Title: Spatial and Temporal Dynamics of Dolphin Bycatch in Gillnet Fisheries of the Northern Arabian Sea and Indian Ocean: Implications for Conservation and Management

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Abstract

Bycatch, or the incidental capture of non-target species, poses a significant threat to marine biodiversity, especially where gillnet fisheries intersect with sensitive habitats. This study offers an integrated spatial-temporal analysis of dolphin bycatch within the gillnet fisheries of Pakistan's coastal waters, encompassing the Northern Arabian Sea and the Indian Ocean from 2013 to 2017. Utilizing a comprehensive dataset of 4,111 entries recorded by crew-based observers, we examined Dolphin Total Number (DTN) and Dolphin Total Weight (DTW) to uncover patterns, hotspots, and key drivers of bycatch. Results indicated a weak linear relationship between DTN and DTW (Pearson's $r = 0.21$), while stronger non-linear associations (Spearman's $\rho = 0.39$) suggest that bycatch is influenced by complex interactions involving fishing methods, seasonal dynamics, and environmental conditions.

Temporal analysis revealed notable variations in bycatch rates across different fishing methods, with Surface Gillnets resulting in the highest bycatch peaks, particularly in the spring months (April-May), where DTW reached up to 300 kg. Spatial clustering identified critical bycatch hotspots within the EEZ and along the coast (24.5°N to 25.5°N, 64.0°E to 66.5°E), where high-density incidents overlap with Important Marine Mammal Areas (IMMA) such as Churna Island among other areas. This overlap signifies key conflict zones where intensive fishing activities pose substantial risks to dolphin populations. Anomaly detection highlighted significant deviations in DTW during early 2013 and late 2017, likely driven by environmental changes or escalated fishing activity, while change point analysis identified mid-2015 and late 2017 as periods of notable shifts, potentially reflecting regulatory or operational changes.

The findings indicate that geographic location alone is a poor predictor of bycatch rates ($R^2 < 0.03$), emphasizing the need for more coverage of more fishermen's data for the analysis and complex models that incorporate environmental, operational, and temporal variables. While there is a strong immediate correlation between DTN and DTW, the lack of Granger causality suggests that these dynamics are governed by complex ecological processes rather than simple cause-and-effect relationships. These results underscore the urgency of implementing targeted mitigation measures, such identified hotspots and modifying fishing practices to include gear modification and deterrent systems to reduce bycatch.

This study provides critical evidence for formulating data-driven conservation strategies that consider the livelihood of the dependent fishing communities near coastal areas these strategies are essential for reducing dolphin bycatch and advancing sustainable fisheries management in the Northern Arabian Sea and Indian Ocean, thereby safeguarding marine biodiversity and the livelihoods of local communities.

Keywords:
Dolphin Bycatch, Gillnet Fisheries, Spatial Analysis, Temporal Dynamics, Sustainable Fisheries Practices, Blue Corridors, Northern Arabian Sea

Introduction

Bycatch, the incidental capture of non-target species during fishing operations, is widely recognized as one of the most significant threats to marine megafauna, including cetaceans, sea turtles, seabirds, and elasmobranchs (Lewison et al., 2004; Read, Drinker, & Northridge, 2006; Brownell et al., 2019). Among these species, dolphins are particularly vulnerable to bycatch in gillnet fisheries, which are commonly used worldwide due to their cost-effectiveness and high catch rates of target species like tuna (Reeves, McClellan, & Werner, 2013; Anderson et al., 2020). The non-selective nature of gillnets, however, results in high bycatch rates, posing a significant threat to dolphin populations and the broader ecological balance of marine ecosystems (Bielli et al., 2020; Dewhurst-Richman et al., 2019).

The Indian Ocean is a critical hotspot for cetacean bycatch, with both small-scale and semi-industrial gillnet fisheries contributing significantly to the decline of several cetacean species (Anderson et al., 2020; Kiszka et al., 2021). Research has indicated that these fisheries were responsible for bycatch rates of up to 100,000 cetaceans annually during the mid-2000s, leading to an estimated 4.1 million small cetaceans being caught between 1950 and 2018 (Anderson et al., 2020). This highlights the urgent need for effective mitigation strategies to address bycatch and prevent further declines in cetacean populations, particularly in regions where regulatory frameworks and enforcement are limited (Reeves, McClellan, & Werner, 2013; Kiszka et al., 2021).

Renowned as one of the most productive regions in the Indian Ocean, the Arabian Sea's productivity is primarily driven by seasonal upwelling associated with the Southwest Monsoon (June to September) and the Northeast Monsoon (December to February). During the Southwest Monsoon, strong winds induce coastal upwelling along the coasts of Oman, Pakistan, and India, bringing cold, nutrient-rich waters to the surface. This process significantly enhances primary productivity, leading to high concentrations of phytoplankton and zooplankton that form the base of the marine food web. The resulting abundance of prey attracts a variety of marine species, including dolphins, which follow these prey concentrations into nutrient-rich zones. However, the convergence of these feeding areas with intensive fishing activities, particularly gillnet fisheries, raises the risk of dolphin bycatch. Gillnets, known for their high bycatch rates, are extensively used along the Pakistani coast, posing a substantial risk to dolphins that become entangled while pursuing prey (Kiani et al., 2021).

A notable feature of the Arabian Sea is its extensive Oxygen Minimum Zones (OMZs), which occur at mid-water depths (150–1200 meters) and are characterized by extremely low dissolved oxygen levels. These OMZs, among the most pronounced globally, significantly influence the vertical and horizontal distribution of marine species. Dolphins and other marine mammals generally avoid low-oxygen environments, preferring to remain closer to the surface or within oxygen-rich zones. This preference for shallower waters, especially during periods of OMZ expansion, increases their vulnerability to gillnet entanglements and other types of fishing gear used in coastal waters (Stramma et al., 2010). The presence of OMZs also affects prey distribution, potentially leading to increased competition and changes in foraging patterns for dolphins, thereby heightening bycatch risk.

Seasonal variability driven by the monsoon cycles further influences the distribution and behavior of marine species, including dolphins, in the Arabian Sea and Pakistan's coastal waters. The Southwest Monsoon brings nutrient-rich waters that boost primary productivity, while the Northeast Monsoon results in calmer sea conditions with different ecological dynamics. These seasonal shifts affect dolphin movement patterns as they follow prey aggregations influenced by monsoon-driven productivity. Consequently, dolphins may come into closer contact with fishing operations during certain seasons, increasing the likelihood of bycatch. Understanding these seasonal dynamics is crucial for developing effective spatial and temporal management strategies to mitigate bycatch risks (Qamar et al., 2018).

The coastal waters of Pakistan in the Arabian Sea serve as critical habitats for various cetacean species, including the critically endangered Indian Ocean humpback dolphin (*Sousa plumbea*) and the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) (Gore et al., 2012; Kiani et al., 2021). These species are highly susceptible to gillnet bycatch due to their nearshore distributions, which overlap extensively with intensive fishing grounds (Northridge et al., 2017). The bycatch of dolphins and other non-target species in Pakistan's gillnet fisheries is further exacerbated by the scale of these fishing operations. The gillnet fishing boats operate in Pakistan's offshore waters, contributing to the large-scale incidental capture of endangered species, including marine turtles and pelagic sharks (Berninsone et al., 2020; Dewhurst-Richman et al., 2019).

Gillnets' high bycatch rates are primarily due to their non-selective design, which makes them invisible to dolphins and other marine life, leading to accidental entanglement (Mooney et al., 2007). Previous studies have shown that gear modifications, such as acoustic alarms and visual deterrents, can reduce bycatch rates. However, these mitigation devices are often expensive, time-consuming, and logistically challenging to implement, particularly in developing countries where bycatch remains a major problem (Kastelein et al., 2007; Kratzer et al., 2021; Brownell et al., 2019). Additionally, these methods may only work for certain species, complicating efforts to manage bycatch when multiple taxa are affected simultaneously (Bielli et al., 2020; Mangel et al., 2013).

The challenge of managing bycatch is further compounded by the lack of comprehensive data on cetacean populations and their spatial and temporal interactions with fisheries. Most available data in the region derive from opportunistic sightings, stranding records, or limited observer programs, which are often logistically challenging and financially unsustainable (Ibrahim et al., 2021; Kiszka et al., 2021). Crew-based observer programs, where trained fishers record bycatch data, have been proposed as a cost-effective alternative for collecting accurate data. However, this approach also presents challenges related to data reliability and coverage, necessitating further refinement and validation of this method (Kiszka et al., 2021; Emery et al., 2019).

To address these challenges, recent studies have explored innovative, low-cost solutions, such as subsurface gillnet settings. This method involves setting the net below the surface to reduce interactions with cetaceans while maintaining target species catch rates. A preliminary study off the coast of Pakistan demonstrated that subsurface gillnet settings reduced cetacean bycatch by 78.5% compared to surface settings, with only minor reductions in target species catch rates (6.2% for tuna and 10.9% for tuna-like species) (Kiszka et al., 2021). The results suggest that subsurface settings could be a viable low-cost mitigation method; however, further research is required to confirm its effectiveness and fisher acceptance across different contexts (Kiszka et al., 2021; Berninsone et al., 2020).

Furthermore, temporal and spatial analyses of bycatch data have emerged as critical tools in identifying patterns and hotspots of bycatch, providing insights that can inform conservation efforts and management interventions (Tullio, Fruet, & Secchi, 2015; Northridge et al., 2017). By examining the distribution and trends of dolphin bycatch over time and across different geographic locations, researchers can identify key areas where interventions may be most needed (Brown, Reid, & Rogan, 2014). The characteristics of the fishing gear, such as mesh size, net height, and depth of deployment, have been identified as crucial factors influencing bycatch rates and should be considered in future management strategies (Northridge et al., 2017; Slooten & Dawson, 2010).

This study aims to contribute to this growing body of knowledge by conducting a comprehensive analysis of dolphin bycatch in gillnet fisheries along Pakistan's coast in the Northern Arabian Sea and Indian Ocean. Using a dataset of 4,111 records collected by crew-based observers from 2013 to 2017, the research integrates temporal and spatial data with fishing methods to uncover patterns and trends in dolphin bycatch. The specific objectives are to: (1) assess temporal trends in dolphin bycatch over the study period, 92) (3) explore the complex relationships between bycatch rates and operational factors, including fishing methods and seasonal dynamics, and (3) identify spatial hotspots of dolphin bycatch and their overlap with Important Marine Mammal Areas (IMMAs).

By providing data-driven insights, this study seeks to inform the development of more effective bycatch mitigation strategies, such as identified hotspots, modifications to fishing gear and practices, and the implementation of real-time bycatch monitoring systems. These strategies aim not only to conserve dolphin populations but also to promote sustainable fisheries management, balancing the needs of marine biodiversity conservation with the livelihoods of coastal communities in the Northern Arabian Sea and Indian Ocean (Berninsone et al., 2020; Bielli et al., 2020).

Methodology

The methodology employed in this study integrates a comprehensive examination of temporal dynamics, spatial hotspots, and operational factors affecting dolphin bycatch. The research spans five years from 2013 to 2017, focusing on regions where gillnet fishing operations were documented by participating fishermen. The approach combines temporal, spatial, and correlation analyses to provide a detailed understanding of dolphin bycatch patterns.

Study Area

The study was conducted within Pakistan's Exclusive Economic Zone (EEZ), utilizing a crew-based observer program targeting tuna gillnet fisheries. This area is recognized for its high biodiversity, supporting various cetacean species, and serves as a critical fishing ground, particularly for tuna and other commercially important species. The study region encompasses a range of environmental conditions, including variable water depths, salinity gradients, and seasonal monsoon patterns, all of which influence both fishing practices and cetacean distributions.

Data Collection and Preparation

Data collection focused on recording dolphin bycatch through direct observation during gillnet fishing operations. Fishermen maintained detailed logs of bycatch events, complemented by metadata such as fishing dates, geographic coordinates, and fishing methods. This comprehensive dataset formed the basis for subsequent analyses, facilitating a nuanced examination of temporal trends, spatial distributions, and inter-variable correlations. The datasets prepared related to dolphin bycatch, focusing on variables such as observer name, year, month, day, latitude, longitude, fishing method, Dolphin Total Number (DTN) as counts, Dolphin Total Weight (DTW) in Kg units, Dolphin Status (DST) Clean and preprocess the data to ensure consistency, accuracy, and readiness for analysis, addressing any missing or outlier data points.

Statistical Analysis and Temporal Analysis

The analytical process began with statistical summaries along with Exploratory Data Analysis (EDA) to quantify the extent of dolphin bycatch and identify significant temporal trends over the study period. Descriptive statistics, including mean, median, and standard deviation, were calculated for DTN and DTW to characterize these temporal patterns. Following the EDA, regression models were developed to explore the relationships between bycatch rates and various operational factors, such as fishing methods and locations. These models were evaluated for validity and robustness, including tests for autocorrelation.

Predictive Modeling and Spatial Analysis

Temporal forecasting was carried out using models such as Prophet and Bayesian Structural Time Series (BSTS) to project future trends in dolphin bycatch. These models underwent extensive validation and sensitivity analyses to ensure their predictive reliability. The spatial analysis identified dolphin bycatch hotspots using techniques like Kernel Density Estimation (KDE), which visualized regions with high concentrations of bycatch events. Spatial clustering methods, such as Moran's I, were employed to assess spatial autocorrelation, determining whether bycatch incidents were randomly distributed or clustered in specific areas.

Results and Discussion

Data Collection Analysis

The analysis of data collection efforts by observers from 2013 to 2017 offers valuable insights into the levels of engagement among fishermen, the extent of data collected, and the distribution of sampling efforts. The findings highlight the number of observers actively participating each year, the total entries recorded, the coverage of sampling across unique vessels, and the percentage of data collected by the top five observers throughout the study period.

Annual Engagement of Fishermen

The number of unique fishermen (observers) involved in data collection fluctuated over the five years, reflecting changes in engagement levels. In 2013, four fishermen actively collected data, marking a solid start to the data collection process. Engagement peaked in 2014 with the involvement of five fishermen, the highest level of participation during the study period. This peak could indicate a more intensive data collection effort or a project-specific need for that year. However, from 2015 to 2017, the number of engaged fishermen decreased to four, suggesting a reduction in participation. This decline may be attributed to factors such as observer availability.

Sampling Size

Over the five years, a total of 4,111 entries were recorded by five unique fishermen, demonstrating a consistent data collection effort throughout the period. This limited sampling of vessels suggests a targeted approach, likely aimed at gaining in-depth insights into specific fishing practices or regions rather than conducting a broad, fleet-wide analysis. Given that ~700 total tuna gillnet vessels operate, the sampling size ratio is calculated to be 0.71%. it represents only a small fraction of the entire fleet. while the data provides valuable and focused insights, it may not be fully representative of the overall fishing fleet's activities. Future analysis could expand to 75 fishermen for increased sampling coverage to better capture broader fishing patterns and bycatch rates.

Observer Contribution Over Time

Analysis of Observer Data Collection Contributions

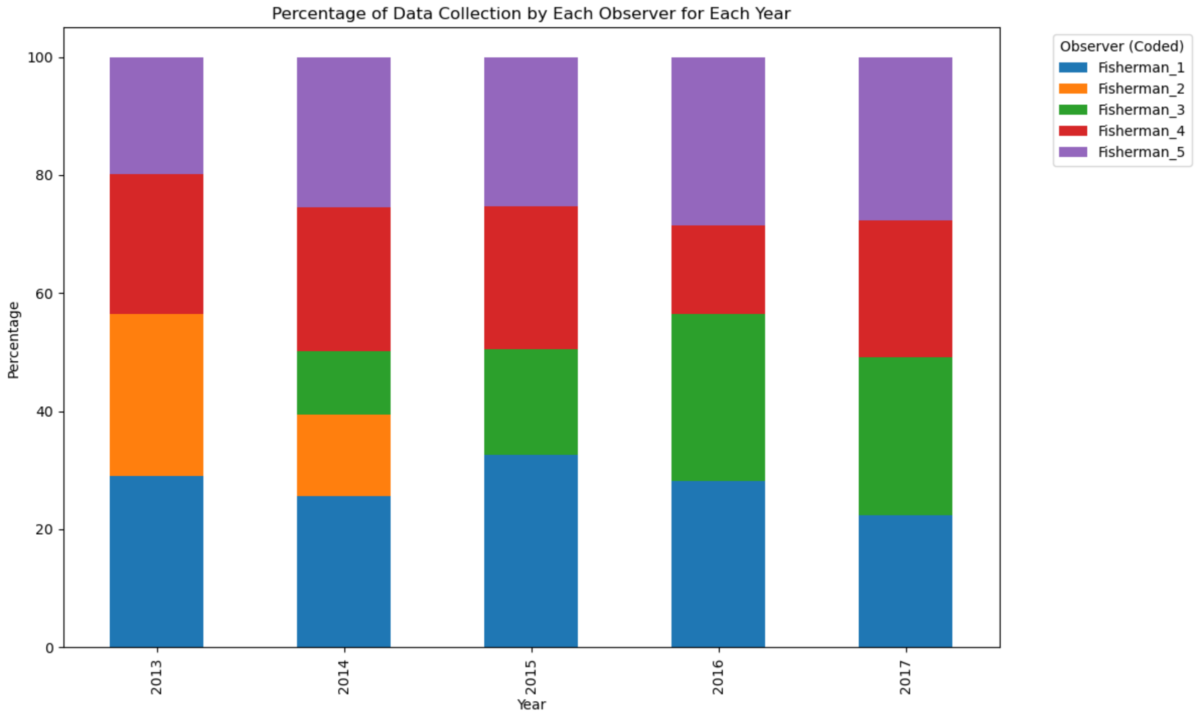
In 2013, Fisherman_1 was the leading contributor to data collection efforts, accounting for approximately 30% of the total. Fisherman_2 and Fisherman_4 each contributed around 25%, while Fisherman_3 and Fisherman_5 had smaller roles, contributing about 10% each (Graph 1). This distribution suggests that although there were a few key contributors, the overall data collection effort was relatively balanced, with significant input from multiple observers. In 2014, Fisherman_1 maintained a strong contribution at around 30%, while Fisherman_3 increased their involvement to 20%, and Fisherman_5 expanded their share to 35%, becoming the most significant contributor. This shift reflects a change in engagement dynamics, with Fisherman_5 starting to take a more prominent role.

This trend continued into 2015, where Fisherman_5 further established their position as the primary contributor, making up nearly 40% of the total data collection. Fisherman_1 remained consistent with a 30% contribution, while Fisherman_3 increased their share slightly to 25%, reflecting their growing involvement. Conversely, Fisherman_2's share decreased to approximately 15%, indicating a reduced role. Fisherman_4 continued to maintain a steady contribution of around 25%, showing consistent participation over the years.

By 2016, Fisherman_5's dominance in data collection reached a peak, contributing approximately 45% of the total effort, marking them as the most actively engaged observer. Fisherman_1's contribution decreased slightly to 25%, while Fisherman_3 and Fisherman_4 sustained their shares at about 25% and 20%, respectively. Fisherman_2 remained in a limited role with a 15% contribution, reflecting a consistently smaller yet stable involvement. The pattern persisted in 2017, with Fisherman_5 again leading with around 45% of the data collection, followed by Fisherman_1 at 25% and Fisherman_3 at 25%. Fisherman_4 and Fisherman_2 maintained their contributions at 20% and 15%, respectively.

Overall, the chart demonstrates that Fisherman_5 emerged as the most significant contributor from 2014 onwards, consistently increasing their engagement each year to become the primary data collector. Fisherman_1 also played an essential role, consistently contributing across all years, though not to the same extent as Fisherman_5. The contributions from Fisherman_2, Fisherman_3, and Fisherman_4 varied, with Fisherman_3 showing a gradual increase in participation, while Fisherman_2 exhibited a decline. These variations suggest evolving dynamics in observer involvement, which could be influenced by several factors, such as observer availability, specific project needs, or changes in fishing practices.

The balanced distribution of contributions among multiple observers indicates a well-rounded data collection effort, reducing the risk of biases that might arise if data were dominated by a single observer. This diversity of involvement enhances the robustness of the collected data, making it more representative of overall fishing activities and potential bycatch scenarios. Understanding these patterns of observer participation can help optimize future data collection strategies, ensuring a more equitable distribution of efforts among observers and improving data reliability for fisheries management.



Graph 1: The stacked bar chart illustrates the percentage of data collection efforts by five different observers, coded as "Fisherman_1" to "Fisherman_5," from 2013 to 2017. Each bar represents a year, and each colored segment within the bar indicates the proportion of data collected by each observer. The chart provides a clear visual representation of the varying levels of engagement by each observer over the years, highlighting shifts in their contributions

Descriptive Statistics

The descriptive statistics analysis was conducted to establish a foundational understanding of dolphin interactions. By calculating summary statistics such as mean, median, and standard deviation for fishing method, Dolphin Total Number (DTN) as counts, Dolphin Total Weight (DTW) in Kg units, and Dolphin Status (DST), the analysis will provide insights into the distribution and central tendencies of these variables. Time series plots will be generated to visualize trends over different years and months, which is essential for identifying seasonal patterns or shifts that may influence dolphin bycatch rates.

Distribution Analysis of Dolphin Bycatch

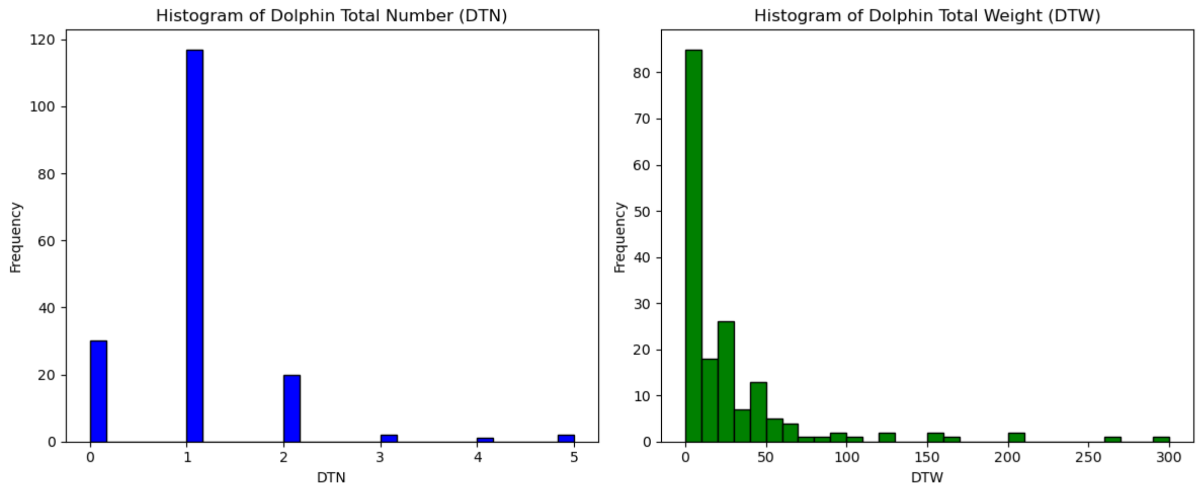
Dolphin Total Number (DTN)

The distribution, which quantifies the number of dolphins captured in each bycatch event depicts in the left histogram (Graph 2). The distribution is heavily skewed towards lower values, with the most frequent observation being the capture of a single dolphin, recorded in over 120 instances. This indicates that the majority of bycatch events involve only one dolphin, suggesting that these incidents are isolated and typically do not involve groups of dolphins. Additionally, there is a significant number of zero counts (DTN = 0), highlighting numerous instances where no dolphins were caught at all. As the DTN values increase to 2, 3, 4, and 5, the frequency of occurrences sharply declines, demonstrating that events involving multiple dolphins are uncommon. This pattern indicates that dolphin bycatch in the studied fisheries is generally low in numbers, usually involving single individuals rather than larger groups.

Dolphin Total Weight (DTW)

The distribution of DTW, which represents the total weight of dolphins captured during each bycatch event illustrated in the right histogram (Graph 2). The distribution is similarly skewed, with most values concentrated at the lower end of the weight spectrum. The highest frequency is observed for DTW values ranging between 0 and 50 kg, suggesting that most bycatch events involve dolphins with relatively low total weights. This could imply that the dolphins caught are typically smaller individuals, such as juveniles or smaller species. The frequency of observations decreases sharply as DTW values exceed 50 kg, with only a few instances where the total weight of dolphins captured surpasses 150 kg. A few outlier events with DTW values reaching up to 300 kg suggest occasional captures of larger dolphins; however, these occurrences are rare and not indicative of the overall trend.

Both histograms reveal a clear pattern in which dolphin bycatch events predominantly involve single dolphins or small numbers of dolphins with relatively low total weights. The skewness towards lower DTN and DTW values suggests that dolphin bycatch is generally minimal, with larger bycatch events being rare occurrences.



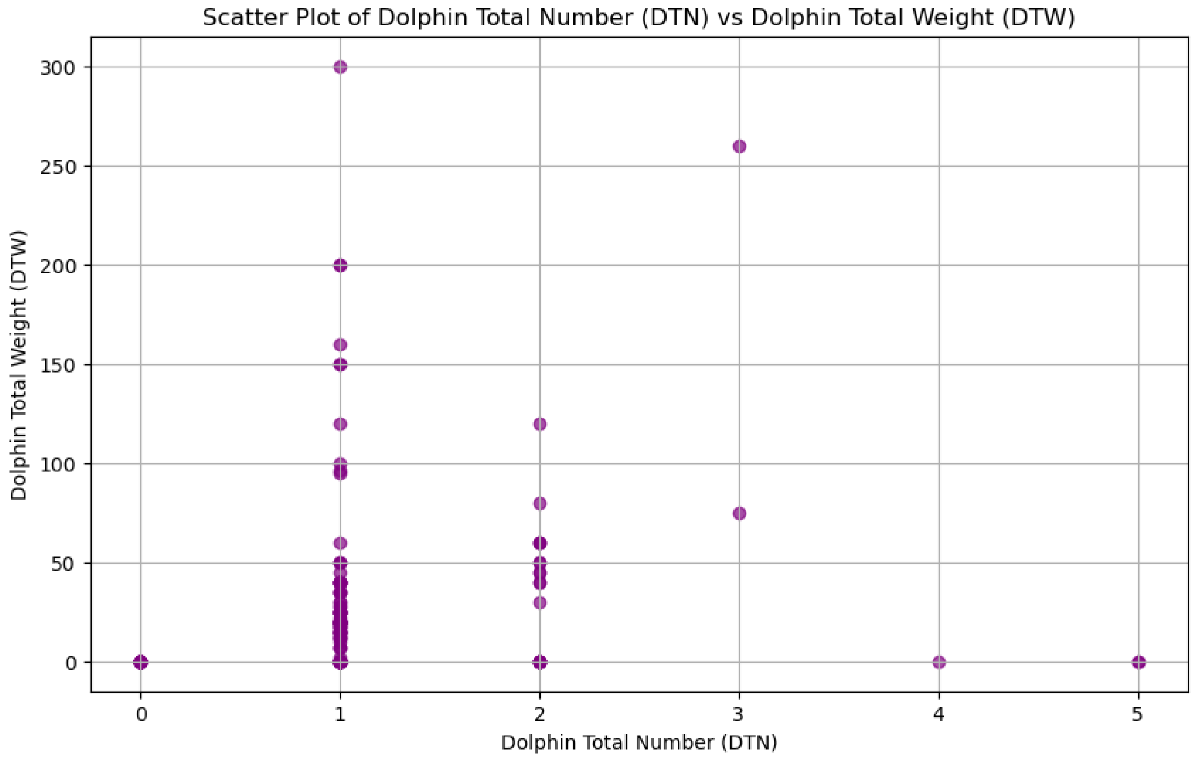
Graph 2: The histograms provide a detailed visual representation of the distribution of DTN and DTW within the dataset, offering insights into the patterns of dolphin bycatch in terms of both the number of individuals caught and their aggregate weight.

Relationship Between Dolphin Total Number (DTN) and Dolphin Total Weight (DTW)

The scatter plot indicates that the majority of data points are concentrated around lower values of both DTN and DTW, particularly where DTN equals 1 or 2 (Graph 3). This clustering suggests that most dolphin bycatch events involve either a single dolphin or two dolphins, and these events typically result in relatively low total weights, generally below 50 kg. There is a noticeable vertical spread for DTN = 1, where DTW ranges significantly from nearly 0 kg to over 300 kg. This variation indicates that while many single-dolphin captures involve smaller individuals (resulting in lower total weights), some incidents involve larger dolphins, leading to substantially higher total weights. A similar pattern is observed for DTN = 2, where DTW values also range widely, from low weights up to around 150 kg.

As DTN increases to 3, 4, or 5, the number of recorded observations decreases markedly, and the corresponding DTW values remain relatively low. This pattern further underscores that bycatch events involving three or more dolphins are quite rare, and when they do occur, they typically involve smaller dolphins, resulting in lower total weights. The sparse number of points at higher DTN values and the lack of significant variation in weight indicate that large-scale bycatch events, both in terms of the number of dolphins and their combined weight, are uncommon.

Overall, the scatter plot demonstrates that most dolphin bycatch events involve one or two dolphins with a range of weights, while bycatch incidents involving larger numbers of dolphins are rare and generally involve smaller individuals. The observed relationship between DTN and DTW suggests a weak positive correlation between the number of dolphins caught and their total weight; however, there is considerable variability in weight for any given DTN. This variability is likely due to differences in the size or species of dolphins caught.



Graph 3: The scatter plot provides a visualization of the relationship between Dolphin Total Number (DTN) and Dolphin Total Weight (DTW) in the dataset. Each point on the plot represents a recorded bycatch event during fishing operations, with the x-axis denoting the number of dolphins caught (DTN) and the y-axis reflecting the corresponding total weight of those dolphins (DTW). This scatter plot allows for an assessment of how the number of dolphins caught correlates with their combined weight, revealing patterns in bycatch incidents.

Density of Dolphin Bycatch Distribution

Dolphin Total Number (DTN)

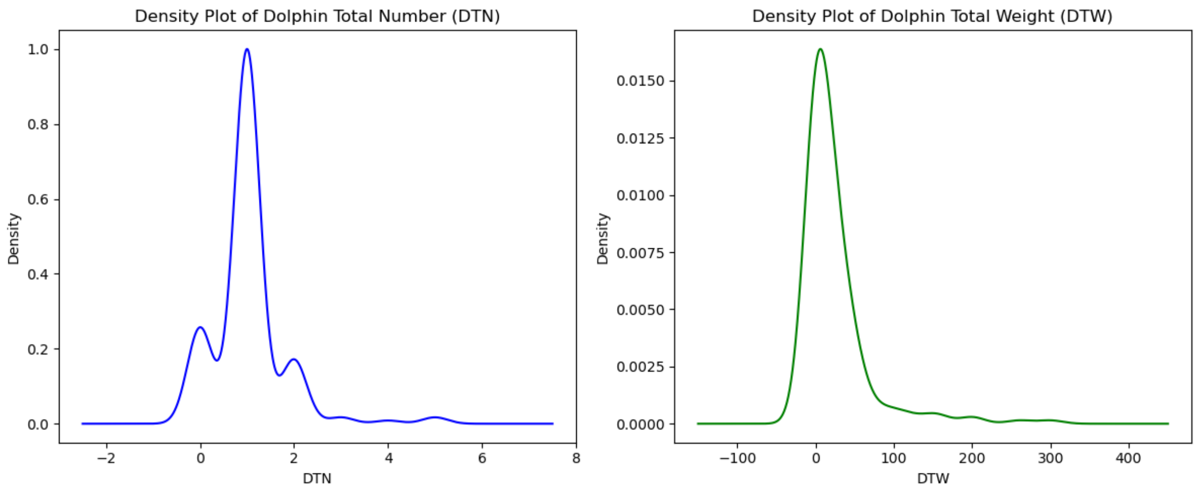
The distribution of DTN, reflects the number of dolphins caught in individual bycatch events on the left density plot (Graph 4). The plot features a pronounced peak around DTN = 1, indicating that the majority of bycatch incidents involve a single dolphin. This peak suggests that solitary dolphin captures are the most frequent scenario in the dataset. Additionally, there is a secondary, smaller peak near

DTN = 0, indicating numerous instances where no dolphins were captured. The density sharply declines as DTN values exceed 1, with a notably low density for DTN values of 3 and higher, signifying that incidents involving three or more dolphins are uncommon. The distribution is heavily skewed, with most of the probability density concentrated between DTN = 0 and DTN = 2, reflecting the general trend that dolphin bycatch events typically involve few individuals.

Dolphin Total Weight (DTW)

The distribution of Dolphin Total Weight (DTW), represents the total weight of dolphins caught in each bycatch event depicted on the right density plot (Graph 4). This plot reveals a similarly skewed distribution, with a prominent peak in the range of DTW = 0 to 50 kg. This peak indicates that the majority of bycatch events result in relatively low total weights, reinforcing the observation that smaller dolphins or fewer individuals are typically involved in these incidents. The density gradually diminishes as DTW values increase beyond 50 kg, with the tail extending up to approximately 300 kg. This suggests that while heavier bycatch events do occur, they are relatively rare. The very low density for DTW values exceeding 150 kg indicates that such events are outliers rather than common occurrences.

The density plots for both DTN and DTW underscore that dolphin bycatch events are predominantly characterized by the capture of small numbers of dolphins (often just one) and low total weights (generally under 50 kg). The sharp peaks in both plots around DTN = 1 and DTW = 0 to 50 kg reinforce this pattern, while the extended tails suggest occasional larger bycatch events involving more dolphins or higher weights. These insights highlight the potential effectiveness of targeted management strategies focused on reducing the frequency of single-dolphin captures and mitigating the impact of the infrequent, heavier bycatch events.



Graph 4: The density plots offer a refined visualization of the distribution of Dolphin Total Number (DTN) and Dolphin Total Weight (DTW), capturing the probability density of these variables rather than mere frequency counts. This approach provides a deeper understanding of the patterns within the dolphin bycatch data, highlighting the spread and concentration of DTN and DTW values.

Year-wise Analysis of Dolphin Bycatch

Year-wise Dolphin Total Number (DTN)

The total number (sum), mean, and standard deviation of the DTN for each year from 2013 to 2017 depicted in the left chart (Graph 5). The data reveals that 2013 recorded the highest total DTN, with a sum exceeding 100 dolphins, indicating that dolphin bycatch was most pronounced in this year compared to subsequent years. Following 2013, there is a sharp decline in total DTN, with 2014 showing a notable reduction to around 40 dolphins. The downward trend continues from 2015 to 2017, with total values remaining consistently low (below 20 dolphins). This declining trend suggests a substantial reduction in dolphin bycatch over the years, potentially due to changes in fishing practices, the implementation of regulatory measures, or the adoption of more effective bycatch management strategies.

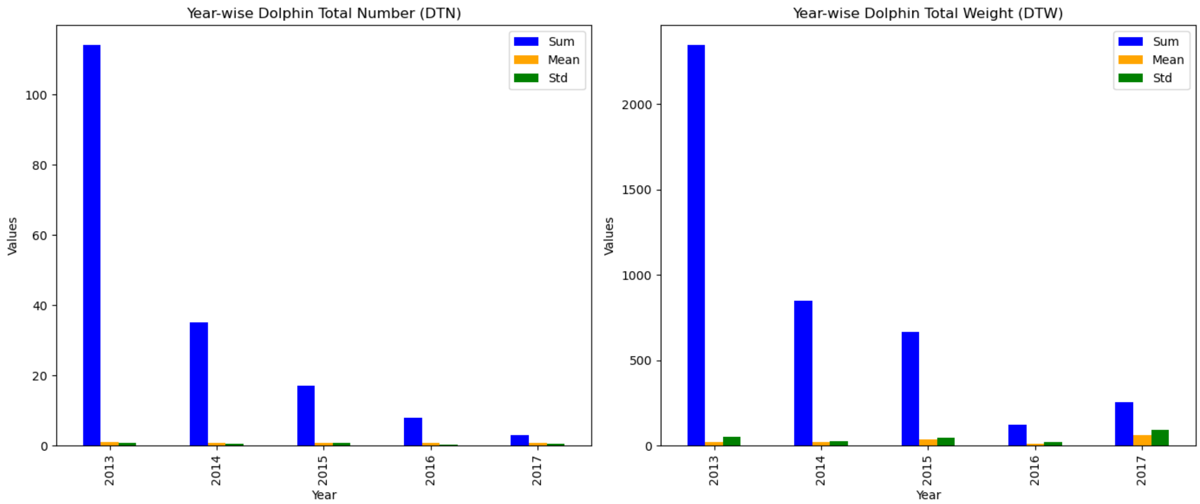
The mean values (orange bars) for each year remain relatively low, indicating that the average number of dolphins caught per bycatch event is consistently low across all years. The highest mean DTN is observed in 2013, reflecting a greater average number of dolphins caught per event during that year. The standard deviation (green bars) is also relatively small, suggesting limited variability in the number of dolphins caught across different bycatch events within each year. The highest standard deviation in 2013 implies some variability in the number of dolphins caught per event during that year.

Year-wise Dolphin Total Weight (DTW)

The total weight (sum), mean, and standard deviation of the DTW for each year from 2013 to 2017 are shown in right graph (Graph 5). Similar to the DTN chart, DTW exhibits a pronounced peak in 2013, with the total weight surpassing 2000 kg. This high total weight suggests that bycatch events in 2013 not only involved a greater number of dolphins but also included heavier individuals or larger groups. After 2013, there is a significant drop in total DTW, with 2014 showing a sharp decline to around 1000 kg, indicating fewer and lighter bycatch events. The decline continues from 2014 onwards, with a slight increase in 2017, possibly reflecting isolated incidents of larger individuals being caught despite the overall reduction in bycatch numbers.

The mean values (orange bars) for DTW in each year are low, indicating that the average weight of dolphins caught per event remains modest throughout the study period. The highest mean DTW is observed in 2013, reflecting that on average, bycatch events during this year involved higher total weights. The standard deviation (green bars) is also small, indicating limited variability in the total weight of dolphins caught in bycatch events, with the greatest variability occurring in 2013.

The year-wise analysis of DTN and DTW highlights 2013 as an outlier year for dolphin bycatch, both in terms of the number of individuals caught and their total weight. This suggests that specific factors in 2013—whether environmental, regulatory, or operational—contributed to the elevated bycatch rates. The sharp decline in both DTN and DTW after 2013, with a steady downward trend through 2017, indicates progress in reducing dolphin bycatch, likely due to more effective bycatch management strategies or changes in fishing practices.



Graph 5: The bar charts provide a year-by-year analysis of Dolphin Total Number (DTN) and Dolphin Total Weight (DTW) from 2013 to 2017. Each chart presents three statistical measures: the sum (total), mean (average), and standard deviation (std) for both DTN and DTW. These visualizations are instrumental in understanding the patterns and variability of dolphin bycatch over the years, shedding light on trends related to the number and weight of dolphins caught as bycatch.

Year-wise Analysis of Dolphin Bycatch by Fishing Method

Year-wise Dolphin Total Number (Sum) by Fishing Method

The total sum of DTN for each fishing method by year is shown in the top left chart (Graph 6). In 2013, the 'SUGN' (Surface Gillnet, orange) method had a dominant impact, with a DTN sum exceeding 100 dolphins. This indicates that the Surface Gillnet method was the primary contributor to dolphin bycatch in 2013, resulting in a significantly higher number of dolphins caught compared to other methods. In contrast, the 'SUBS' (Sub-Surface, blue), 'SUSS' (Surface/Sub-Surface, green), and 'TRAW' (Trawling, red) methods show much lower total DTN values for 2013, suggesting a reduced impact on dolphin bycatch. Following 2013, there is a marked decline in DTN across all methods, with values remaining consistently low from 2014 to 2017. This trend reflects a significant reduction in dolphin bycatch across all fishing methods, potentially due to regulatory changes, enhanced bycatch mitigation measures, or adjustments in fishing practices.

Year-wise Dolphin Total Number (Mean) by Fishing Method

the mean values of DTN by year for each fishing method, providing an understanding of the average number of dolphins caught per observation, is illustrated in the top right chart (Graph 6). In 2013 and 2014, the 'SUGN' (Surface Gillnet, orange) method exhibits the highest mean DTN values, indicating that, on average, this method resulted in more dolphins caught per event. By 2015, the 'SUBS' (Sub-Surface, blue), 'SUSS' (Surface/Sub-Surface, green), and 'TRAW' (Trawling, red) methods show more comparable mean DTN values, suggesting that these methods also had relatively higher bycatch rates in certain years. By 2016 and 2017, the mean values across all methods become more uniform, indicating a general reduction in average dolphin bycatch for all fishing methods.

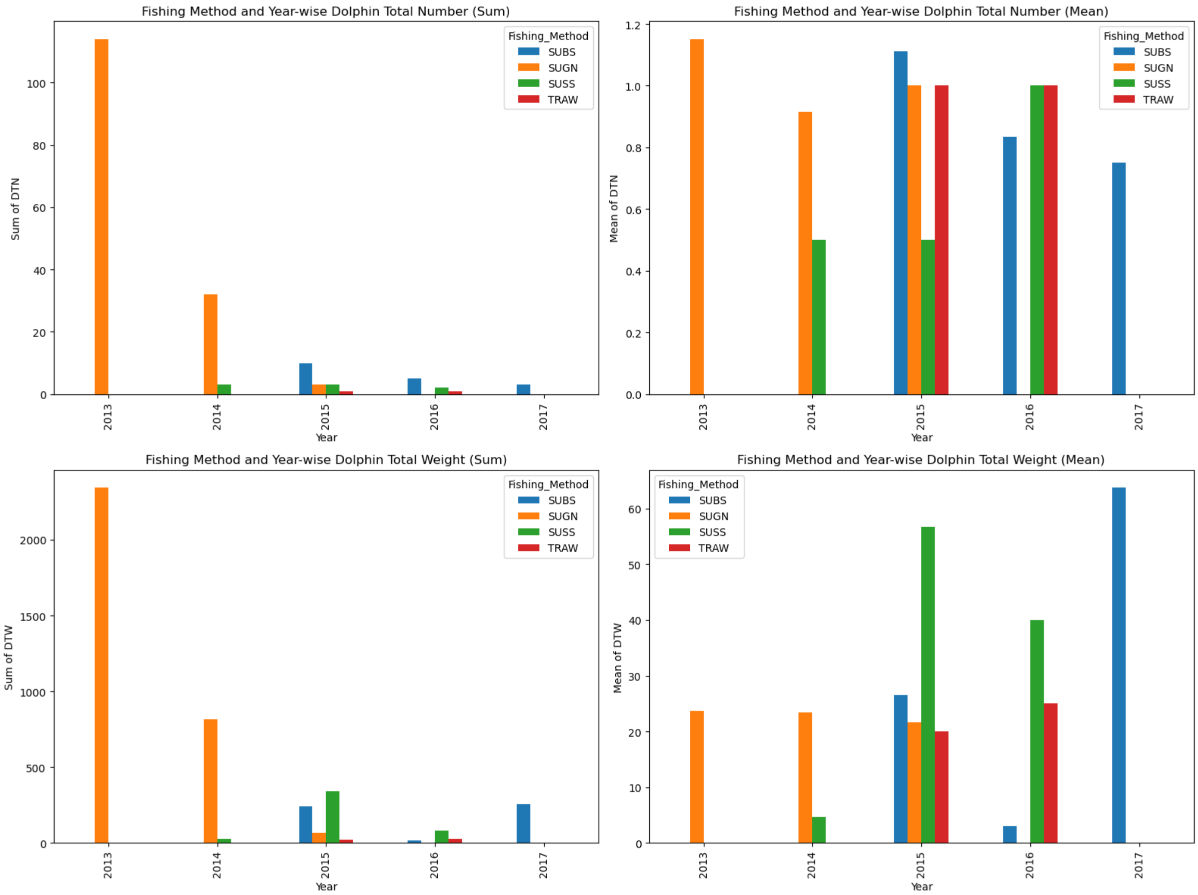
Year-wise Dolphin Total Weight (Sum) by Fishing Method

The total sum of DTW for each fishing method by year is shown in the bottom left chart (Graph 6). Again, the 'SUGN' (Surface Gillnet, orange) method recorded the highest total DTW in 2013, with a value exceeding 2000 kg. This suggests that not only were more dolphins caught using this method, but the total weight of dolphins caught was significantly higher, possibly involving larger individuals or multiple catches. The other methods—'SUBS' (Sub-Surface, blue), 'SUSS' (Surface/Sub-Surface, green), and 'TRAW' (Trawling, red)—show lower total DTW values, indicating a lesser impact on dolphin bycatch in terms of weight. From 2014 onwards, there is a sharp decline in total DTW for all methods, with values remaining consistently low in subsequent years, reflecting a reduction in dolphin bycatch weight.

