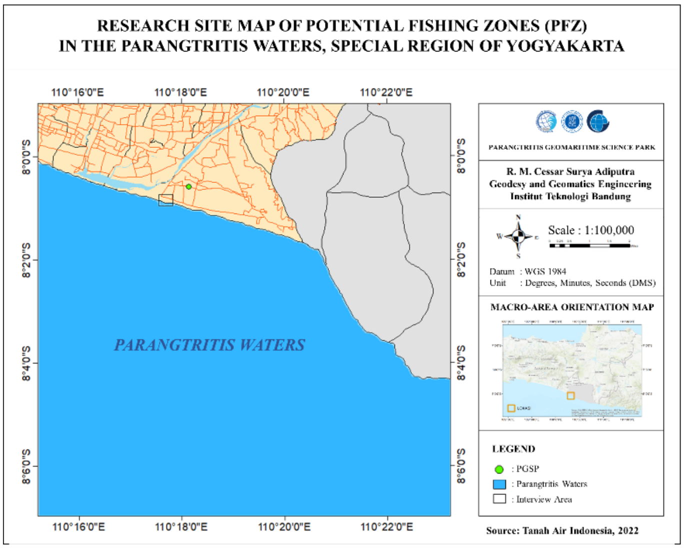

Figure 1. Research location

2.2 Data Sources and Instrumentation

The study utilized a combination of primary and secondary data obtained through both field observations and remote sensing archives. Primary data were collected via structured interviews with artisanal tuna fishers operating along Depok Beach and Parangtritis Beach, both of which are situated in Kretek Subdistrict, Bantul Regency. These interviews were audio-recorded using mobile devices and subsequently transcribed into concise summaries for qualitative comparison with spatial model outputs. Secondary data comprised several key geospatial datasets, as detailed in Table 1. Administrative boundary data of Bantul and Gunung Kidul Regencies were acquired in SHP format from Ina-Geoportal in 2022. Monthly composites of sea surface temperature and chlorophyll-a concentration for the years 2021 to 2022 were retrieved from Aqua MODIS Level-3 satellite imagery in NetCDF format, accessible via the NASA OceanColor web portal. These datasets possess a spatial resolution of 4 kilometers and have been preprocessed to Level-3, which includes both radiometric and geometric corrections, as well as automated application of remote sensing algorithms for oceanographic parameters. Bathymetric data were obtained from the GEBCO database in 2022 in GeoTIFF format, providing depth information with global consistency and integration-ready structure for GIS-based modeling.

Table 1. Research data

No	Data Type	Format	Source	Year
1	Administrative Boundaries of Bantul and Gunung Kidul Regencies (1:100,000)	SHP	Ina Geoportal http://tanahair.indonesia.go.id	2022
2	Sea Surface Temperature from Aqua MODIS Level-3 Satellite Imagery	Nc.	NASA https://oceancolor.gsfc.nasa.gov/	2021-2022
3	Chlorophyll-a from Aqua MODIS Level-3 Satellite Imagery	Nc.	NASA https://oceancolor.gsfc.nasa.gov/	2021-2022
4	Bathymetry	TIF	GEBCO https://www.gebco.net/	2022

The data processing and spatial analysis were carried out using a Lenovo laptop equipped with an AMD Ryzen 7 4700U processor, Radeon Graphics, 16 GB RAM, and Windows 11 Home 64-bit operating system. This hardware was used to run several essential software tools as listed in Table 2. SeaDAS version 8.2.0 was employed for image subsetting and pixel-based data extraction. Microsoft Excel was used for basic data statistics, including the calculation of minimum, maximum, and mean values for chlorophyll-a, SST, and bathymetry. ArcGIS version 10.6.1 was utilized for spatial interpolation, reclassification, overlay analysis, and cartographic visualization. Microsoft Word served as the primary platform for compiling the research report and documentation.

Table 2. Research equipment

No	Equipment	Description
1	Laptop Lenovo AMD Ryzen 7 4700U with Radeon Graphics CPU @2.00GHz (8 CPUs) RAM 16GB OS Windows 11 Home 64-bit	Used for research report preparation, data processing, and analysis

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2	SeaDAS 8.2.0	Used for satellite image cropping
3	Microsoft Excel	Used for data extraction and calculation of maximum, minimum, and average values of chlorophyll-a, SST, and bathymetry
4	ArcGIS 10.6.1	Used for data processing
5	Microsoft Word	Used for writing the research report

2.3 Data Processing and Spatial Analysis Workflow

The methodological workflow is comprehensively visualized in Figure 2, which presents a sequential diagram of the data acquisition, processing, and analytical procedures undertaken throughout the study. The first stage involved data collection from three principal sources, namely remote sensing imagery, bathymetric databases, and field interviews. Aqua MODIS satellite data were downloaded in monthly temporal resolution to overcome cloud cover interference prevalent in daily scenes, which often results in missing digital numbers. These composite images were radiometrically and geometrically corrected and are thus suitable for spatial modeling of ocean parameters. The satellite imagery was cropped to match the geographical extent of Parangtritis waters using SeaDAS 8.2.0, followed by extraction of pixel-based values for SST, chlorophyll-a, and bathymetry.

The second stage involved spatial interpolation using the Inverse Distance Weighting (IDW) algorithm implemented in ArcGIS 10.6.1. This algorithm estimates values for unsampled locations based on the proximity of known data points and was applied separately to each oceanographic parameter. The interpolated raster surfaces were then converted into contour maps to facilitate visual interpretation and spatial segmentation. Subsequently, a reclassification process was carried out to categorize each raster dataset into ecologically relevant suitability classes that reflect tuna habitat preferences. These reclassified layers were further processed through overlay analysis to identify zones where optimal SST, chlorophyll-a, and bathymetric conditions intersect spatially.

Overlay operations were conducted to generate a composite map containing only the intersecting zones from all three parameters. These intersecting points were exported into a new shapefile format, and their X and Y coordinates were extracted and stored in the attribute table. A spatial query was executed on the attribute table to isolate features that satisfied the criteria for potential tuna habitats, based on the combined suitability of SST, chlorophyll-a, and depth. Fields that did not contribute to the indication of tuna presence were removed using the delete field function. The resulting dataset provided a precise spatial distribution of PFZ for tuna within the Parangtritis study area.