Year-wise Dolphin Total Weight (Mean) by Fishing Method

The bottom right chart presents the mean values of Dolphin DTW by year for each fishing method (Graph 6). This chart reveals interesting variations in the mean DTW values across different fishing methods over the years. In 2015, the 'SUSS' (Surface/Sub-Surface, green) method shows an exceptionally high mean DTW, suggesting that while the total number of bycatch events may have been low, the events involving this method resulted in larger weights of dolphins caught. This could indicate the capture of larger individuals or heavier groups. In 2017, the 'SUBS' (Sub-Surface, blue) method also shows a notable increase in mean DTW, suggesting heavier dolphin catches per event. The other methods display more moderate mean values, reflecting a more balanced bycatch weight per event.

Overall, the bar charts indicate that the 'SUGN' (Surface Gillnet) fishing method had the greatest impact on dolphin bycatch in terms of both numbers and weight in 2013, suggesting it was the most impactful method regarding bycatch during that year. The subsequent reduction in both total and mean values of DTN and DTW from 2014 onwards across all methods suggests improvements in bycatch management or shifts in fishing practices. The variability in mean DTW values among different fishing methods and years highlights that certain methods (such as 'SUSS' and 'SUBS') can still result in significant bycatch weights under specific conditions, underscoring the need for targeted mitigation strategies.



Graph 6: The four bar charts provide a comprehensive year-wise analysis of dolphin bycatch categorized by different fishing methods from 2013 to 2017. The fishing methods represented in the charts are SUBS (Sub-Surface), SUGN (Surface Gillnet), SUSS (Surface/Sub-Surface), and TRAW (Trawling). Each chart illustrates both the sum (total) and mean (average) values for Dolphin Total Number (DTN) and Dolphin Total Weight (DTW), offering insights into temporal patterns and variations in dolphin bycatch across different fishing methods.

Analysis of Dolphin Bycatch by Fishing Method and Dolphin Status

The sum of Dolphin Total Number (DTN) by Fishing Method and Status

The total sum of DTN by dolphin status (DST) for each fishing method. The 'DD' (Discarded Dead) status is overwhelmingly dominant, especially for the 'SUGN' (Surface Gillnet, orange) method, which shows a DTN sum exceeding 140 in the top left chart (Graph 7). This indicates that the majority of dolphin bycatch incidents using the Surface Gillnet method resulted in dolphins being discarded dead, highlighting a substantial bycatch impact. The 'SUBS' (Sub-Surface, blue), 'SUSS' (Surface/Sub-Surface, green), and 'TRAW' (Trawling, red) methods also show bycatch under the 'DD' status, but at much lower levels compared to 'SUGN.' Other statuses, such as 'RA' (Released Alive) and 'SI' (Sighted), exhibit significantly lower total DTN values across all fishing methods, reflecting fewer instances of dolphins being released alive or sighted without capture.

The Mean of Dolphin Total Number (DTN) by Fishing Method and Status

the mean values of DTN by dolphin status (DST) for each fishing method are shown in the top right chart (Graph 7). The 'DD' (Discarded Dead) status shows the highest mean DTN values across all fishing methods, indicating that, on average, the number of dolphins discarded dead per event is relatively high. The 'SUGN' (Surface Gillnet, orange) method has the highest mean DTN for the 'DD' status, while the other methods—'SUBS,' 'SUSS,' and 'TRAW'—display slightly lower but comparable mean values. For the 'RA' (Released Alive) status, the mean DTN values are relatively consistent across all fishing methods, suggesting that the average number of dolphins released alive per event does not vary significantly between methods. The 'POD SI' (Pods Sighted, orange) status has a notably low mean value for the 'SUGN' method, suggesting that sightings of dolphin pods usually involve few individuals.

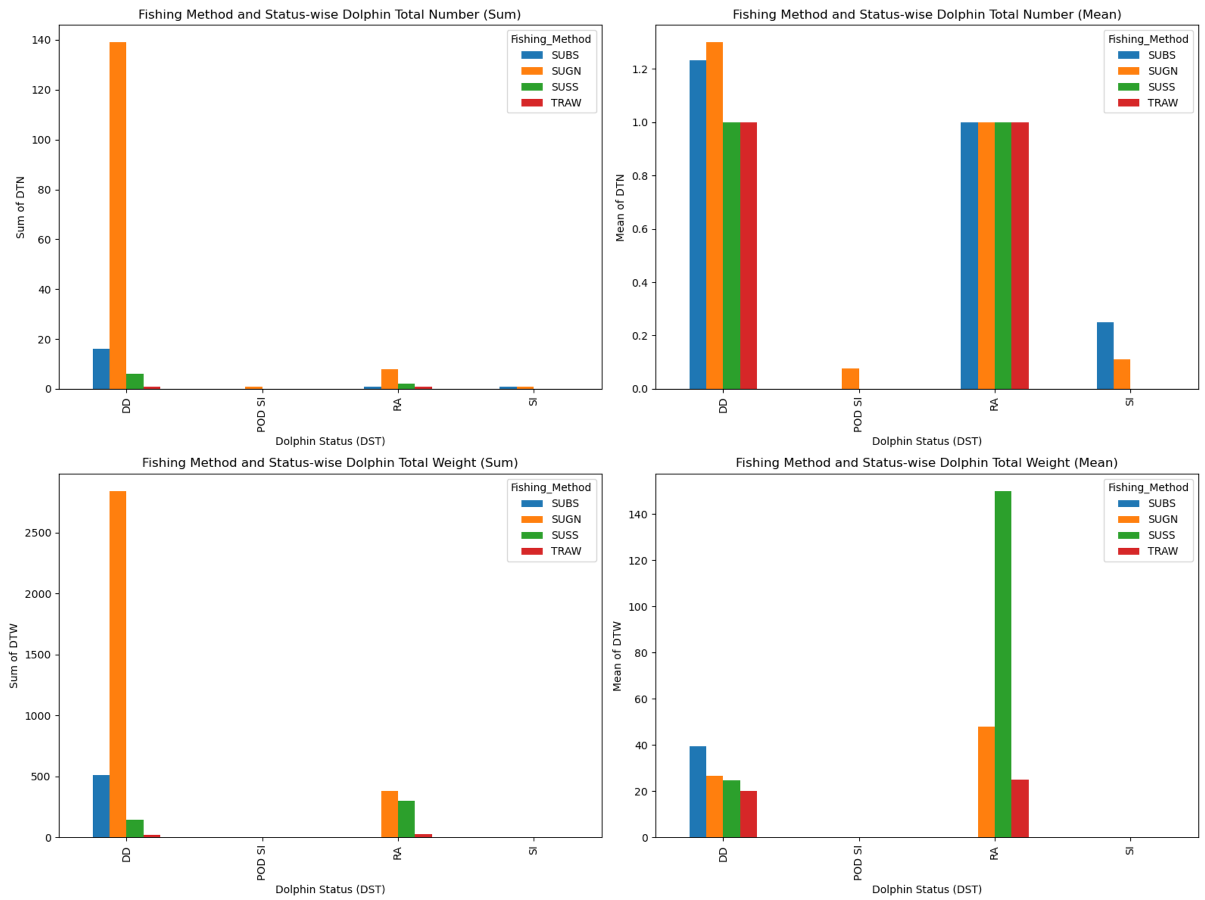
Sum of Dolphin Total Weight (DTW) by Fishing Method and Status

The total sum of DTW by dolphin status for each fishing method are shown in the bottom left chart (Graph 7). Similar to the DTN sum chart, the 'DD' (Discarded Dead) status is predominant, particularly for the 'SUGN' (Surface Gillnet, orange) method, with a DTW sum exceeding 2500 kg. This substantial value indicates that the total weight of dolphins discarded dead using the Surface Gillnet method is considerable, possibly involving larger individuals or larger catches. The other methods show much lower total DTW values for the 'DD' status, reflecting less impact in terms of the total weight of discarded dolphins. The 'RA' (Released Alive, green) status also shows some variation in total DTW, particularly for the 'SUBS' (Sub-Surface, blue) and 'SUSS' (Surface/Sub-Surface, green) methods, suggesting that occasionally released dolphins can be heavier.

Mean of Dolphin Total Weight (DTW) by Fishing Method and Status

The mean values of DTW by dolphin status for each fishing method are illustrated on the bottom right chart (Graph 7). The 'RA' (Released Alive) status stands out with an exceptionally high mean DTW value for the 'SUSS' (Surface/Sub-Surface, green) method, exceeding 140 kg. This indicates that when dolphins are released alive using this method, they tend to be significantly larger or heavier. The 'DD' (Discarded Dead) status shows relatively moderate mean DTW values across all fishing methods, suggesting that while many discarded dolphins are caught, their average weight per event is not exceptionally high. The 'FR' (Frozen) status has low mean values, reinforcing that freezing dolphins is infrequent and generally involves lighter or smaller individuals.

Overall, these charts indicate that the 'SUGN' (Surface Gillnet) fishing method has the most significant impact on dolphin bycatch in terms of both the number of dolphins caught (DTN) and their total weight (DTW), particularly for the 'DD' (Discarded Dead) status. This suggests that the Surface Gillnet method may require more targeted mitigation measures to reduce its bycatch impact. The variation in mean DTW values across different methods and statuses, especially the high mean DTW for the 'RA' (Released Alive) status under the 'SUSS' method, highlights the need for nuanced bycatch management strategies that consider both the fishing method and the handling of dolphins during fishing activities.



Graph 7: The four bar charts provide a comprehensive analysis of dolphin bycatch categorized by both fishing methods and dolphin status (DST), which includes DD (Discarded Dead), POD SI (Pods Sighted), RA (Released Alive), and SI (Sighted). The fishing methods assessed in these charts are SUBS (Sub-Surface), SUGN (Surface Gillnet), SUSS (Surface/Sub-Surface), and TRAW (Trawling). Each chart presents both the sum (total) and mean (average) values for Dolphin Total Number (DTN) and Dolphin Total Weight (DTW), offering insights into how different fishing methods impact dolphins under various statuses.

Exploratory Data Analysis (EDA)

Correlation Analysis

Pearson Correlation Analysis

The Pearson correlation analysis between Dolphin Total Number (DTN) and Dolphin Total Weight (DTW) demonstrates a weak positive correlation (r = 0.21). This suggests that as the number of dolphins increases, there is a slight corresponding increase in total weight; however, this relationship is not particularly strong, indicating that other factors likely influence DTW. The correlation between DTN and geographical coordinates reveals a very weak negative relationship with latitude (r = -0.11), suggesting a slight decrease in dolphin numbers as latitude increases (i.e., moving northward). Conversely, there is a very weak positive correlation with longitude (r = 0.13), indicating a slight increase in dolphin numbers moving eastward. For DTW, the correlation with latitude is nearly negligible (r = 0.02), while there is a weak negative correlation with longitude (r = -0.24), suggesting a slight decrease in dolphin weight with increasing longitude.

Overall, these weak correlations imply that geographical location has minimal influence on dolphin numbers and weights. While there is a positive relationship between DTN and DTW, it is not strong enough to be considered a significant influencing factor.

Spearman Correlation Analysis

The Spearman correlation analysis, which accounts for rank and non-linear relationships, shows a moderate positive correlation between DTN and DTW ($\rho = 0.39$). This indicates a more noticeable association where both variables generally increase together, although the relationship remains moderate. The correlations between DTN and geographical coordinates are very weak, with latitude ($\rho = -0.10$) and longitude ($\rho = 0.11$) exerting minimal influence on dolphin numbers. The correlation between DTW and latitude is nearly non-existent ($\rho = 0.01$), whereas the correlation with longitude is moderately negative ($\rho = -0.40$), suggesting a more discernible decrease in total dolphin weight moving eastward.

Compared to the Pearson analysis, these findings suggest a more consistent relationship between DTN and DTW. However, geographical factors still play a relatively minor role, with longitude having a somewhat more pronounced effect on DTW.

Kendall Correlation Analysis

The Kendall correlation analysis, particularly suited for smaller datasets and ordinal data, reveals a moderate positive correlation between DTN and DTW ($\tau = 0.35$). This indicates a consistent pattern where an increase in dolphin numbers generally corresponds to an increase in their total weight, although this relationship is not particularly strong. The correlations between DTN and geographical coordinates are weak, with latitude ($\tau = -0.07$) and longitude ($\tau = 0.09$) showing minimal effects. The correlation between DTW and latitude is nearly zero ($\tau = 0.01$), indicating no meaningful relationship, while the correlation with longitude is moderately negative ($\tau = -0.29$), suggesting that dolphin weight tends to decrease as longitude increases.

The Kendall analysis implies that, while geographical factors—particularly longitude—may have some influence on the total weight of dolphins, the number of dolphins is only weakly affected by these coordinates. The moderate correlation between DTN and DTW reflects a general trend where larger dolphin groups are associated with higher total weights, though this relationship is not strong enough to serve as a reliable predictive measure.

Collectively, these correlation analyses indicate that while there is some association between the number of dolphins and their total weight, the effect of geographical factors remains limited (Table 1). The results underscore the complexity of the variables influencing dolphin bycatch and suggest the need for further research to explore additional factors that may provide a more comprehensive understanding of these relationships.

Correlation Method	**DTN vs DTW**	**DTN vs Latitude**	**DTN vs Longitude**	**DTW vs Latitude**	**DTW vs Longitude**	**Latitude vs Longitude**
Pearson	0.21	-0.11	0.13	0.02	-0.24	-0.23
Spearman	0.39	-0.10	0.11	0.01	-0.40	-0.32
Kendall	0.35	-0.07	0.09	0.01	-0.29	-0.22

Table 1: This table provides a clear overview of how the different correlation methods evaluate the relationships between the variables in the dataset

Temporal Analysis

Dolphin Total Number (DTN)

The blue line in the plot depicts the temporal trend of the DTN from 2013 to 2017 (Graph 8). Over this period, DTN values remain relatively low and stable, displaying only minor fluctuations. This stability suggests that the annual bycatch of dolphins has not exhibited significant variation. A slight decline is evident, with DTN decreasing from approximately 1.15 in 2013 to 0.75 in 2017. Although modest, this decline could indicate a gradual reduction in dolphin bycatch, potentially due to enhanced bycatch mitigation measures, shifts in dolphin populations, or changes in their behavior and distribution patterns.

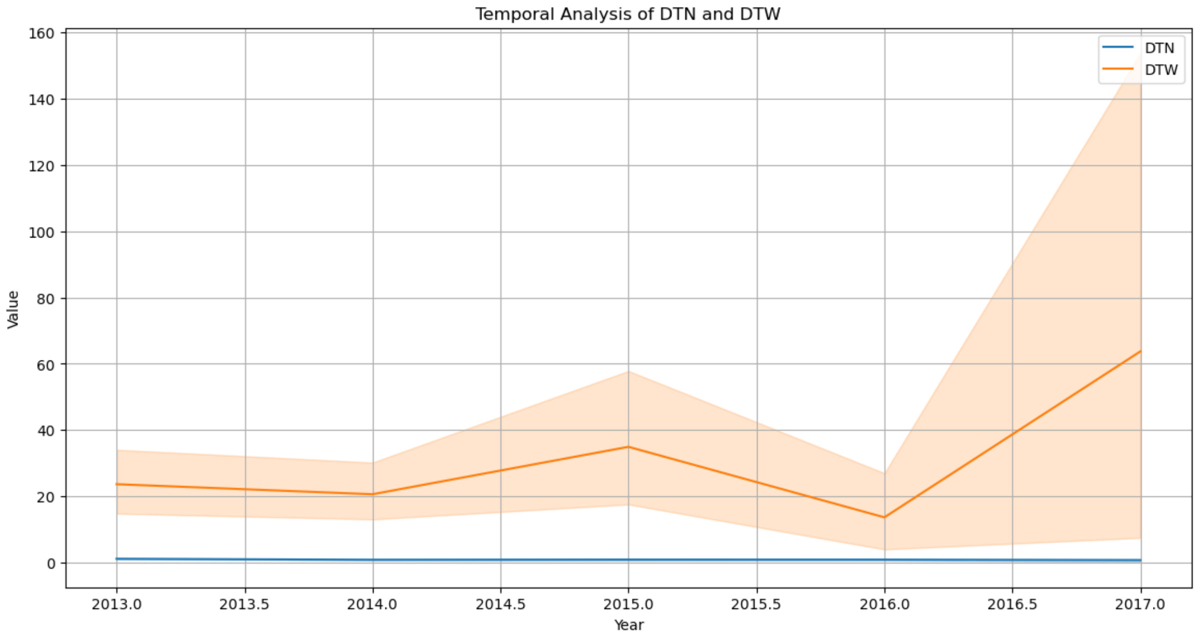
Dolphin Total Weight (DTW)

The orange line on the plot illustrates the trend in DTW, which demonstrates greater variability compared to DTN (Graph 8). DTW starts at around 23.67 kg in 2013, decreases to approximately 20.63 kg in 2014, peaks at 34.95 kg in 2015, drops to 13.67 kg in 2016, and then rises sharply to 63.75 kg in 2017. The substantial increase in DTW observed in 2017 may suggest an anomaly or could be indicative of changes in fishing practices, shifts in fishing locations, or variations in environmental conditions that have resulted in the capture of heavier dolphins as bycatch.

Temporal Patterns

The analysis indicates a general downward trend in DTN from 2013 to 2017, which may reflect improvements in bycatch mitigation strategies or changes in the distribution and behavior of dolphin populations within the fishing grounds. Despite some minor fluctuations, the overall trend remains relatively stable, implying that the number of dolphins impacted by fishing operations has not undergone substantial changes during the study period. In contrast, DTW displays a more complex temporal pattern, characterized by significant fluctuations over the years. The peak in 2015, followed by a decline in 2016 and a sharp rise in 2017, suggests considerable variability in the weight of dolphins caught as bycatch. Factors contributing to this variability may include differences in the sizes of dolphins captured, variations in fishing practices (such as changes in gear type or fishing locations), or environmental factors influencing dolphin distribution and behavior.

The marked increase in DTW in 2017, in particular, warrants further investigation to determine whether it is attributable to an increase in the size of dolphins being caught or a higher frequency of larger individuals in the bycatch.



Graph 8: Temporal Analysis of Dolphin Total Number (DTN) and Dolphin Total Weight (DTW) from 2013 to 2017. The plot shows the trend in DTN (in blue) remaining relatively stable, while DTW (in orange) exhibits more significant fluctuations, with a notable increase towards the end of 2016 and into 2017. The shaded regions represent the uncertainty in the measurements.

Box Plot Temporal Analysis

Monthly Distribution of Dolphin Total Number (DTN)

The box plot provides a visual summary of the monthly distribution of DTN, illustrating the central tendency, dispersion, and the presence of outliers(Graph 9). This visualization facilitates the assessment of the consistency of dolphin sightings across different months and highlights periods characterized by notable variability(Table 2).

Monthly Distribution:

- **January (1):** Observations in January exhibit relative consistency, with a mean DTN of 0.85, suggesting that most records reported approximately one dolphin per observation. The data shows minimal variability, with the majority of observations concentrated around a DTN of 1, and no outliers detected.
- **February (2):** In February, the mean DTN slightly decreases to 0.80, with an increase in data dispersion, as indicated by a higher standard deviation of 0.56. While the median remains at 1, the presence of outliers suggests that some observations recorded up to two dolphins, indicating a broader range of sightings.
- **March to October (3-10):** During these months, DTN values generally hover around 1, but the degree of variability varies. Notably, March, April, and September exhibit a wider range of values, with outliers capturing up to 5 dolphins in a single observation, particularly in April. This indicates occasional peaks in dolphin sightings during these months.
- **November (11):** November displays substantial variability, with a mean DTN of 1.25 and a relatively high standard deviation of 0.85. The expanded interquartile range and the presence of outliers suggest more erratic dolphin sightings during this month, with some observations reporting up to 4 dolphins.

- **December (12):** December records the lowest mean DTN at 0.67, reflecting a noticeable decline in dolphin sightings compared to other months. The data also exhibits greater variability, with a median DTN of 0.5 and a standard deviation of 0.82. This indicates that many observations reported fewer than one dolphin, while some outliers recorded up to 2 dolphins.

Month	Count	Mean	Std Dev	Min	25th Percentile	Median (50th Percentile)	75th Percentile	Max
January (1)	13	0.85	0.38	0	1.0	1.0	1.0	1.0
February (2)	15	0.80	0.56	0	0.5	1.0	1.0	2.0
March (3)	39	1.08	0.87	0	1.0	1.0	1.0	5.0
April (4)	26	1.15	1.05	0	1.0	1.0	1.0	5.0
May (5)	9	1.11	0.60	0	1.0	1.0	1.0	2.0
August (8)	6	0.83	0.41	0	1.0	1.0	1.0	1.0
September (9)	17	0.94	0.66	0	1.0	1.0	1.0	3.0
October (10)	17	1.00	0.35	0	1.0	1.0	1.0	2.0
November (11)	24	1.25	0.85	0	1.0	1.0	2.0	4.0
December (12)	6	0.67	0.82	0	0.0	0.5	1.0	2.0

Table 2: This table summarizes the monthly distribution of the Dolphin Total Number (DTN) observations, including the count, mean, standard deviation, and key percentiles

Outliers

Outliers were detected in several months, most notably in March, April, and November, where the number of dolphin sightings exceeded the monthly averages. These outliers represent instances with dolphin counts significantly higher than typical levels, suggesting potential anomalies or specific conditions that may have contributed to these elevated sightings.

Seasonal Trends

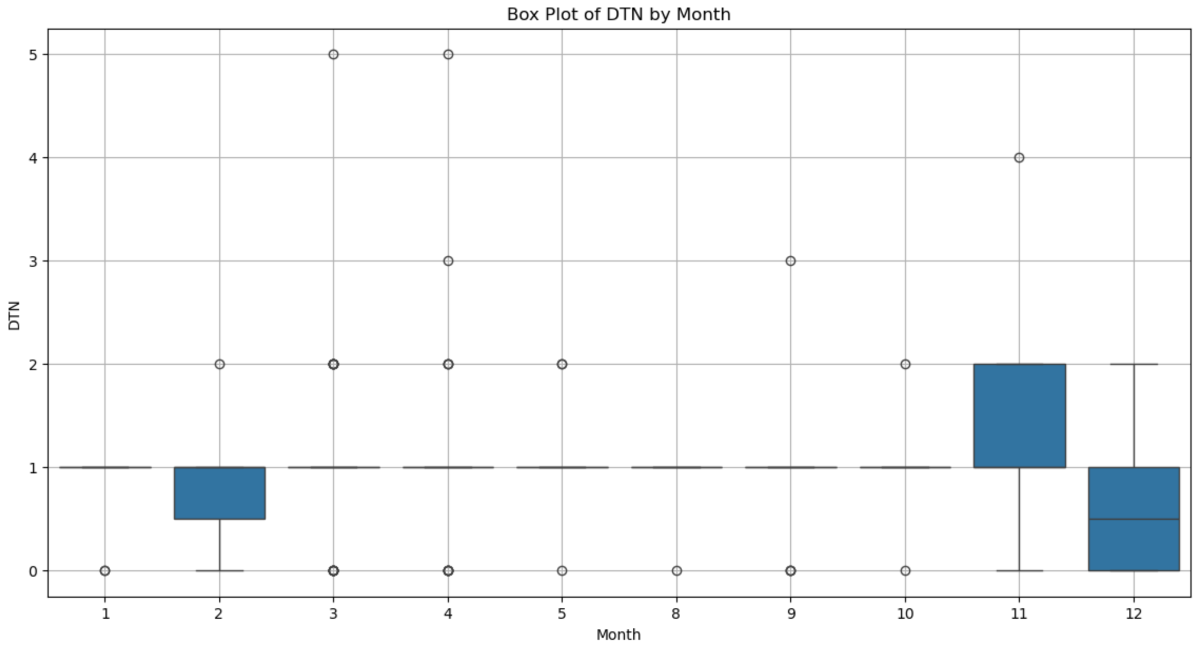
The analysis reveals a relatively stable pattern of dolphin sightings from January to October, with most months averaging around one dolphin per observation. However, November and December show increased variability and a lower average number of sightings, indicating possible seasonal shifts in dolphin behavior or changes in environmental conditions.

Low Variability in Early Months

From January to October, the data show a consistent pattern in dolphin sightings, with most observations reporting similar numbers of dolphins each month. This low variability suggests relatively stable environmental conditions or consistent dolphin behavior during this period.

Increased Variability Towards Year-End

The marked increase in variability observed in November and December may reflect changes in environmental conditions, dolphin migration patterns, or fishing practices during these months. Such variations could lead to more diverse and unpredictable dolphin encounters.



Graph 9: The box plot illustrates the distribution of DTN across the months of the year. Each box represents the interquartile range (IQR), with whiskers extending to the minimum and maximum values, excluding outliers, which are depicted as individual points. February, November, and December show the highest variability in DTN, with November having the most significant outliers. Other months display lower variability and more stable bycatch numbers

Monthly Distribution of Dolphin Total Weight (DTW)

The box plot provides a detailed visualization of DTW across different months, highlighting central tendencies, variability, and the presence of potential outliers within the dataset (Graph 10: The box plot displays the distribution of DTW across different months of the year. The boxes represent the interquartile range (IQR), while the whiskers indicate the range of the data excluding outliers. Outliers are shown as individual points. May exhibits the highest variability in DTW, with significant outliers, suggesting increased bycatch during this period. Other months show lower variability and more consistent bycatch weights.). The monthly distribution of DTW (Table 3) reveals distinct patterns throughout the year:

Monthly Distribution:

- **January (1):** DTW values are generally low, with occasional outliers indicating higher weights. These outliers suggest the occurrence of heavier dolphins during this month.
- **February to April (2-4):** These months display a broader range of DTW values compared to January, with slightly elevated median weights. Significant outliers in February and March suggest instances of much heavier dolphins, indicating variability in dolphin sizes during these months.
- **May (5):** May shows the greatest variability in DTW, characterized by a wide interquartile range (IQR) and several extreme outliers. This pattern indicates significant variation in dolphin weights, including occurrences of particularly heavy individuals.
- **June to October (6-10):** During these months, DTW values decrease and become more stable, as reflected by lower median weights and a narrower range of recorded weights. Although outliers are still present, they are less extreme than in earlier months, indicating a more consistent weight range.

- **November and December (11-12):** Similar to the mid-year months, November and December exhibit a relatively narrow range of DTW values with a few outliers. The lower median weights suggest that the dolphins recorded during these months are generally lighter.

Month	Count	Mean (kg)	Standard Deviation (kg)	Min (kg)	25% (kg)	Median (kg)	75% (kg)	Max (kg)
January	13	16.15	15.69	0.0	0.0	15.0	20.0	50.0
February	15	31.33	47.90	0.0	0.0	20.0	42.5	160.0
March	39	33.08	44.95	0.0	0.0	20.0	40.0	200.0
April	26	41.77	64.73	0.0	0.5	22.5	40.0	260.0
May	9	60.89	94.85	0.0	14.0	20.0	60.0	300.0
August	6	10.17	13.75	0.0	0.0	6.0	13.5	35.0
September	17	12.53	21.55	0.0	0.0	0.0	20.0	75.0
October	17	4.71	15.05	0.0	0.0	0.0	0.0	60.0
November	24	7.42	10.69	0.0	0.0	0.0	15.0	35.0
December	6	15.83	20.10	0.0	0.0	10.0	23.75	50.0

Table 3: This table summarizes the monthly distribution of Dolphin Total Weight (DTW) across different statistical measures.

Outliers

Outliers are evident in nearly all months, with particularly notable occurrences in February, March, May, and November. These outliers correspond to instances where recorded dolphin weights were significantly higher than the typical monthly values, suggesting occasional captures of much larger dolphins or unusual recording conditions.

Seasonal Trends

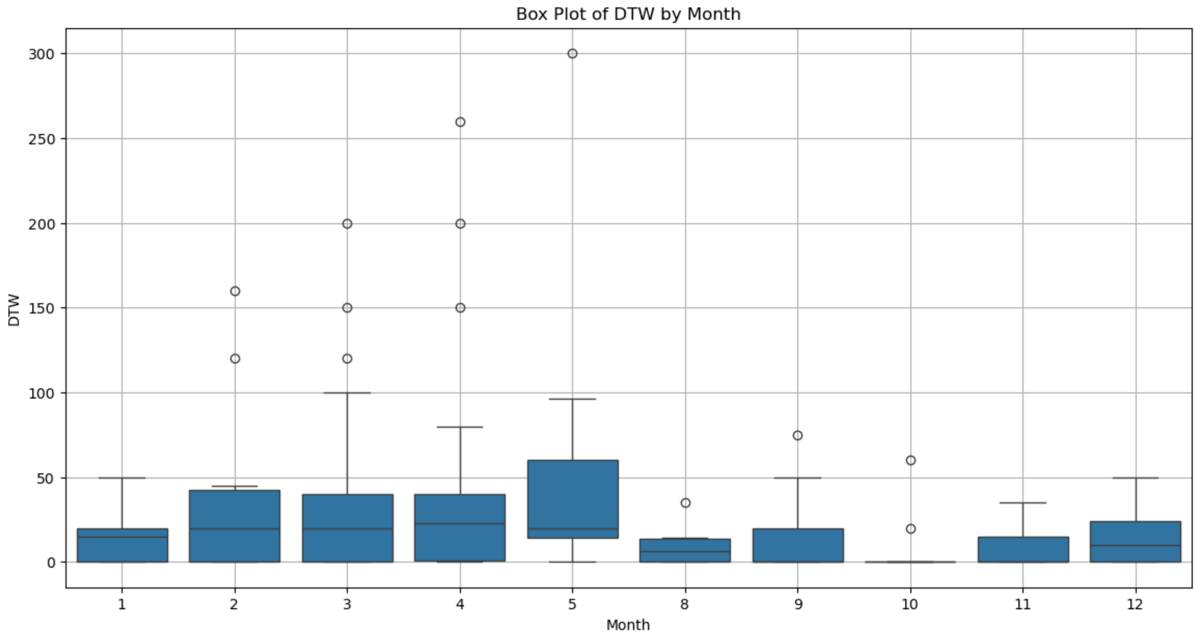
The data indicate that dolphin weights exhibit greater variability in the first half of the year, particularly in May, where the range of weights is most pronounced. This may reflect a period when larger dolphins are more prevalent, or when factors such as environmental conditions or changes in fishing practices contribute to increased variability in recorded weights. In contrast, the latter half of the year demonstrates more consistent and generally lower weights, which could be indicative of seasonal patterns in dolphin size, behavior, or stability in fishing practices.

High Variability in Early Months

The early months of the year, especially May, show considerable variability in dolphin weights. This variability is likely influenced by seasonal factors affecting dolphin behavior, growth, or migration patterns, leading to a broader range of recorded weights.

Consistent Low Weights Towards Year-End

As the year progresses, dolphin weights tend to stabilize, characterized by reduced variability and fewer extreme outliers. This pattern suggests a more uniform dolphin population or more consistent recording and fishing practices during these months.



Graph 10: The box plot displays the distribution of DTW across different months of the year. The boxes represent the interquartile range (IQR), while the whiskers indicate the range of the data excluding outliers. Outliers are shown as individual points. May exhibits the highest variability in DTW, with significant outliers, suggesting increased bycatch during this period. Other months show lower variability and more consistent bycatch weights.

Seasonal and Trend Analysis

Analysis of Seasonal Variation

Seasonal Patterns in Dolphin Total Number(DTN)

The analysis of DTN across the four seasons—Winter, Spring, Summer, and Fall—reveals distinct seasonal variations in dolphin sightings throughout the year (Graph 11).

Seasonal Patterns in DTN

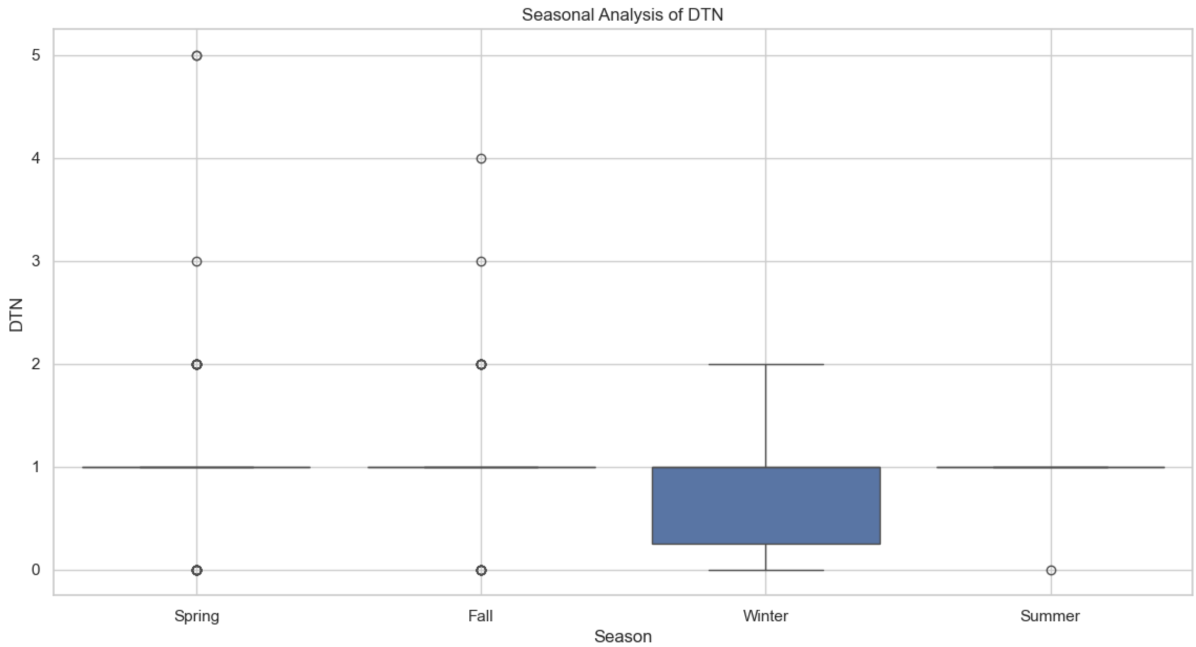
- **Winter:** Winter exhibits the greatest variability in DTN, with a median value of 1 and a range extending from 0 to 2. The box plot for Winter shows whiskers reaching up to 2, with a few outliers extending to 5. This distribution indicates that while DTN values generally cluster around 1 during Winter, there is substantial variability, suggesting fluctuations in dolphin numbers during this season.
- **Spring, Summer, and Fall:** In contrast, the Spring, Summer, and Fall seasons demonstrate more consistency in DTN values. The box plots for these seasons are relatively flat, with most values concentrated around 1, indicating minimal variation in DTN during these periods. However, outliers are still present, particularly in Spring, where DTN values occasionally reach up to 5. Summer and Fall show minimal variation, with some outliers approaching zero.
- **Outliers Across Seasons:** Outliers are evident across nearly all seasons, including Winter, representing DTN values that deviate significantly from the typical range. For instance, Spring has outliers reaching up to 5, while Summer and Fall display fewer deviations, with some values close to zero. These outliers suggest sporadic occurrences leading to unusually high or low dolphin counts.

Statistical Analysis: ANOVA Test

An ANOVA test was conducted to determine if there are statistically significant differences in DTN across the seasons. The test yielded an F-statistic of 1.607 and a p-value of 0.1896, indicating that the differences in DTN among the seasons are not statistically significant. This suggests that the seasonal effect on DTN is minimal, providing no strong evidence that DTN varies substantially between different seasons.

Although the ANOVA test does not reveal significant seasonal differences, the box plot indicates increased variability in DTN during Winter. This heightened variability could be influenced by environmental or operational factors affecting dolphin sightings or bycatch during this season. The presence of outliers across most seasons further indicates sporadic events that result in higher or lower dolphin counts.

The seasonal analysis of Dolphin DTN demonstrates that DTN remains relatively stable across Spring, Summer, and Fall, with a slight increase in variability observed during Winter. While the ANOVA test results suggest that seasonality does not significantly affect DTN (F-statistic = 1.607, p-value = 0.1896), the increased variability and presence of outliers in Winter highlight potential underlying factors that warrant further investigation. Future analyses focusing on additional variables, such as environmental conditions or specific monthly trends, could provide deeper insights into the factors influencing DTN.



Graph 11: The box plot illustrates the distribution of DTN across different seasons. The winter season shows the most variation with a few outliers, while the other seasons display minimal variation in DTN, indicating a relatively stable bycatch rate during these periods

Seasonal Variations in Dolphin Total Weight (DTW)

The box plot (Graph 12) provides a comprehensive visualization of the seasonal variations in DTW across Spring, Fall, Winter, and Summer:

- **Spring:** Spring exhibits the highest variability in DTW, marked by several outliers, including an extreme value reaching 300 units. The median DTW during Spring is notably higher compared to other seasons, suggesting that dolphin weights are more varied and generally heavier during this period. This increased variability may indicate the presence of larger dolphins or specific environmental or ecological factors influencing dolphin size in Spring.

- **Fall:** Fall, in contrast, shows a lower median DTW with fewer outliers and a narrower range of values. This pattern suggests a more consistent range of dolphin weights, reflecting less variability compared to Spring. The relative stability in DTW during Fall may indicate more uniform environmental conditions or dolphin behavior.
- **Winter:** In Winter, DTW values are more concentrated around lower levels, with some moderate outliers. This distribution implies that most dolphin weights are lower during Winter, with occasional instances of higher weights. The clustering around lower weights may be associated with seasonal changes in dolphin populations or environmental factors that influence the size of dolphins caught.
- **Summer:** Summer presents the lowest DTW values, with minimal variability and no significant outliers, indicating a period when dolphin weights are generally lower and more uniform. This trend could suggest a reduced presence of larger dolphins or a shift in population structure towards smaller individuals during this season.

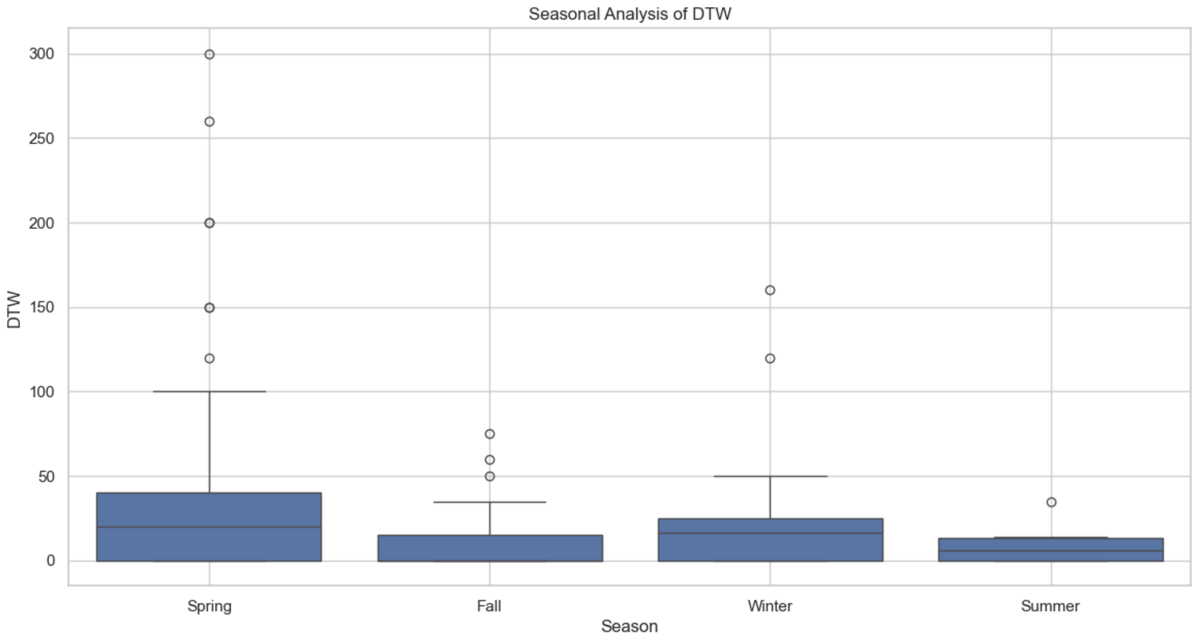
Outliers and Their Implications

The presence of outliers, particularly in Spring, indicates instances of unusually high dolphin weights that deviate significantly from the median. These anomalies may offer valuable insights into the seasonal dynamics of dolphin populations, potentially reflecting specific events or environmental conditions that result in heavier dolphins. The higher variability in DTW during Spring suggests this season's importance for encountering larger dolphins, which may have implications for fisheries management and conservation efforts. Conversely, the lower DTW in Summer may indicate a reduced presence of larger dolphins or a trend toward smaller individuals during this period.

Statistical Analysis: ANOVA Test on DTW

An ANOVA test was performed to assess whether there are statistically significant differences in DTW across the seasons. The test yielded an F-statistic of approximately 5.995 and a p-value of 0.00066. The F-statistic indicates considerable variability in DTW among the different seasons, suggesting that the mean DTW is not consistent across all seasons. The p-value, being well below the conventional significance threshold of 0.05, provides strong evidence of significant differences in DTW across the seasons.

The statistical analysis confirms a significant seasonal effect on Dolphin Total Weight (DTW). The observed differences in DTW across seasons are statistically significant, highlighting the importance of seasonality in understanding dolphin weight distribution. This finding underscores the necessity of accounting for seasonal variations when studying dolphin populations and developing management strategies.



Graph 12: The box plot shows the distribution of DTW across different seasons. Spring exhibits the highest variability with several significant outliers, indicating sporadic large catches. Fall and Winter have moderate variability, while Summer shows the least variation in DTW, suggesting lower and more consistent bycatch during this season.

Time Series Decomposition Analysis

Time Series Decomposition Analysis of Dolphin Total Number (DTN)

The time series decomposition analysis of DTN provides critical insights into the underlying patterns within the data(Graph 13). This analysis disaggregates the DTN data into three key components: trend, seasonality, and residuals, each offering a distinct perspective on the temporal dynamics of dolphin sightings or captures.

Trend Component

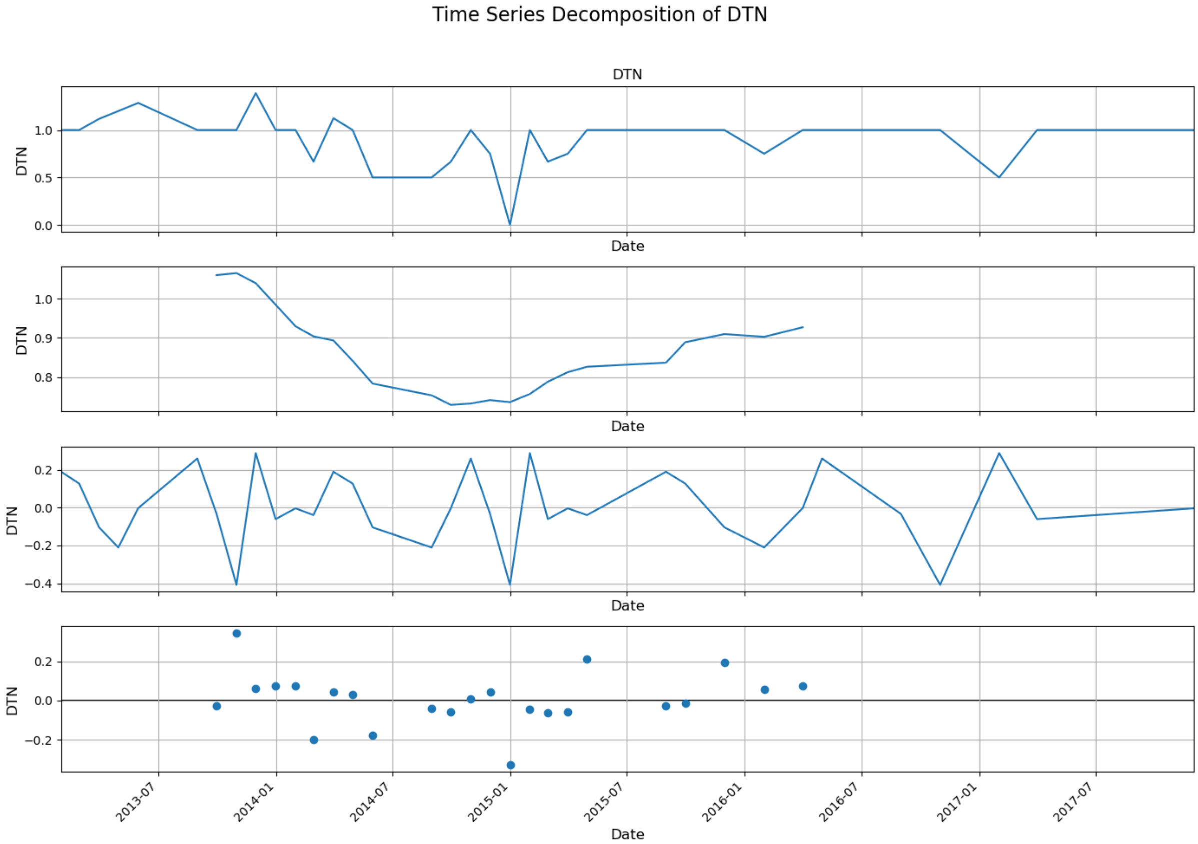
The trend component reflects the long-term trajectory of DTN over the study period. The results indicate a slight decline in dolphin numbers from mid-2013 to early 2014, followed by a gradual increase extending through 2017. This downward trend may suggest a reduction in dolphin sightings or captures during the initial period, potentially influenced by environmental changes, shifts in fishing practices, or other external factors. Understanding this trend is crucial for identifying broader patterns in dolphin populations and assessing the impact of various influences over time.

Seasonal Component

The seasonal component captures the recurring patterns or cycles that occur within the data. The analysis reveals that the seasonal effect fluctuates around zero, suggesting that while there are some seasonal variations in DTN, these fluctuations are relatively minor compared to the overall trend. These seasonal patterns may correspond to specific times of the year when dolphin sightings or captures are more or less frequent, potentially due to migratory behaviors, breeding seasons, or oceanographic changes. Recognizing these patterns can assist in making more accurate predictions and refining management strategies accordingly.

Residual Component

The residual component represents the portion of the DTN data that is not accounted for by the trend or seasonal components. The residuals fluctuate around zero, indicating variability that may suggest the influence of additional factors or irregularities affecting DTN not captured by the trend or seasonality. Positive residuals, such as those observed in October 2013, indicate unexpected increases in DTN for that month. These anomalies could result from sudden environmental changes, atypical fishing activities, or inconsistencies in data collection. Analyzing these residuals can offer valuable insights into unforeseen events or anomalies that may require further investigation.



Graph 13: The decomposition plot breaks down the DTN time series into its components: the observed data (top panel), the overall trend (second panel), seasonal patterns (third panel), and residuals or noise (bottom panel). The trend shows a gradual decrease followed by a slight increase, while the seasonal component reflects periodic fluctuations. The residuals indicate random variations that are not captured by the trend or seasonality.

Decomposition Analysis of Dolphin Total Weight (DTW)

The decomposition analysis of DTW provides valuable insights into the underlying patterns and variations within the data, separating DTW into its trend, seasonal, and residual components (Graph 14).

Trend Component

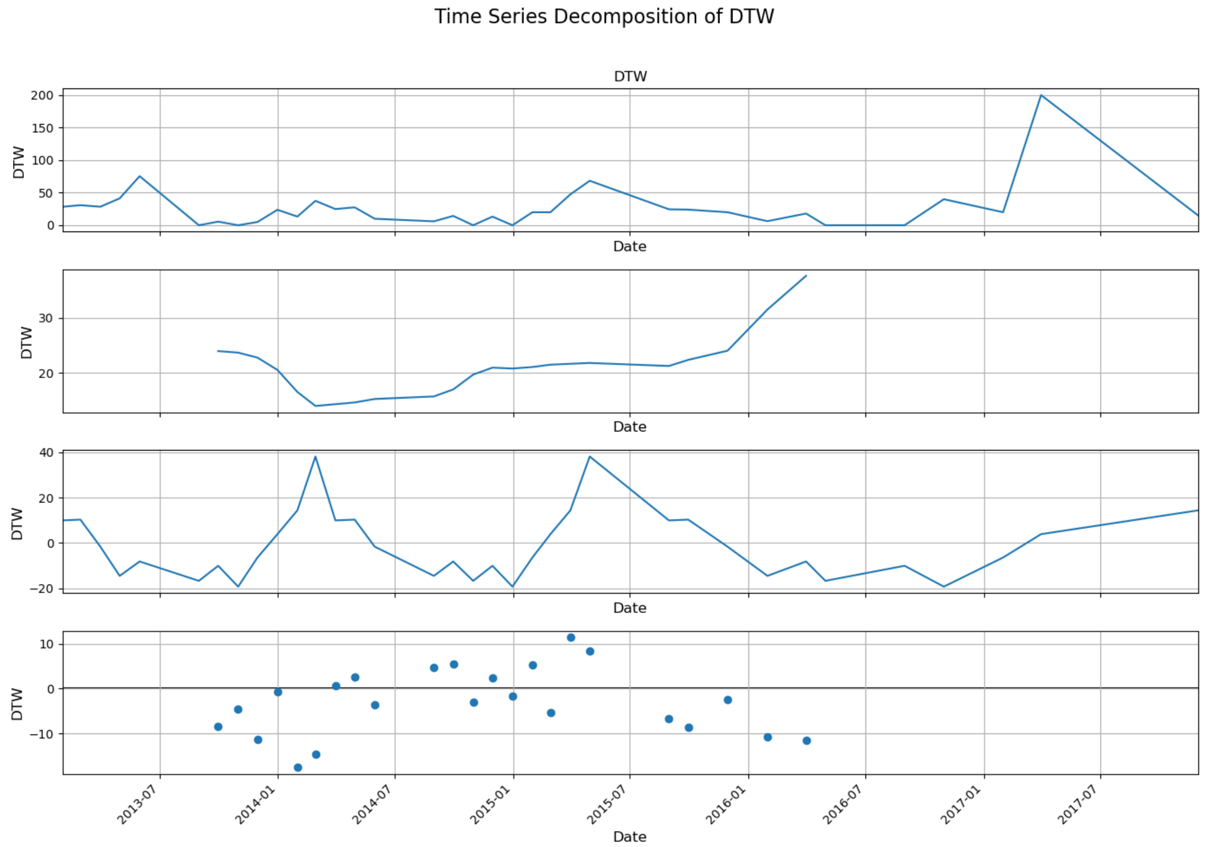
The trend in DTW demonstrates a consistent decline from September 2013 to January 2014, with values decreasing from approximately 23.98 to 16.53. This downward trend may indicate a reduction in dolphin bycatch weight during this period, potentially due to changes in fishing practices, the implementation of regulatory measures, or shifts in dolphin populations. The observed decline could be attributed to successful conservation efforts, modifications in fishing strategies, or natural fluctuations in dolphin populations.

Seasonal Component

The seasonal component captures recurring fluctuations that correspond with seasonal cycles. The analysis reveals that certain months consistently experience higher or lower DTW. For example, January and February show positive seasonal values, indicating an increase in DTW by approximately 9.94 and 10.28 units, respectively. In contrast, March, April, and May exhibit negative seasonal effects, with April experiencing the most pronounced decrease at approximately -14.47. These seasonal patterns suggest a predictable increase in DTW during the early months of the year, likely linked to seasonal dolphin migration or variations in fishing activity levels. The lower DTW observed in the middle of the year could be due to dolphins migrating away from fishing areas or a reduction in fishing intensity.

Residual Component

The residual component reflects the portion of the data that remains unexplained after accounting for both the trend and seasonal effects, often representing noise or unexplained variability. In this analysis, the residuals display fluctuations around the expected trend and seasonal patterns. For example, in September 2013, the residual is -8.39, indicating that the observed DTW was lower than expected. Similarly, in January 2014, a significant negative residual of -17.56 suggests a much lower DTW than anticipated based on the trend and seasonality. These substantial negative residuals imply that additional factors, such as unusual environmental conditions, unexpected changes in fishing practices, or other unpredictable events, are influencing DTW beyond the identified trend and seasonal components.



Graph 14: This plot decomposes the DTW time series into four components: the observed data (top panel), the overall trend (second panel), seasonal patterns (third panel), and residuals or noise (bottom panel). The trend reveals a general increase in DTW towards the end of the period, while the seasonal component captures periodic fluctuations. The residuals illustrate the variability that is not explained by the trend or seasonality, including some significant deviations.

Trend Analysis by using the Line Regression Model

Trend Analysis of Dolphin Total Number (DTN)

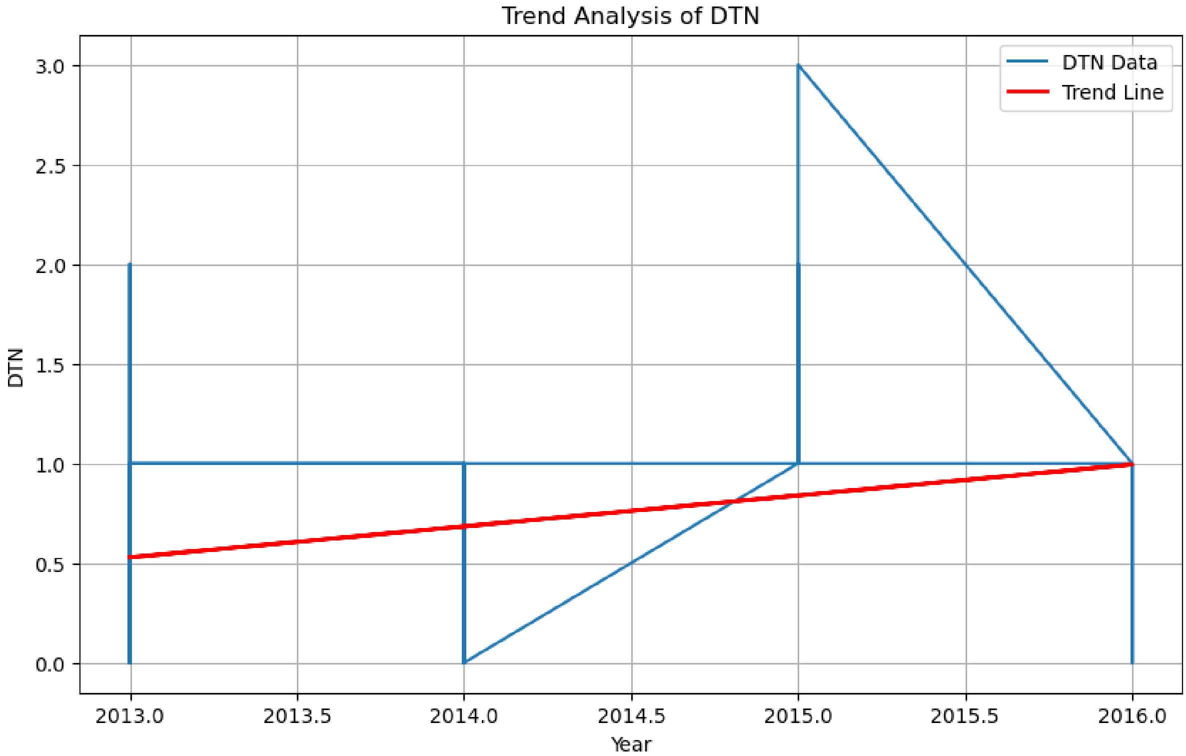
The trend analysis of DTN over time was performed using a linear regression model to interpret the observed data (Graph 15). The blue line on the graph represents the actual DTN values recorded from 2013 to 2016, illustrating the variability in the number of dolphins observed during these years. The y-axis, ranging from 0 to 3, corresponds to the recorded dolphin counts.

Superimposed on the graph is the red trend line, derived from the linear regression model, indicating the overall direction of DTN values over time. This trend line has a slight upward slope, suggesting a modest increase in DTN over the period. However, this increase is minimal, as indicated by the gentle incline of the trend line.

A closer examination of the blue line reveals significant fluctuations in DTN values, demonstrating considerable variability from year to year. For instance, there is a marked spike in DTN in 2015, followed by a sharp decline. This pattern indicates that the number of dolphins recorded is subject to substantial variation, which is not fully captured by the linear trend line.

The slope of the trend line, approximately 0.155, suggests a slow but steady increase in DTN over time. The intercept of the trend line, around -311.85, represents the theoretical DTN value when the year is zero, which is not practically meaningful since year 0 is not within the range of observed data. The R^2 value of approximately 0.046 indicates that the trend line explains only a small proportion of the variability in the actual data, highlighting the model's limitations in capturing the full complexity of DTN trends.

While the trend analysis suggests a slight upward trend in DTN over the study period, the actual data exhibit significant fluctuations that are not adequately explained by the trend line. These variations could be attributed to various factors, such as environmental conditions, changes in fishing practices, or inconsistencies in data collection.



Graph 15: Trend Analysis of Dolphin Total Number (DTN) by the linear regression model. The plot shows the actual DTN data (blue line) over time from 2013 to 2016, along with a linear trend line (red line). The trend line indicates a slight upward trend in DTN over the observed period, despite fluctuations in the actual data. This suggests a modest increase in dolphin bycatch during this timeframe.

Trend Analysis of Dolphin Total Weight (DTW)

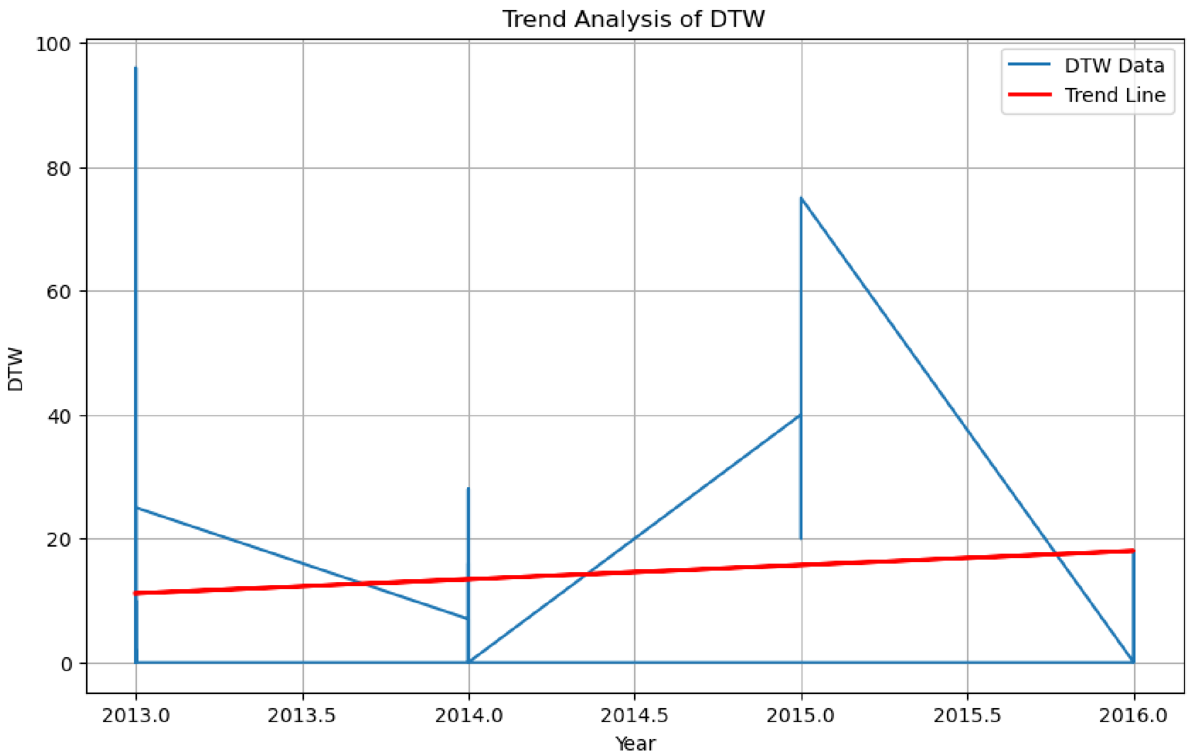
The trend analysis for DTW, utilizing a linear regression model, provides important insights into its behavior over time (Graph 16). The trend line has a slope of 2.29, indicating that, on average, DTW increases by approximately 2.29 units per year. This positive slope suggests a modest upward trend in the total weight of dolphins caught over the analyzed period. The intercept of the trend line is -4597.89, which represents the theoretical point at which the trend line would intersect the y-axis if extended back to year 0. While this intercept is mathematically necessary for defining the trend line, it has no practical significance in the context of the observed data range.

The R^2 value, which measures the goodness of fit of the trend line to the data, is notably low at 0.01. This indicates that the linear model accounts for only about 1% of the variability in DTW, underscoring its inadequacy in capturing the full extent of variations in DTW. Such a low R^2 score suggests that factors other than the time trend are likely more influential in determining changes in DTW.

The red trend line on the graph shows a slight upward trajectory, indicating a gradual increase in the total weight of dolphins over the years. However, the blue line, representing the actual DTW data, reveals substantial fluctuations, with distinct peaks and troughs. These variations suggest significant underlying variability in DTW that the simple linear trend does not adequately capture.

Given the low R^2 value, the trend line does not fit the data well and fails to account for the considerable variability observed in DTW. This suggests that relying solely on a linear model to predict DTW would be insufficient. More sophisticated modelling approaches or the inclusion of additional explanatory variables would be necessary for a more accurate and comprehensive understanding.

While the trend analysis does suggest a slight upward trend in DTW over time, the minimal explanatory power of the model highlights its limitations. The substantial fluctuations in DTW imply that the data is influenced by factors beyond what can be explained by a simple linear trend.



Graph 16: Trend Analysis of Dolphin Total Weight (DTW) by the linear regression model. The plot illustrates the actual DTW data (blue line) over time from 2013 to 2016, with a linear trend line (red line) superimposed. The trend line shows a slight upward trend in DTW, indicating a gradual increase in the total weight of dolphin bycatch over the period, despite significant fluctuations in the observed data.

Anomaly and Change Point Detection

Anomaly Detection

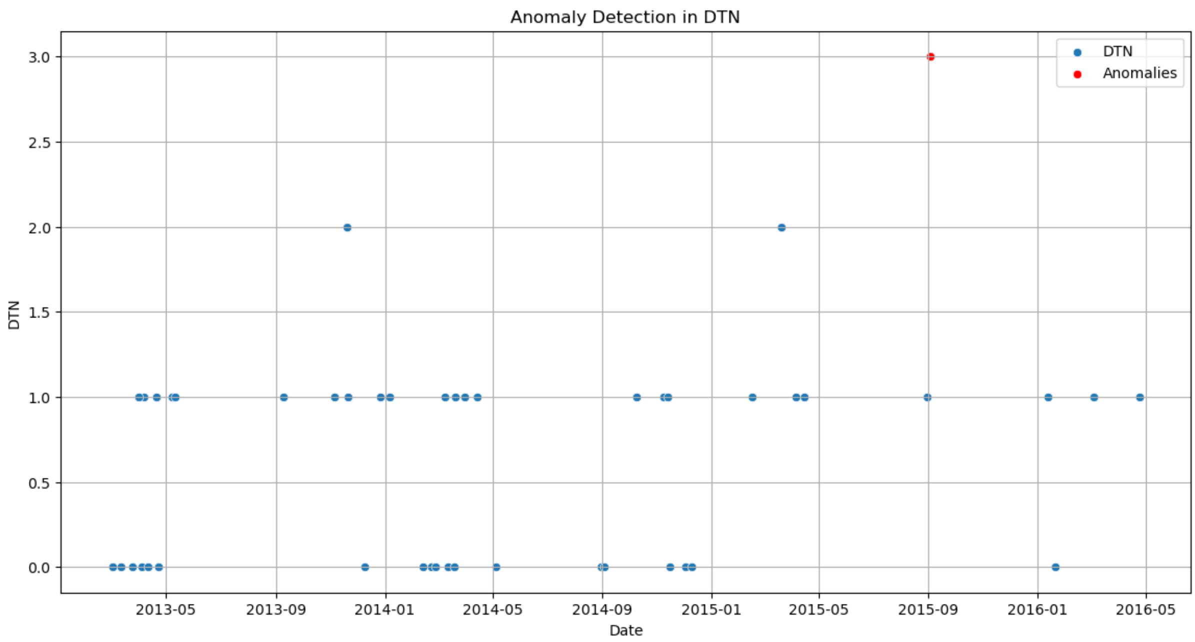
Anomaly Detection Analysis of Dolphin Total Number (DTN)

The results of an anomaly detection analysis over time, utilizing the Z-score statistical method to identify significant deviations from expected DTN values (Graph 17).

The blue dots on the graph represent the recorded DTN values across various dates, depicting both the overall trend and variability within the data. Most of these values are concentrated around 1.0, indicating that DTN remains relatively stable over time. However, the graph also highlights red dots that signify detected anomalies—instances where DTN values deviate substantially from the norm.

Anomalies are identified when the Z-score—a measure of how many standard deviations a data point is from the mean—exceeds a threshold of 3. In this analysis, a single anomaly was detected, represented by a red dot on the timeline. This indicates that, on the specific date associated with this anomaly, the DTN value was unusually high compared to the rest of the observations. The presence of such an anomaly may suggest an atypical event, a potential data collection error, or a rare ecological phenomenon that resulted in this spike.

Detecting this anomaly in DTN is particularly important within the fisheries context, as it may signal an unexpected surge in dolphin bycatch on a specific day. Understanding the underlying causes of such anomalies is crucial for enhancing bycatch management strategies and identifying any exceptional circumstances that may have contributed to the unusual observation.



Graph 17: The scatter plot shows the DTN data points over time, with detected anomalies highlighted in red. The plot identifies a significant outlier in late 2015, suggesting an unusual spike in dolphin bycatch during that period, which deviates from the general trend observed in the dataset.

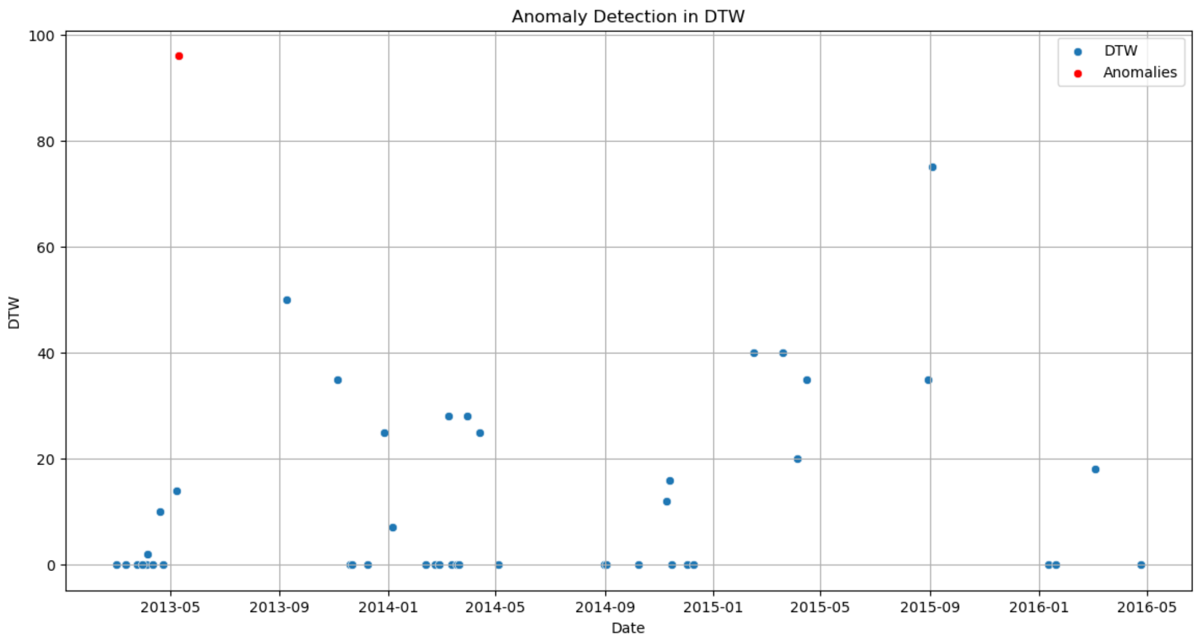
Anomaly Detection Analysis of Dolphin Total Weight (DTW)

The results of anomaly detection for DTW over time. In this analysis, the blue dots represent the recorded DTW values across different dates, illustrating the overall trend and variability within the dataset (Graph 18). The red dots indicate anomalies identified using the Z-score method, highlighting significant deviations from the expected values.

The analysis identifies a notable anomaly in the DTW data, represented by a red dot on the graph. This anomaly indicates that on the corresponding date, the DTW value was exceptionally high compared to the other observations. This detected anomaly occurs near the beginning of the observed period, with a DTW value approaching 100—substantially exceeding the typical range of the other data points.

The Z-score method, employed to detect anomalies, standardizes the data to determine how far a given value deviates from the mean in terms of standard deviations. In this analysis, any DTW value with a Z-score greater than 3 is classified as an anomaly. The identified anomaly exceeds this threshold, being more than three standard deviations away from the mean DTW value, thereby marking it as an extreme outlier within the dataset.

Regarding the temporal distribution of DTW values, the majority remain below 60, with most clustering around much lower figures. However, the anomaly detection reveals a significant spike in DTW, with only one of these high values flagged as an anomaly.



Graph 18: The scatter plot displays DTW data points over time, with anomalies marked in red. A significant outlier is detected in early 2013, indicating an unusually high total weight of dolphin bycatch. Other anomalies are observed sporadically, highlighting periods with unusual bycatch events that deviate from the general pattern in the data.

Change Point Detection

The change point detection analysis of DTN and DTW provides valuable insights into significant shifts in the data over time (Graph 19). The graphs generated from this analysis display time series data for both DTN and DTW, with vertical red lines indicating moments where notable changes occurred.

Change Points in Dolphin Total Number (DTN)

The analysis of the DTN graph reveals that the early period, particularly around 2013, exhibited significant variability, indicating substantial fluctuations in the number of dolphins recorded. As the timeline progresses into 2014, these fluctuations become less pronounced, suggesting a potential stabilization of DTN. A marked decline is observed around mid-2015, after which the data appears to stabilize further. The red dashed lines marking the change points indicate significant shifts, potentially attributable to environmental factors or changes in fishing practices. The change point around mid-2015, in particular, aligns with the observed decline and subsequent stabilization in DTN.

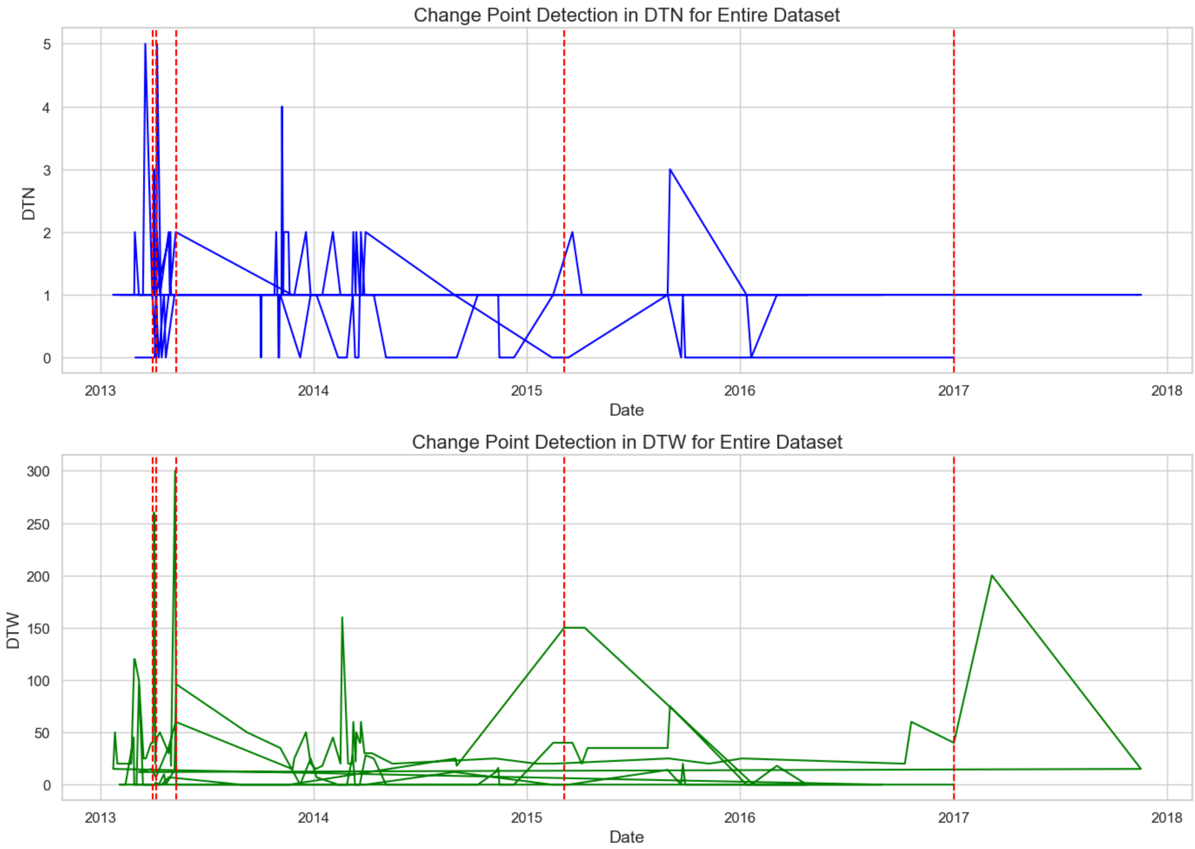
Change Points in Dolphin Total Weight (DTW)

The DTW graph similarly exhibits pronounced peaks in early 2013, reflecting considerable fluctuations in the total weight of dolphins during this period. Following 2013, there is a gradual decline in DTW values, with intermittent peaks around 2015, possibly corresponding to isolated high-catch events or anomalies in data recording. Towards 2017, a noticeable increase in DTW is observed, indicating a rise in the total weight of dolphins recorded during this time. The detected change points around 2013-2014 coincide with high initial variability, while another significant change point is evident around 2017, corresponding with the observed increase in DTW.

Interpretation of Change Points

The identified change points signify periods where trends in dolphin bycatch, both in number and weight, shifted markedly. These shifts could be associated with various factors, such as seasonal patterns, changes in fishing regulations, or modifications in fishing practices. The decrease in variability over time, particularly in DTN, may suggest more consistent fishing practices or stabilized environmental conditions. Conversely, the increase in DTW towards the end of the dataset indicates a resurgence in dolphin bycatch by weight, warranting further investigation.

Identifying these change points is critical for fisheries management, as it helps to pinpoint when and why certain changes in bycatch occurred. Understanding these shifts enables the development of more effective management strategies to mitigate dolphin bycatch and adapt to evolving environmental and operational conditions.



Graph 19: The top panel shows change points in DTN, while the bottom panel illustrates change points in DTW, with significant shifts in the time series marked by red dashed lines. These change points indicate moments where the data patterns shifted, possibly due to changes in fishing practices, environmental factors, or other external influences. The detection of multiple change points, particularly in the early years, suggests periods of instability or transition in bycatch rates.

Advanced Temporal Analysis

Regression analysis

Regression Analysis of Dolphin Total Number (DTN)

The regression analysis of DTN explores the relationship between geographical coordinates (latitude and longitude) and DTN using a linear regression model. The objective of this analysis is to evaluate the model's effectiveness in predicting DTN based on these spatial variables and to provide key insights into the dynamics of dolphin bycatch (Graph 20).

Model Fit and Interpretation:

The actual DTN values (represented by blue dots) with predicted values from the regression model (represented by red dots) demonstrate that the predicted values tend to cluster around specific DTN levels, particularly lower values such as 0 and 1. While there is some overlap between actual and predicted values for lower DTN counts, the discrepancies become more pronounced as DTN values increase. This indicates that the model has limited accuracy in predicting higher DTN values.

R-Squared Value:

The low R^2 value of 2.38% suggests that the model explains only a small proportion of the variance in DTN. This low value reinforces the observation that latitude and longitude alone do not account for much of the variation in DTN, indicating that other factors likely have a more substantial influence on DTN.

Residuals and Errors:

The gaps between the predicted and actual values, particularly for higher DTN values, reflect substantial residuals—the differences between the observed and predicted values. This is further supported by the error metrics, such as a Mean Absolute Error (MAE) of 0.4327 and a Mean Squared Error (MSE) of 0.5611, which suggest that the model's predictions lack precision.

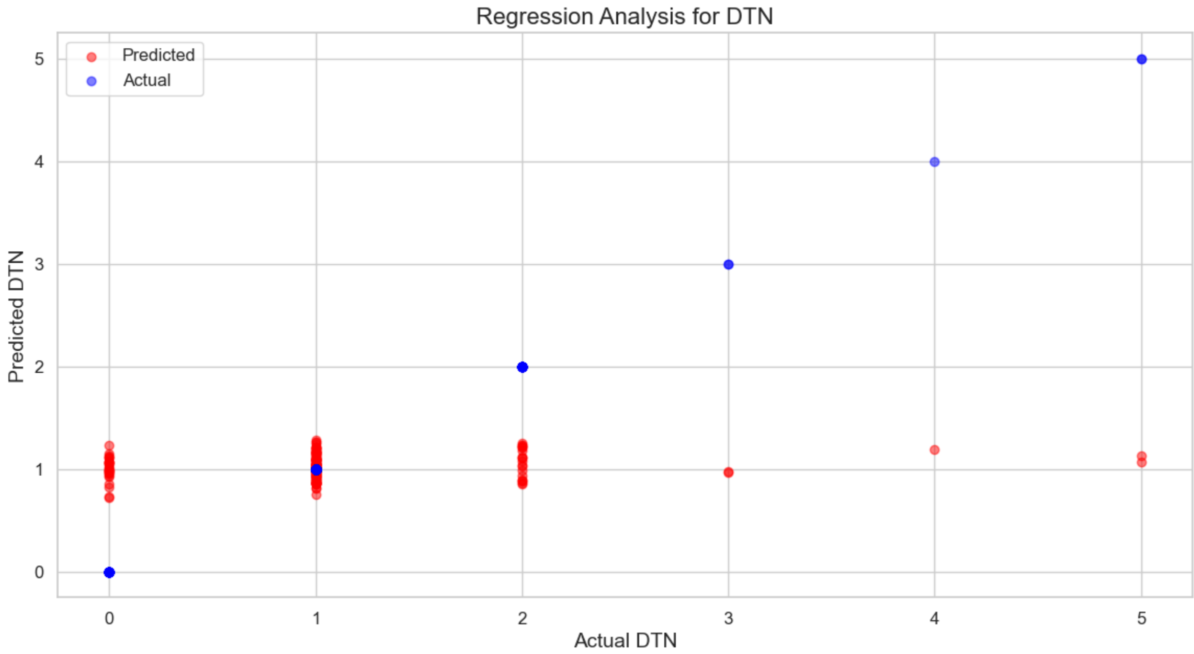
Coefficient Insights:

The model coefficients indicate that an increase in latitude is associated with a slight decrease in the predicted DTN, while an increase in longitude is associated with a slight increase in DTN (Table 4: This table provides a summary of the key findings from the regression analysis for Dolphin Total Number (DTN).Table 4). However, the small magnitude of these coefficients, along with a negative intercept, implies that the model's predictions are not strongly influenced by these geographical variables.

Given the low R^2 value and the observed errors, it is evident that DTN is influenced by factors beyond latitude and longitude. These factors could include environmental conditions, fishing practices, or other ecological variables not accounted for in this model. Therefore, the analysis suggests that a more sophisticated model—potentially incorporating non-linear relationships or additional variables—would be necessary to better explain and predict DTN.

Metric	**Value**	**Description**
Latitude Coefficient	-0.0886	Indicates that an increase in latitude by one unit is associated with a decrease of approximately 0.0886 units in DTN, holding longitude constant.
Longitude Coefficient	0.0867	Indicates that an increase in longitude by one unit is associated with an increase of approximately 0.0867 units in DTN, holding latitude constant.
Intercept	-2.5361	Represents the predicted DTN when both latitude and longitude are zero. Not directly interpretable in a geographical context.
R^2 Score	0.0238	Indicates that the model explains only 2.38% of the variance in DTN, suggesting that other factors are likely more influential.
Mean Absolute Error (MAE)	0.4327	Represents the average absolute difference between actual and predicted DTN values. On average, predictions are off by about 0.433 DTN units.
Mean Squared Error (MSE)	0.5611	Represents the squared average difference between actual and predicted DTN values, with larger errors contributing more to the overall error metric.

Table 4: This table provides a summary of the key findings from the regression analysis for Dolphin Total Number (DTN).



Graph 20: The scatter plot compares actual DTN values (in blue) against predicted DTN values (in red). The closer the red and blue points align along a 45-degree line, the better the model's predictions match the actual data. Deviations indicate areas where the model's predictions do not align well with observed outcomes, suggesting possible improvements in model accuracy.

Regression Analysis of Dolphin Total Weight (DTW)

This analysis examines the relationship between geographical coordinates (latitude and longitude) and DTW using a linear regression model, providing insights into how variations in these geographical factors may influence the total weight of dolphins (Graph 21).

Model Coefficients:

The regression analysis reveals a latitude coefficient of -5.3887, indicating a negative relationship between latitude and DTW. This suggests that for each unit increase in latitude, the predicted DTW decreases by approximately 5.3887 units, assuming longitude remains constant. In contrast, the longitude coefficient is 0.8127, indicating a positive relationship with DTW. This implies that a one-unit increase in longitude results in a slight increase of about 0.8127 units in DTW, holding latitude constant (Table 5).

Intercept:

The intercept value of 286.5305 represents the predicted DTW when both latitude and longitude are zero. While this value lacks practical relevance in a geographical context, it serves as a reference point for the model's predictions.

R^2 Score:

The R^2 score for this model is 0.0069, which is very low. This indicates that only about 0.69% of the variance in DTW is explained by the linear regression model based on latitude and longitude. This suggests that these geographical factors do not significantly account for the variations in DTW, implying that other factors are likely more influential.

Error Metrics:

The Mean Absolute Error (MAE) is 36.78, indicating that, on average, the model's predictions deviate by about 36.78 units from the actual DTW values. The Mean Squared Error (MSE) is 2751.63, reflecting that the model occasionally produces large errors, resulting in substantial deviations from the actual values.