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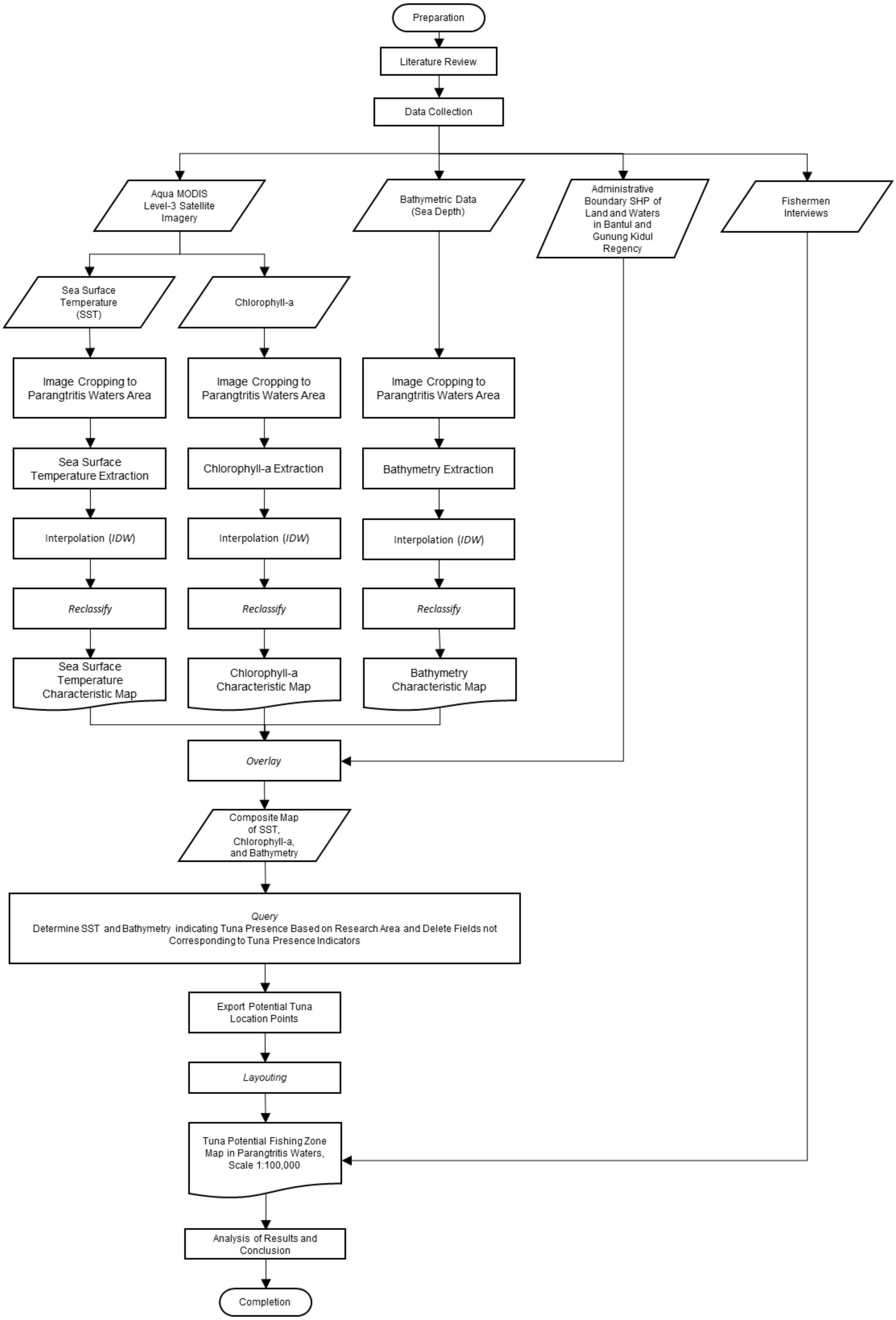

Figure 2. Data processing flowchart

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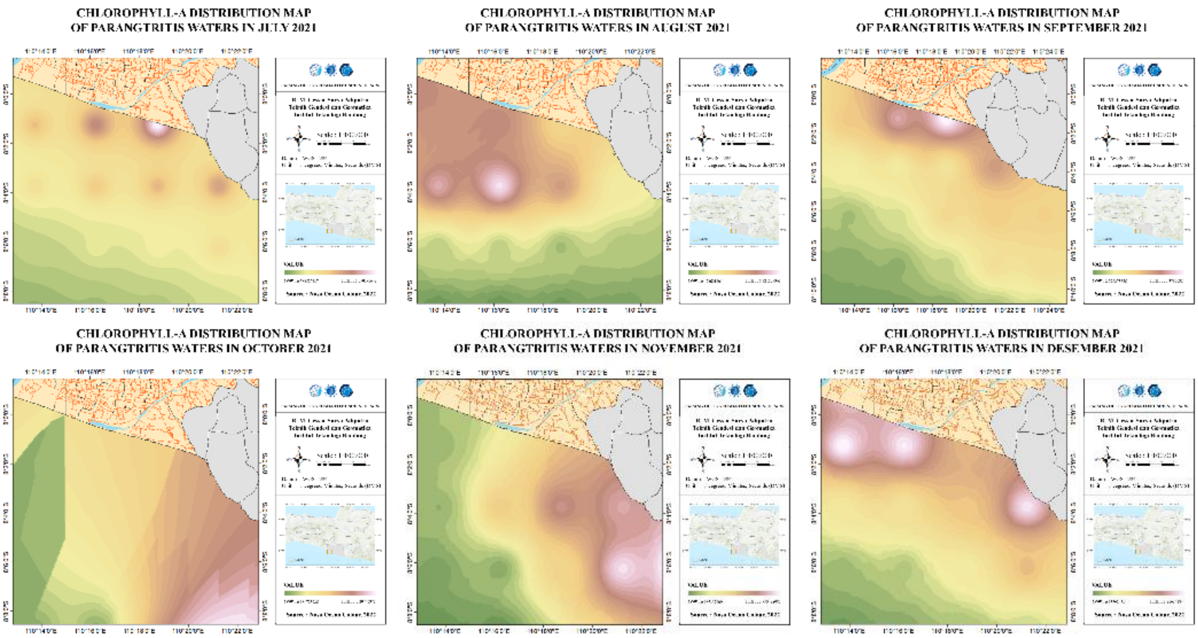
2.4 Mapping and Validation

After determining the PFZ, the spatial data were exported and plotted to visualize the point distribution of potential tuna habitats. A final cartographic layout was developed at a scale of 1 to 100,000 to ensure readability and applicability for resource management and fisheries planning. The resulting spatial distribution was then compared against empirical knowledge obtained from local fishers during the interview stage. This qualitative validation approach was used to assess the coherence between modeled PFZ and traditional ecological knowledge of tuna occurrence. The analytical process concluded with a comprehensive interpretation of the influence of sea surface temperature, chlorophyll-a concentration, and bathymetric depth on the spatial distribution of tuna fishing grounds in the study area. Insights drawn from this analysis provide evidence-based recommendations for sustainable tuna fisheries management and spatial planning in southern Yogyakarta's coastal zone.

3. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the oceanographic parameters that influence the presence and distribution of tuna in Parangtritis waters. Spatial and temporal variations in SST, chlorophyll-a concentration, and bathymetry were examined to determine their ecological relevance to tuna habitat preferences and potential fishing zones. These parameters were selected based on their established roles in pelagic fish ecology, particularly in supporting biological productivity and structuring trophic interactions in the marine environment. To facilitate a detailed understanding, each parameter is analyzed individually using spatial maps, temporal graphs, and statistical tables, allowing for the identification of patterns and potential zones with favorable conditions for tuna aggregation. The following subsections describe the monthly distribution and dynamics of each variable, starting with chlorophyll-a concentration, which serves as a proxy for phytoplankton biomass and overall primary productivity in the study area.



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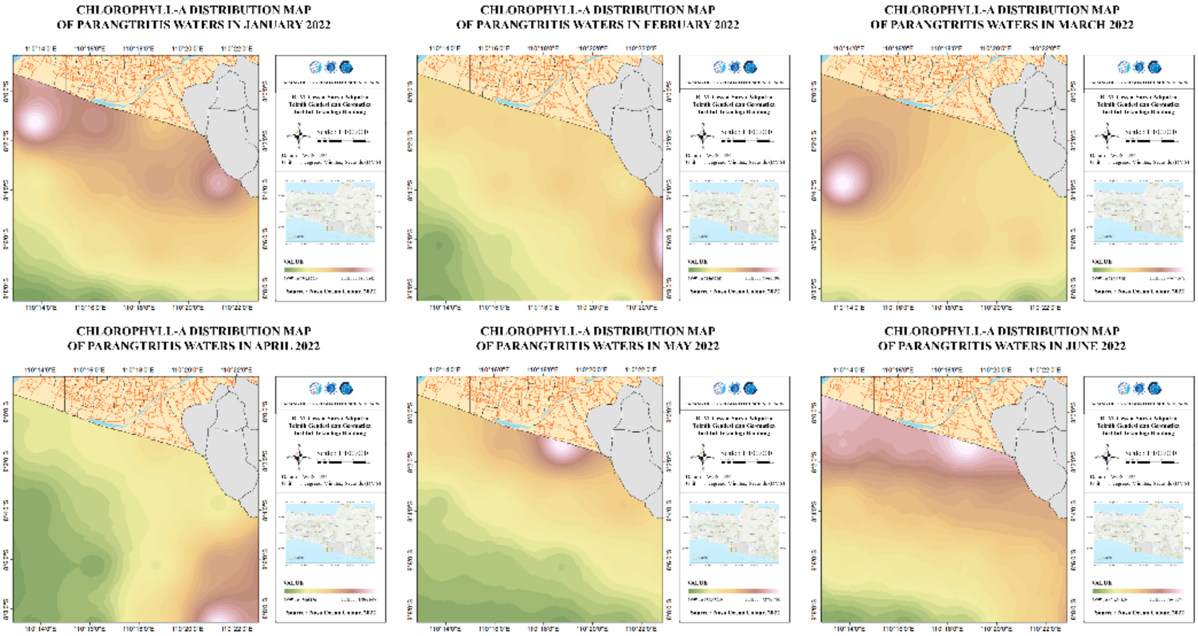
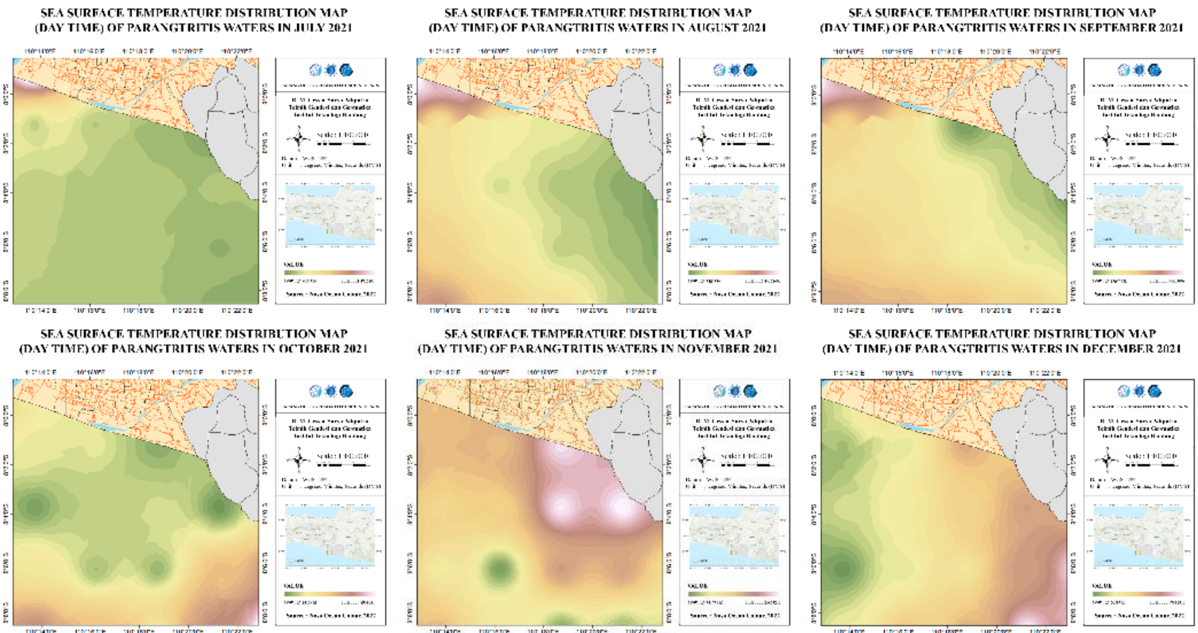