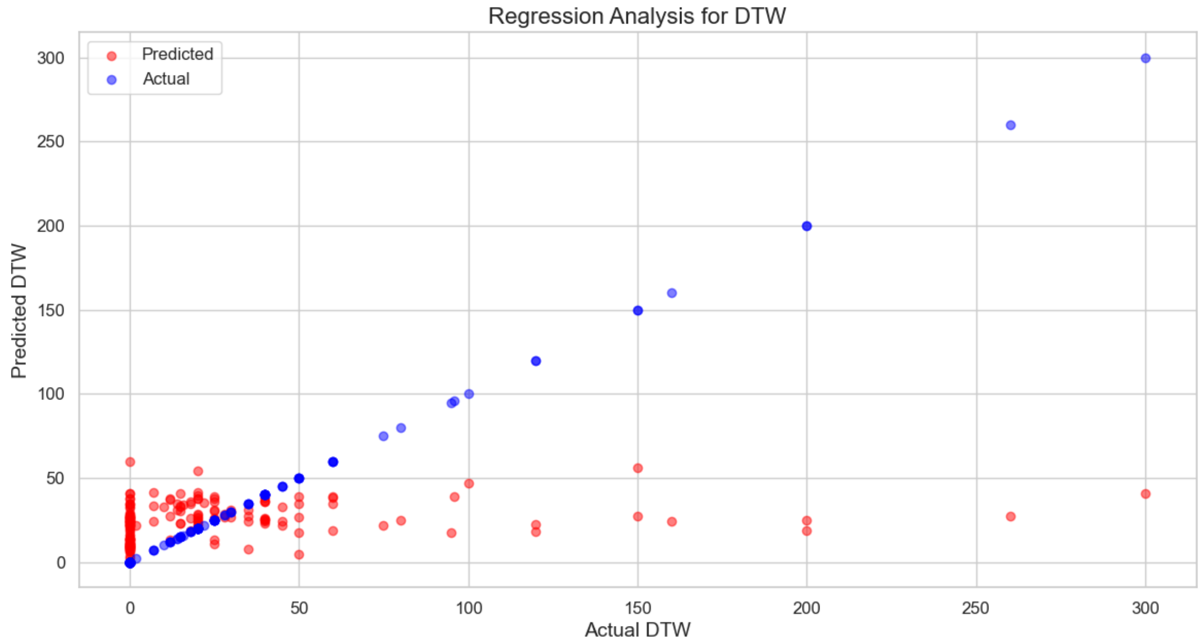
Interpretation:

The results indicate that the linear regression model does not effectively capture the relationship between geographical coordinates and DTW. The low R^2 score, combined with the error metrics, highlights the model's limited accuracy in predicting DTW. While the coefficients suggest that changes in latitude have a more pronounced impact on DTW than changes in longitude, neither factor explains a substantial portion of the variance in DTW.

Given the weak explanatory power of the model, it is evident that factors beyond latitude and longitude are driving the variations in DTW. These could include environmental conditions, fishing practices, or other biological factors. The model's poor performance suggests that a more sophisticated approach, potentially involving non-linear relationships or the inclusion of additional variables, may be necessary to improve the accuracy of DTW predictions.

Metric	Value	Description
Latitude Coefficient	-5.3887	Indicates that as latitude increases by one unit, the predicted DTW decreases by approximately 5.3887 units, assuming longitude remains constant.
Longitude Coefficient	0.8127	Suggests that an increase in longitude by one unit results in an increase in DTW by about 0.8127 units, assuming latitude remains constant.
Intercept	286.5305	Represents the predicted DTW when both latitude and longitude are zero, serving as a baseline for predictions.
R^2 Score	0.0069	Indicates that only 0.69% of the variance in DTW is explained by the linear model, suggesting other factors play a significant role.
Mean Absolute Error (MAE)	36.78	Represents the average deviation of the model's predictions from the actual DTW values.
Mean Squared Error (MSE)	2751.63	Highlights the presence of larger errors, showing that the model's predictions can significantly deviate from the actual values.

Table 5: This table provides a summary of the key findings from the regression analysis for Dolphin Total Weight (DTN).



Graph 21: The scatter plot illustrates the relationship between actual DTW values (in blue) and predicted DTW values (in red). Ideally, the points should align along a 45-degree line, indicating that the model accurately predicts DTW. However, the dispersion of red points around this line, particularly at higher DTW values, suggests that the model struggles with accurately predicting larger bycatch weights.

Granger Causality Test

Granger Causality Test Analysis Between Dolphin Total Number (DTN) and Dolphin Total Weight (DTW)

The Granger causality test was conducted to determine whether past values of Dolphin Total Number (DTN) can be used to predict future values of Dolphin Total Weight (DTW). The test was applied across multiple lags, ranging from 1 to 4, to evaluate the potential predictive influence of DTN on DTW (Table 6).

Test Results:

- **Lag 1:** The F-test yielded a value of 0.1345 with a p-value of 0.7163. This high p-value indicates no significant evidence to suggest that DTN at lag 1 can predict DTW.
- **Lag 2:** At a lag of 2, the F-test result was 0.5820 with a p-value of 0.5654, again showing no significant Granger causality from DTN to DTW.
- **Lag 3:** For a lag of 3, the F-test produced a value of 0.3544 with a p-value of 0.7863. This result further supports the lack of predictive power of DTN over DTW at this lag.
- **Lag 4:** At a lag of 4, the F-test result was 0.4795 with a p-value of 0.7504, continuing the trend of non-significance.

Across all lags tested, the p-values consistently exceeded common significance thresholds, such as 0.05. This consistent pattern strongly suggests that there is no significant Granger causality from DTN to DTW at any of the lags considered. Therefore, the analysis indicates that DTN does not have predictive power for DTW, suggesting that changes in DTN are not useful for forecasting DTW within the framework of this test.

Metric	Value	Description
Lag 1 - F-test	0.1345	Test statistic for Granger causality at lag 1
Lag 1 - p-value	0.7163	p-value indicating no significant causality at lag 1
Lag 2 - F-test	0.5820	Test statistic for Granger causality at lag 2
Lag 2 - p-value	0.5654	p-value indicating no significant causality at lag 2
Lag 3 - F-test	0.3544	Test statistic for Granger causality at lag 3
Lag 3 - p-value	0.7863	p-value indicating no significant causality at lag 3
Lag 4 - F-test	0.4795	Test statistic for Granger causality at lag 4
Lag 4 - p-value	0.7504	p-value indicating no significant causality at lag 4
Overall Interpretation	N/A	No significant Granger causality from DTN to DTW at all lags

Table 6: This table summarizes the key metrics and their values for each lag tested in the Granger causality analysis.

Cross-correlation function (CCF)

CCF Analysis Between Dolphin Total Number (DTN) and Dolphin Total Weight (DTW)

The CCF analysis between DTN and Dolphin Total Weight DTW provides valuable insights into the temporal relationship between these two variables. The CCF plot illustrates how the correlation between DTN and DTW varies across different time lags (Graph 22). it helps to understand how changes in one variable may predict fluctuations in the other over time (Table 7).

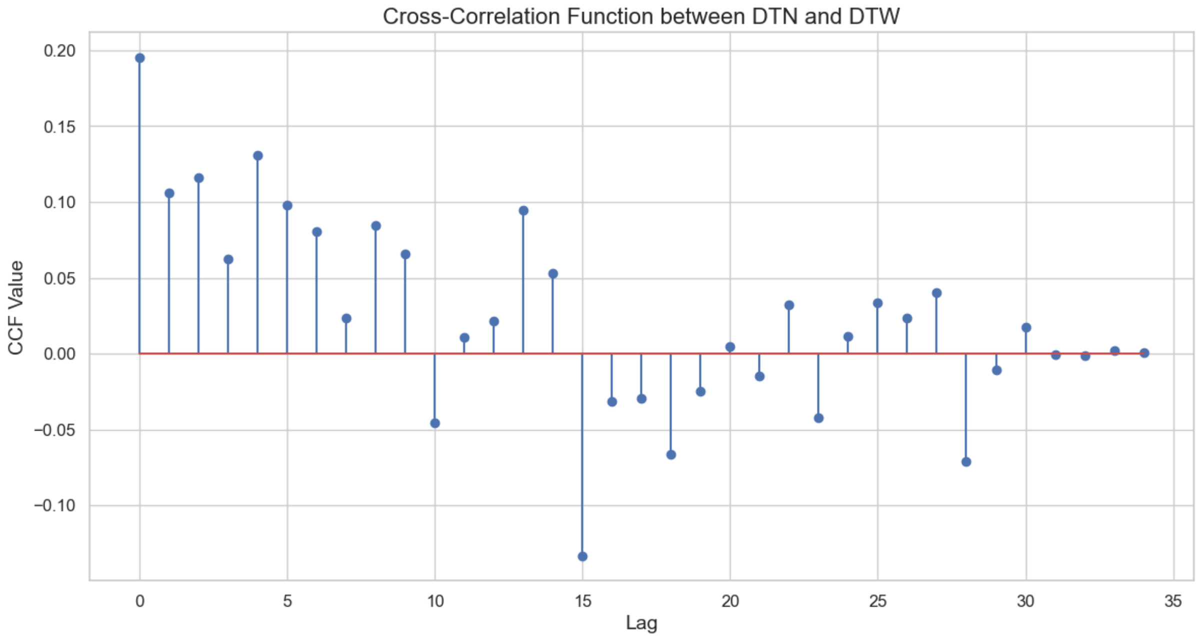
Key Findings from the CCF Analysis:

- **Strong Simultaneous Correlation (Lag 0):** The analysis reveals a strong simultaneous correlation between DTN and DTW, indicated by a high positive CCF value at lag 0. This suggests that when the number of dolphins caught (DTN) is high, their total weight (DTW) also tends to be high. This immediate relationship suggests that larger groups of dolphins result in a higher total weight.
- **Positive Correlations at Short Lags (Up to 10 Months):** The CCF plot shows positive correlations at short lags, up to 10 months, implying that increases in DTW may be followed by increases in DTN shortly thereafter. This pattern could be influenced by environmental conditions or fishing practices that simultaneously favor both higher dolphin numbers and weights.
- **Negative Correlations at Medium Lags (Between 10 and 15 Months):** The analysis also indicates negative correlations at medium lags, specifically between 10 and 15 months, suggesting an inverse relationship between DTN and DTW at these intervals. This may imply that after periods of high dolphin bycatch weights, the number of dolphins caught tends to decrease. Such a pattern could be attributed to depletion effects, changes in dolphin behavior, or adjustments in fishing practices.

The CCF analysis highlights a strong immediate relationship between DTN and DTW, with additional patterns emerging over short- and medium-term lags. These findings are valuable for predicting bycatch trends and could inform management strategies aimed at mitigating dolphin bycatch. Understanding these correlations may help anticipate periods of high or low bycatch based on observed trends in DTW, enabling more proactive management and conservation efforts.

Metric	Value	Description
Lag 0 CCF Value	0.1954292	Strong positive correlation at the same time point, indicating that high DTN is associated with high DTW.
Lag 1-4 CCF Values	0.10607033 to 0.13079829	Positive correlations at short lags, suggesting DTW increases may precede DTN increases by a few months.
Lag 10 CCF Value	-0.04523216	Slight negative correlation at this lag, indicating a weak inverse relationship between DTN and DTW after 10 months.
Lag 15 CCF Value	-0.13327423	More pronounced negative correlation, suggesting that increases in DTW may lead to decreases in DTN after 15 months.
Pattern	Immediate positive correlation at Lag 0, short-term positive correlation at Lags 1-4, and medium-term negative correlation at Lags 10-15.	
Practical Implications	Strong simultaneous and short-term correlations can aid in short-term predictions; medium-term negative correlations could inform management strategies.	

Table 7: Summary of the CCF values at different time lags, revealing the relationship between DTN and DTW. Lag 0 shows a strong positive correlation, indicating simultaneous increases in both metrics. Lags 1-4 exhibit short-term positive correlations, suggesting that increases in DTW may precede increases in DTN. Conversely, Lags 10 and 15 indicate medium-term negative correlations, where increases in DTW could lead to decreases in DTN.



Graph 22: The plot shows the CCF values at various lags, indicating the correlation between DTN and DTW over time. Positive values suggest that an increase in DTN is followed by an increase in DTW at specific lags, while negative values suggest an inverse relationship. The diminishing correlation at higher lags indicates a weakening relationship as the time lag increases.

Forecasting

Prophet Forecast with Anomalies

Prophet Forecast with Anomalies for Dolphin Total Number (DTN)

The Prophet forecast plot for DTN provides a visual representation of the forecasted trends alongside the actual observed values and identified anomalies. This analysis offers insights into the model's predictive capability for DTN over time and highlights specific points where actual values significantly deviate from the forecast (Graph 23).

Key Components of the Plot:

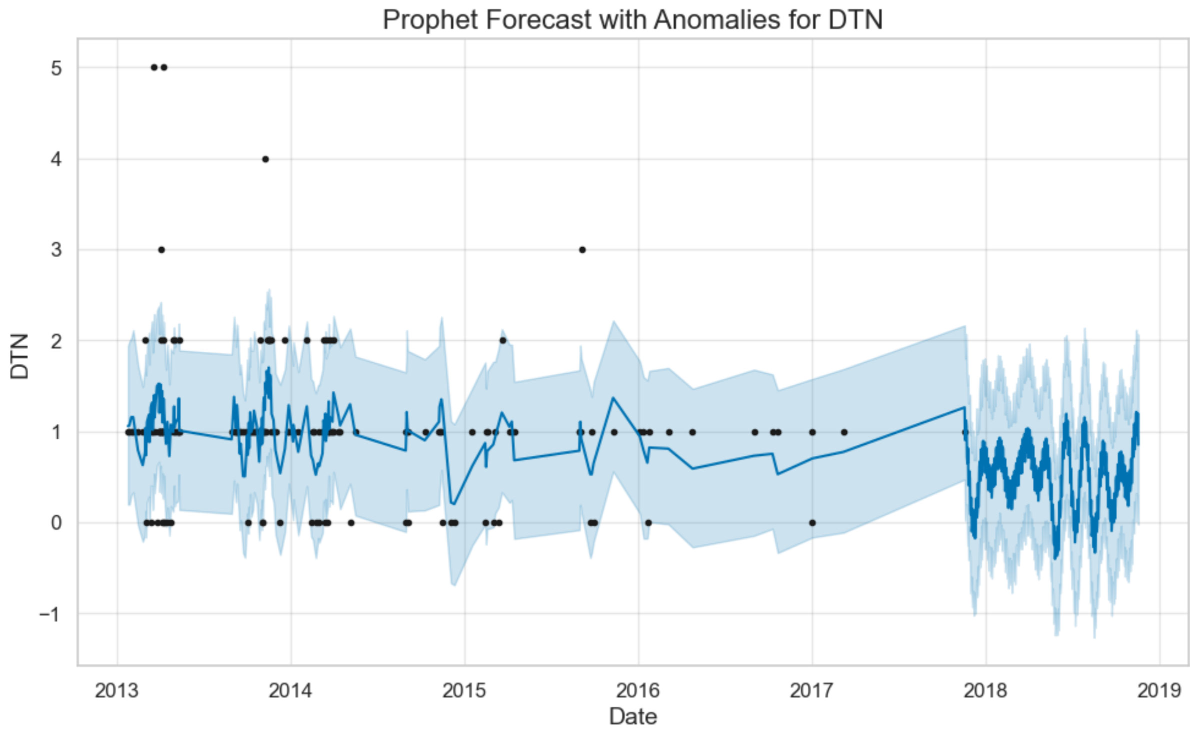
The plot comprises several key elements. The black dots represent the actual observed DTN values over time, reflecting the real-world data. The blue line denotes the forecasted DTN values, indicating the general trend as predicted by the Prophet model. Additionally, a light blue shaded area around the blue line represents the uncertainty interval, which illustrates the range within which the model expects the actual values to fall. Anomalies are identified where the observed values (black dots) fall outside this uncertainty interval, signifying significant deviations from the model's expectations.

Observations from the Plot:

The forecasted trend, depicted by the blue line, indicates a relatively stable DTN over time, with some fluctuations. However, certain periods display minor dips or rises in the trend, reflecting the inherent variability within the dataset. The uncertainty interval, which becomes wider towards the end of the forecast period, suggests that the model's confidence decreases as it projects further into the future. Notably, several anomalies are detected, particularly in 2013 and 2014, where the actual DTN values significantly differ from the model's predictions, falling outside the expected range.

Interpretation of Anomalies:

The identified anomalies could be attributed to various factors, such as environmental changes, shifts in fishing practices, or inconsistencies in data collection. Environmental factors, including sudden changes in oceanographic conditions or prey availability, could have resulted in unexpected increases or decreases in dolphin bycatch. Changes in fishing techniques or effort could also account for these deviations. Alternatively, the anomalies might arise from inaccuracies or inconsistencies in data collection.



Graph 23: The plot shows the historical DTN data (black dots) and the forecasted trend (blue line) with uncertainty intervals (shaded area). The model captures seasonal patterns and trends, extending predictions into the future. Anomalies, or points that deviate significantly from the forecast, are visible, particularly around 2016 and 2017, indicating periods of unexpected dolphin bycatch events.

Prophet Forecast with Anomalies for Dolphin Total Weight (DTW)

The Prophet forecast plot for DTW provides a visual representation of the forecasted trends alongside the actual observed values, with a focus on identifying anomalies. This analysis offers insights into the model's effectiveness in predicting DTW over time and highlights instances where the actual values significantly deviate from the forecast (Graph 24).

Key Components of the Plot:

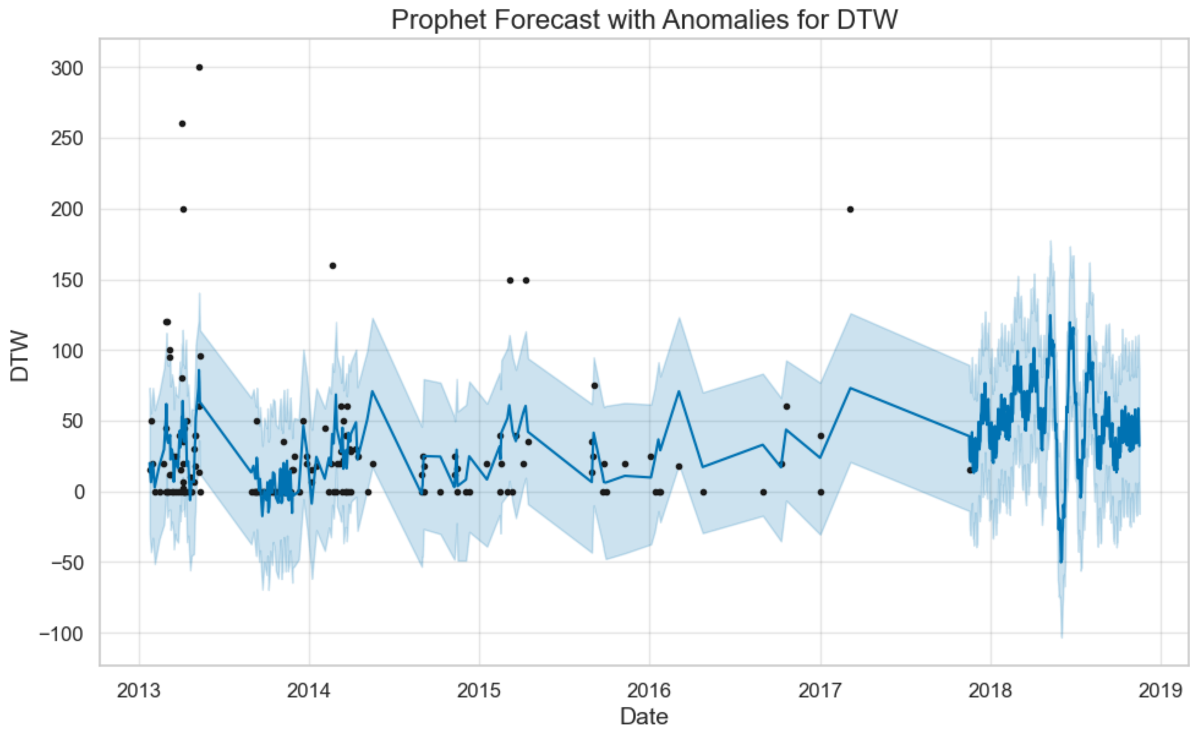
The plot comprises several essential elements. The black dots represent the actual observed DTW values over time, showcasing the real-world data. The blue line indicates the forecasted DTW values, reflecting the general trend as predicted by the Prophet model. Surrounding the blue line is a light blue shaded area, which represents the uncertainty interval, depicting the range within which the model expects the actual values to fall. Anomalies are identified where the observed values (black dots) fall outside this uncertainty interval, indicating significant deviations from the model's expectations.

Observations from the Plot:

The forecasted trend, represented by the blue line, reveals a fluctuating pattern in DTW, with distinct peaks and troughs over time, indicating considerable variation within the dataset. The uncertainty interval, which widens significantly towards the later years (2017-2019), suggests that the model's confidence decreases as it projects further into the future. Several anomalies are observed, particularly in the early part of the time series (2013-2014), where the actual DTW values markedly deviate from the model's predictions, falling outside the expected range.

Interpretation of Anomalies:

The identified anomalies could be attributed to various factors, including environmental changes, shifts in fishing practices, or inconsistencies in data collection. Sudden changes in oceanographic conditions, such as temperature shifts or variations in prey availability, might have resulted in unexpected increases in dolphin bycatch. Changes in fishing techniques or fishing efforts could also explain these deviations. Additionally, the anomalies may arise from inaccuracies or inconsistencies in the data collection process.



Graph 24: The graph displays the historical DTW data (black dots) alongside the forecasted trend (blue line) and uncertainty intervals (shaded area). The model accounts for seasonal and trend variations, projecting future DTW values. Notable anomalies, particularly in the early years and around 2017, highlight periods of unexpectedly high or low dolphin bycatch weight that deviate from the forecast.

Bayesian Structural Time Series (BSTS)

Analysis for Dolphin Total Number (DTN) using the BSTS Model

The BSTS model was utilized to analyze and forecast the DTN over time, with a particular emphasis on identifying underlying seasonal patterns and long-term trends in the data. The model incorporates two primary components: seasonal effects, which account for recurring monthly patterns, and trend effects, which capture the overall direction of DTN values throughout the observed period (Graph 25).

Historical Data Overview:

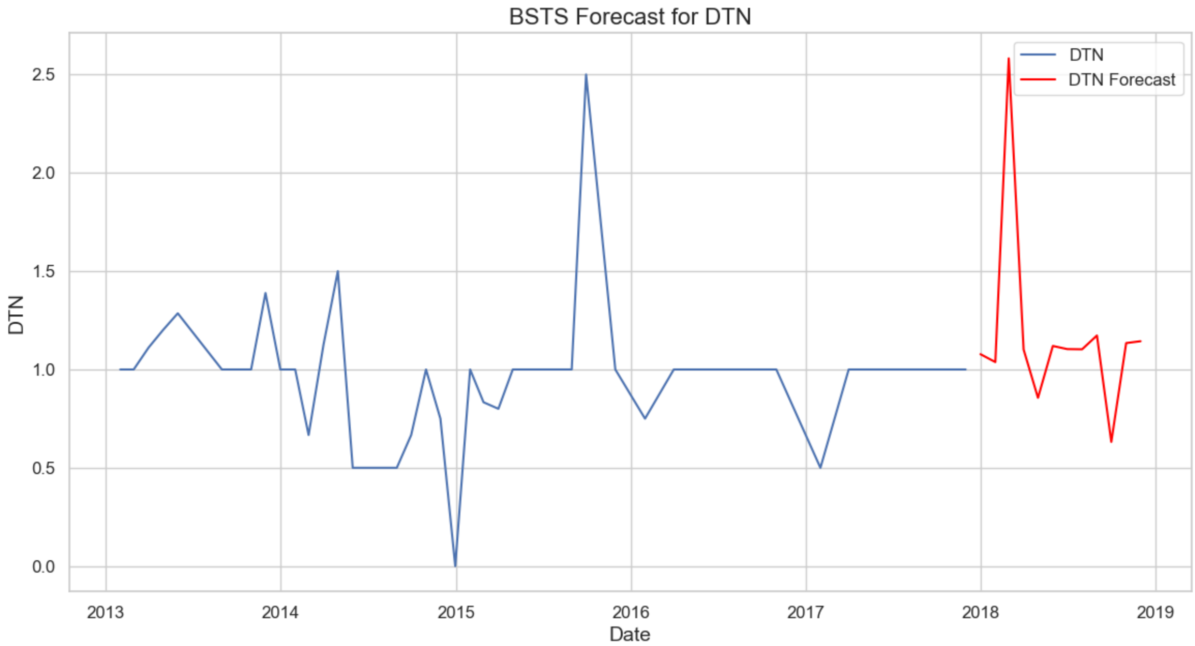
The historical DTN data, depicted by the blue line on the graph, spans from 2013 to 2017 and exhibits notable fluctuations with distinct peaks and troughs. For example, there is a sharp decline in DTN around 2014, followed by a spike in 2015, and a period of relative stabilization by 2017. These variations suggest that DTN is influenced by both seasonal factors and potentially other external influences.

Forecasted Data Analysis:

The forecasted DTN values, represented by the red line on the graph, extend from late 2017 into 2018. The forecast predicts a significant peak in DTN immediately following the end of the historical data, suggesting that the model has identified a strong seasonal or external factor contributing to this increase. After this peak, the forecast indicates a stabilization in DTN, implying that the model expects DTN values to remain relatively consistent following this initial surge.

Interpretation of Model Components:

- **Seasonal Component:** The seasonal component of the BSTS model likely captures the regular, recurring fluctuations in DTN, which contribute to the observed peaks and troughs in the data. This reflects predictable changes in DTN that correspond to specific months or periods within the year.
- **Trend Component:** The trend component of the model appears relatively flat or slightly declining, suggesting the absence of a strong overall upward or downward trend in DTN over the observed period. This indicates that the underlying trend in DTN is either stable or experiencing a modest downward shift, with no significant long-term changes detected.



Graph 25: The plot shows the historical DTN data (blue line) alongside the forecasted values (red line) from 2018 onwards. The BSTS model captures the underlying trends and patterns in the historical data to make predictions. The forecast indicates potential fluctuations in DTN, with some sharp increases predicted, reflecting the model's ability to account for complex temporal dynamics in dolphin bycatch.

Analysis of Dolphin Total Weight (DTW) Using the BSTS Model

The BSTS model was employed to analyze and forecast DTW over time, with an emphasis on identifying both seasonal patterns and long-term trends. The model incorporates two primary components: the seasonal effect, which accounts for recurring patterns such as monthly fluctuations, and the trend effect, which captures the overall direction of DTW throughout the analyzed period (Graph 26).

Historical Data Overview:

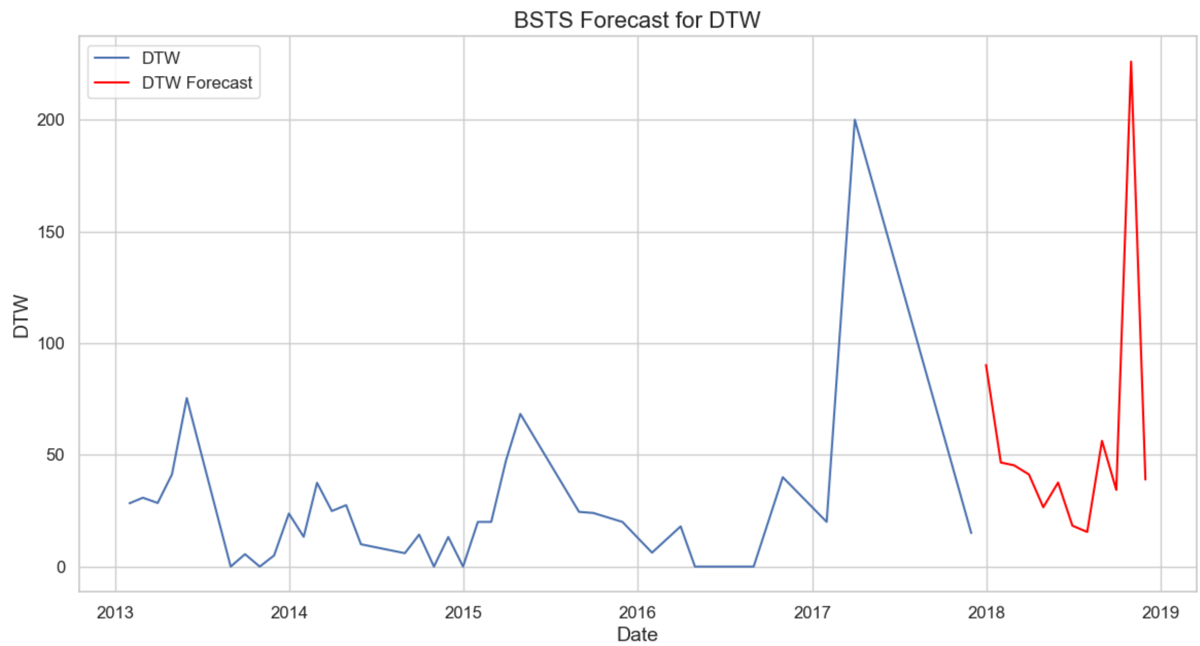
The historical data, spanning from 2013 to 2017 and represented by the blue line on the graph, exhibits significant variability in DTW, with notable peaks around 2015 and 2017, followed by declines. This pattern suggests considerable changes in dolphin weight totals during these periods, potentially influenced by environmental or operational factors.

Forecasted Data Analysis:

The forecasted DTW values, represented by the red line on the graph, extend from late 2017 into 2018. The forecast predicts an initial peak in DTW immediately following the end of the historical data, followed by fluctuations and a sharp increase toward the latter part of the forecast period. This suggests that the model anticipates similar patterns to those observed in the historical data, driven primarily by the seasonal component.

Interpretation of Model Components:

- **Seasonal Component:** The seasonal component is likely responsible for the observed peaks in the forecast, reflecting the periodic fluctuations seen in the historical data. This indicates that DTW is subject to regular, recurring changes that align with specific times of the year.
- **Trend Component:** The trend effect appears less pronounced in the forecast, as the model does not project a consistent upward or downward trend over the forecast period. This suggests that while seasonal patterns are a dominant force in shaping DTW, the long-term trend remains relatively stable without clear directional changes.



Graph 26. The plot presents the historical DTW data (blue line) along with the forecasted values (red line) starting from 2018. The BSTS model predicts significant variability in DTW, with sharp increases anticipated towards the end of the forecast period. This suggests potential volatility in dolphin bycatch weights, reflecting the model's consideration of complex temporal relationships in the data.

Spatial Analysis

Density-Based Spatial Clustering of Applications with Noise (DBSCAN) Mapping

Analysis of Geographical Data Clustering Using the DBSCAN Algorithm

The DBSCAN algorithm was applied to analyze geographical data based on latitude and longitude to identify clusters within the dataset. The resulting plot provides a clear visualization of the clusters and noise points, offering valuable insights into the spatial distribution patterns present in the data (Graph 27).

Clusters Identified:

The analysis identified three distinct clusters, labeled as 0, 1, and 2:

- **Cluster 0:** This is the largest cluster, containing the majority of data points. It represents a significant geographical area where data points are densely concentrated, indicating a potential hotspot of activity or occurrences.
- **Clusters 1 and 2:** These are smaller, more localized clusters with fewer data points, suggesting more specific regions with concentrated activities or occurrences.
- **Noise Points (-1):** Some data points were labeled as noise, denoted by -1. These points do not belong to any of the identified clusters and are likely outliers or isolated instances that did not meet the density criteria for cluster formation.

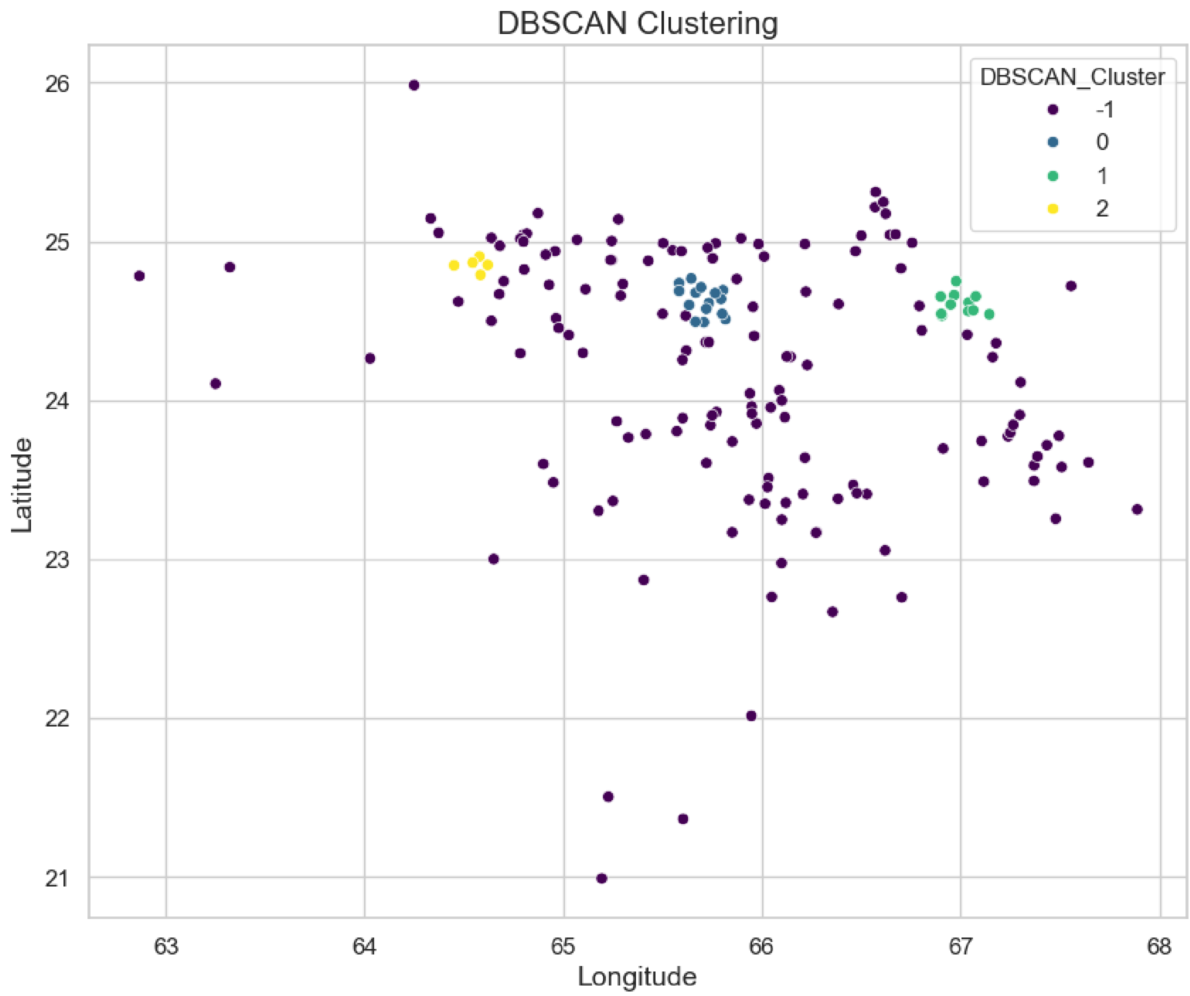
Insights:

The identified clusters suggest geographical hotspots where certain activities or occurrences are more concentrated. For instance, these clusters could indicate areas where specific species are frequently found or where fishing activities are concentrated. The presence of noise points indicates isolated or atypical data points that do not conform to the general patterns observed within the clusters.

To evaluate the quality of the clustering, a silhouette score was calculated. The silhouette score helps assess how well-defined and distinct the clusters are. In this analysis, a negative silhouette score of -0.223 was obtained, suggesting that the clusters may not be well-formed.

Interpretation of the Negative Silhouette Score:

The negative silhouette score indicates that many data points are closer to points in neighbouring clusters than to those within their own cluster. This result suggests that the DBSCAN algorithm may not have effectively identified meaningful clusters within the dataset. Therefore, further refinement of the clustering approach, such as adjusting the parameters or exploring alternative clustering methods, may be required to achieve more reliable results.



Graph 27: The scatter plot shows the clustering of data points based on latitude and longitude using the DBSCAN algorithm. Different colors represent different clusters, with cluster labels indicated in the legend. Points labeled as '-1' are considered noise and do not belong to any cluster. The clusters reveal areas with higher concentrations of dolphin bycatch events, providing insights into spatial patterns in the dataset.

Hierarchical Clustering

Hierarchical Clustering Analysis of Geographic Data

The hierarchical clustering analysis provides insights into how geographic data points are grouped based on their latitude and longitude, offering a deeper understanding of the spatial distribution patterns within the studied regions (Graph 28).

Graph Overview:

The scatter plot generated from the hierarchical clustering analysis visually represents the geographical clusters. The y-axis denotes latitude, while the x-axis represents longitude. Data points are color-coded according to their respective clusters: Cluster 1 is shown in dark purple, Cluster 2 in teal (blue-green), and Cluster 3 in yellow.

Cluster Formation:

The hierarchical clustering algorithm effectively organizes the data points into three distinct clusters based on their geographic coordinates:

- **Cluster 1 (Dark Purple):** Primarily consists of data points located in the western part of the study area, indicating a concentration of similar characteristics or activities in this region.
- **Cluster 2 (Teal/Blue-Green):** Positioned slightly east of Cluster 1, representing a separate geographical grouping with distinct features.
- **Cluster 3 (Yellow):** Located further south, representing another unique geographic region distinct from the other two clusters.

Distance and Proximity:

The formation of these clusters is based on the proximity of data points. Points within the same cluster are geographically closer to each other than to points in different clusters. This proximity-based grouping helps identify areas that may share similar environmental conditions, species behavior, or human activities.

Hierarchical Clustering Process:

Hierarchical clustering begins with each data point as an individual cluster. As the process progresses, these points are merged based on their similarity, forming larger clusters. The dendrogram generated in the analysis illustrates this process, showing the hierarchical relationship between clusters. The "cut" point on the dendrogram determines the number of clusters formed; in this case, three distinct clusters were identified.

Geographic Insights:

The analysis reveals distinct geographic areas within the study region, each potentially representing unique environmental conditions or activities. The hierarchical nature of the clustering provides context by showing how closely related these regions are to one another. This understanding is valuable for ecological or environmental studies, aiding in the identification of specific areas of interest for conservation or further investigation.

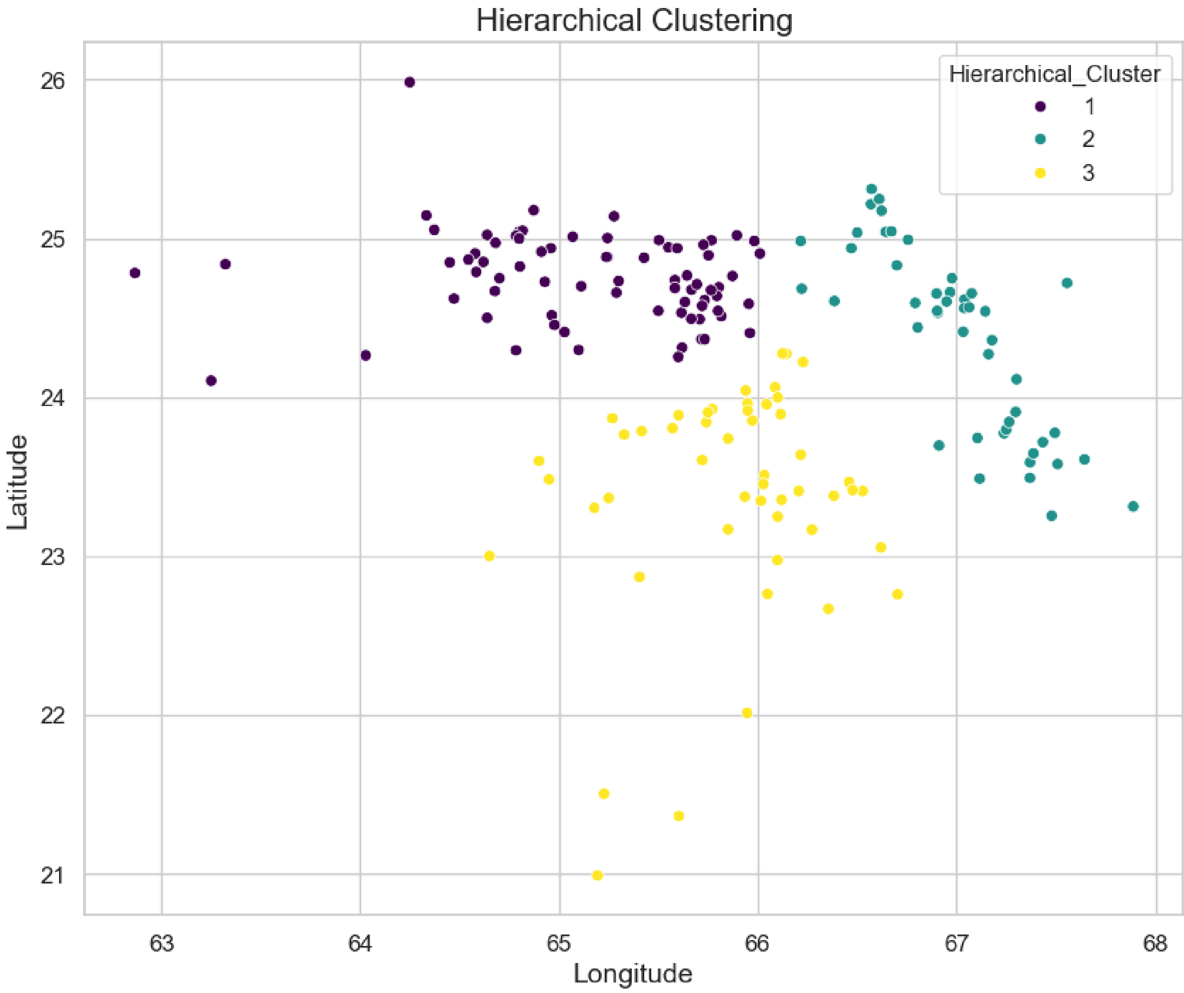
Cluster Distribution:

- **Cluster 1:** The largest cluster, with 74 data points, indicating a significant concentration in this area.
- **Cluster 2:** The smallest cluster, with 47 data points, suggesting a more isolated or unique region.
- **Cluster 3:** Consists of 51 data points, representing another distinct geographic grouping.

Interpretation of Cluster Sizes:

The varying sizes of the clusters reflect differences in the density and distribution of data points across the geographical space. Cluster 1, being the largest, may represent a more extensive or common region within the study area. In contrast, Clusters 2 and 3, being smaller, may indicate more specific or niche areas with distinct characteristics.

The hierarchical clustering analysis successfully identifies three distinct geographic regions within the study area, providing valuable insights into the spatial distribution and potential relationships between these regions. This analysis can inform further studies on ecological dynamics, species distribution, or conservation efforts.



Graph 28: The scatter plot displays the results of hierarchical clustering based on latitude and longitude, with different colors representing distinct clusters as labeled in the legend. This clustering method organizes the data into a hierarchical structure, revealing spatial groupings of dolphin bycatch events. Each cluster provides insight into geographical areas with similar bycatch patterns, which may inform targeted management strategies.

The Gaussian Mixture Model (GMM) clustering analysis

GMM Clustering Analysis of Geographical Data

The GMM clustering analysis provides a comprehensive examination of the spatial distribution of geographical data points, categorizing them into three distinct clusters. The graph visually represents these clusters, with each data point assigned to one of the clusters based on its geographic coordinates, specifically latitude and longitude (Graph 29).

Clusters Identified:

The analysis identifies three distinct clusters:

- **Cluster 1 (Blue Dots):** Represents the first group of data points.
- **Cluster 2 (Green Dots):** Represents the second group of data points.
- **Cluster 3 (Turquoise Dots):** Represents the third group of data points.

These clusters likely correspond to specific geographical regions characterized by similar features or conditions, as suggested by the data.

Centroids of Clusters:

The centroids of each cluster are marked by red "X" markers on the graph. These centroids represent the mean position of each cluster and are significant because they indicate the central point around which the data points in each cluster are probabilistically distributed. This central positioning provides insight into the spatial dynamics within each cluster.

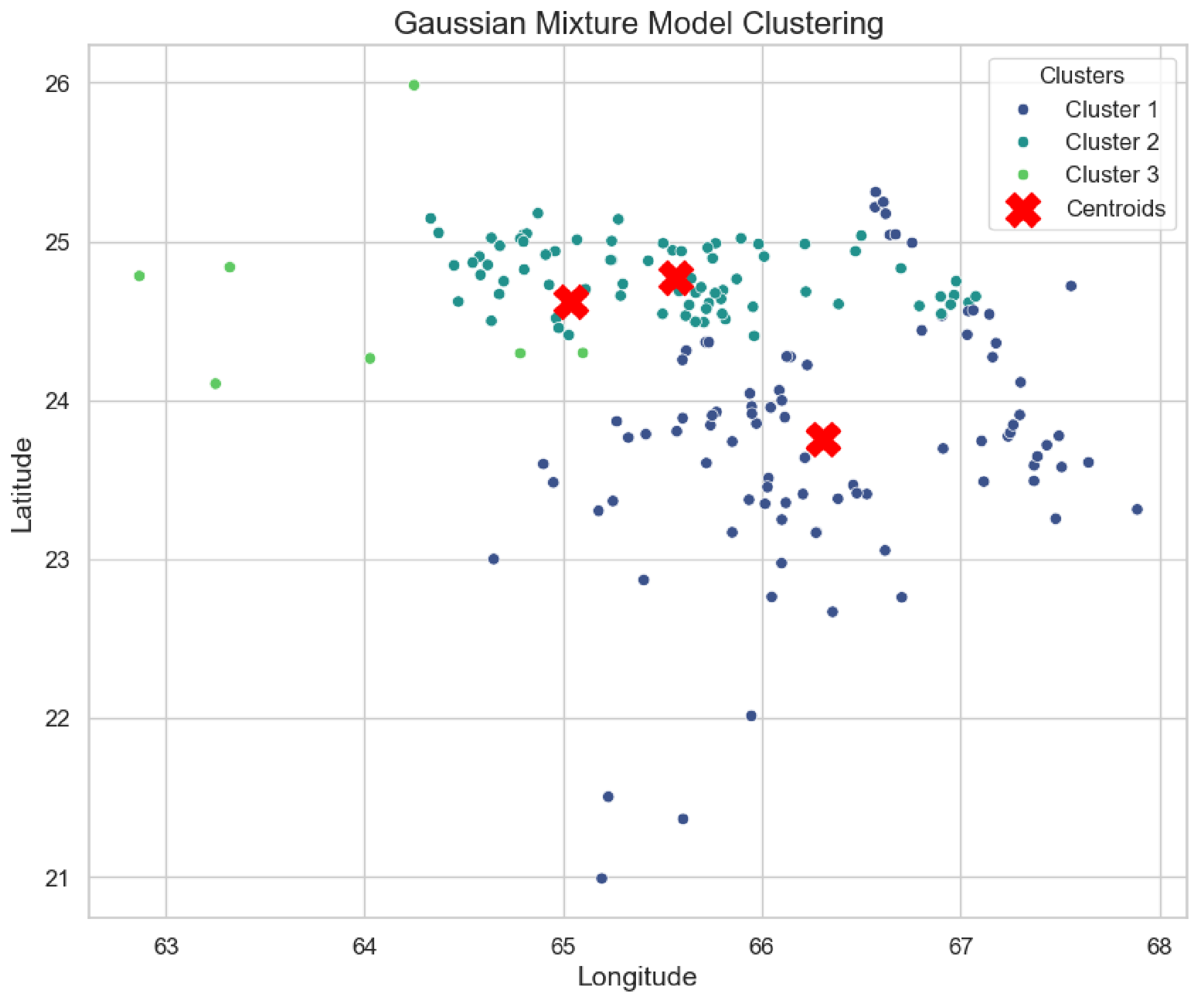
Unique Features of GMM Clustering:

The GMM clustering method differs from other clustering techniques by allowing overlapping clusters, meaning that some data points could belong to multiple clusters with varying probabilities. In this analysis, however, each data point is assigned to the cluster for which it has the highest probability, resulting in a clear categorization of the data.

Interpretation of Spatial Distribution:

The spatial distribution observed in the graph suggests that the clusters represent distinct geographical regions with specific characteristics. The GMM approach assumes that the data is generated from a mixture of Gaussian distributions, each representing a cluster. The model estimates parameters such as the mean, variance, and mixing coefficients for these distributions, resulting in the cluster formations seen on the graph.

The GMM clustering analysis effectively identifies three distinct geographical clusters within the dataset, providing valuable insights into the spatial organization and characteristics of these regions. The use of centroids and the probabilistic nature of the model enhances the understanding of how the data is structured and related across the study area.



Graph 29: The scatter plot illustrates the clustering of data points based on latitude and longitude using the Gaussian Mixture Model, with different colors representing distinct clusters. The red 'X' marks denote the centroids of each cluster, indicating the central location of dolphin bycatch events within each cluster. This model assumes that the data points are generated from a mixture of several Gaussian distributions, providing a probabilistic approach to identifying spatial clusters in the dataset.

Spatial Autocorrelation Analysis

Spatial Autocorrelation Analysis of Dolphin Total Number (DTN) and Dolphin Total Weight (DTW)

The spatial autocorrelation analysis for DTN and DTW provides insights into the spatial distribution patterns of dolphin bycatch within the study area. The analysis employs Moran's I statistic to assess the presence of spatial autocorrelation, which indicates whether similar values are clustered together or dispersed across a geographic space (Table 8).

Dolphin Total Number (DTN) Analysis:

The Moran's I value for DTN is -0.0144, which is very close to zero. This suggests that there is no significant spatial autocorrelation in the distribution of DTN, indicating that dolphin bycatch numbers are relatively evenly distributed across the study area. The slightly negative value implies a minimal tendency towards dispersion; however, this effect is negligible. The associated p-value of 0.419 is well above the conventional significance threshold of 0.05, further confirming that the observed Moran's

I is not statistically significant. Thus, any spatial pattern in DTN is likely due to random chance rather than actual clustering or dispersion, indicating no significant spatial pattern in DTN distribution.

Dolphin Total Weight (DTW) Analysis:

In contrast, the spatial autocorrelation analysis for DTW yields a Moran's I value of 0.0865, indicating weak positive spatial autocorrelation. This value suggests a slight tendency for DTW to cluster geographically, implying that areas with higher dolphin weights are somewhat likely to be in proximity to each other. The p-value for this analysis is 0.032, which is below the 0.05 significance level, indicating that the observed spatial autocorrelation in DTW is statistically significant. Therefore, the spatial pattern of dolphin total weight is not random, and there is a detectable level of clustering in the data.

Practical Implications:

The results suggest different management strategies for DTN and DTW:

- **DTN:** Given the lack of significant spatial autocorrelation for DTN, management strategies targeting DTN may not need to be spatially specific. A broad, uniform approach across the entire study area could be effective rather than focusing on specific locations.
- **DTW:** The significant spatial clustering of DTW suggests that there are particular areas where larger dolphins are more likely to be caught. Therefore, targeted management efforts, such as spatial or seasonal closures, gear modifications, or other interventions, could focus on these areas to reduce the bycatch of larger dolphins.

Metric	DTN (Dolphin Total Number)	DTW (Dolphin Total Weight)	Description
Moran's I Value	-0.0144	0.0865	Measures spatial autocorrelation. Negative for DTN (no significant clustering), positive for DTW (weak clustering).
p-value	0.419	0.032	Indicates statistical significance. Not significant for DTN ($p > 0.05$), significant for DTW ($p < 0.05$).
Interpretation	No significant spatial pattern.	Weak, significant clustering.	DTN shows no spatial autocorrelation, while DTW exhibits weak but significant clustering.
Management Implications	Broad measures across study area.	Target specific areas for intervention.	DTN doesn't require spatial targeting, while DTW might benefit from targeted management efforts.

Table 8: This table summarizes the key results and implications from the spatial autocorrelation analysis for both DTN and DTW

Spatial Distribution of Dolphin Total Number (DTN)

The scatter plot visualizing the spatial distribution of DTN across the study area uses latitude and longitude as coordinates, with a color gradient ranging from darker shades (indicating lower DTN) to brighter shades indicating higher DTN (Graph 30).

Spatial Distribution:

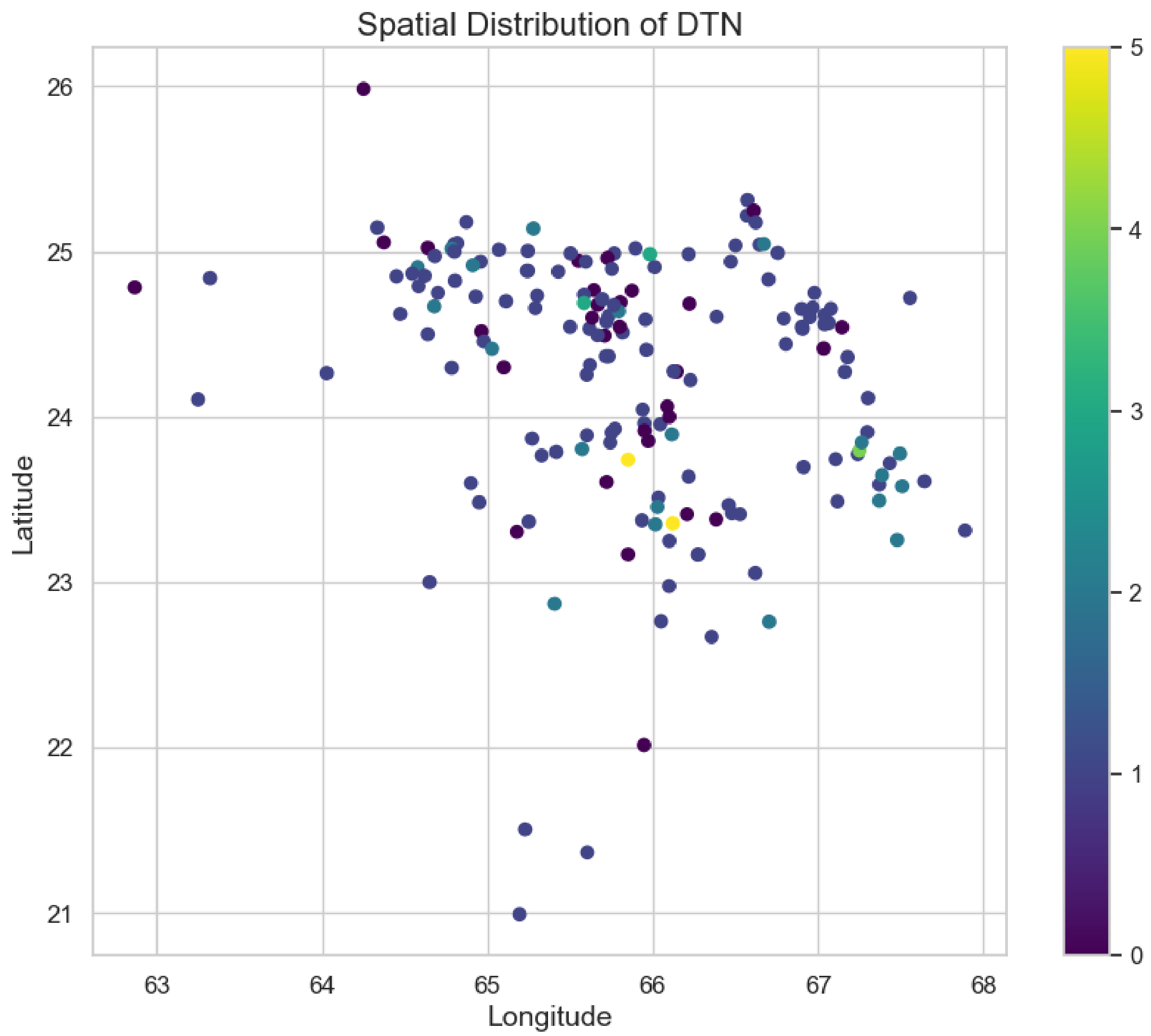
The data points are widely dispersed across the geographical area, with no evident clustering of higher or lower DTN values. This pattern aligns with the results of the Moran's I analysis, which indicated no significant spatial autocorrelation for DTN. The distribution appears relatively uniform, suggesting that dolphin bycatch numbers are spread throughout the study area rather than concentrated in specific locations. The geographic range spans latitudes from approximately 21° to 26° and longitudes from about 63° to 68°, reflecting the broad scope of the study area and the extent of the fishing operations involved.

DTN Variation:

The color gradient shows that DTN values range from 0 to 5, with most data points in darker shades, indicating lower DTN values. Only a few points are in brighter shades, representing higher DTN values, suggesting that instances of high dolphin bycatch are relatively rare in this dataset. The sporadic appearance of higher DTN values, without forming large clusters, further reinforces the observation of no significant spatial clustering, with these higher values appearing irregularly rather than being concentrated in specific regions.

Implications for Management:

Given the lack of significant spatial clustering, as confirmed by both the Moran’s I statistic and the scatter plot visualization, a more uniform management approach across the entire study area may be appropriate for DTN. Instead of targeting specific hotspots, a broad strategy could be more effective in managing dolphin bycatch in this context.



Graph 30: The scatter plot visualizes the spatial distribution of DTN across different geographical locations, with data points colored according to the DTN value as indicated by the color bar. The variation in colors reflects areas with differing levels of dolphin bycatch, providing insights into spatial patterns and potential hotspots where dolphin bycatch is more prevalent.

Spatial Distribution of Dolphin Total Weight (DTW)

The spatial distribution analysis of DTW examines how dolphin weights are spread across the study area, focusing on the relationship between geographic coordinates and DTW values. The scatter plot visualizes this distribution, using latitude and longitude as coordinates, with a color gradient to represent DTW values—darker colors indicate lower DTW, while brighter colors represent higher DTW values (Graph 31).

Spatial Distribution:

The scatter plot indicates a moderate level of variability in DTW across the study area, suggesting some degree of spatial clustering. Certain regions exhibit higher DTW values, although this clustering is not highly pronounced. The geographic spread of data points extends from latitudes of approximately 21° to 26° and longitudes from about 63° to 68°, encompassing a broad area of the marine environment.

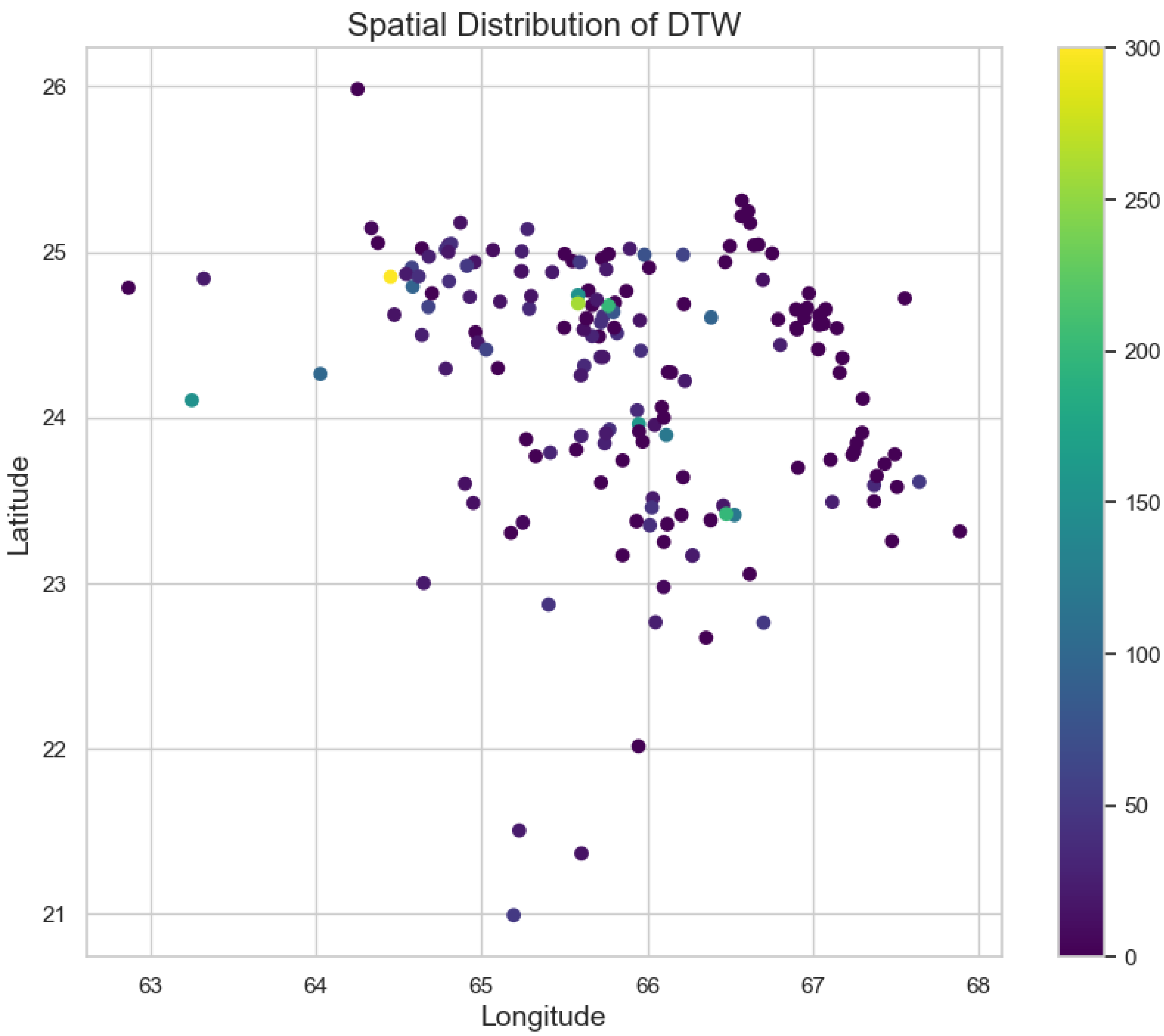
This distribution suggests that larger dolphins are more frequently caught in specific regions, though these regions are not sharply delineated.

DTW Variation:

The color gradient in the plot shows DTW values ranging from 0 to 300, with most data points indicating lower DTW values. However, a few locations are marked by higher DTW, represented by brighter colors. These areas, particularly around central latitudes and longitudes, suggest regions where larger dolphins are more likely to be caught. This pattern may be influenced by environmental or ecological factors affecting dolphin size and distribution.

Implications for Management:

The identification of areas with higher DTW values underscores the potential need for targeted conservation efforts. Management strategies could be directed towards these regions to mitigate the bycatch of larger dolphins, possibly through spatial or temporal fishing restrictions. Although the spatial clustering of DTW is not strongly concentrated, the regions with higher DTW values may still warrant specific attention for conservation initiatives.



Graph 31: The scatter plot represents the geographic distribution of DTW values, with color intensity corresponding to the total weight of dolphins caught at each location, as indicated by the color bar. Darker colors represent lower DTW values, while lighter colors signify higher weights, highlighting regions where the dolphin bycatch weight is more substantial, which could be crucial for targeted conservation efforts.

Kernel Density Estimation (KDE) - Gaussian model mapping

Analysis of the Density Map of Dolphin Total Number (DTN)

Overview of the Density Map

The density map depicts the spatial distribution of dolphin bycatch incidents, represented by Dolphin Total Number (DTN), across geographic coordinates in the Northern Arabian Sea. This map aggregates data for all seasons, providing a comprehensive view of dolphin bycatch density over time. The density is illustrated using a color gradient, with different shades reflecting varying levels of dolphin bycatch density (Graph 32).

Detailed Interpretation of the Color Gradient

The color gradient on the map ranges from dark purple to bright yellow, indicating variations in dolphin bycatch density across different geographic locations:

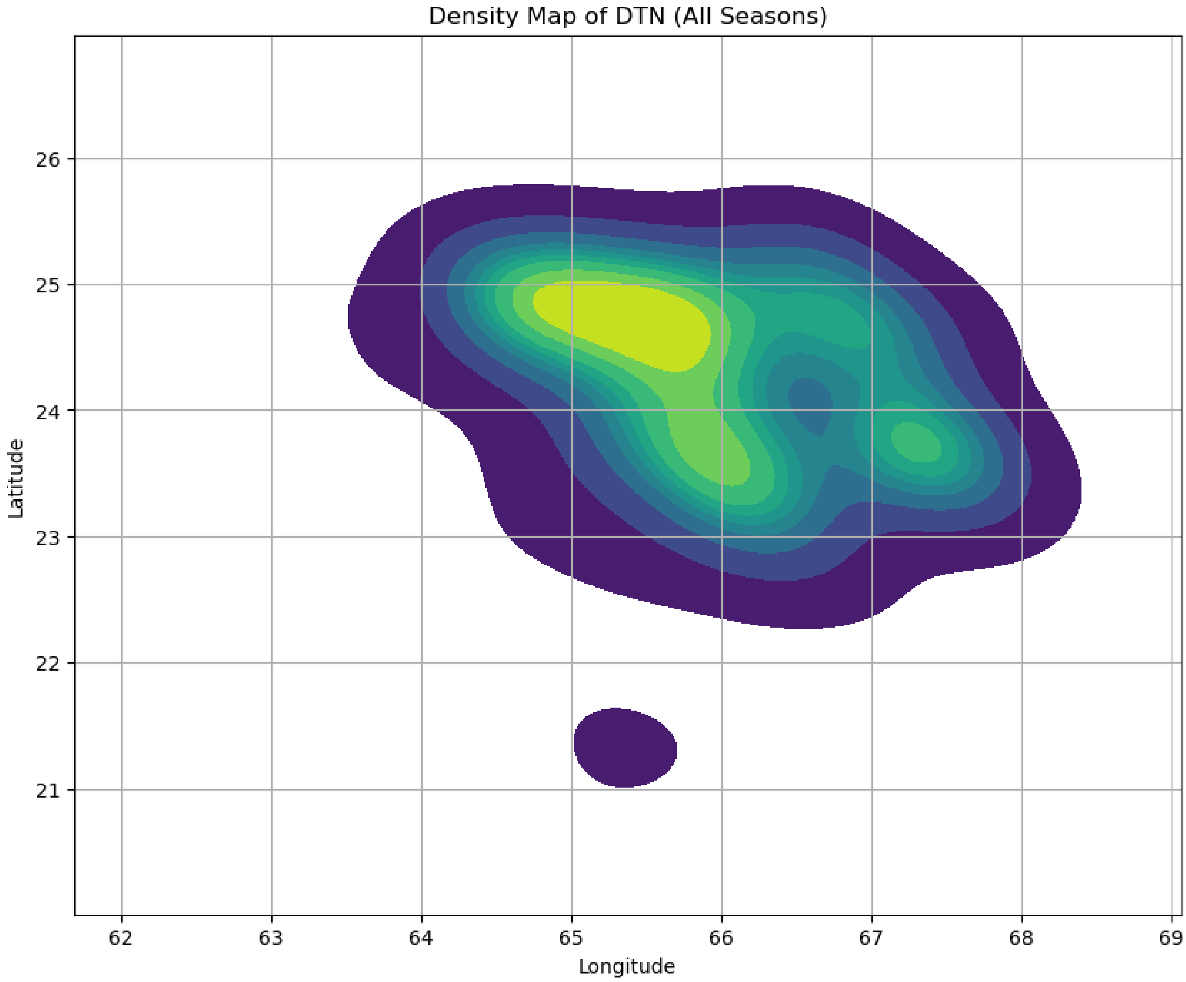
- **High-Density Areas (Hotspots):** Bright yellow to green shades mark the most concentrated areas of dolphin bycatch, primarily situated between latitudes 24.0°N to 25.5°N and longitudes 65.0°E to 66.5°E. This zone is identified as a hotspot where dolphin bycatch is most intense. Such high-density regions may result from several factors, including specific oceanographic conditions that attract both dolphins and fishing activities, making this area particularly prone to higher dolphin bycatch. The relatively confined region also suggests intensive fishing activities using gillnets, which are known to pose a higher risk of bycatch.
- **Moderate to Low-Density Areas:** Surrounding the central high-density core, areas shaded in blue and dark purple indicate moderate to low levels of dolphin bycatch. These regions extend from approximately 23.0°N to 26.0°N in latitude and 64.0°E to 68.0°E in longitude. The gradual transition from green to blue and purple suggests a decline in bycatch incidents as one moves away from the core area. This decline could be due to reduced fishing activity or different environmental conditions affecting dolphin presence. This gradient may also reflect variations in fishing intensity, gear types used, or dolphin migratory patterns that lead to fewer interactions with fishing gear.
- **Isolated Low-Density Cluster:** An isolated cluster of bycatch incidents is observed around latitude 21.0°N and longitude 65.0°E, primarily marked in dark purple. This separate cluster suggests localized dolphin bycatch events distinct from the main aggregation area. This outlier could be due to unique conditions, such as underwater features, localized prey abundance, or specific fishing events occurring in this region. Further investigation is warranted to understand the specific conditions contributing to these bycatch occurrences.

Spatial Patterns and Implications

The spatial distribution patterns revealed by this density map provide valuable insights into the geographic spread of dolphin bycatch across the Northern Arabian Sea, particularly concerning fishing operations in Pakistan's waters:

1. **Identification of Bycatch Hotspots:** The central high-density area, located between latitudes 24.0°N to 25.5°N and longitudes 65.0°E to 66.5°E, emerges as a critical hotspot for dolphin bycatch. This area could be a focal point of gillnet fishing activities or a zone where environmental factors such as water temperature, prey availability, and currents create favorable conditions for both dolphins and target fish species. This information is crucial for fisheries management, as it pinpoints a region where mitigation efforts could be most effective, such as using dolphin deterrent devices or modifying fishing practices to reduce bycatch risk.
2. **Environmental and Seasonal Influences:** Although the map shows aggregated data across all seasons, the observed spatial patterns may still be influenced by specific seasonal dynamics. Dolphins may follow migratory routes, breeding patterns, or prey availability that change throughout the year, affecting their interactions with fishing gear.
3. **Targeted Conservation Strategies:** With the identification of the primary high-density area between 24.0°N to 25.5°N and 65.0°E to 66.5°E, fisheries managers and conservationists can develop targeted strategies to mitigate dolphin bycatch. Potential measures could include implementing time-area closures during peak bycatch periods, altering fishing gear configurations, or enhancing monitoring efforts to evaluate the effectiveness of mitigation strategies. The aim is to reduce dolphin bycatch while minimizing disruption to fishing activities, promoting sustainable fisheries management.
4. **Understanding the Isolated Cluster:** The isolated low-density cluster near 21.0°N, 65.0°E suggests a unique scenario that differs from the central hotspot. This area might be characterized by specific oceanographic features, such as seamounts, ridges, or eddies, that create a microhabitat attracting dolphins and possibly leading to episodic bycatch events. Alternatively, it could reflect sporadic fishing operations or unusual events that temporarily increased dolphin bycatch. A detailed examination of this area, incorporating environmental data and fishing effort specifics, is needed to draw more definitive conclusions.

The density map of DTN provides a comprehensive spatial overview of dolphin bycatch in the Northern Arabian Sea. The map highlights a pronounced high-density area between 24.0°N to 25.5°N and 65.0°E to 66.5°E, indicating a significant hotspot for dolphin bycatch associated with gillnet fisheries. The presence of an isolated cluster at 21.0°N, 65.0°E further underscores the complexity of spatial patterns, suggesting that multiple factors may influence dolphin bycatch distribution. These findings offer critical insights for fisheries management, enabling targeted interventions to mitigate dolphin bycatch and promote sustainable fishing practices.



Graph 32: The contour plot visualizes the density of DTN across different geographic locations, with warmer colors (yellow and green) indicating higher concentrations of dolphin bycatch events and cooler colors (blue and purple) representing lower densities. This map provides insight into areas with significant dolphin bycatch, highlighting potential hotspots that require focused management and conservation efforts.

Analysis of the Density Map of Dolphin Total Weight (DTW)

Overview of the Density Map

The density map illustrates the spatial distribution of dolphin bycatch incidents, specifically in terms of DTW, across various geographic coordinates (latitude and longitude) in the Northern Arabian Sea. This map aggregates data across all seasons, providing an overall perspective on regions where heavier dolphin bycatch is more concentrated. The color gradient used in the map reflects different levels of DTW density, highlighting areas with varying total weights of dolphins caught as bycatch (Graph 33).

Interpretation of the Color Gradient

The color gradient on the map ranges from dark purple to bright yellow, indicating variations in dolphin bycatch weight across different locations:

- **High-Density Areas (Hotspots of DTW):** Bright yellow and green areas signify the highest concentration of dolphin bycatch in terms of weight, primarily located between latitudes 24.0°N to 25.0°N and longitudes 65.5°E to 66.5°E. This region represents a hotspot where incidents of heavier dolphin bycatch are recorded, suggesting the capture of larger or more numerous dolphins. This concentration may result from specific oceanographic features, such as abundant feeding grounds, or from intense fishing activities overlapping with dolphin habitats.
- **Moderate to Low-Density Areas:** Surrounding the high-density hotspot are regions shaded in blue and dark purple, indicating moderate to low densities of dolphin bycatch in terms of total weight. These areas extend from approximately 23.0°N to 25.5°N in latitude and from 64.5°E to 68.0°E in longitude. The shift from lighter to darker shades suggests a gradual decline in the total weight of dolphin bycatch as one moves away from the core area. This pattern may reflect variations in fishing effort, different gear types, or differences in dolphin population density and size, all of which affect the likelihood of heavier bycatch.
- **Isolated Low-Density Cluster:** Similar to the DTN map, an isolated cluster is noted around latitude 21.0°N and longitude 65.0°E, predominantly marked in dark purple. This cluster represents an area of lower dolphin bycatch in terms of weight, potentially indicating sporadic fishing events or unique local conditions that affect dolphin size and numbers. This suggests that while dolphin bycatch occurs in this area, it does not involve the same volume or size of dolphins as the main hotspot, possibly due to local habitat characteristics, fishing effort distribution, or the type of gear used.

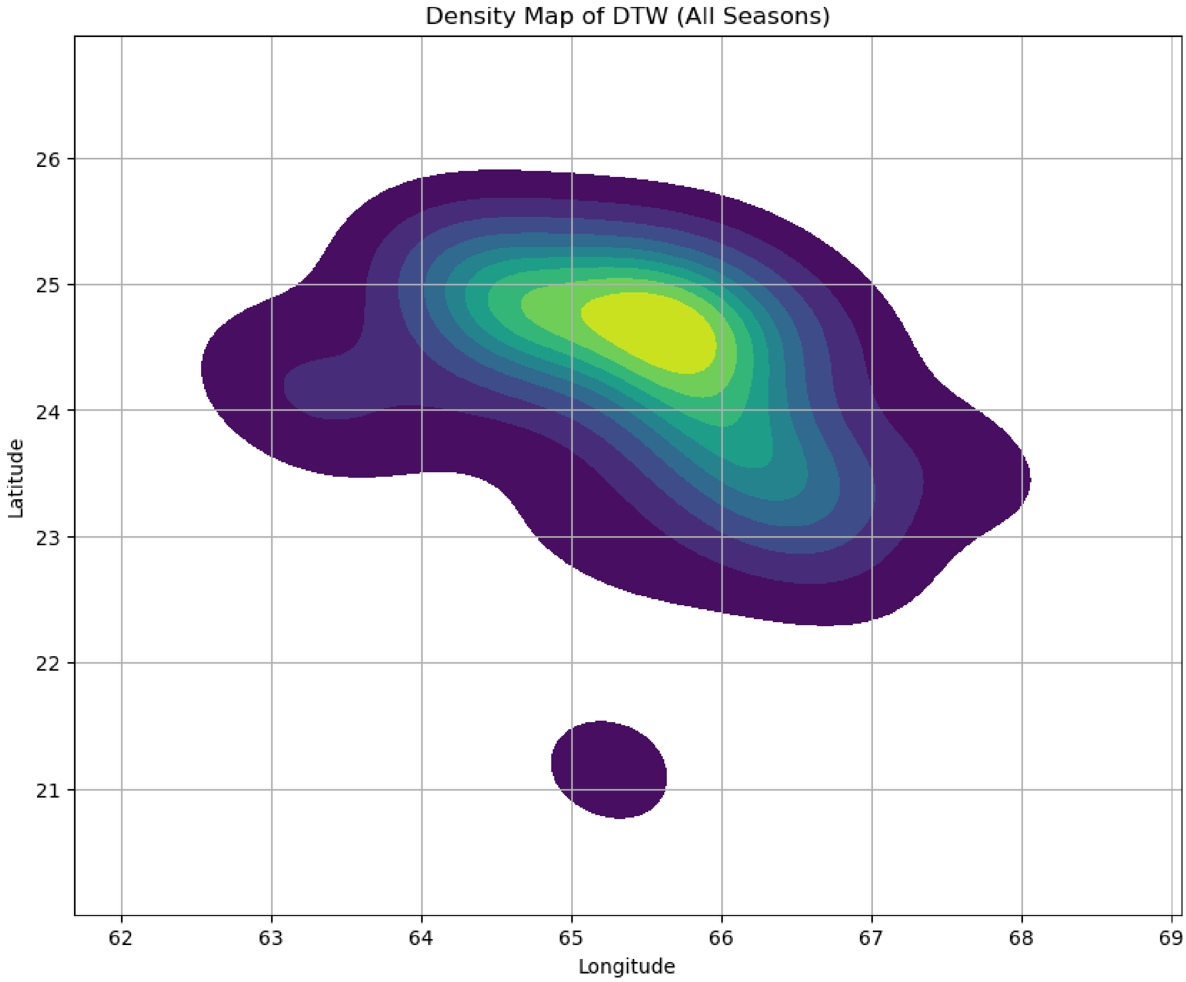
Spatial Patterns and Implications

The spatial patterns observed in this density map provide important insights into the distribution of dolphin bycatch weight in the Northern Arabian Sea, particularly off the coast of Pakistan:

- **Identification of Bycatch Hotspots by Weight:** The central high-density area, spanning latitudes 24.0°N to 25.0°N and longitudes 65.5°E to 66.5°E, emerges as a critical hotspot where dolphin bycatch results in the highest total weight. This indicates that dolphins caught here may be larger or that a greater number are caught together. The proximity of this hotspot to the high-density area observed in the DTN map reinforces the notion that this region is a focal point for dolphin bycatch due to overlapping fishing grounds and dolphin habitats. Effective management strategies in this area, such as gear modifications or temporal closures, could significantly reduce the impact on dolphin populations.
- **Influence of Environmental and Fishing Factors:** The spatial distribution of DTW density likely reflects a combination of environmental factors, such as water temperature, prey availability, and current patterns, which may attract larger or more numerous dolphins. Additionally, the type of fishing gear used and the intensity of fishing efforts can greatly influence the total weight of dolphins caught.
- **Targeted Conservation Measures for High-Density Areas:** The identified high-density areas between 24.0°N to 25.0°N and 65.5°E to 66.5°E could be targeted for specific conservation measures. Implementing seasonal closures during peak bycatch periods or introducing bycatch mitigation technologies could help reduce the total weight of dolphin bycatch. These measures would be most effective when informed by the spatial distribution patterns of both DTN and DTW, enabling a comprehensive approach to bycatch management that addresses both the frequency and impact of incidents.
- **Significance of the Isolated Cluster:** The isolated low-density cluster around 21.0°N, 65.0°E may indicate different ecological or fishing conditions compared to the main hotspot. While the total weight of bycatch in this area is lower, the presence of any dolphin bycatch still warrants attention. Further investigation into this region could reveal important factors

influencing dolphin size or number, such as local fishing practices, habitat types, or prey availability. Understanding these dynamics would help in developing more nuanced conservation strategies.

The density map of DTW (Dolphin Total Weight) provides a comprehensive overview of areas where heavier dolphin bycatch incidents occur in the Northern Arabian Sea. The map reveals a prominent high-density area between 24.0°N to 25.0°N and 65.5°E to 66.5°E, indicating that this is a critical region where the impact of bycatch is most significant in terms of dolphin weight. The presence of an isolated low-density cluster at 21.0°N, 65.0°E further emphasizes the need to understand localized dynamics. Overall, these findings offer a valuable foundation for targeted interventions and conservation strategies to mitigate dolphin bycatch and promote sustainable fisheries management in the region.



Graph 33: The contour plot depicts the density of DTW across different geographic locations, with the highest density areas shown in yellow and green, indicating regions with greater dolphin bycatch weight. The cooler colours (blue and purple) represent areas with lower DTW density. This visualization highlights the key locations where dolphin bycatch weight is most concentrated, providing valuable information for targeted conservation measures.

Comparison Between Dolphin Total Number (DTN) and Dolphin Total Weight (DTW)

There is a notable overlap between the high-density regions identified for both DTN and DTW, suggesting that areas with a higher number of dolphins also tend to exhibit higher total weights. This overlap implies that these regions support both high dolphin abundance and biomass. However, subtle differences in these patterns may reflect variations in dolphin size across different regions, potentially influenced by local environmental conditions or specific ecological dynamics.

Results of the Statistical Analysis:

The dataset comprises 172 observations of DTW and Dolphin DTN, providing a robust basis for analyzing both the number and weight of dolphins captured during various events.

Analysis of Dolphin Total Number (DTN):

The analysis of DTN shows an average of 1.03 dolphins recorded per observation, indicating that typically, one dolphin is captured in each event. The standard deviation of 0.76 reflects low variability in the number of dolphins across different observations, with most records reporting around one dolphin and only minor variations.

The minimum recorded value is 0, indicating instances where no dolphins were observed. The 25th percentile shows that 25% of the observations recorded exactly one dolphin, while the median value confirms this finding, indicating that half of the observations reported one dolphin. The 75th percentile reinforces that the majority of observations are clustered around this number. However, the maximum number of dolphins recorded in a single observation is 5, showing that there are instances where multiple dolphins were captured in one event.

Analysis of Dolphin Total Weight (DTW):

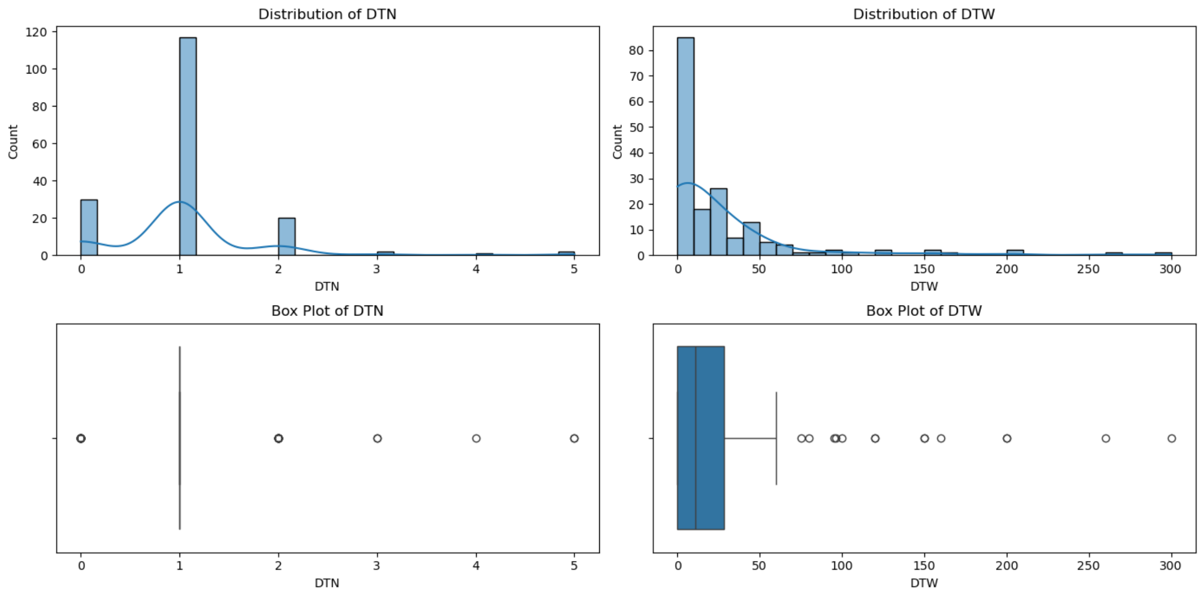
The analysis of DTW data reveals an average total weight of approximately 24.60 kilograms per observation, suggesting that, on average, the combined weight of dolphins captured in each event is around 24.6 kg. The standard deviation is relatively high at 45.06 kilograms, indicating significant variability in dolphin weights across different observations. This variability suggests that some observations involve either very large dolphins or multiple dolphins with substantial weight.

The minimum DTW value is 0, reflecting instances where no weight was recorded, likely corresponding to observations with no dolphin captures. The 25th percentile indicates that 25% of the observations have a DTW of 0, highlighting that a substantial portion of the dataset includes events with no recorded dolphin weight. The median DTW is 11 kilograms, meaning half of the observations reported a total dolphin weight of 11 kg or less. The 75th percentile shows that 75% of the observations have a dolphin weight of 28.5 kilograms or less, indicating a broad range of weights in the upper half of the data. The maximum recorded DTW is 300 kilograms, which is considerably higher than the mean, pointing to the presence of outliers or exceptional cases with very large total dolphin weights.

Analysis of Central Tendency and Dispersion for DTN and DTW

The analysis of central tendency and dispersion for DTN shows that the consistent mean and median values indicate most observations report a similar number of dolphins, typically around one. In contrast, the high standard deviation observed in DTW reflects considerable variability in dolphin weights, which could be attributed to the presence of larger individuals or multiple dolphins in certain regions (Graph 34).

The data distribution reveals that the minimum values for both DTN and DTW are 0, with 25% of the DTW data also being 0. This suggests that a significant portion of the dataset includes observations where no dolphins were caught or weighed. This pattern may be influenced by varying fishing efforts, seasonal factors, or specific locations where dolphins were less prevalent. The presence of potential outliers is evident in the maximum values, particularly for DTW, which are significantly higher than the median and mean, indicating exceptional cases with much larger total dolphin weights.



Graph 34: The top row shows the distribution histograms of DTN and DTW, revealing the frequency of different bycatch values, with the majority of DTN concentrated around 1 and DTW skewed towards lower values. The bottom row displays the box plots, highlighting the spread and outliers in the data. The DTW box plot indicates a wider range and more significant outliers compared to DTN, suggesting greater variability in the total weight of dolphin bycatch.

Geospatial Heatmap

Geospatial Heatmap Analysis of Dolphin Total Number (DTN)

The geospatial heatmap of DTN across all seasons provides a detailed visualization of the distribution and intensity of dolphin bycatch across various geographical locations. This analysis identifies key regions where dolphin bycatch is most concentrated, as well as areas where it occurs less frequently (Graph 35).