Figure 3. Chlorophyll-a distribution map in Parangtritis waters (July 2021 – June 2022)

The spatial distribution of chlorophyll-a concentration in Parangtritis waters from July 2021 to June 2022 displayed notable monthly variability, reflecting dynamic primary productivity levels. The average chlorophyll-a concentration across this period was 3.005 mg/m³, which is considerably higher than the 0.2 mg/m³ threshold commonly recognized as an indicator of fertile marine areas. The highest recorded concentration occurred in September 2021, reaching 25.378 mg/m³, a value indicative of phytoplankton blooms. These elevated concentrations were primarily concentrated in nearshore zones, possibly driven by terrestrial nutrient input, river discharge, or wind-driven upwelling. The abundance of chlorophyll-a suggests increased phytoplankton biomass, which forms the base of the marine food web and directly supports higher trophic levels, including zooplankton, small pelagic fish, and ultimately tuna. This is ecologically significant because tuna species such as Thunnus albacares and Thunnus obesus rely on these prey organisms for foraging, particularly in areas where prey density is sufficient to support energy-efficient feeding. Reports from local fishers further support this observation, noting that tuna catches are more substantial during nighttime operations in shallow waters, where high chlorophyll concentrations coincide with prey accumulation. Thus, chlorophyll-a serves as a strong biological indicator for identifying productive feeding grounds and potential tuna fishing zones.



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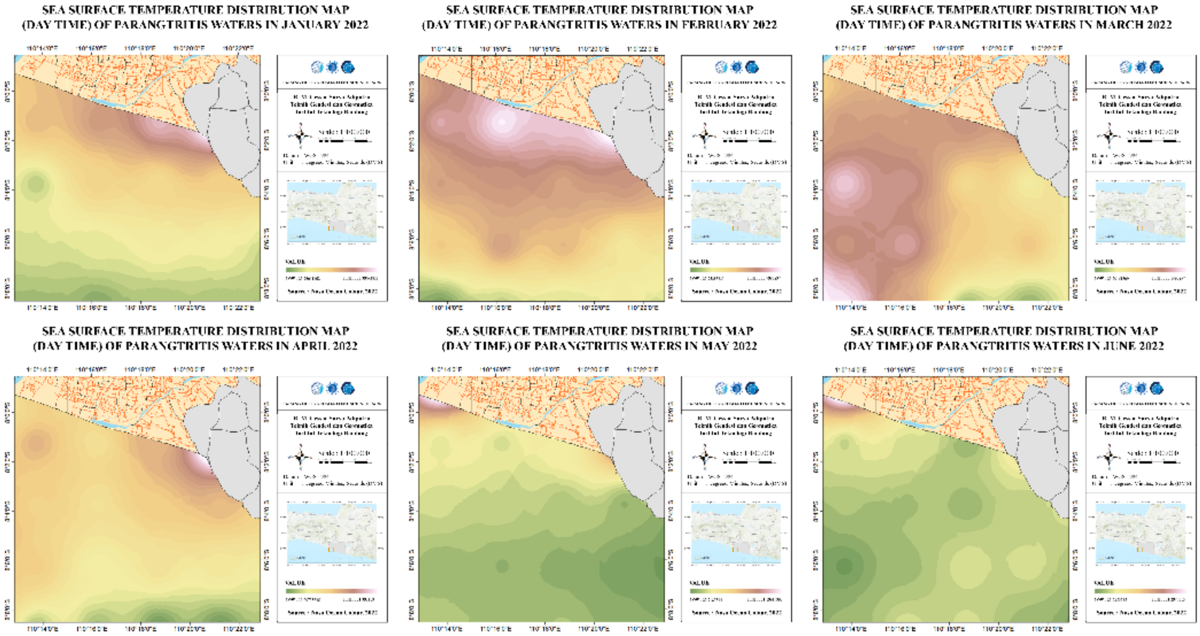
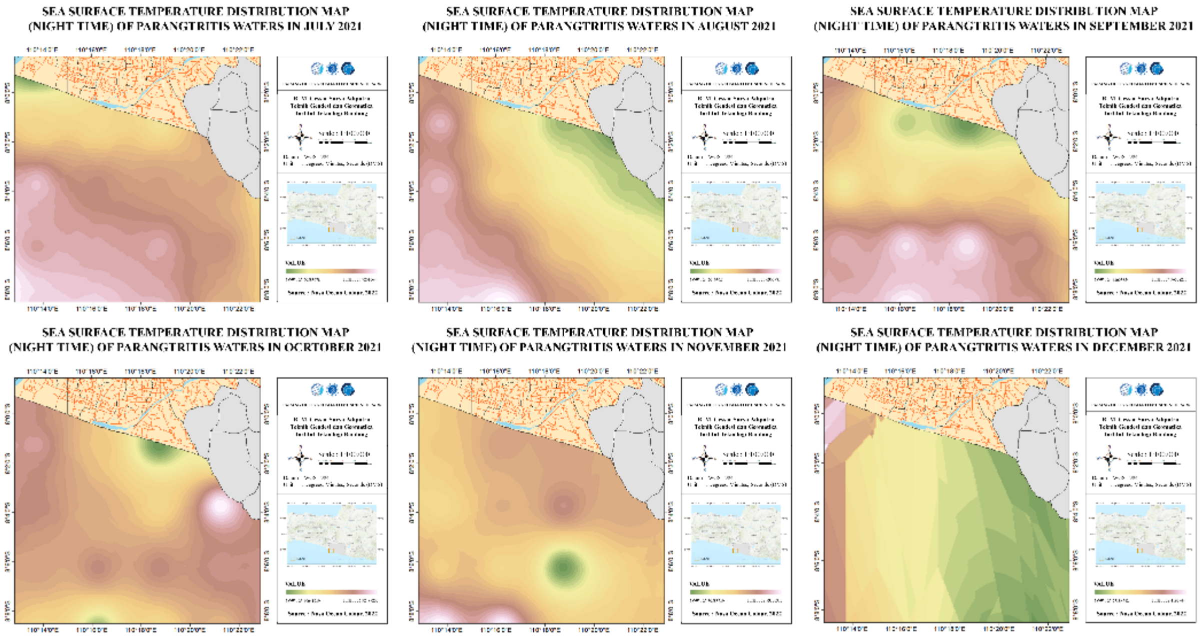


Figure 4. SST daytime distribution map in Parangtritis waters (July 2021 – June 2022)