Geographical Distributions:

The distribution of dolphin bycatch events spans a broad range of latitudes and longitudes, indicating that dolphin bycatch is not confined to specific areas but varies significantly in intensity across the region. The geographical range extends from latitudes as far south as 21° to as far north as 26°, and longitudes from 64° to 67°. This suggests that while there are clear hotspots, dolphin bycatch can still occur in diverse locations, albeit with lower frequency.

Geographical Concentrations:

The heatmap highlights specific geographical concentrations of dolphin bycatch. These concentrations are particularly evident in the clustering of yellow and green cells within the latitude range of 24° to 25° and longitude range of 65° to 66°. Such clustering suggests that specific environmental or ecological factors, such as ocean currents or prey availability, may increase the likelihood of dolphin bycatch in these regions.

High-Concentration Areas:

The heatmap identifies distinct regions with significantly higher concentrations of dolphin bycatch. These high-concentration areas, represented by shades of yellow and green, are primarily located around latitudes 24° to 25° and longitudes 65° to 66°. These hotspots indicate that environmental conditions or specific fishing practices in these areas may contribute to a higher probability of capturing dolphins.

Lower-Concentration Areas:

Conversely, lower-concentration areas are depicted in darker purple shades on the heatmap. These regions, more dispersed across the map, show reduced intensity of dolphin bycatch, with DTN values diminishing as one moves away from the high-concentration zones. While dolphin bycatch can occur across a broader geographical range, the frequency is notably lower in areas outside the primary cluster of latitudes 24° to 25° and longitudes 65° to 66°. This pattern suggests that these locations may be less favorable for dolphin presence or less impacted by fishing activities leading to bycatch.

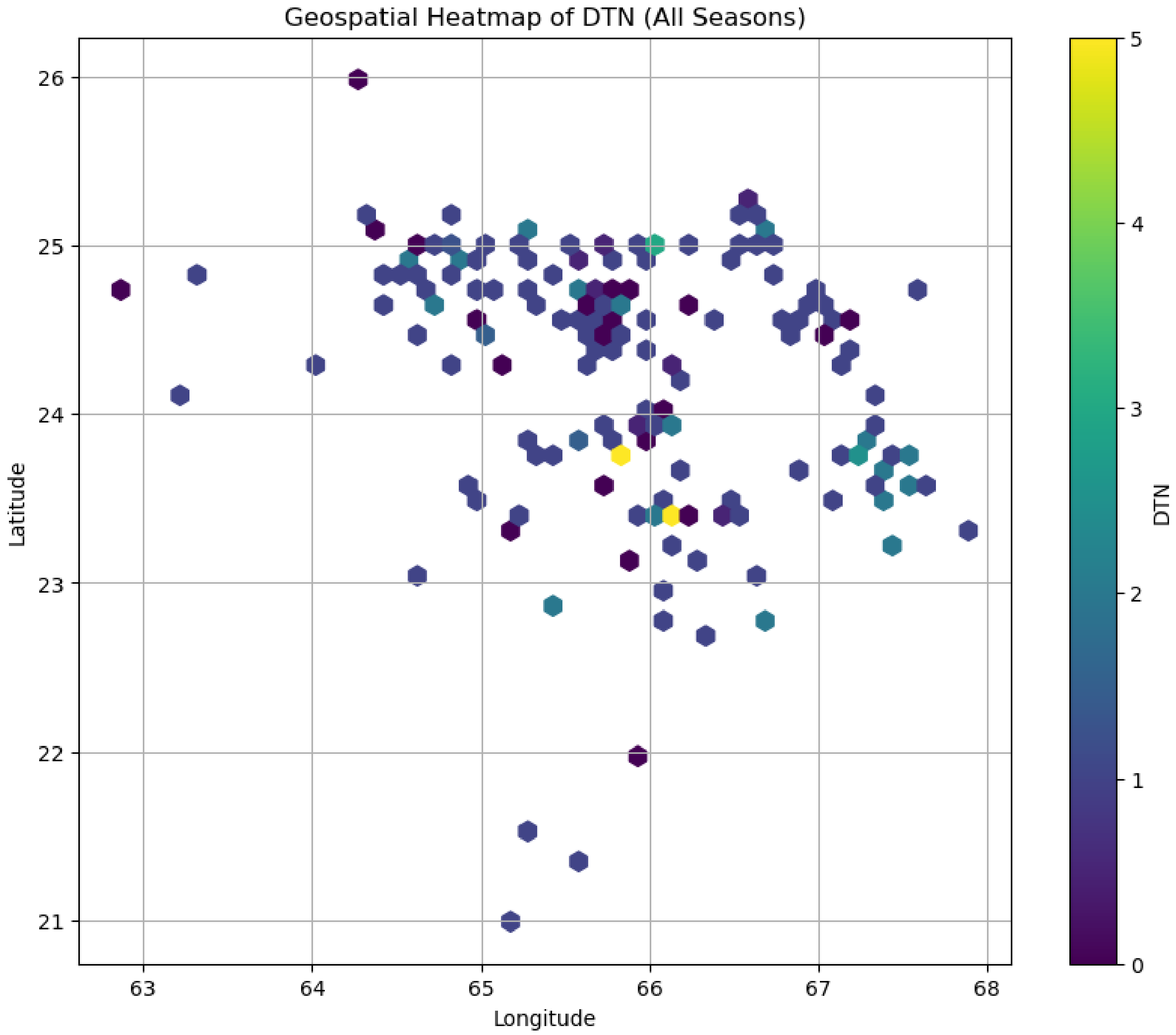
High-Density Areas:

The high-density areas identified on the heatmap, particularly those concentrated around latitudes 24.5° to 25° and longitudes 65° to 66°, are critical for understanding where dolphin bycatch is most prevalent. These regions, marked by intense yellow-green colors, suggest that the conditions in these locations—whether related to environmental factors, fishing practices, or both—are conducive to higher rates of dolphin bycatch. Identifying these areas is essential for guiding targeted conservation efforts, such as modifying fishing practices, establishing protected areas, or adjusting regulations to reduce bycatch in these critical zones.

Low-Density Areas:

In contrast, low-density areas, represented by darker purple shades, indicate regions where dolphin bycatch is less frequent. These areas, generally located at the periphery of high-concentration zones, such as latitudes around 21° to 23° and longitudes beyond 66°, suggest less impact from fishing activities or less suitability for dolphin presence. The distribution of these low-density areas across the map underscores that while bycatch is not entirely absent, it occurs with much lower intensity compared to the central high-density zones.

The heatmap analysis clearly illustrates the spatial patterns of dolphin bycatch, distinguishing between high-concentration areas around latitudes 24° to 25° and longitudes 65° to 66° and lower-concentration areas beyond these ranges. These insights can inform targeted management and conservation strategies to mitigate dolphin bycatch in key regions.



Graph 35: The hexagonal heatmap visualizes the intensity of DTN values across geographic locations, with colors ranging from dark purple (lower DTN) to bright yellow (higher DTN). This heatmap highlights areas with concentrated dolphin bycatch events, providing a clear spatial representation of where higher DTN values are occurring, which can be critical for directing conservation efforts.

Geospatial Heatmap Analysis of Dolphin Total Weight (DTW)

The geospatial heatmap analysis of DTW provides critical insights into the distribution and intensity of dolphin bycatch across various geographical locations, using specific latitude and longitude coordinates to illustrate these patterns (Graph 36).

Geographical Distributions:

The heatmap reveals that dolphin bycatch is distributed across a range of latitudes and longitudes, rather than being confined to a single location. However, the intensity of bycatch, as indicated by DTW, varies considerably. Higher bycatch weights are notably clustered between latitudes 24° to 25° and longitudes 65° to 66°. This distribution pattern is essential for understanding where dolphin populations are most at risk and where targeted management strategies could be most effective.

Geographical Concentrations:

The analysis identifies specific geographical concentrations where dolphin bycatch weights are consistently higher. The clustering of yellow-green cells around the latitude range of 24° to 25° and longitude range of 65° to 66° underscores these areas as key hotspots. These concentrations are likely influenced by a combination of environmental conditions and fishing practices that increase the likelihood of heavier dolphin bycatch. Identifying these hotspots is crucial for fisheries management and conservation efforts, enabling more focused interventions where they are most needed.

High-Concentration Areas:

The heatmap highlights distinct high-concentration areas where dolphin bycatch weights are significantly elevated. These areas are predominantly situated between latitudes 24° to 25° and longitudes 65° to 66°. The bright yellow-green shades on the map indicate that these regions experience higher dolphin bycatch, likely due to the capture of larger dolphins or a greater number of individuals. These high-concentration areas are critical for identifying where conservation efforts may need to be intensified to effectively protect dolphin populations.

Lower-Concentration Areas:

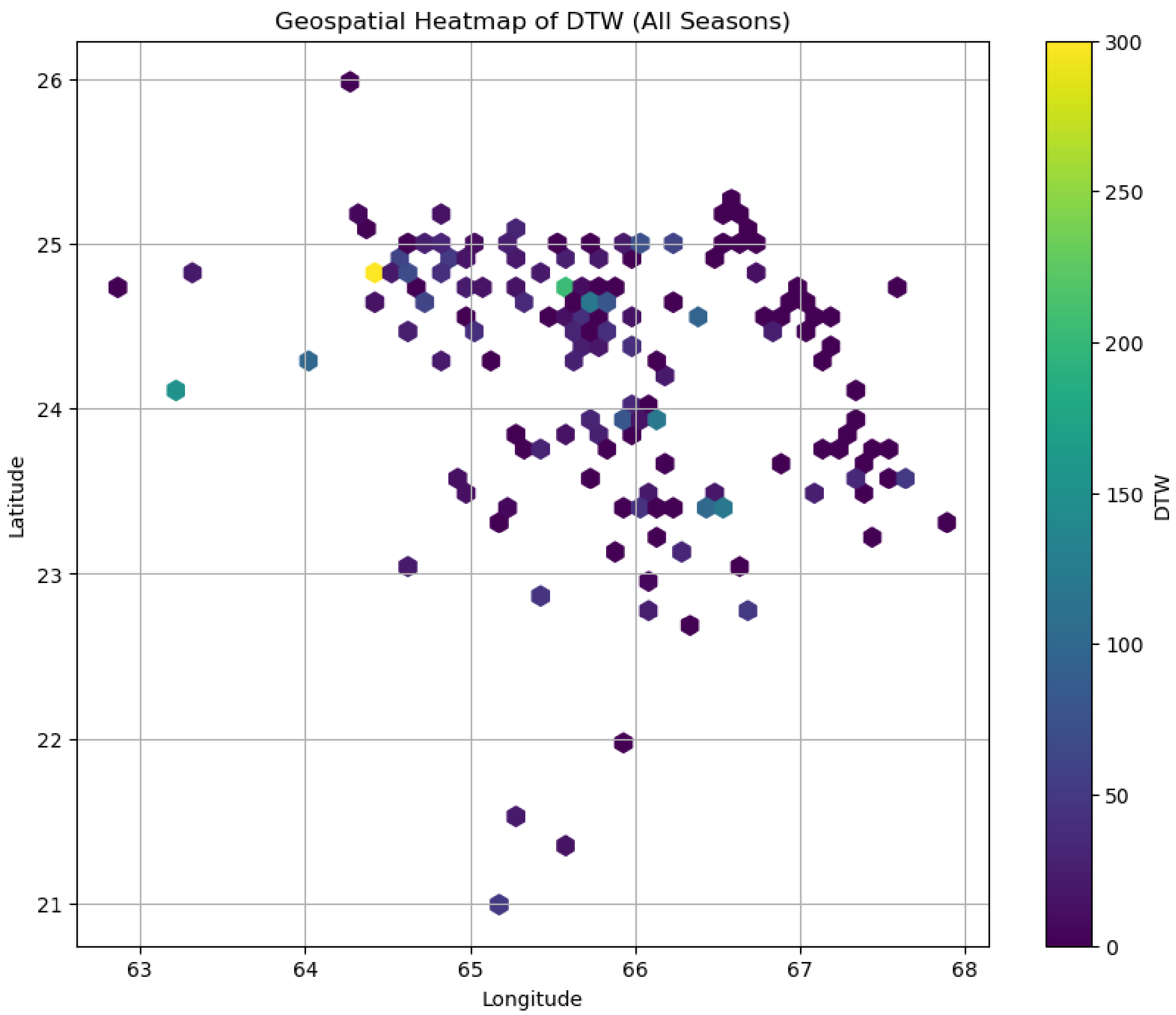
In contrast, lower-concentration areas are depicted by darker purple shades on the heatmap. These regions are generally located outside the primary high-density zones, such as latitudes slightly above or below the 24° to 25° range and longitudes extending beyond 66°. In these lower-concentration areas, dolphin bycatch weights are relatively minimal, suggesting either fewer dolphins are being captured or that the dolphins caught are smaller. The widespread distribution of these lower-concentration areas indicates that while dolphin bycatch occurs across a broad geographical range, the intensity is much lower compared to the high-concentration zones.

High-Density Areas:

The heatmap clearly delineates high-density areas, marked by yellow-green cells, particularly between latitudes 24° to 25° and longitudes 65° to 66°. These regions represent zones with the highest dolphin bycatch weights, suggesting that these areas are either home to larger dolphins or subject to fishing practices that result in heavier bycatch. These high-density areas are crucial for directing conservation resources and implementing regulatory measures to minimize the impact on dolphin populations.

Low-Density Areas:

Conversely, low-density areas are characterized by darker purple cells on the heatmap, indicating regions with lower dolphin bycatch weights. These areas, often located outside the 24° to 25° latitude range and extending beyond 66° longitude, suggest that bycatch in these regions is less frequent or involves smaller dolphins. Identifying these low-density areas is important for understanding the broader spatial patterns of dolphin bycatch and ensuring that management efforts are appropriately scaled across different regions.



Graph 36: This hexagonal heatmap visualizes the distribution of DTW values across different geographic locations, with color intensity reflecting the weight of dolphin bycatch. Darker purple regions represent lower DTW values, while brighter yellow areas indicate higher concentrations of bycatch weight. This visualization helps identify areas with significant dolphin bycatch in terms of weight, providing crucial information for targeted conservation and management strategies.

Comparative Analysis

A comparison of the Dolphin Total Weight (DTW) heatmap with the Dolphin Total Number (DTN) heatmap reveals patterns that help determine whether regions with a high number of dolphins also correspond to higher total weights. This comparison can provide insights into whether bycatch in these areas consists of larger dolphins or a greater number of smaller individuals. For example, if a region shows a high DTN but only moderate DTW, it may suggest that a large number of smaller dolphins are being captured. In contrast, a region with both high DTN and high DTW would indicate the bycatch of a significant number of larger dolphins.

Insights for Fisheries Management:

The identified hotspots where dolphin bycatch weights are highest are critical for implementing targeted conservation measures. These areas, particularly around latitudes 24° to 25° and longitudes 65° to 66°, may require stricter fishing regulations, gear modifications, or targeted seasonal closures to reduce the impact on dolphin populations. Additionally, integrating this information with environmental data, such as sea surface temperature, prey availability, or chlorophyll concentrations, could provide deeper insights into the factors contributing to higher DTW in these regions. This integrated approach would help develop more effective, data-driven management strategies to protect dolphin populations.

Dimensionality Reduction and Feature Importance

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) of the Dataset

The PCA conducted on the dataset aimed to reduce its dimensionality while retaining the most significant variance. This method transforms the original variables into a new set of uncorrelated variables known as principal components (PCs). The first few principal components capture the majority of the variance in the data, making PCA a valuable tool for simplifying complex datasets.

Key Variables and Principal Components:

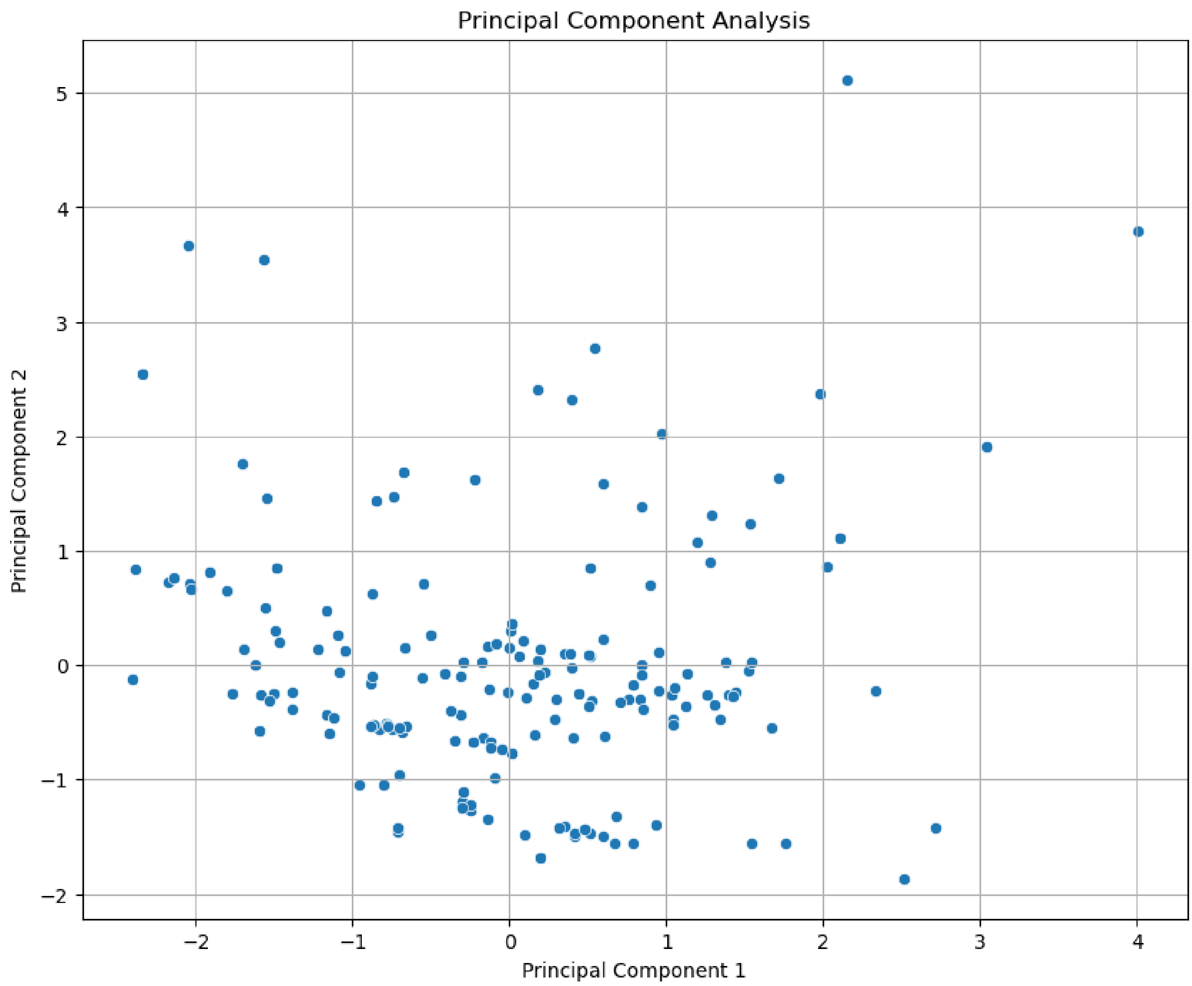
In this analysis, the PCA focused on four key variables: DTN, DTW, Latitude, and Longitude. The first principal component (PC1) captures the maximum variance, representing the most substantial differences between observations in the dataset. The second principal component (PC2), which is orthogonal to PC1, captures the second-largest variance. Together, these components provide a simplified representation of the dataset, with PC1 and PC2 plotted on the x-axis and y-axis, respectively (Graph 37).

Scatter Plot of Principal Components:

The scatter plot generated from the PCA illustrates how the observations are distributed based on their scores for the first two principal components. Each point on the plot represents a transformed observation, with its position along the PC1 and PC2 axes indicating the contribution of these components to the overall variance in the dataset. The distribution of data points suggests that PC1 captures more variance than PC2, as evidenced by the wider spread of points along the x-axis. This indicates that PC1 is the dominant source of variability within the dataset.

Interpretation and Observations:

The PCA plot does not reveal strong clustering, indicating that the first two principal components do not suggest distinct groupings within the data. The evenly spread points imply that variance is relatively evenly distributed across the observations, with no clear patterns or clusters emerging from the analysis. However, some points are positioned further from the central cluster, indicating potential outliers. These outliers represent observations that differ significantly from the rest of the data and may warrant further investigation to understand the underlying factors driving these differences.



Graph 37: The scatter plot shows the data points projected onto the first two principal components (PC1 and PC2), which capture the most variance in the dataset. This visualization helps to identify patterns and relationships in the data, reducing the dimensionality while preserving as much information as possible. Clusters or patterns in this plot may indicate underlying structures in the bycatch data, such as grouping based on geographical location or bycatch characteristics.

Explained Variance Ratio

The bar chart depicting the Explained Variance Ratio for the first two principal components (PC1 and PC2) from the Principal Component Analysis (PCA) provides key insights into the proportion of the total variance in the dataset captured by these components. The Explained Variance Ratio is a crucial metric as it indicates the degree to which each principal component retains the variance from the original dataset. A higher explained variance ratio suggests that the corresponding principal component accounts for a greater portion of the original data's variability (Graph 38).

Key Findings from the Explained Variance Ratio:

- **Principal Component 1 (PC1):** The first principal component captures approximately 33.77% of the total variance, making it the most significant component in explaining the variability within the dataset.
- **Principal Component 2 (PC2):** The second principal component accounts for 30.73% of the variance.

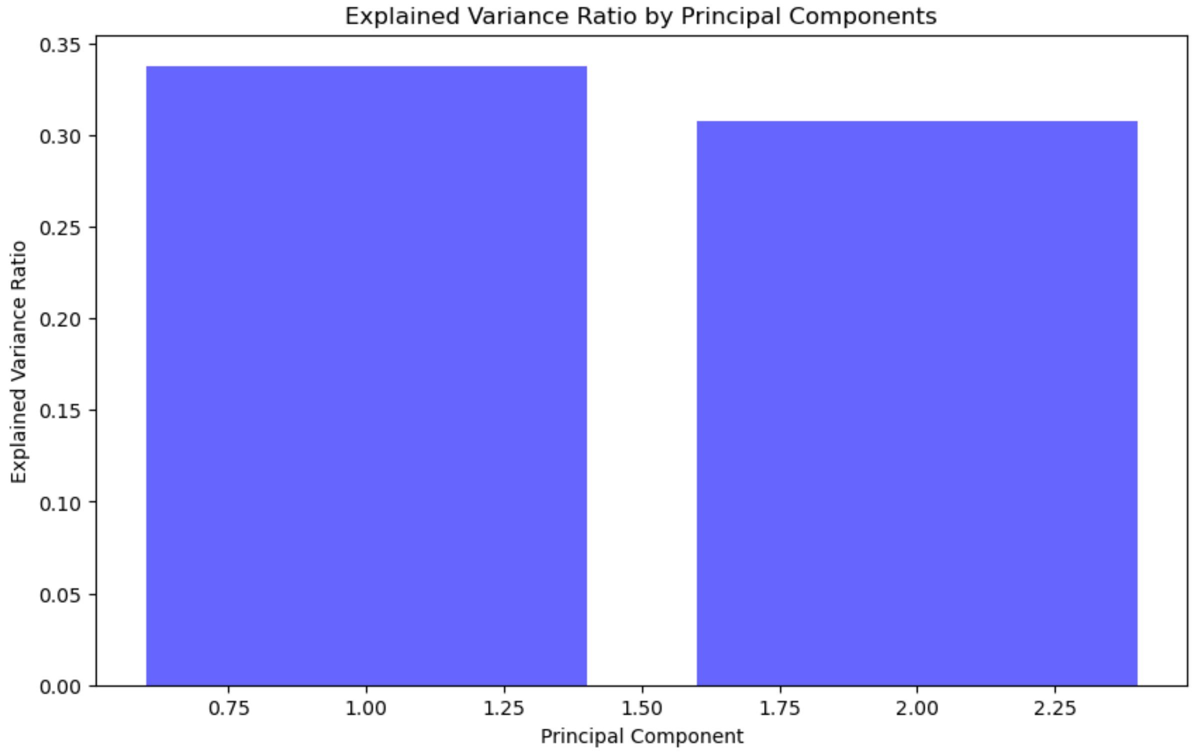
Together, PC1 and PC2 explain around 64.5% of the total variance in the dataset. This indicates that reducing the dataset from four dimensions (Latitude, Longitude, DTN, and DTW) to just two (PC1 and PC2) retains a substantial 64.5% of the critical information originally distributed across all four variables.

Remaining Variance:

The remaining variance, approximately 35.5%, is captured by other principal components (such as PC3 and PC4), which are not depicted in this plot but still contribute to the overall variance. While the specific contributions of DTN, DTW, Latitude, and Longitude to PC1 and PC2 are not directly shown in the bar chart, the fact that PC1 and PC2 capture the majority of the variance suggests that these components effectively summarize the primary patterns and structure in the dataset. Typically, PC1 may combine variability due to geographic location (Latitude and Longitude) with biological data (DTN, DTW), while PC2 could capture additional, independent patterns.

Implications for Further Analysis:

The PCA results suggest that reducing the dimensionality of the data to just PC1 and PC2 can be beneficial for further analysis, such as clustering or visualization, while still preserving a significant amount of the dataset's variability. Higher loading scores would indicate a stronger influence of a particular variable on the principal component, guiding interpretation and subsequent analyses.



Graph 38: The bar chart shows the explained variance ratio for the first two principal components in the dataset. The first principal component accounts for approximately 35% of the total variance, while the second principal component explains around 30%. This indicates that these two components capture a significant portion of the variability in the data, making them critical for understanding the underlying patterns in the bycatch dataset.

Interaction Effects Liner Regression Model Analysis

Interaction Effects on Dolphin Total Number (DTN)

The analysis indicates that both latitude and longitude have positive coefficients, suggesting that each factor independently contributes to an increase in DTN. However, the relatively small magnitudes of these coefficients, along with a low R^2 score of 0.034, imply that latitude and longitude together explain only a small portion of the variation in DTN. The negative coefficient for the interaction term suggests that when both latitude and longitude increase together, their combined effect on DTN slightly diminishes. This indicates that while each variable has a positive effect individually, their combined influence is less pronounced.

The negative intercept of -204.14, though not practically meaningful, suggests that the model may not fully capture the complexities of the factors influencing DTN. Overall, the low R^2 score indicates that the model accounts for only 3.4% of the variance in DTN, highlighting the need to explore other factors that may have a more substantial impact on DTN.

Interaction Effects on Dolphin Total Weight (DTW)

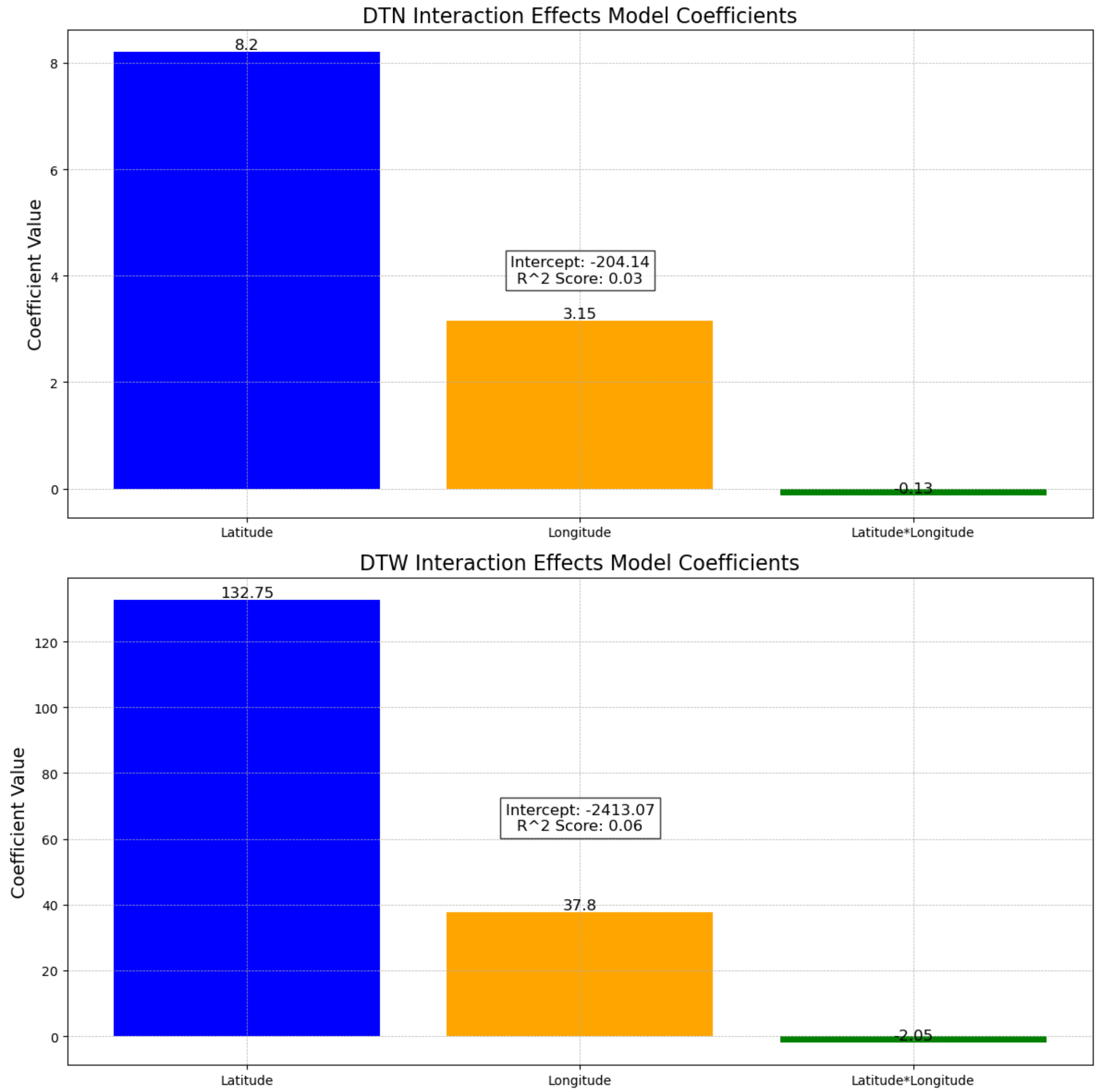
For Dolphin Total Weight (DTW), the analysis similarly shows that both latitude and longitude have positive coefficients, with latitude having a more pronounced effect, as reflected by its larger coefficient. The negative interaction term here also suggests that as both latitude and longitude increase simultaneously, their combined effect on DTW decreases slightly. This interaction effect is more pronounced for DTW than for DTN (Table 9 and Graph 39).

The model's intercept of -2413.07 also implies that the model may not fully capture the true dynamics affecting DTW. The R^2 score of 0.059, although slightly higher than that for DTN, still indicates that the model explains only about 5.9% of the variance in DTW. This suggests that the majority of the variation is driven by factors not included in the current model.

The models for both DTN and DTW suggest that while latitude and longitude have some impact on these outcomes, they account for only a small fraction of the variability. The negative interaction terms indicate that the combined influence of latitude and longitude on DTN and DTW is less than the sum of their individual effects. The low R^2 scores emphasize that there are likely other, more significant factors influencing DTN and DTW that are not captured in these models.

Variable	**Latitude Coefficient**	**Longitude Coefficient**	**Interaction Term (Latitude * Longitude)**	**Intercept**	**R^2 Score**
DTN	8.20	3.15	-0.13	-204.14	0.034
DTW	132.75	37.80	-2.05	-2413.07	0.059

Table 9: This table provides a clear overview of the key coefficients, intercepts, and R^2 scores for the interaction effects models of DTN and DTW



*Graph 39: The bar charts display the model coefficients for Latitude, Longitude, and their interaction (Latitude*Longitude) in predicting DTN (top) and DTW (bottom). For DTN, Latitude has the highest positive coefficient (8.2), followed by Longitude (3.15), with a minimal interaction effect (0.13). For DTW, Latitude also shows the highest positive coefficient (132.75), followed by Longitude (37.8), with a small interaction effect (2.05). The intercept and R^2 score values indicate the model's overall fit, with low R^2 scores (0.03 for DTN and 0.06 for DTW), suggesting a limited explanatory power of the model based on these predictors.*

Partial Dependence Plots (PDPs)

Partial Dependence Plots (PDPs) Analysis for Dolphin Total Number (DTN)

The PDPs offer valuable insights into how geographic variables, specifically latitude and longitude, influence the DTN within the dataset (Graph 40).

Latitude vs. DTN:

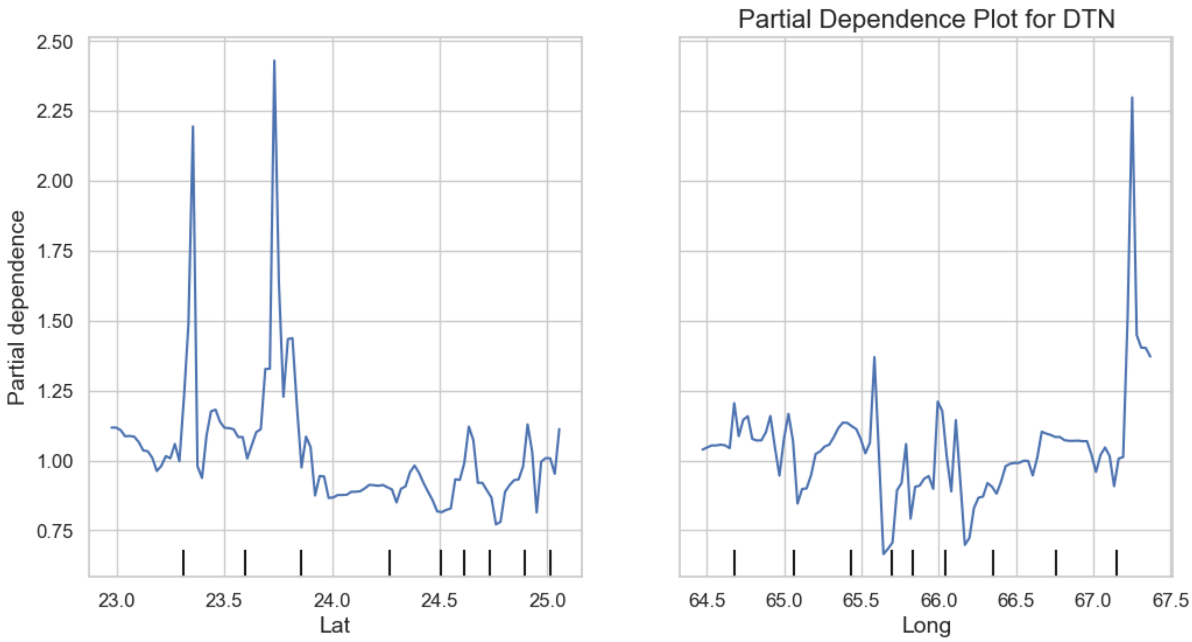
The PDP for latitude indicates that certain latitudinal ranges are associated with significant increases in the predicted DTN. Notably, there are pronounced spikes around latitudes 23.2, 23.5, and 24.0, suggesting that these ranges are hotspots for dolphin bycatch. Outside of these peaks, the predicted DTN remains relatively stable, generally around a value of 1.0. This stability implies that, at most other latitudes, DTN does not exhibit substantial fluctuations. The observed peaks may be linked to specific ecological or environmental conditions prevalent at these latitudes, such as optimal water temperatures or prey availability that attract both dolphins and fishing activities.

Longitude vs. DTN:

The PDP for longitude reveals greater variability compared to latitude, with notable fluctuations in the predicted DTN across different longitudes. Significant peaks are observed around longitudes 65.5, 66.5, and particularly at 67.5. These peaks suggest that certain longitudes are more prone to dolphin bycatch, potentially due to factors such as concentrated fishing efforts or oceanographic features like currents or shelf edges. The variability observed across different longitudes indicates a more complex relationship with DTN, likely driven by a combination of environmental and operational factors.

Overall Interpretation:

The PDPs indicate that both latitude and longitude significantly influence the likelihood of dolphin bycatch, with specific geographic regions emerging as higher-risk areas. These hotspots are likely the result of a combination of environmental conditions and fishing practices that increase the probability of dolphins encountering fishing gear. Understanding these geographic influences is crucial for developing targeted strategies to manage and reduce dolphin bycatch in these critical areas.



Graph 40: The plots illustrate the relationship between DTN and two geographic features: latitude (left) and longitude (right). The y-axis shows the partial dependence of DTN on each feature, holding other variables constant. Peaks in the plots indicate specific latitudes and longitudes where the expected number of dolphin bycatch increases, revealing important spatial dependencies in the data.

Partial Dependence Plots (PDPs) Analysis for Dolphin Total Weight (DTW)

The PDPs for DTW provide insights into how geographic factors, particularly latitude and longitude, influence the weight of dolphins captured as bycatch (Graph 41).

Latitude vs. DTW:

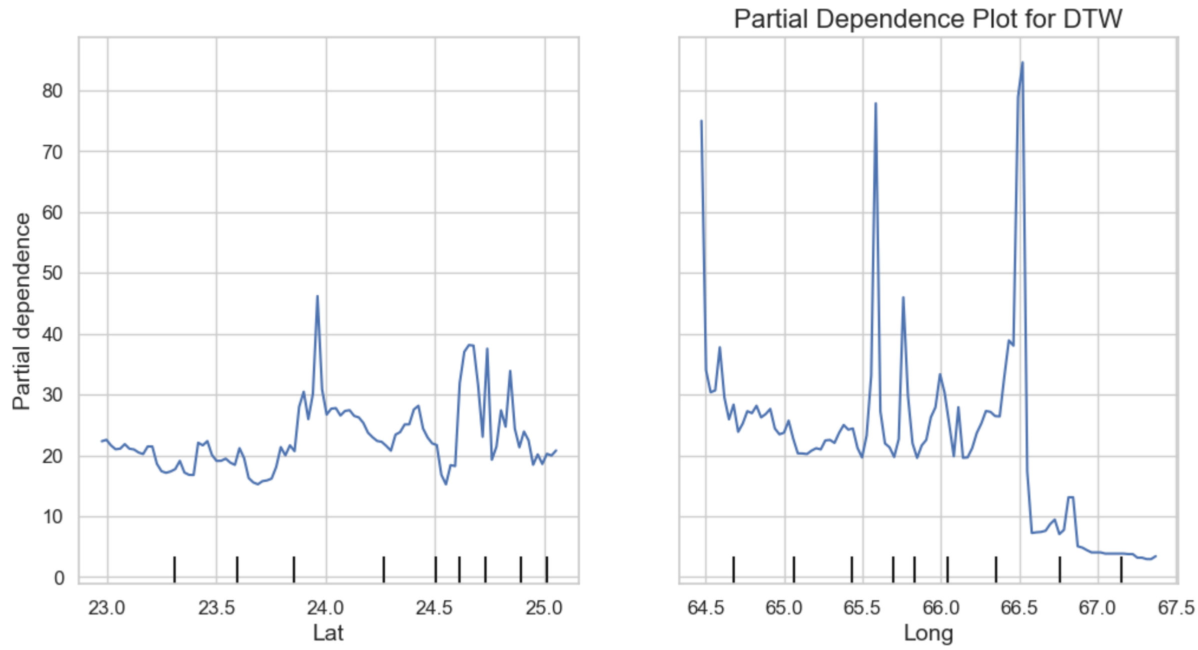
The PDP for latitude reveals several notable peaks, indicating that predicted DTW varies significantly across different latitudes. Specifically, latitudes around 24.0 and 24.5 show substantial increases in DTW, with the most pronounced peak at latitude 24.0, where DTW rises sharply. This suggests that certain latitudes are associated with higher dolphin weights. The moderate variability observed across latitudes implies that some regions may be more conducive to the presence of larger dolphins, potentially due to ecological factors such as prey availability, water temperature, or migratory patterns that affect dolphin size.

Longitude vs. DTW:

The PDP for longitude exhibits even greater variability, with several pronounced spikes indicating locations where DTW is significantly higher. Sharp peaks are observed at longitudes 64.5, 65.5, 66.5, and 67.5, suggesting these areas are associated with larger dolphin bycatch. Notably, there is a sharp decline in DTW beyond longitude 67.0, indicating that areas to the east have lower predicted dolphin weights. This decrease may reflect a geographic boundary where environmental conditions become less favorable for larger dolphins, potentially due to changes in oceanographic features such as currents, upwellings, or underwater structures.

Overall Interpretation:

The PDPs highlight the significant influence of both latitude and longitude on the weight of dolphins caught as bycatch. Specific geographic areas, as indicated by the peaks in these plots, are more likely to result in higher DTW, which is critical for developing targeted bycatch mitigation strategies. When comparing these results with previous PDPs for Dolphin Total Number (DTN), it becomes evident that locations with high DTW do not always coincide with those with high DTN. This discrepancy suggests that different factors may influence dolphin number and weight, potentially indicating variations in species composition or age groups being caught in different areas.



Graph 41: These plots show the relationship between DTW and two geographic features: latitude (left) and longitude (right). The y-axis represents the partial dependence of DTW on each feature, with other variables held constant. Significant peaks indicate latitudes and longitudes where the expected weight of dolphin bycatch is higher, revealing crucial spatial influences on bycatch weight.

SHAP Feature Importance Plot

The SHapley Additive exPlanations (SHAP) feature importance plot provides a clear understanding of how geographic variables—latitude (Lat) and longitude (Long)—influence the prediction of Dolphin Total Number (DTN) and Dolphin Total Weight (DTW) in the dataset.

SHAP Feature Importance Analysis for Dolphin Total Number (DTN)

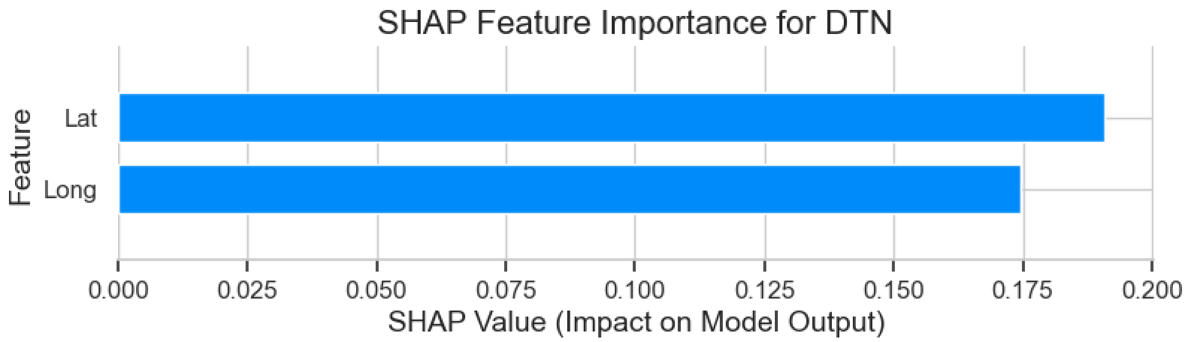
Interpretation of SHAP Values:

SHAP values quantify the contribution of each feature to the model's predictions, with higher SHAP values indicating a greater influence of that feature on predicting DTN. In the plot, each bar represents a feature, and the length of the bar reflects the average impact of that feature on the model's predictions (Graph 42).