The SST daytime over the study period varied between 25.17°C and 32.39°C, with a mean of 29.323°C. This range encompasses the optimal thermal window for several tropical tuna species. Specifically, previous studies have demonstrated that Yellowfin tuna (Thunnus albacares) and Albacore (Thunnus alalunga) exhibit strong physiological and behavioral preferences for surface waters within the 28°C to 31°C range. Monthly analysis indicates that SST values during January, February, and April 2022 consistently fell within this range, indicating periods of enhanced thermal suitability. These conditions likely facilitated favorable metabolic performance, feeding efficiency, and habitat utilization for tuna. In tropical pelagic systems, such thermal conditions often coincide with thermocline shoaling and increased prey availability in upper water layers. From a fisheries perspective, these periods represent windows of opportunity for maximizing catch efficiency, particularly when integrated with chlorophyll-a data to locate biologically active zones. Furthermore, the SST spatial patterns observed in Figure 4 may reflect the influence of large-scale ocean-atmosphere interactions, such as monsoonal cycles or equatorial current variations, which modulate heat distribution across the southern Java coastal waters.



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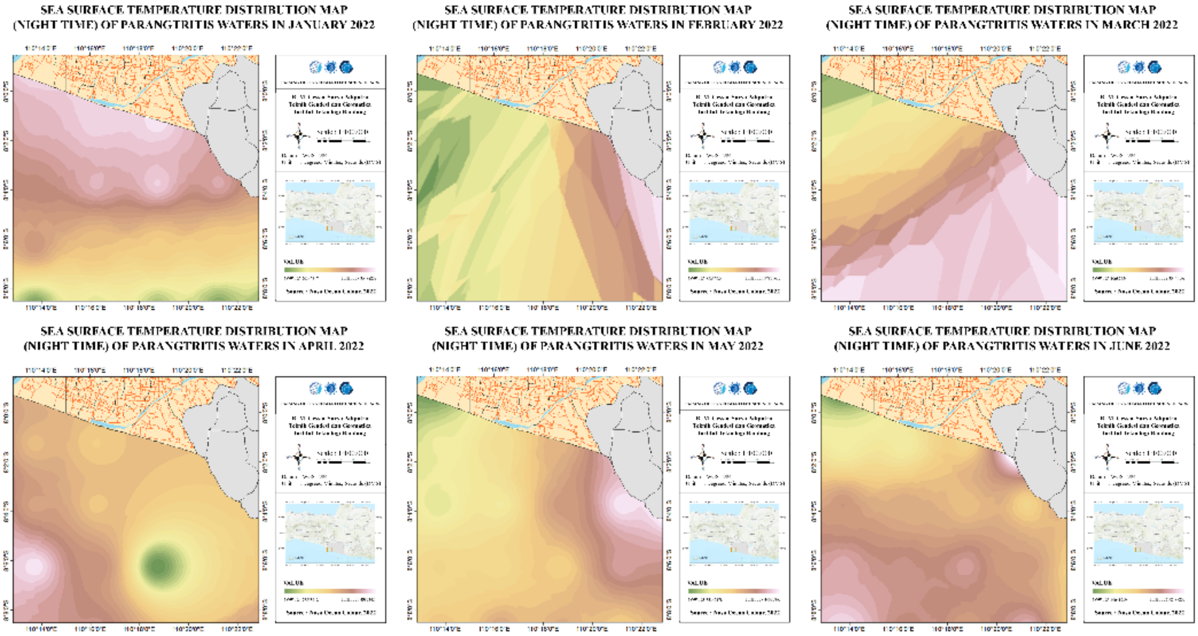

Figure 5. SST nighttime distribution map in Parangtritis waters (July 2021 – June 2022)

Nighttime SST ranged from 24.43°C to 29.45°C, with an overall mean of 27.341°C. These values tend to be slightly lower than their daytime counterparts, consistent with diurnal cooling effects due to reduced solar radiation and enhanced longwave radiation loss. Importantly, the lower nighttime SST may promote vertical migration behaviors among pelagic predators such as tuna, which often ascend from deeper, cooler waters to the surface at night to feed. This diel vertical migration (DVM) strategy enables tuna to balance foraging needs with predator avoidance and thermoregulation. The SST night data in several months, including September 2021 and March 2022, show conditions just below or at the lower bound of the optimal thermal range, potentially acting as a cue for surface aggregation of tuna. These findings align with observational data from artisanal fisheries, where catch rates are reportedly higher during nocturnal hours. The nighttime SST analysis further highlights the importance of temporal dynamics in tuna habitat modeling, as static or averaged SST maps may fail to capture diel ecological processes relevant to fishing success.

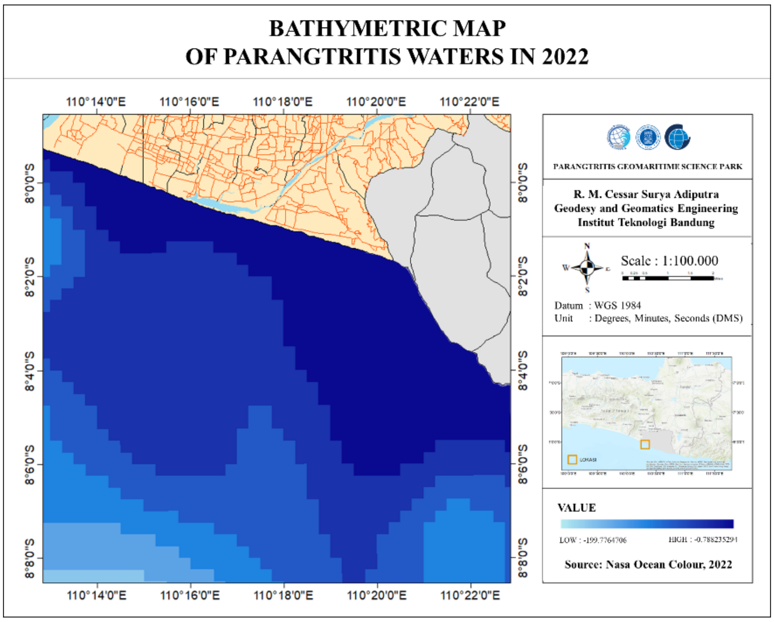

Figure 6. Bathymetric map of Parangtritis waters (2022)

The bathymetric profile of Parangtritis waters reveals a complex seabed morphology, with depths ranging from approximately -0.79 m nearshore to -199.78 m offshore, and a mean depth of -100.28 m. This depth range overlaps with the vertical habitat preference of major tuna species. Yellowfin tuna, for example, are known to occupy depths of 80–100

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meters during daylight hours, especially when surface temperatures rise beyond their thermal optimum. In contrast, Bigeye tuna (Thunnus obesus) exhibit deeper diel foraging patterns, often descending to mesopelagic zones during the day and ascending at night. The bathymetric structure of the study area, with its moderate slope and accessible depth gradient, allows for these vertical movements while also promoting the aggregation of prey species such as squid and small fish. Moreover, the interaction between bathymetry and ocean currents can result in localized upwelling and nutrient enrichment, indirectly boosting surface productivity. The observed alignment between bathymetric contours and fishing effort intensity in this region supports the hypothesis that seafloor topography plays a crucial role in shaping tuna distribution and availability.