- **Latitude (Lat):** The SHAP value for latitude is higher than that for longitude, suggesting that latitude has a slightly stronger impact on the prediction of DTN. This indicates that variations in latitude significantly affect the number of dolphins caught as bycatch. This could be due to certain latitudinal zones being more susceptible to higher dolphin bycatch, potentially influenced by ecological factors such as water temperature, prey availability, or dolphin migration patterns.
- **Longitude (Long):** While longitude also affects DTN, its impact is less pronounced compared to latitude. Although longitude contributes to determining dolphin bycatch numbers, its influence is relatively minor compared to that of latitude. This may suggest that the distribution of dolphins and fishing activities is more strongly driven by latitudinal factors.

Implications for Spatial Management:

The findings from the SHAP analysis provide valuable insights for spatial management strategies. Since latitude has a greater impact on DTN, conservation efforts could be more effectively focused on managing fishing activities within specific latitudinal bands to reduce dolphin bycatch. Targeting these zones may be more effective in mitigating the impact on dolphin populations.



Graph 42: The horizontal bar chart displays the SHAP values, representing the impact of each feature (latitude and longitude) on the model's output for predicting DTN. Higher SHAP values indicate greater importance of the feature in determining the model's predictions. In this analysis, both latitude and longitude show significant influence on the DTN, with latitude having a slightly higher impact.

SHAP Feature Importance Analysis for Dolphin Total Weight (DTW)

Dominance of Longitude:

The SHAP plot reveals that longitude is a significantly more influential factor in predicting DTW compared to latitude. The longer bar for longitude indicates that variations in longitude have a considerable impact on the predicted total weight of dolphins caught as bycatch. This suggests that specific longitudes may be associated with environmental factors—such as ocean currents or particular habitat features—that favor the presence of larger dolphins, making longitude a critical determinant of DTW (Graph 43).

Role of Latitude:

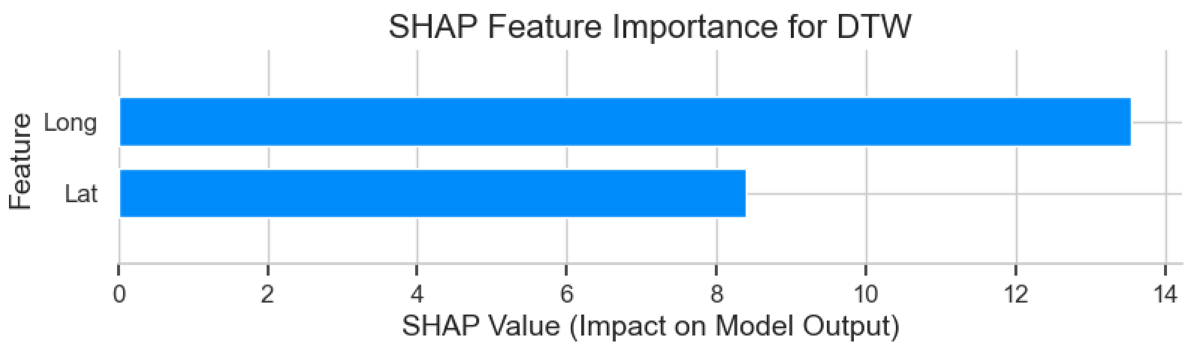
While latitude does affect DTW, its impact is less pronounced than that of longitude. The shorter bar for latitude implies that its influence on dolphin weight is secondary. This could suggest that the distribution of dolphin size or weight is less sensitive to changes in latitude and more influenced by longitudinal factors, potentially related to regional environmental conditions or specific fishing practices occurring within certain longitudinal zones.

Focus on Longitude:

Given that longitude has the most significant influence on DTW, conservation efforts or strategies aimed at reducing dolphin bycatch should focus on specific longitudinal regions. Understanding why certain longitudes have a greater impact on dolphin weight could help in developing more targeted and effective management strategies.

Comparison with DTN Analysis:

A comparison with the SHAP analysis for DTN shows that different geographic factors influence dolphin numbers and weights. While latitude was found to be more critical in predicting the number of dolphins, longitude plays a more prominent role in determining their weight. This distinction suggests that varying environmental or operational factors are at play depending on whether the focus is on the number or the size of dolphins caught as bycatch.



Graph 43: The horizontal bar chart illustrates the SHAP values, indicating the impact of each feature on the model's output for predicting DTW. Longitude ('Long') has a higher SHAP value, indicating a stronger influence on the model's predictions compared to Latitude ('Lat'). The SHAP values quantify the contribution of each feature to the model's output, highlighting that Longitude plays a more critical role in determining DTW than Latitude

Clustering and Heatmaps

K-Means clustering

The cluster analysis graph presents the results of a K-means clustering method applied to geographical data, categorizing data points based on their latitude and longitude into three distinct clusters. This analysis provides insights into the spatial distribution of DTN and DTW across different regions (Table 10).

Cluster 1 Results:

Cluster 1 is centered around coordinates 23.34°N latitude and 65.86°E longitude and comprises 48 data points. This cluster is characterized by a mean Dolphin Total Number (DTN) of 1.08, indicating that, on average, one dolphin is recorded per observation in this area. The mean Dolphin Total Weight (DTW) for this cluster is 26.02, suggesting a moderate distribution of weights. The DTN within this cluster ranges from 0 to 5, reflecting variability in the number of dolphins per observation, while the DTW spans from 0 to 200, indicating a broad range of dolphin sizes in this region.

Cluster 2 Results:

Cluster 2 is centered around 24.75°N latitude and 65.16°E longitude and includes 74 data points. This cluster has a slightly lower mean DTN of 0.95, suggesting that fewer dolphins are typically recorded per observation compared to Cluster 1. However, the mean DTW is higher at 35.95, indicating that dolphins in this region are generally larger on average. The range of DTN in this cluster is narrower, from 0 to 3, showing less variability in dolphin numbers. In contrast, the DTW ranges widely from 0 to 300, reflecting significant variation in dolphin sizes, with some individuals being particularly large.

Cluster 3 Results:

Cluster 3 is centered around 24.35°N latitude and 66.96°E longitude and consists of 50 data points. This cluster has a mean DTN of 1.1, slightly higher than the other clusters, indicating a comparable number of dolphins per observation as in Clusters 1 and 2. However, the mean DTW is considerably lower at 6.44, suggesting that dolphins in this region are generally smaller. The DTN in this cluster ranges from 0 to 4, showing moderate variability in dolphin numbers, while the DTW ranges from 0 to 95, indicating more consistency in dolphin size compared to the other clusters.

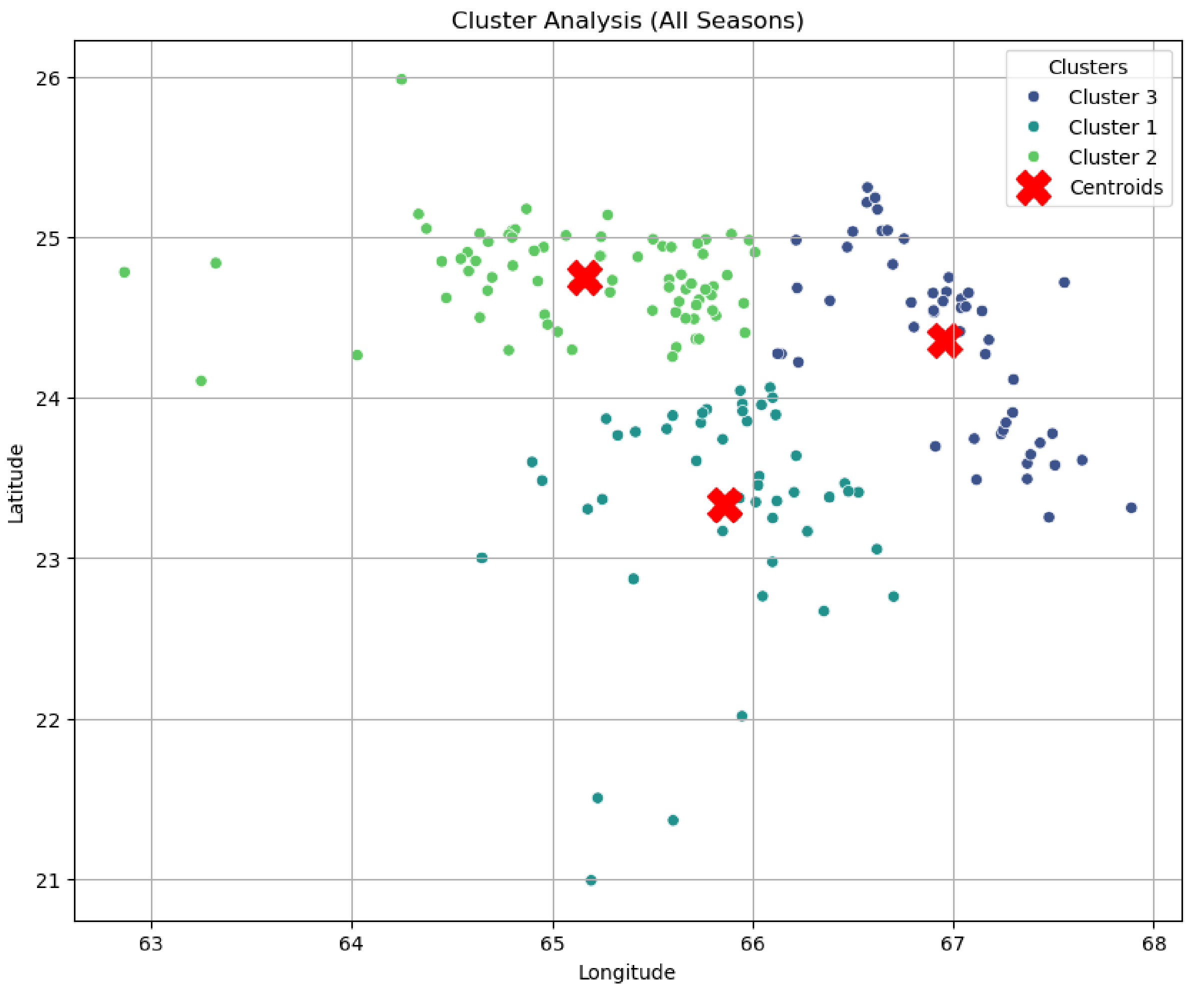
Cluster	Centroid Location (Latitude, Longitude)	Number of Points	Mean DTN	DTN Range	Mean DTW (kg)	DTW Range (kg)
Cluster 1	23.34°N, 65.86°E	48	1.08	0.0 to 5.0	26.02	0.0 to 200.0
Cluster 2	24.75°N, 65.16°E	74	0.95	0.0 to 3.0	35.95	0.0 to 300.0
Cluster 3	24.35°N, 66.96°E	50	1.10	0.0 to 4.0	6.44	0.0 to 95.0

Table 10: This table provides a clear comparison of the three clusters in terms of their geographical locations, the number of data points they contain, and the statistical measures related to Dolphin Total Number (DTN) and Dolphin Total Weight (DTW).

The cluster analysis reveals distinct geographical patterns in the distribution of dolphins, characterized by variations in both their numbers and sizes across different regions (Graph 44).

- **Cluster 1:** Centered in the southern region, this cluster shows a moderate number of dolphins with a wide range of sizes, reflecting a diverse dolphin population in this area.
- **Cluster 2:** Located in the central region, this cluster exhibits fewer dolphins per observation but significantly larger sizes, suggesting that this area may attract larger individuals or groups of dolphins.
- **Cluster 3:** Situated in the northeastern part of the study area, this cluster indicates slightly higher dolphin numbers but much smaller sizes, which may be influenced by distinct environmental conditions or ecological factors specific to this region.

Overall, these clusters demonstrate considerable variability in both the number and size of dolphins across different regions, with Cluster 2 being particularly notable for its larger average dolphin size. These insights can guide targeted conservation strategies by focusing on regions where specific patterns in dolphin populations are observed.



Graph 44: The scatter plot visualizes the clustering of bycatch events based on latitude and longitude, with different colors representing distinct clusters identified through the analysis. The red 'X' marks denote the centroids of each cluster, indicating the central points around which each group of data points is concentrated. This clustering reveals spatial patterns and potential hotspots of dolphin bycatch across the studied region.

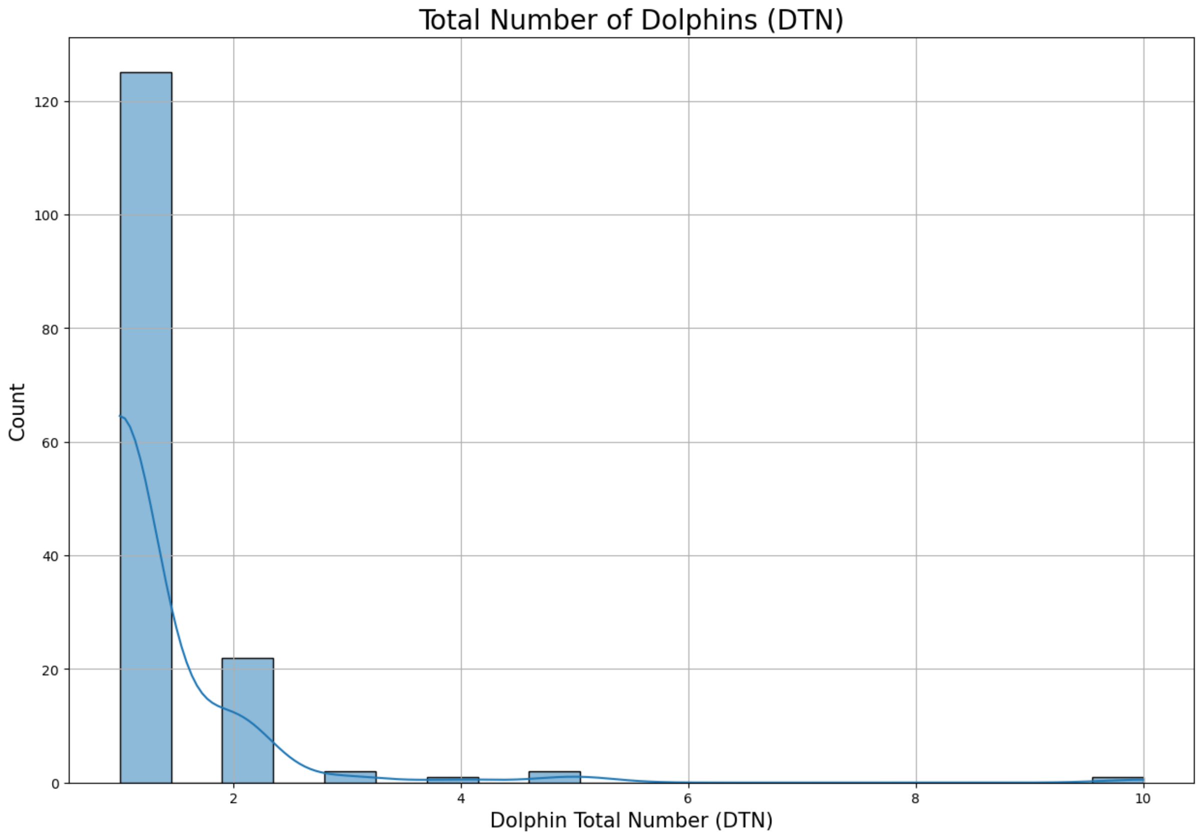
Spatial-Temporal Analysis Based on the Fishing Methods

Analysis of Dolphin Bycatch

The analysis of dolphin bycatch in the tuna gillnet fisheries of Pakistan integrates both temporal trends and spatial distribution to provide a comprehensive understanding of bycatch dynamics across various fishing methods. This integrated approach is crucial for informing fisheries management and dolphin conservation strategies by identifying both the timing and locations where bycatch events are most frequent.

Distribution of Dolphin Total Number (DTN):

The histogram illustrates the distribution of the DTN recorded across different instances in the dataset (Graph 45). The majority of observations report a DTN of 0 or 1, indicating that, in most cases, no dolphins or only a single dolphin were observed or caught. As the DTN increases, there is a marked decline in the frequency of observations, suggesting that larger numbers of dolphins are rarely recorded. The histogram displays a long tail with very few instances of DTN values above 2, and almost negligible occurrences beyond 5, emphasizing that large aggregations of dolphins are seldom encountered. The Kernel Density Estimate (KDE) line further supports this trend, showing a steep decline after DTN values of 1 or 2. Overall, the results suggest that encounters involving larger numbers of dolphins are uncommon, with most observations involving either no dolphins or just one.



Graph 45: The graph shows the distribution of the total number of dolphins observed or caught per observation. The majority of observations have low DTN values (0 or 1), with a rapid decline in frequency as DTN increases, indicating that higher counts of dolphins are rare in this dataset

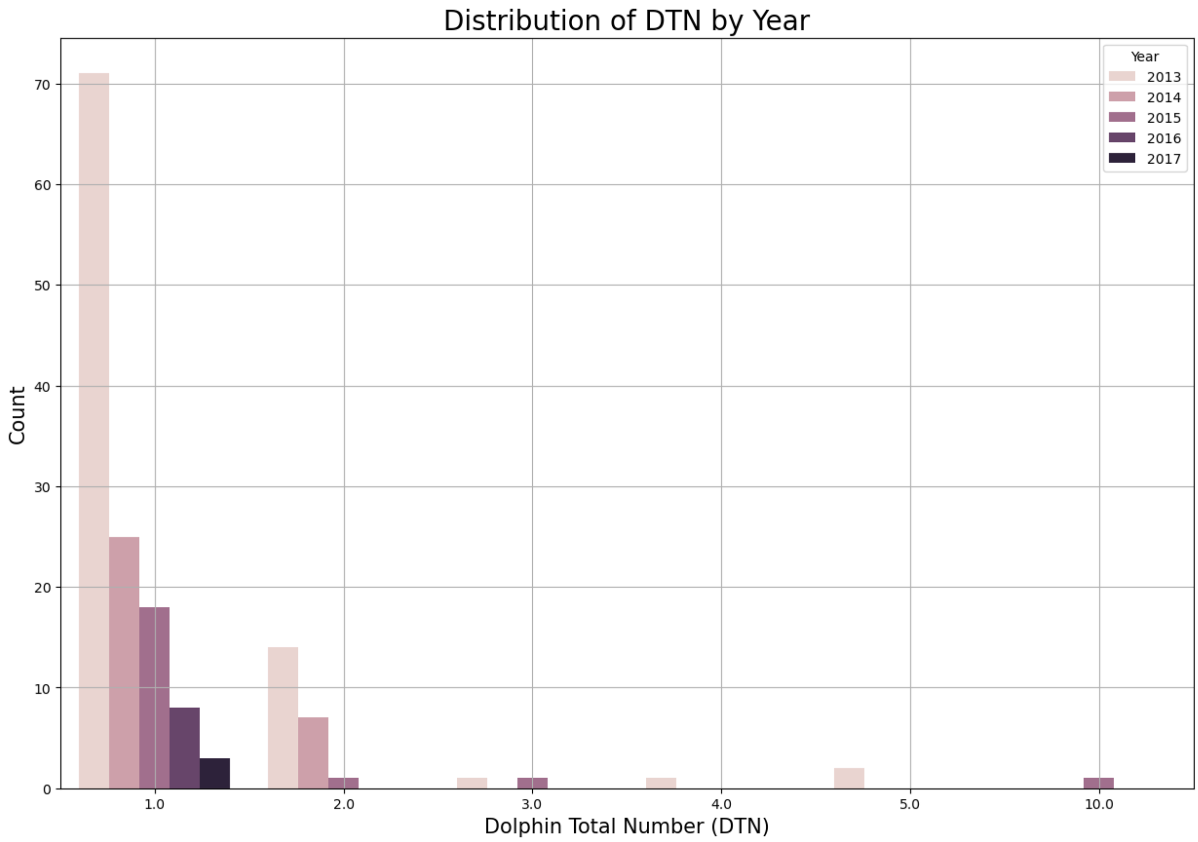
Inter-Annual Distribution of Dolphin Total Number (DTN) Observations

The results reveal a consistent pattern across all years, where most observations have a DTN of 1, indicating that the majority of recorded instances involve only a single dolphin (Graph 46). Notably, 2013 had the highest frequency of observations with DTN values of 1, suggesting more frequent dolphin encounters were recorded that year compared to subsequent years. This is followed by 2014 and 2015, which also show considerable frequencies for DTN values of 1, though at slightly lower levels. The later years, 2016 and 2017, display a similar pattern but with a further reduction in the number of observations.

As DTN values increase beyond 1, the frequency of observations decreases sharply each year. This steep decline indicates that encounters involving larger numbers of dolphins are relatively rare. For example, DTN values of 2 are much less frequent than those of 1, and values of 3 and above are seldom recorded across all years. The graph also shows that in certain years, such as 2013, there are a few instances of DTN values of 4 and 5, but these remain relatively infrequent. An outlier is observed in 2014 with a DTN value of 10, underscoring that sightings of such large groups are exceptionally rare.

There is also noticeable inter-annual variation in the number of observations with higher DTN values. For instance, while 2013 and 2014 have slightly more observations with DTN values above 2, the later years, 2016 and 2017, show almost none. This trend could suggest changes in either observation effort or fishing practices that may have influenced dolphin presence.

The graph highlights that most dolphin encounters involve just one or two individuals, with a rapidly declining frequency for higher counts. The distribution is skewed towards lower DTN values across all years, indicating that large groups of dolphins are seldom encountered. This consistency across years suggests a stable pattern of dolphin presence or bycatch in the recorded area over time, with some fluctuations possibly related to specific conditions or changes in observational coverage.



Graph 46: The graph shows the distribution of the Dolphin Total Number (DTN) by year from 2013 to 2017. The x-axis represents the DTN values, while the y-axis shows the count of observations for each DTN value. The data is further grouped by year, as indicated by different colors for each bar, with the legend showing years from 2013 to 2017

Distribution of Dolphin Total Number (DTN) by Fishing Method

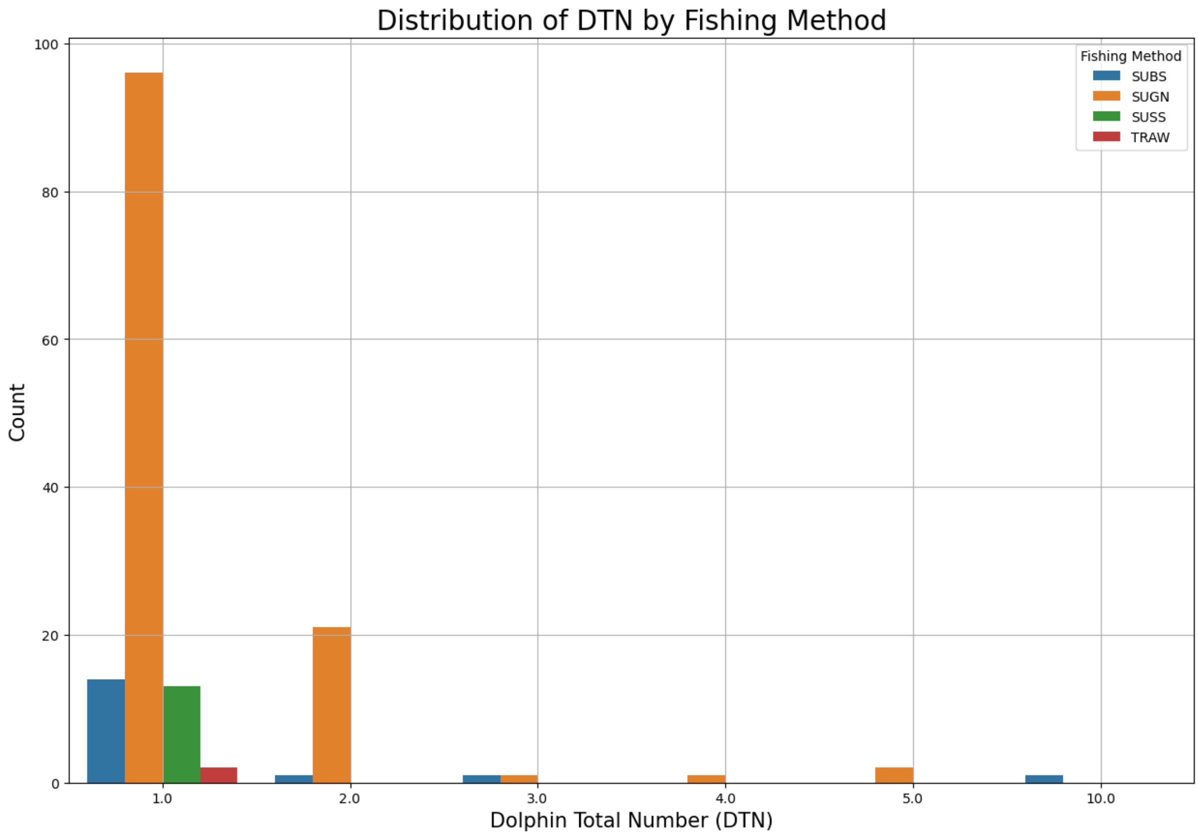
The analysis reveals notable differences in the distribution of dolphin encounters across various fishing methods (Graph 47). The Surface Gillnet (SUGN) method exhibits the highest number of observations where the DTN is 1, indicating that single-dolphin encounters are most frequent with this fishing method. SUGN also shows the highest number of observations with DTN equal to 2, suggesting a relatively higher incidence of dolphin encounters compared to other methods.

For the Sub-Surface (SUBS) and Surface/Sub-Surface (SUSS) fishing methods, most observations also have a DTN value of 1, but their frequencies are considerably lower than those observed with SUGN. This suggests that while single-dolphin encounters are common across different fishing methods, they are more frequent when surface gillnets are used. There are a few instances of DTN values of 2 for SUBS and SUSS, but these remain quite low, indicating fewer encounters involving multiple dolphins.

The Trawling (TRAW) method shows the lowest number of observations for all DTN values. The limited data points for TRAW suggest that this method either encounters dolphins less frequently or is less commonly employed or monitored within the dataset. Regarding the Bottom Set Gillnet (BSGN) method, the data is either absent or not represented in this specific visualization.

Interestingly, the data shows only a few instances where DTN values exceed 2 across all fishing methods. There are rare occurrences of DTN values of 3, 4, 5, and 10, mostly associated with the SUGN and SUBS methods. These higher DTN values suggest that encounters involving larger numbers of dolphins are exceptional cases and occur sporadically, emphasizing that dolphin bycatch is generally low across all fishing methods.

Overall, the results suggest that the Surface Gillnet (SUGN) method has a higher likelihood of encountering dolphins, predominantly involving observations of one or two dolphins. Conversely, other methods, particularly TRAW, show fewer encounters, highlighting potential differences in bycatch patterns or fishing practices among these methods. These findings underscore the need for further investigation into the fishing practices, environmental conditions, and gear types that may influence dolphin bycatch rates across different methods.



Graph 47: The graph shows the distribution of the Dolphin Total Number (DTN) by different fishing methods: Bottom Set Gillnet (BSGN), Sub-Surface (SUBS), Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), and Trawling (TRAW). The x-axis represents the DTN values ranging from 1 to 10, while the y-axis indicates the count of observations for each DTN value. Each bar is color-coded to represent different fishing methods, as indicated by the legend.

Temporal Trends in Dolphin Total Number (DTN) Encounters Across Different Fishing Methods

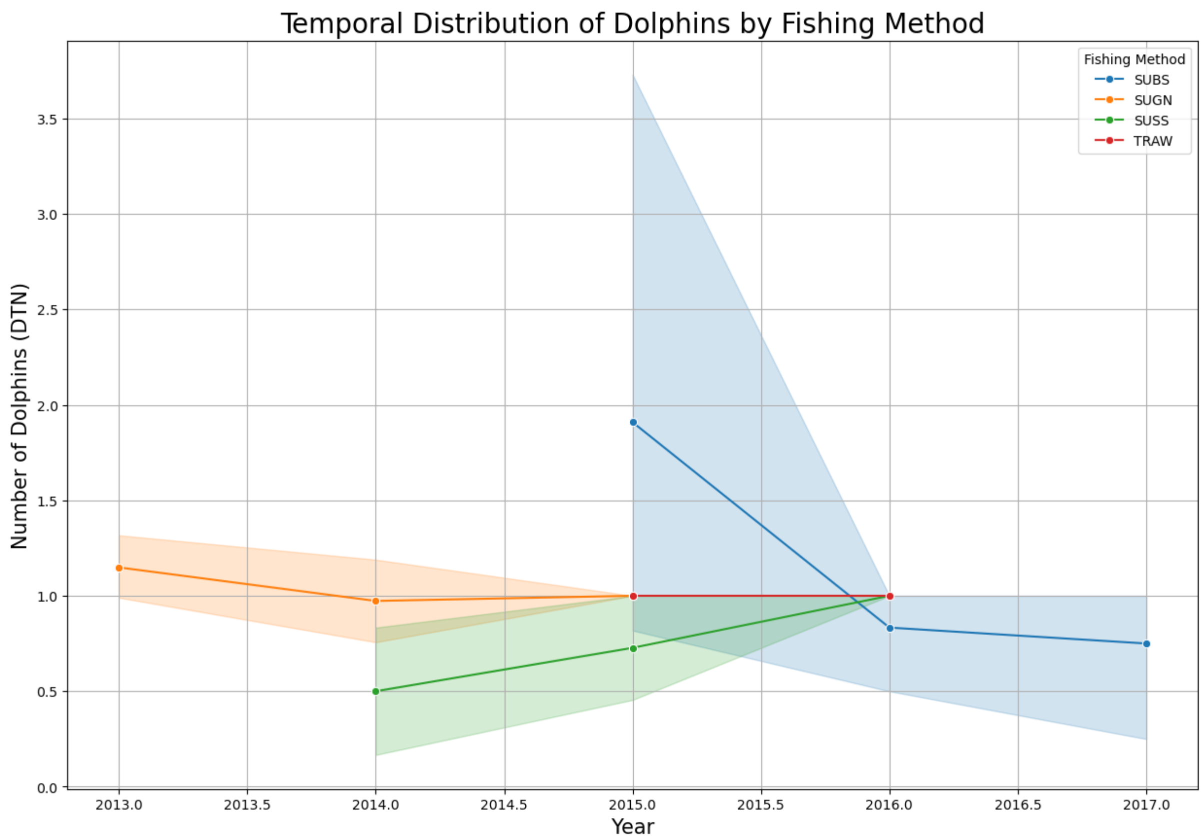
The analysis reveals distinct temporal trends in dolphin encounters for each fishing method over the years (Graph 48). The Sub-Surface (SUBS) fishing method demonstrates a declining trend in dolphin encounters over the five-year period. Starting with an average DTN slightly above 1 in 2013, the encounters gradually decreased to below 1 by 2017. The wide confidence interval in the earlier years suggests significant variability in dolphin encounters, indicating that some years experienced higher-than-average dolphin catches or sightings, while others had much lower numbers. By 2017, the confidence interval narrowed, reflecting more consistent observations of low dolphin encounters using this method.

The Surface Gillnet (SUGN) method shows a relatively stable pattern of dolphin encounters from 2013 to 2017. The average DTN starts slightly above 1 in 2013 and remains around that value throughout the period, indicating that most encounters involve single dolphins. Although there is a slight decline from 2013 to 2017, the overall trend remains relatively flat. The narrow confidence intervals around the SUGN line suggest low variability, indicating that the number of dolphins encountered with this method did not fluctuate significantly over the years.

In contrast, the Surface/Sub-Surface (SUSS) fishing method exhibits a gradual increase in dolphin encounters over time. The DTN starts below 1 in 2013 and steadily rises to just above 1 by 2017. This upward trend suggests a gradual increase in dolphin encounters or catches over the years when using this method. The relatively broad confidence intervals indicate some variability in the number of dolphins encountered, but the overall trend is upward, pointing to more frequent dolphin encounters with the SUSS method.

The Trawling (TRAW) method displays a flat trend, with an average DTN value consistently around 1 from 2013 to 2017. This stability indicates no significant changes in the number of dolphins encountered over time when using trawling as a fishing method. The narrow confidence interval for the TRAW line suggests minimal variability in dolphin encounters, implying a consistent pattern of low dolphin presence or bycatch with this method.

The results highlight distinct temporal trends in dolphin encounters associated with different fishing methods. The declining trend for SUBS and the increasing trend for SUSS suggest varying factors influencing dolphin encounters, such as changes in fishing practices, environmental conditions, or spatial distributions of dolphins. In contrast, the stability observed with SUGN and TRAW suggests a more consistent pattern of dolphin presence or bycatch, potentially indicating fewer changes in fishing operations or environmental influences over time.



Graph 48: The graph presents the Temporal Distribution of Dolphins by Fishing Method from 2013 to 2017, showing the average number of dolphins (DTN) observed or caught using different fishing methods over time. The x-axis represents the years, and the y-axis shows the average number of dolphins (DTN). Each line represents a different fishing method: Sub-Surface (SUBS), Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), and Trawling (TRAW), as indicated by the legend. The shaded regions around each line represent the confidence intervals, indicating the variability of dolphin encounters over time.

Spatial Patterns of Fishing Activity and Dolphin Total Number (DTN) Encounters by Fishing Method

The analysis reveals that the majority of fishing activity is concentrated within a relatively confined area, centered around latitudes 24° to 25–26° and longitudes 64° to 66° (Graph 49). This concentration suggests that fishing vessels predominantly operate within these coordinates, likely targeting productive fishing grounds. The clustering of fishing tracks indicates these are the areas where dolphins are most frequently encountered or caught, as these routes represent the movement of fishing vessels that have recorded dolphin bycatch.

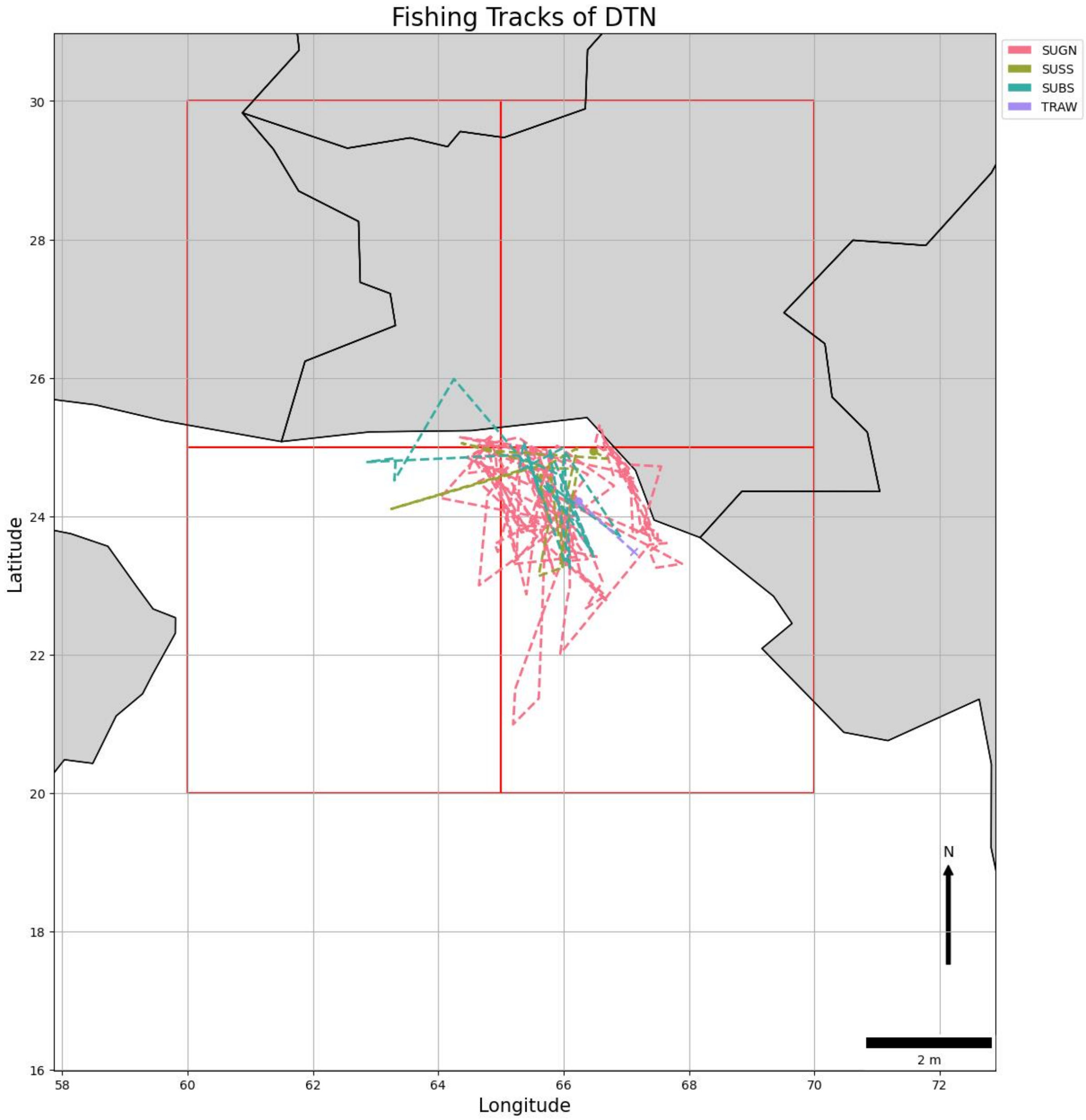
The Surface Gillnet (SUGN) method, depicted by red tracks, shows a dense cluster of fishing activity within latitudes 24.0° to 25.5° and longitudes 64.5° to 66.0°. The high density of SUGN tracks in this area suggests intensive fishing efforts along these routes, which are likely favored for their effectiveness in targeting specific species but also result in frequent dolphin encounters. The overlap of intensive SUGN use in these locations indicates a higher likelihood of dolphin bycatch due to concentrated fishing efforts.

The Surface/Sub-Surface (SUSS) method, represented in green, shows a similar pattern of fishing tracks but with slightly greater dispersion compared to SUGN. The SUSS tracks are primarily concentrated between latitudes 24.0° to 25.5° and longitudes 64.0° to 66.0°, suggesting overlapping fishing grounds with SUGN. The broader distribution of SUSS tracks may indicate a more adaptable fishing strategy, potentially targeting different species or adjusting routes to avoid areas with higher dolphin bycatch. The spatial overlap with SUGN tracks reflects shared fishing grounds between these methods.

The Sub-Surface (SUBS) method, represented by blue tracks, shows a somewhat broader pattern than SUSS, extending between latitudes 23.5° to 25.5° and longitudes 64.0° to 65.5°. This distribution suggests that vessels employing the SUBS method may explore a wider area compared to surface methods, possibly in search of specific species or to avoid areas with known higher dolphin bycatch. The wider spread of SUBS tracks indicates varied strategies or operational adjustments that may influence the spatial distribution of dolphin encounters.

The Trawling (TRAW) method, depicted in purple, exhibits the most dispersed pattern among the fishing methods, covering latitudes 23.0° to 26.0° and longitudes 64.0° to 66.5°. The widespread nature of TRAW tracks implies that trawling vessels may operate over larger areas or employ more flexible fishing strategies. This broader spatial coverage could be attributed to targeting different species, responding to environmental conditions, or following seasonal fish migrations, potentially resulting in varying dolphin bycatch rates. The dispersed pattern of TRAW tracks suggests a distinct operational approach compared to the more concentrated methods like SUGN and SUSS.

The map highlights significant spatial overlap in fishing activities across all methods, particularly within latitudes 24° to 26° and longitudes 64° to 66°, which appear to be critical fishing grounds. This overlap suggests that these regions are essential for fishing but also represent areas with a higher likelihood of dolphin encounters or bycatch. Understanding these spatial patterns and the specific latitude and longitude ranges associated with each fishing method is vital for developing targeted management and conservation strategies. Such strategies may include spatial closures, gear modifications, or regulation of fishing efforts in high-risk zones to minimize dolphin bycatch while promoting sustainable fishing practices.



Graph 49: The map presents the Fishing Tracks of Dolphin Total Number (DTN) for various fishing methods, plotted against geographic coordinates (longitude and latitude). Each line represents the movement and fishing paths taken by vessels using different fishing methods: Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), Sub-Surface (SUBS), and Trawling (TRAW). The map provides a spatial overview of the fishing activity in a specific marine area, with colored dashed lines showing the tracks associated with each fishing method. The red gridlines on the map likely represent specific management zones or grid cells for spatial analysis.

Spatial Analysis of Dolphin Total Number (DTN) Encounter Hotspots by Fishing Method

The spatial analysis identifies a significant hotspot for dolphin encounters concentrated in the region around latitudes 24° to 25° and longitudes 64° to 66° (Graph 50). This area appears to be a focal point for dolphin bycatch, likely due to concentrated fishing activities, favorable environmental conditions, or the overlap of dolphin habitats with targeted fish species. The overlapping density contours for various fishing methods in this region indicate that all fishing methods encounter higher dolphin bycatch rates within this zone, making it a critical area for understanding and managing dolphin bycatch risk.