Table 3. Summary of minimum, maximum, and average values for chlorophyll-a, SST (Daytime), and SST (Nighttime)

	Min			Max			Mean		
Month	Chlorophyll-a (mg/m^3)	SST Daytime (°C)	SST Nighttime (°C)	Chlorophyll-a (mg/m^3)	SST Daytime (°C)	SST Nighttime (°C)	Chlorophyll-a (mg/m^3)	SST Daytime (°C)	SST Nighttime (°C)
Jul-21	0.363	27.695	27.206	5.050	31.483	27.726	2.706	29.589	27.466
Aug-21	0.473	25.856	29.902	6.322	26.444	25.697	3.397	26.150	27.799
Sep-21	2.998	25.170	24.430	25.378	25.948	24.965	14.188	25.559	24.698
Oct-21	0.162	27.153	25.490	0.207	27.896	26.925	0.185	27.525	26.208
Nov-21	0.167	29.354	27.306	3.993	30.260	28.591	2.080	29.807	27.948
Dec-21	0.158	29.906	27.974	1.816	30.588	28.419	0.987	30.247	28.197
Jan-22	0.060	29.960	27.903	2.382	32.391	29.355	1.221	31.176	28.629
Feb-22	0.215	29.953	27.683	3.497	30.798	27.979	1.856	30.376	27.831
Mar-22	0.218	29.702	27.101	1.977	30.149	28.334	1.098	29.925	27.718
Apr-22	0.489	30.007	24.976	7.200	31.393	27.498	3.845	30.700	26.237
May-22	0.188	29.918	28.853	4.427	31.199	29.447	2.308	30.559	29.150
Jun-22	0.602	29.235	25.490	3.786	31.298	26.925	2.194	30.266	26.208
Average	0.508	28.659	27.026	5.503	29.987	27.655	3.005	29.323	27.341

Quantitative analysis of chlorophyll-a and SST across the twelve-month observation period reveals significant ecological variability. The minimum chlorophyll-a value of 0.06 mg/m^3 was recorded in January 2022, while the maximum of 25.378 mg/m^3 occurred in September 2021. The substantial seasonal fluctuation highlights dynamic nutrient cycling, likely influenced by both natural oceanographic processes and anthropogenic inputs. SST (daytime) ranged from 25.17°C to 32.39°C, with a monthly mean peaking in January 2022, while nighttime SST showed a narrower range but retained ecological relevance due to its role in nocturnal tuna activity. These inter-monthly variations underscore the importance of multi-temporal analysis in identifying periods of optimal habitat suitability for target species.

Table 4. Summary of bathymetric data

	Min	Max	Mean
Year	Bathymetry		
2022	-199.776	-0.788	-100.282

The depth data compiled in Table 4 confirm that the study area encompasses both shallow coastal zones and deeper offshore regions, forming a gradient that supports a variety of pelagic habitats. The average depth of -100.28 m provides sufficient water column for vertical stratification, which in turn supports species-specific behavioral patterns such as foraging, spawning, and diel vertical migration. This variability in seafloor depth is also advantageous for small-scale fisheries, as it permits the use of multiple gear types and increases the likelihood of intercepting different life stages of tuna and associated species.

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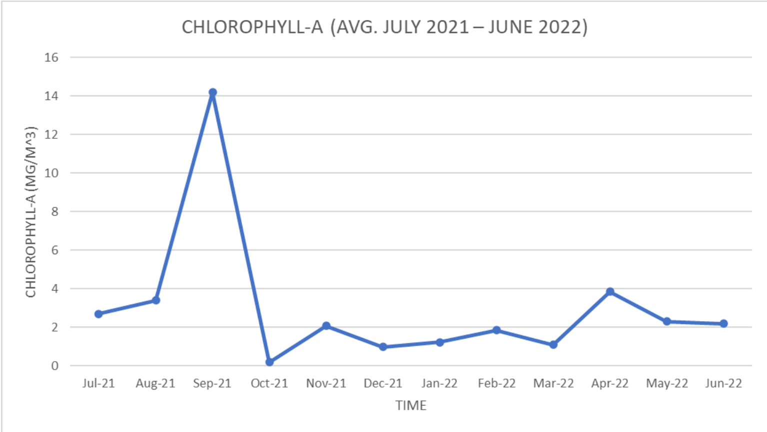

Figure 7. Average chlorophyll-a graph (July 2021 – June 2022)

Monthly chlorophyll-a trends illustrate distinct peaks and troughs across the study period. The most pronounced spike occurred in September 2021, likely reflecting a significant upwelling event or freshwater-induced nutrient enrichment. Such primary productivity surges are typically followed by trophic responses across higher levels, including zooplankton blooms and small pelagic fish aggregation. The correspondence between high chlorophyll-a levels and reported fishing success suggests that this parameter can be used not only for ecological monitoring but also for operational fisheries forecasting.

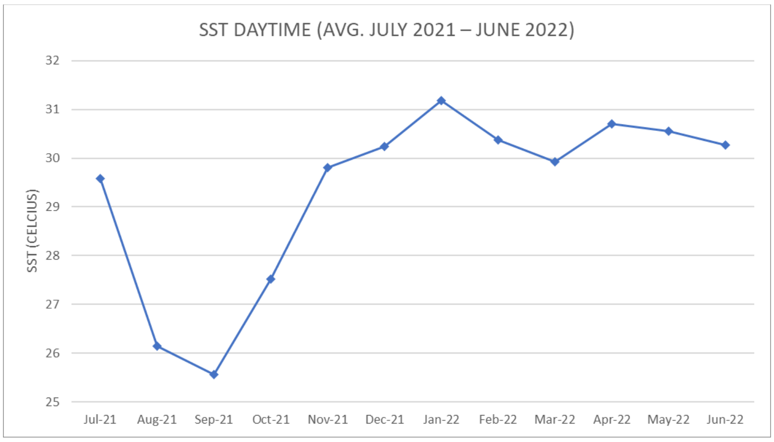

Figure 8. Average SST daytime graph (July 2021 – June 2022)

Daytime SST trends exhibit a general warming tendency from mid-2021 through early 2022, peaking in the austral summer months. This thermal increase may correspond with seasonal solar heating and the weakening of the southeast monsoon, which normally brings cooler waters to southern Java. The data indicate that optimal thermal conditions for tuna were more prevalent in the early months of 2022, offering predictable periods for strategic fishing deployment.

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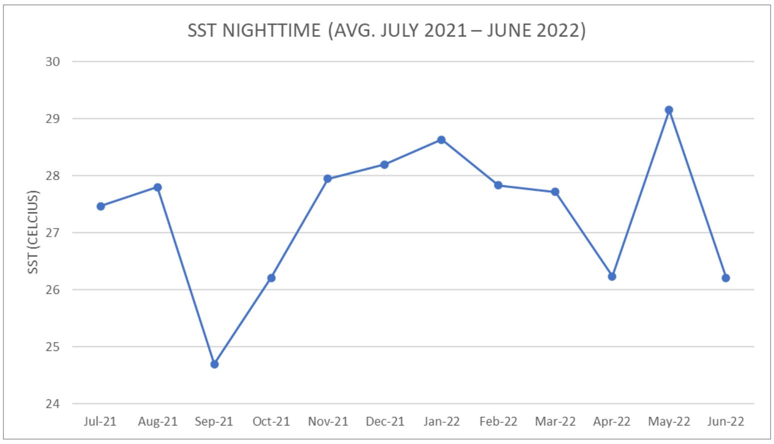
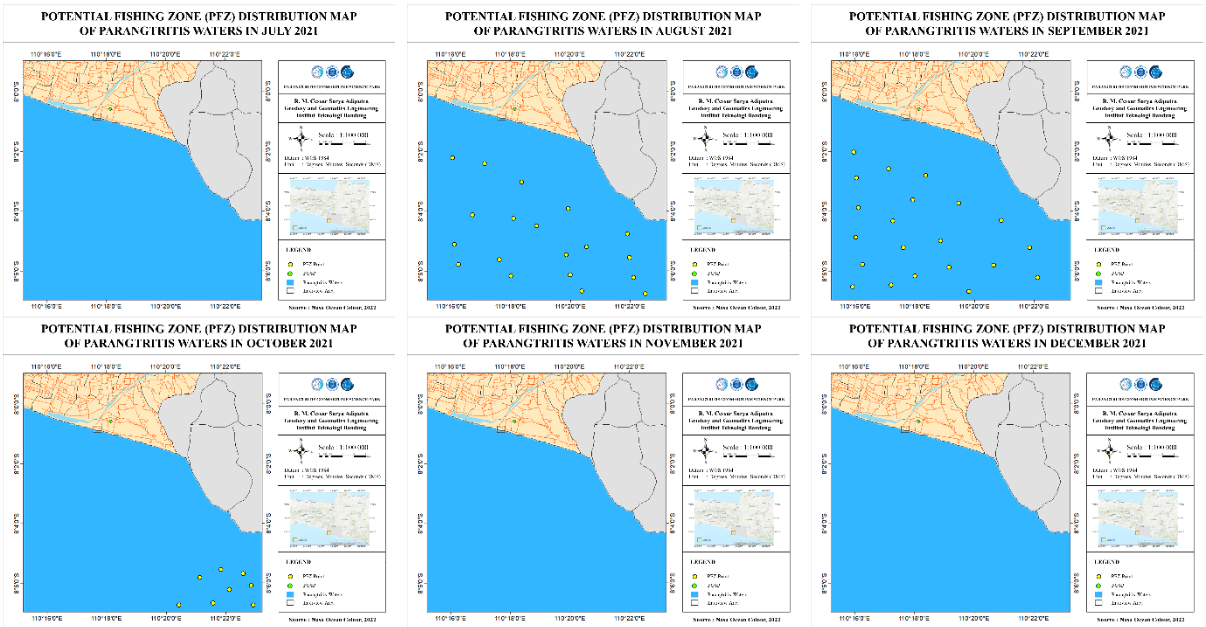


Figure 9. Average SST nighttime graph (July 2021 – June 2022)

Nighttime SST patterns reflect gradual cooling during the monsoon transition months, particularly in September and October. These cooler surface conditions, in combination with high chlorophyll-a concentrations, provide ecologically favorable settings for tuna foraging. The SST minima in these months suggest increased vertical mixing or surface heat loss, which may enhance nutrient resupply and phytoplankton growth, as well as support diel tuna behavior.

The integrated analysis of chlorophyll-a, SST (day and night), and bathymetry reveals a coherent ecological narrative for tuna habitat dynamics in Parangtritis waters. The exceptional productivity observed in September 2021, marked by high chlorophyll-a levels and moderate SST, indicates a likely upwelling event that enhanced primary production and fish aggregation. This is consistent with the broader principles of fisheries oceanography, which link physical ocean processes to biological productivity and fish distribution. The vertical and temporal alignment of bathymetric depth and SST further supports the presence of vertically migrating tuna, particularly during nighttime hours when surface conditions are optimal. From a technological standpoint, the use of MODIS satellite imagery and GEBCO bathymetric data proved effective in capturing spatial and temporal patterns essential for PFZ mapping. This geospatial approach provides a data-driven alternative to traditional fishing methods, which often rely on visual cues and experiential knowledge. By integrating remote sensing and GIS, the study offers a replicable framework for enhancing fisheries management and operational planning, particularly for small to medium-scale tuna fisheries. The findings also underscore the potential of satellite-based PFZ analysis to bridge traditional ecological knowledge and modern scientific tools, contributing to a more sustainable and informed fisheries sector in Indonesia.



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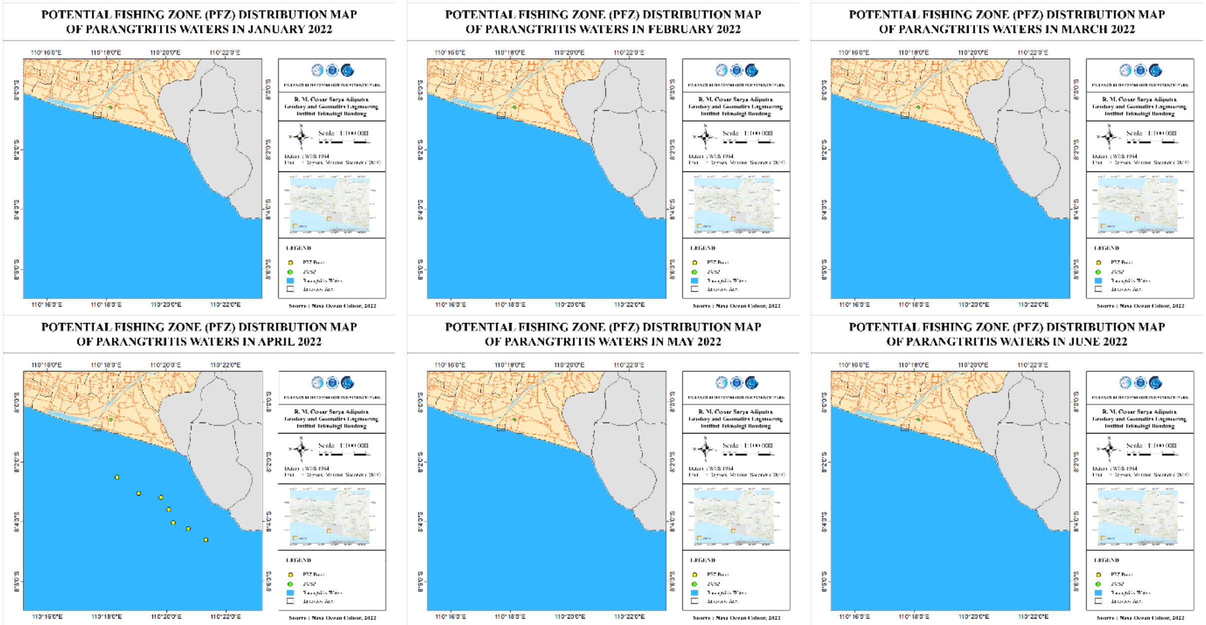

Figure 10. PFZ map in Parangtritis waters (July 2021 – June 2022)

Table 5. Number of PFZ distribution points (July 2021 – June 2022)

Month	PFZ Points
Jul-21	0
Aug-21	19
Sep-21	21
Oct-21	8
Nov-21	0
Dec-21	0
Jan-22	0
Feb-22	0
Mar-22	0
Apr-22	7
May-22	0
Jun-22	0
Total	55

The spatial analysis revealed that PFZ for tuna in the Parangtritis waters were only identified in four specific months: August, September, and October 2021, and April 2022. A total of 55 PFZ points were recorded during the twelve-month observation period from July 2021 to June 2022. These zones were predominantly concentrated in the central to southern portions of the study area and were primarily located more than 3.5 nautical miles from the shoreline. This spatial distribution pattern suggests a habitat preference of tuna for deeper offshore waters, away from the coastal shelf, which is consistent with the known behavior of pelagic tuna species seeking cooler, nutrient-rich habitats in the open ocean.

Among all observed months, September 2021 exhibited the highest number of PFZ points (21 points), coinciding with optimal oceanographic conditions. During this month, the sea surface temperature ranged from 25.17°C to 25.95°C which is relatively cooler than other months, and chlorophyll-a concentration peaked at 25.378 mg/m³, indicating high primary productivity. Such conditions are ecologically favorable for supporting dense populations of zooplankton and small pelagic fish, which constitute the main prey for tuna. This peak in productivity aligns with the trophic cascade theory, where primary production directly influences the abundance of higher trophic levels, including large pelagic predators such as tuna.

The spatial pattern of PFZ distribution supports findings from previous studies, which report that tuna aggregations often occur in areas with low thermal gradients and high prey availability. The absence of PFZ points in the remaining months particularly from November 2021 through March 2022, can be attributed to suboptimal oceanographic conditions, characterized by either elevated sea surface temperatures or low chlorophyll-a concentrations. These conditions likely reduced habitat suitability, thereby limiting the presence and detectability of tuna schools.

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This finding emphasizes the critical importance of integrating spatio-temporal environmental data into fishery planning and resource management. Unlike traditional fishing practices that rely heavily on fisher intuition and experience, the use of oceanographic data and satellite-based indicators enables more objective, efficient, and sustainable identification of fishing zones. As shown in Figure 10, the PFZ are spatially explicit and temporally intermittent, reinforcing the need for dynamic monitoring approaches. The data in Table 5 clearly demonstrate the episodic nature of PFZ occurrence, highlighting September 2021 as a key period for fishing activity optimization.

In conclusion, the application of remote sensing and GIS-based spatial analysis has proven effective in identifying tuna PFZ in the Parangtritis region. This method offers a powerful decision-support tool for small-scale and artisanal fisheries, promoting both ecological sustainability and economic efficiency. Continued monitoring and model refinement are recommended to improve prediction accuracy and further align fishing efforts with environmentally suitable conditions.

4. CONCLUSION

This study demonstrates that oceanographic conditions, particularly SST, chlorophyll-a concentration, and bathymetry, significantly influence the formation of Potential Fishing Zones PFZ for tuna in the Parangtritis waters. Spatial and temporal analysis using MODIS Aqua satellite imagery and GEBCO bathymetric data from July 2021 to June 2022 identified the presence of PFZ exclusively in August, September, and October 2021, and in April 2022. The peak occurrence was observed in September 2021 with a total of 21 PFZ points, coinciding with extremely high chlorophyll-a concentrations of up to 25.378 mg/m³ and relatively low SST ranging from 25.17°C to 25.95°C. These conditions support the hypothesis that tropical tuna species are more likely to aggregate in productive waters with optimal thermal ranges. Most PFZ were located more than 3.5 nautical miles offshore, indicating a habitat preference for deeper waters, with average depths reaching approximately 100 meters. The findings confirm that the integration of GIS and remote sensing technologies offers a reliable and objective method for informing tuna fishing activities. This scientific approach complements and enhances traditional ecological knowledge and opens pathways for developing data-driven PFZ prediction systems, particularly in support of efficient and sustainable small-scale fisheries.

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