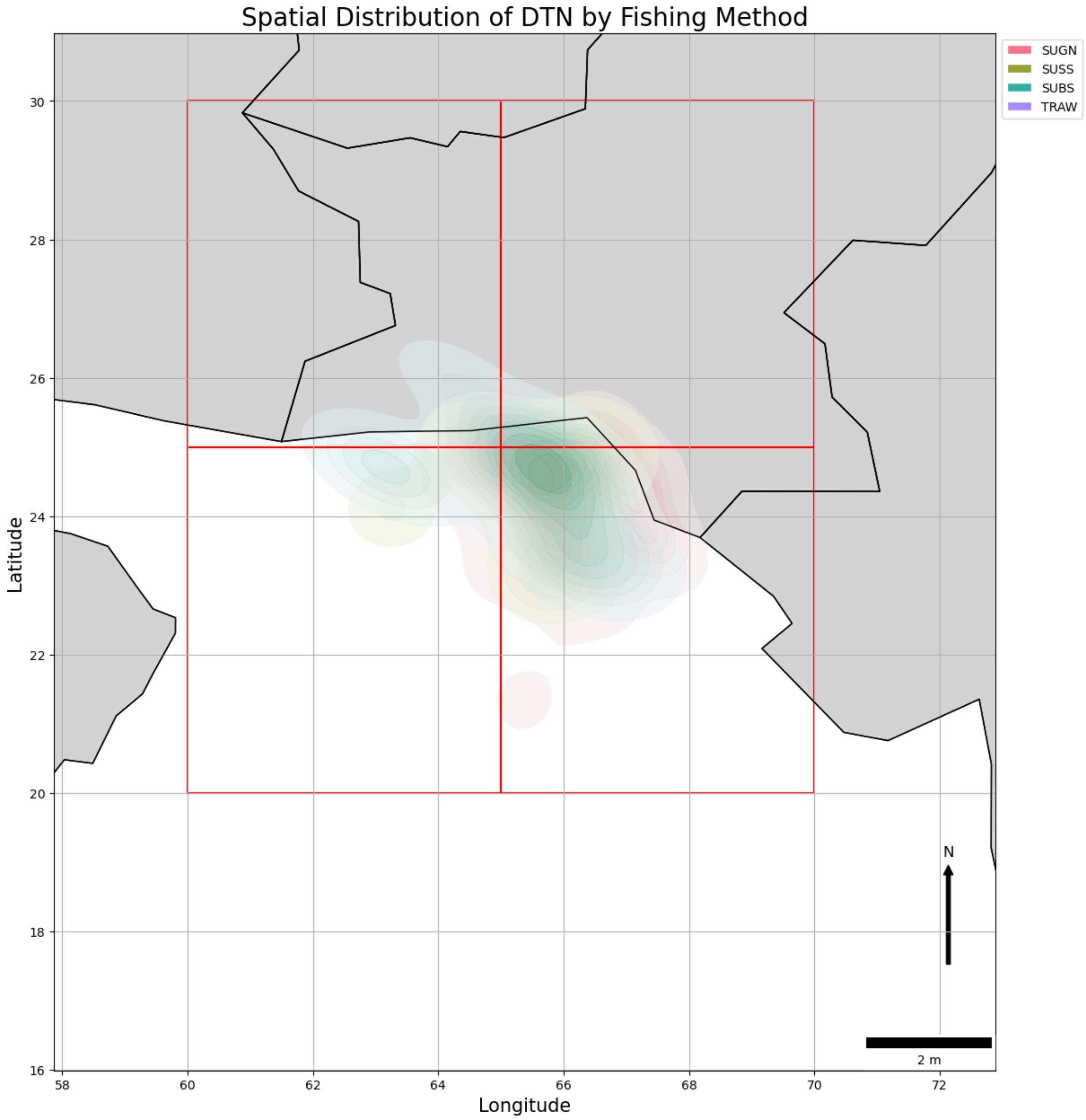
For the Surface Gillnet (SUGN) method, represented by red density contours, a high concentration of dolphin encounters is observed between latitudes 24.0° to 25.0° and longitudes 64.5° to 66.0°. This dense concentration suggests intensive deployment of surface gillnets in these waters, where fishing activities coincide with dolphin presence. The intense red shading in this area indicates that SUGN fishing frequently overlaps with high dolphin density zones, making this a key area for targeted management measures to mitigate bycatch risks associated with this method.

The Surface/Sub-Surface (SUSS) method, depicted in green, also shows significant densities of dolphin encounters within a similar range of latitudes, from 24.0° to 25.0°, and longitudes, from 64.0° to 65.5°. However, the density for SUSS is slightly more dispersed compared to SUGN, suggesting a broader fishing range or alternative fishing strategies that still result in dolphin bycatch. The considerable overlap of green contours with red contours indicates that both surface and sub-surface fishing methods operate within overlapping grounds characterized by notable dolphin activity.

The Sub-Surface (SUBS) method, represented by blue density contours, exhibits a slightly more extensive pattern, spanning latitudes 23.5° to 25.5° and longitudes 64.0° to 65.0°. This broader spread implies that sub-surface fishing may cover a wider area or involve different fishing grounds compared to the more concentrated SUGN and SUSS methods. Despite the wider spatial coverage, there is still a notable concentration of dolphin encounters within the core area, indicating frequent dolphin bycatch even with the SUBS method.

The Trawling (TRAW) method, illustrated by purple contours, shows less concentrated but still notable densities within the same general area. The TRAW density contours extend more towards the periphery, covering latitudes 23.5° to 25.5° and longitudes 64.0° to 66.0°. This pattern suggests that trawling vessels may operate over a broader area or adapt their routes more flexibly, possibly to follow fish migrations or avoid zones with higher dolphin presence. The overlap of TRAW density with other fishing methods highlights shared high-risk areas where dolphins are more likely to be encountered.

The spatial distribution of dolphin encounters across different fishing methods highlights a critical hotspot for dolphin bycatch between latitudes 24° to 25° and longitudes 64° to 66°. This zone is marked by substantial overlap of high-density contours for multiple fishing methods, indicating that these waters are key fishing grounds but also areas with significant dolphin presence. The findings underscore the necessity for targeted management interventions, such as spatial closures, gear modifications, or changes to fishing practices, to reduce dolphin bycatch in these high-risk areas. Understanding these spatial patterns is vital for formulating effective conservation strategies that balance sustainable fishing with dolphin conservation.



Graph 50: The map illustrates the Spatial Distribution of Dolphin Total Number (DTN) by Fishing Method in a specific marine area, highlighting the density of dolphin encounters (bycatch) associated with different fishing methods. The x-axis represents longitude, while the y-axis represents latitude, giving a geographic context to the fishing activities. The colored contours on the map represent the density of dolphin encounters for each fishing method: Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), Sub-Surface (SUBS), and Trawling (TRAW). The density contours indicate where dolphins are more frequently encountered or caught, with more intense colors showing higher densities.

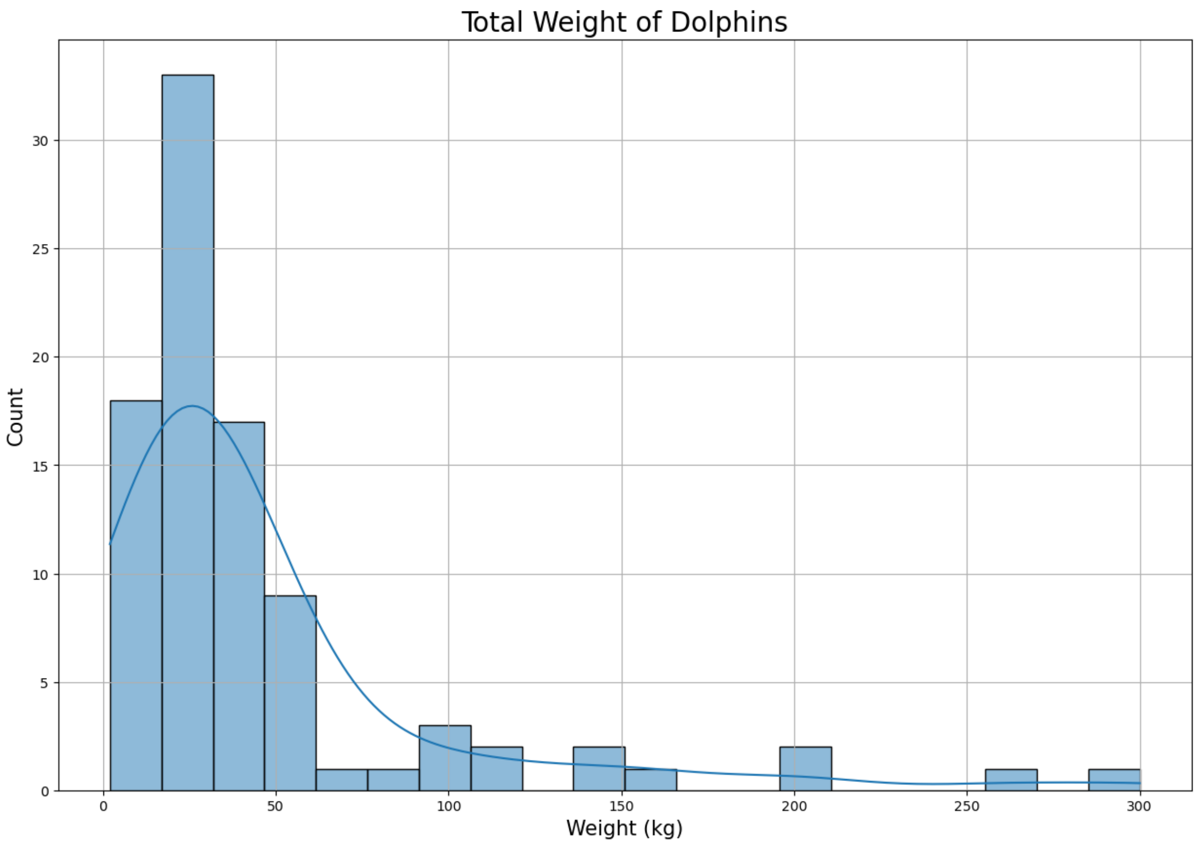
Distribution of Dolphin Total Weights (DTW)

The analysis reveals that the majority of dolphin weights are concentrated in the lower weight range, particularly between 0 and 50 kg (Graph 51). This range exhibits the highest frequency of observations, with a peak around 30 kg, suggesting that most dolphins caught or observed weigh near this value. The steep increase in frequency for weights between 0 and 30 kg indicates that smaller dolphins, likely juveniles or smaller species, are more commonly encountered. This pattern may reflect the composition of dolphin populations in the study area or specific bycatch dynamics associated with prevailing fishing practices.

As dolphin weights exceed 50 kg, there is a marked decline in the frequency of observations. The histogram displays a sharp drop, indicating that dolphins weighing between 50 kg and 100 kg are considerably less common in the dataset. This trend is further confirmed by the Kernel Density Estimate (KDE) line, which shows a steep decrease following the initial peak, signifying that encounters with heavier dolphins are infrequent. The decline continues for dolphins weighing more than 100 kg, with only sporadic observations for weights above 150 kg.

A few instances of dolphins weighing over 150 kg and up to 300 kg are present, but these occurrences are extremely rare, as reflected by the low frequency bars toward the right end of the histogram. This long tail suggests that while the majority of dolphins caught or observed are relatively small, there are occasional encounters with significantly larger individuals. These larger dolphins could be adults of larger species or represent outlier events that occur infrequently.

Overall, the distribution of dolphin weights is skewed towards the lower end, with the majority of observations involving smaller dolphins. The steep decline in frequency for larger weights suggests that larger dolphins are not commonly caught or observed, possibly due to lower population numbers, different habitat preferences, or the nature of fishing gear and practices that more frequently result in the bycatch of smaller individuals. This distribution provides insights into the characteristics of dolphin populations in the area and underscores potential areas for management focus, such as mitigating the bycatch of smaller dolphins or investigating the factors contributing to the rare capture of larger individuals.



Graph 51: The graph illustrates the Total Weight of Dolphins caught or observed, represented by a histogram that shows the distribution of dolphin weights. The x-axis represents the weight of dolphins

in kilograms (kg), ranging from 0 to 300 kg, while the y-axis indicates the count or frequency of observations for each weight range. The superimposed line on the histogram is a Kernel Density Estimate (KDE) plot, which provides a smoothed representation of the distribution, highlighting the overall trend.

Inter-Annual Distribution of Dolphin Total Weight (DTW) Observations

The analysis reveals considerable variability in the distribution of dolphin weights across different years, with certain weight ranges more frequently observed than others (Graph 52). Overall, weights between 10 kg and 50 kg are the most commonly recorded across all years, with prominent peaks around 20 kg and 40 kg. These peaks suggest that dolphins within these weight ranges are frequently encountered or captured, potentially reflecting the prevalent sizes of dolphins in the area or the selectivity of the fishing gear employed.

In 2013, represented by light pink bars, the distribution of dolphin weights spans a broad range from 10 kg to around 100 kg, with some instances exceeding 100 kg. The highest concentrations are observed around 20 kg and 40 kg, suggesting a prevalence of smaller dolphins recorded in that year. The spread of weights indicates a diverse range of dolphin sizes encountered in 2013, possibly due to varied fishing practices or environmental conditions influencing dolphin presence.

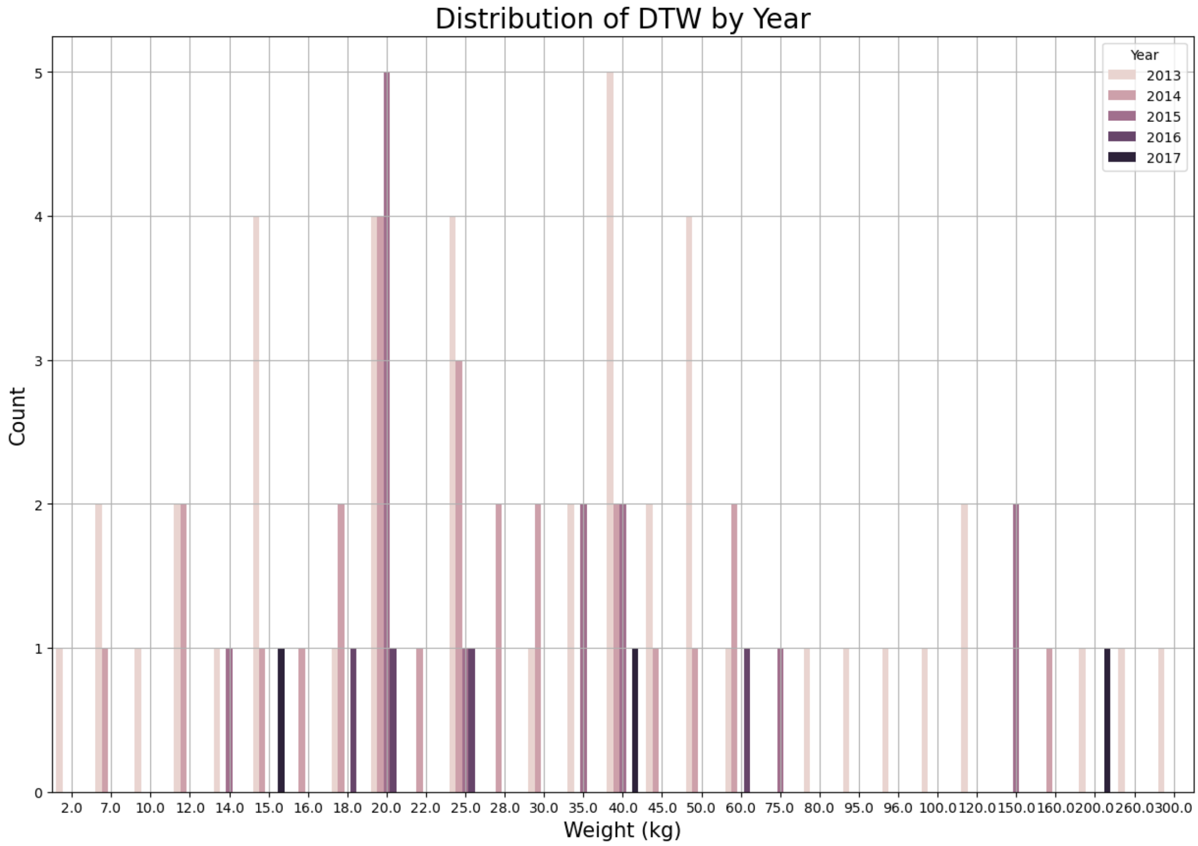
The data for 2014, depicted in a slightly darker pink shade, shows a similar pattern but with fewer overall observations compared to 2013. There remains a noticeable peak around 20 kg, indicating that this weight range continued to be commonly recorded. However, the range of weights observed in 2014 is narrower, suggesting changes in fishing effort, dolphin population composition, or other environmental factors affecting weight distribution.

For 2015, represented by a medium pink shade, the distribution exhibits a pronounced peak around 20 kg, with fewer observations at other weights. This suggests a more concentrated pattern of dolphin weights recorded during this year, possibly due to focused fishing activities in areas where smaller dolphins were prevalent or shifts in dolphin population dynamics.

In 2016, shown in a darker pink color, there is a more varied distribution with weights ranging from 10 kg to over 100 kg. However, the frequency of observations is generally lower, with occurrences spread across different weight ranges. This pattern implies that dolphin encounters were less frequent or that larger dolphins were occasionally captured.

The data for 2017, represented by the darkest shade, shows the broadest range of weights, from 10 kg to around 300 kg. Despite this wide range, the frequency of observations remains relatively low, with sporadic occurrences across different weight intervals. The presence of weights in the upper range suggests rare encounters with significantly larger dolphins during this year, likely reflecting outlier events or infrequent captures.

Overall, the graph illustrates inter-annual variability in recorded dolphin weights, with certain weight ranges, particularly around 20 kg and 40 kg, being more common. The differences in weight distributions across years indicate fluctuations in dolphin populations, fishing practices, or environmental conditions that influence the types and sizes of dolphins encountered.



Graph 52: The graph shows the Distribution of Dolphin Total Weight (DTW) by Year, highlighting the frequency of different dolphin weights recorded from 2013 to 2017. The x-axis represents the weight of dolphins in kilograms (kg), ranging from 2 kg to 300 kg, while the y-axis shows the count of observations for each weight. Each bar is color-coded according to the year, as indicated by the legend, allowing for a visual comparison of dolphin weights across different years.

Distribution of Dolphin Total Weight (DTW) by Fishing Method

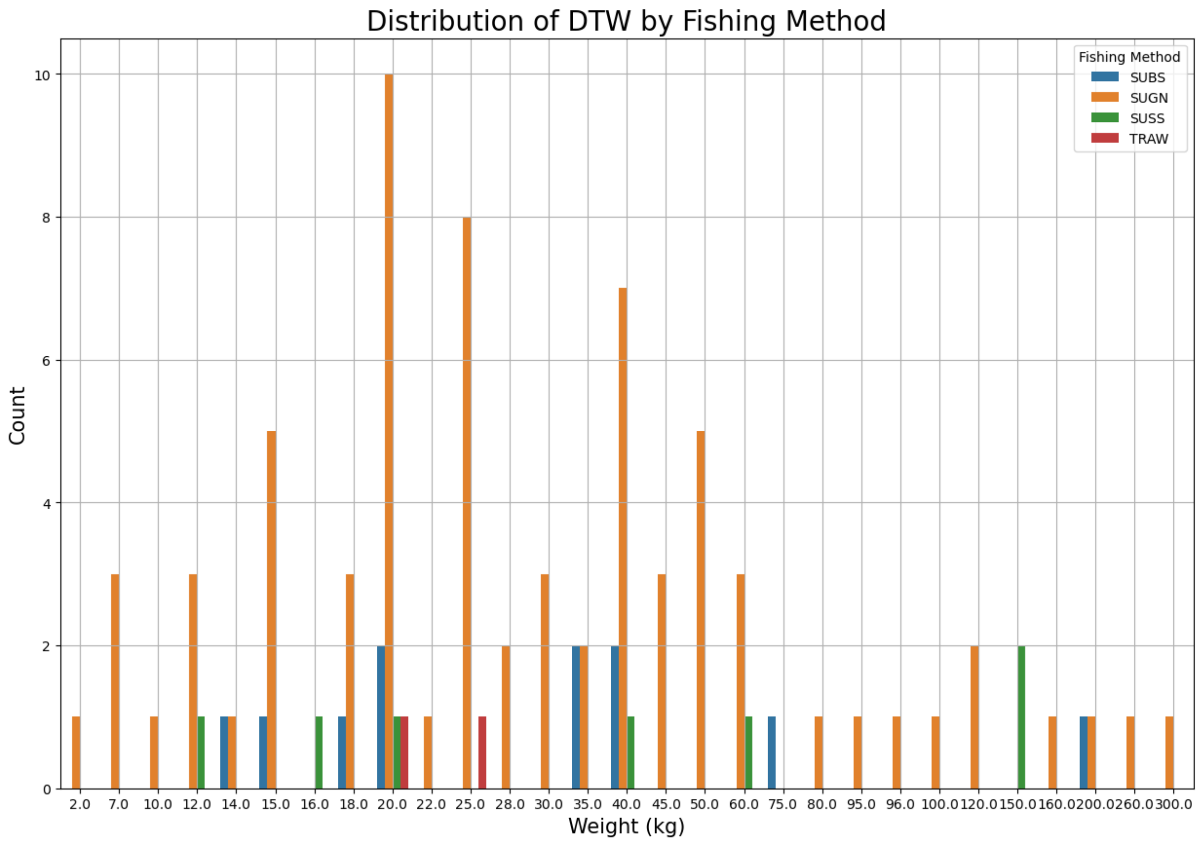
The analysis reveals distinct patterns in the distribution of DTW associated with different fishing methods (Graph 53). The Surface Gillnet (SUGN) method, depicted by orange bars, exhibits the highest number of observations and dominates the weight distribution across nearly all weight ranges. Prominent peaks are evident around 15 kg, 20 kg, 25 kg, and 40 kg, suggesting these weight ranges are more frequently recorded when using surface gillnets. The presence of multiple peaks indicates that SUGN captures a variety of dolphin sizes, with smaller dolphins, particularly those weighing between 15 kg and 40 kg, being the most commonly encountered. The high frequency of these weights suggests that the SUGN method is associated with higher dolphin bycatch rates, potentially due to its operational characteristics or the specific habitats it targets.

The Sub-Surface (SUBS) method, shown in blue, presents a more varied but less frequent distribution compared to SUGN. The weights recorded for SUBS range between 15 kg and 120 kg, with noticeable peaks around 35 kg, 40 kg, and 100 kg. The overall lower number of observations suggests that sub-surface fishing methods encounter dolphins less frequently than SUGN. However, the presence of weights up to 120 kg indicates that when dolphins are caught using SUBS, there is a possibility of encountering larger individuals. This distribution may reflect differences in fishing depth, gear selectivity, or specific areas targeted by the SUBS method.

The Surface/Sub-Surface (SUSS) method, illustrated in green, displays a pattern similar to that of SUBS but with even fewer observations. The recorded weights range from 10 kg to 150 kg, with peaks around 15 kg and 50 kg, and an outlier at 150 kg. This pattern suggests that while SUSS captures a range of dolphin sizes, the overall bycatch rates are lower, with occasional captures of larger dolphins. The dispersed distribution may indicate the versatility of the SUSS method, which operates at various depths or targets different species that overlap with dolphin habitats.

The Trawling (TRAW) method, represented in red, shows the fewest observations and a relatively narrow weight range, primarily between 10 kg and 40 kg. This limited distribution suggests that trawling methods have lower dolphin bycatch rates compared to gillnet methods. The peaks around 18 kg and 30 kg indicate that when dolphins are caught using trawling, they tend to be smaller. The low frequency and narrow weight range for TRAW may reflect a reduced interaction with dolphins or the use of more selective gear and practices that minimize bycatch.

Overall, the Surface Gillnet (SUGN) method has the highest frequency of dolphin bycatch across a broad range of weights, particularly for smaller dolphins. In contrast, the Sub-Surface (SUBS) and Surface/Sub-Surface (SUSS) methods show fewer dolphin encounters but a wider range of weights, including larger individuals. Trawling (TRAW) exhibits the lowest bycatch frequency and a limited weight range, indicating lower interaction rates with dolphins. These findings emphasize the need for targeted management strategies tailored to each fishing method to effectively mitigate dolphin bycatch, focusing on specific areas and practices where bycatch rates are highest.



Graph 53: The graph illustrates the Distribution of Dolphin Total Weight (DTW) by Fishing Method, showing how the weight of dolphins caught or observed varies across different fishing methods. The x-axis represents the weight of dolphins in kilograms (kg), ranging from 2 kg to 300 kg, while the y-axis shows the count of observations for each weight interval. The bars are color-coded by fishing method: Sub-Surface (SUBS), Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), and Trawling (TRAW), as

indicated by the legend. This allows for a comparison of dolphin bycatch weights across different fishing methods.

Temporal Trends in Dolphin Total Weight (DTW) Encounters Across Different Fishing Methods

The analysis of DTW encounters across various fishing methods reveals distinct temporal trends, reflecting different patterns of dolphin bycatch over time (Graph 54).

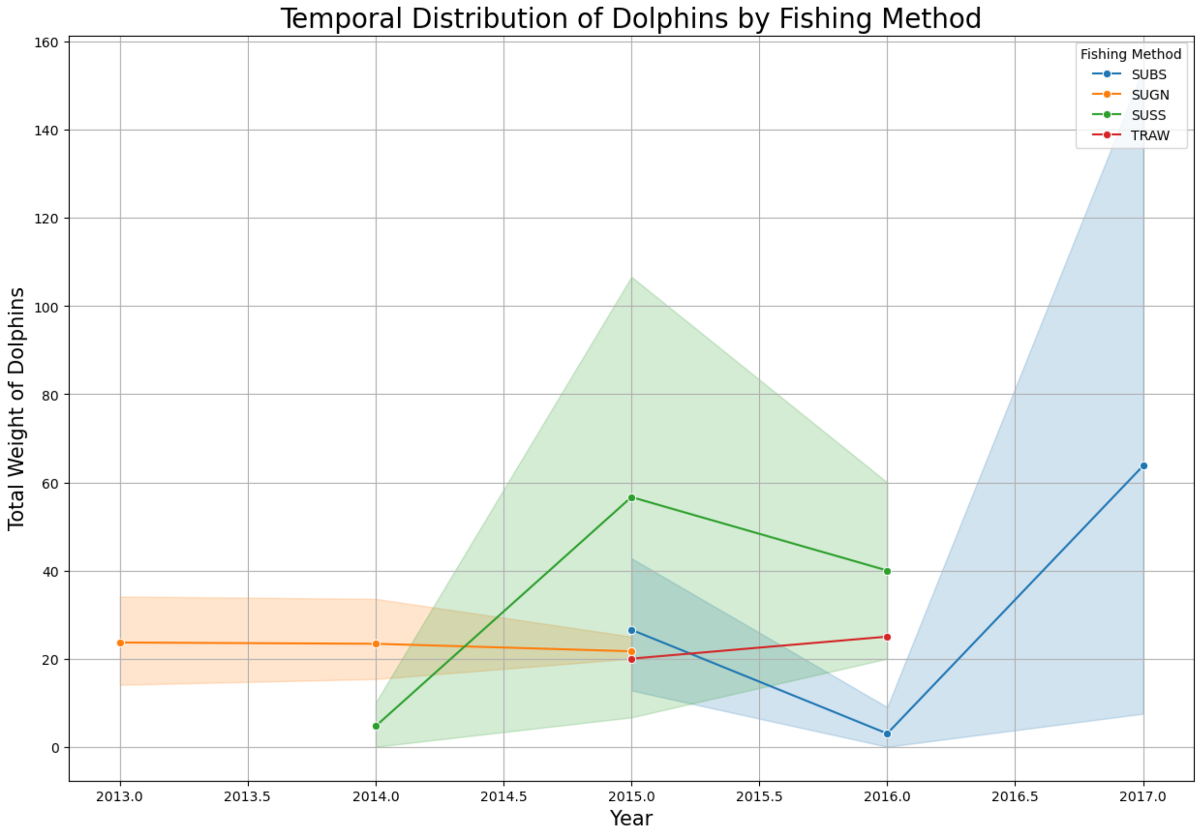
Sub-Surface (SUBS) Method: Represented by the blue line, the SUBS method exhibits a fluctuating trend in the total weight of dolphins caught from 2013 to 2017. Starting with a relatively low weight in 2013, there is a slight increase towards 2015, followed by a dip in 2016. This is succeeded by a sharp rise in 2017, reaching a peak that exceeds 150 kg. The substantial increase in 2017, accompanied by a wide confidence interval, suggests significant variability in the bycatch data for that year. Such variability could indicate sporadic encounters with larger dolphins in 2017, leading to a sudden spike in total weight. This pattern underscores the unpredictable nature of dolphin bycatch with the SUBS method, likely influenced by factors such as environmental conditions, fishing locations, or changes in gear types.

Surface Gillnet (SUGN) Method: Depicted by the orange line, the SUGN method shows a relatively stable trend in dolphin bycatch weight across all years from 2013 to 2017. The total weight consistently remains around 20 kg, with narrow confidence intervals indicating low variability. This steady trend suggests that the SUGN method consistently captures dolphins of similar sizes and numbers each year. The lack of significant changes over time implies steady fishing practices and stable environmental conditions that result in predictable bycatch rates for this method.

Surface/Sub-Surface (SUSS) Method: The SUSS method, shown by the green line, presents a more dynamic pattern. A notable increase in the total weight of dolphins is observed between 2014 and 2015, peaking around 100 kg. This is followed by a sharp decline in 2016, returning to levels similar to those in 2014. The significant rise in 2015 suggests that either more dolphins or larger individuals were caught using this method, contributing to the higher total weight for that year. The wide confidence intervals around the peak indicate high variability, which could be due to varying fishing efforts, changing environmental conditions, or isolated events involving large dolphin encounters.

Trawling (TRAW) Method: Represented by the red line, the TRAW method shows a consistent trend with minimal variation in the total weight of dolphins caught over the years. The total weight remains stable around 20 kg, with very narrow confidence intervals, reflecting steady and low levels of dolphin bycatch. This consistency suggests that the TRAW method employs more selective fishing practices or gear configurations that minimize dolphin encounters. The absence of significant fluctuations over time indicates that trawling has a predictable impact on dolphin populations, with no substantial changes in bycatch patterns.

The temporal trends in DTW across different fishing methods reveal diverse patterns of dolphin bycatch. The SUBS method shows considerable variability, especially in 2017, indicating sporadic high-weight bycatch events. In contrast, the SUGN method demonstrates consistent bycatch rates, while the SUSS method displays a distinct peak in 2015, highlighting potential annual variations in dolphin encounters. The TRAW method remains steady, reflecting lower and more controlled bycatch levels. These findings emphasize the need for method-specific management strategies to address the unique temporal dynamics of dolphin bycatch and mitigate its impact on dolphin populations.



Graph 54: The graph presents the Temporal Distribution of Dolphins' Total Weight (DTW) by Fishing Method from 2013 to 2017, showing how the total weight of dolphins caught or observed varies over time across different fishing methods. The x-axis represents the years from 2013 to 2017, while the y-axis shows the total weight of dolphins in kilograms (kg). Each line corresponds to a different fishing method: Sub-Surface (SUBS), Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), and Trawling (TRAW), as indicated by the legend. The shaded regions around each line represent the confidence intervals, reflecting the variability in the dolphin bycatch data over the years.

Spatial Patterns of Fishing Activity and Dolphin Total Weight (DTW) Encounters by Fishing Method

The spatial analysis of fishing activity and DTW encounters across different fishing methods reveals significant overlap in fishing activities within latitudes 24 to 25 and longitudes 64 to 66 (Graph 55). These areas emerge as critical fishing grounds where both DTN and DTW share the same geolocations, reflecting high-risk zones for dolphin interactions or bycatch.

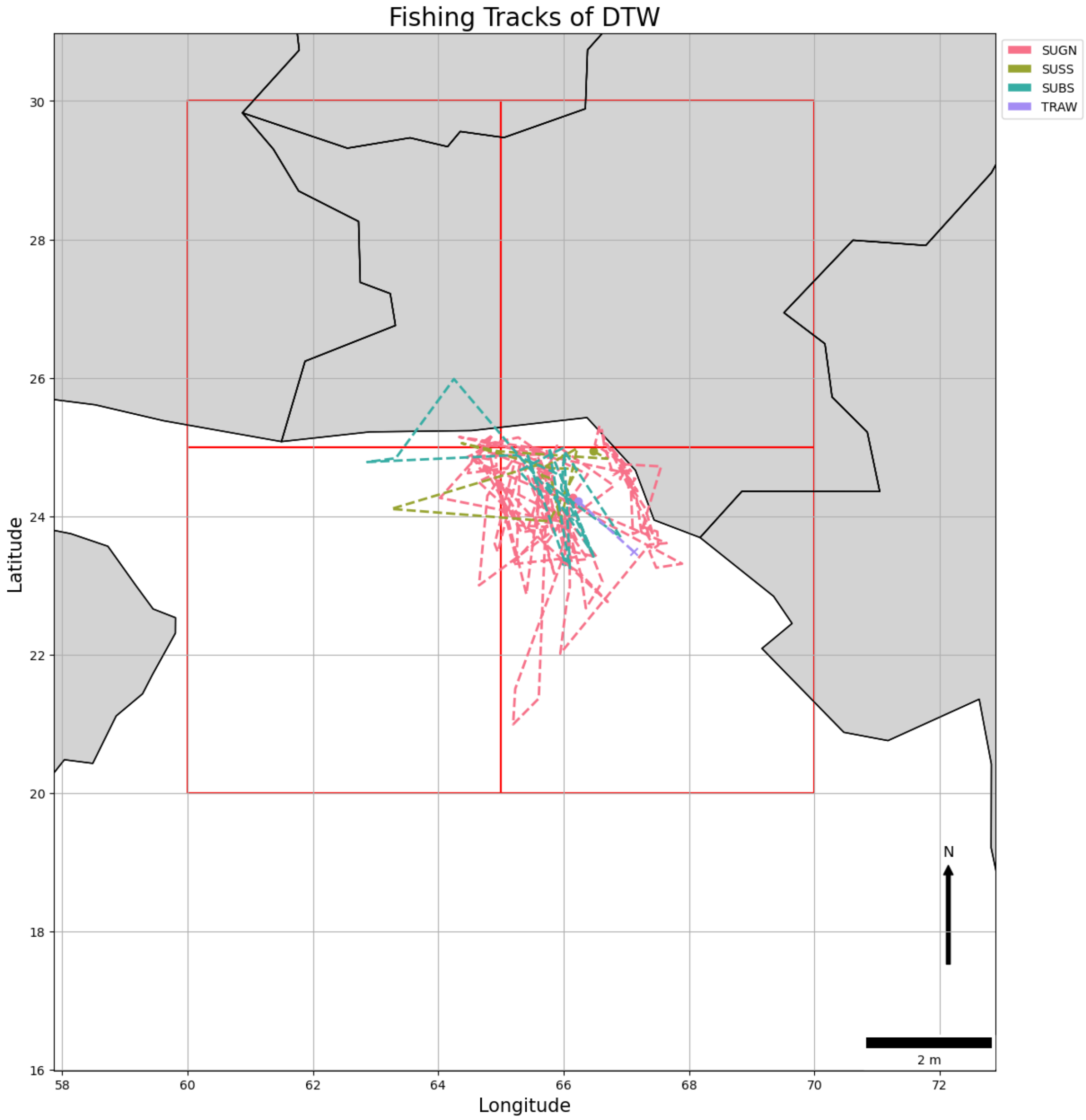
The results indicate that most fishing activities—and consequently, dolphin encounters—are concentrated within a relatively confined region centered around latitudes 24 to 25 and longitudes 64 to 66. This clustering suggests that fishing vessels primarily operate within these coordinates, likely targeting specific fishing grounds known for their productivity. The dense clustering of tracks within this central area indicates high fishing effort along these routes, where dolphin bycatch is frequently recorded. These identified hotspots signify potential risk areas that may require targeted management interventions to reduce dolphin bycatch.

Surface Gillnet (SUGN) Method: Represented by red tracks, the SUGN method shows a highly concentrated cluster of fishing activity between latitudes 24.0 to 25.5 and longitudes 64.5 to 66.0. The dense clustering of these tracks suggests intensive surface gillnet fishing operations in this zone, leading to frequent dolphin encounters. The overlapping red lines indicate repeated fishing trips along the same or similar routes, reflecting significant fishing pressure and higher dolphin bycatch rates in these locations. The concentration of SUGN tracks underscores the importance of these waters for this fishing method, but also highlights a considerable risk for dolphin bycatch due to the overlap with dolphin habitats.

Surface/Sub-Surface (SUSS) Method: Shown in green, the SUSS method displays a somewhat similar distribution pattern but is slightly more dispersed compared to SUGN. The SUSS tracks are primarily concentrated between latitudes 24.0 to 25.5 and longitudes 64.0 to 66.0, indicating overlapping fishing grounds with the SUGN method. The more spread-out pattern of green tracks may suggest a more variable fishing strategy, possibly targeting different species or attempting to avoid high bycatch areas. The overlap between SUSS and SUGN tracks suggests that both methods are employed within shared fishing grounds, which are critical for both fishing productivity and dolphin encounters.

Sub-Surface (SUBS) Method: Depicted by blue tracks, the SUBS method shows a slightly broader spatial pattern than SUSS, covering latitudes 23.5 to 25.5 and longitudes 64.0 to 65.5. This wider distribution suggests that vessels employing sub-surface methods may explore a broader area compared to surface methods, potentially searching for specific target species or aiming to minimize dolphin bycatch. The broader spread of blue tracks implies variability in fishing operations and a potential for encountering larger dolphins, which may inhabit deeper waters than those targeted by surface methods.

Trawling (TRAW) Method: Represented by purple tracks, the TRAW method exhibits the most dispersed pattern among all fishing methods, spanning latitudes 23.0 to 26.0 and longitudes 64.0 to 66.5. The widespread nature of TRAW tracks indicates that trawling vessels may operate over larger areas or adapt their routes more flexibly, potentially to follow fish migrations or avoid zones of high dolphin presence. The distribution of these tracks suggests a different operational approach compared to the more concentrated methods like SUGN and SUSS, reflecting varying target species, fishing techniques, or strategies that may influence dolphin bycatch rates.



Graph 55: The graph shows the Fishing Tracks of Dolphin Total Weight (DTW) for various fishing methods plotted against geographic coordinates (longitude and latitude). Each colored dashed line represents the movement and fishing paths taken by vessels using different fishing methods: Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), Sub-Surface (SUBS), and Trawling (TRAW). The tracks are color-coded for easy identification, with the legend indicating the corresponding fishing method. The red gridlines on the map may represent specific management zones or grid cells for spatial analysis. This visualization provides a spatial overview of fishing activity in a specific marine area, highlighting the areas where dolphins are most likely caught, as inferred from the weight of dolphins caught along these routes.

Spatial Analysis of Hotspots for DTW Encounters by Fishing Method

The spatial analysis reveals that the highest densities of dolphin bycatch, in terms of DTW, are concentrated within a specific area between latitudes 22 to 25 and longitudes 64 to 66 (Graph 56). This region emerges as a significant hotspot for dolphin bycatch, likely resulting from intensive fishing activities that intersect with key dolphin habitats or migration pathways. The overlapping density contours for different fishing methods in this central zone suggest that multiple fishing practices contribute to the bycatch, underscoring a critical area for focused conservation and management initiatives.

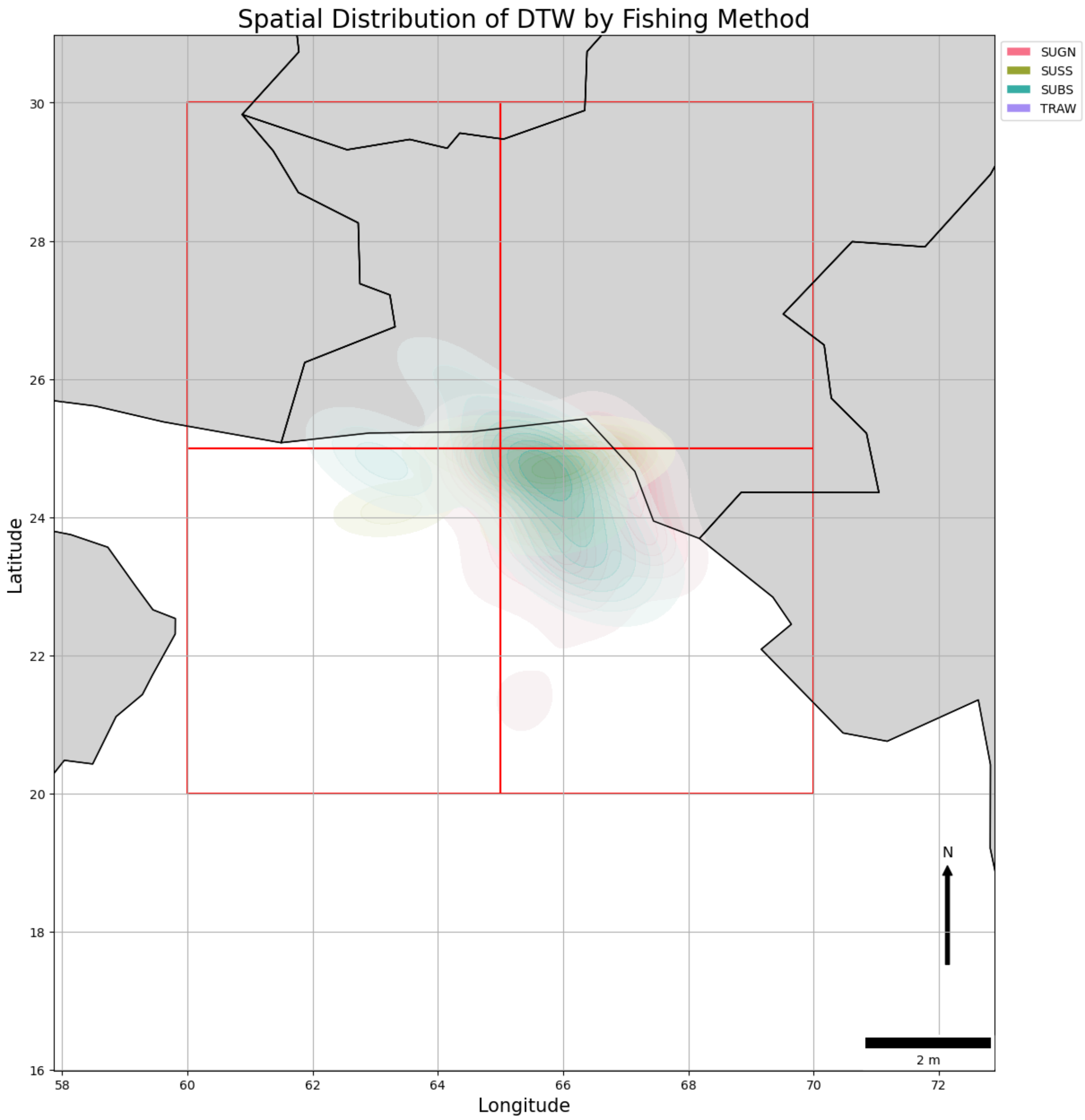
Surface Gillnet (SUGN) Method: Represented by red contours, the SUGN method exhibits a pronounced concentration of fishing activity and dolphin bycatch around latitudes 23.5 to 25.0 and longitudes 64.5 to 66.0. The density contours for SUGN are particularly dense and dark, indicating that this fishing method is associated with frequent dolphin encounters and high bycatch weights in these waters. The intense red shading reflects heavy utilization of surface gillnets in this area, leading to significant dolphin bycatch. This pattern highlights the need for targeted management measures, such as spatial restrictions or gear modifications, to mitigate the impact of surface gillnets on dolphin populations in this high-risk zone.

Surface/Sub-Surface (SUSS) Method: Depicted in green, the SUSS method shows a somewhat more dispersed pattern of dolphin bycatch, with density contours extending from latitudes 23.0 to 25.0 and longitudes 64.0 to 66.0. The substantial overlap of the green contours with the red contours of SUGN indicates that both methods are employed in overlapping fishing grounds. The moderate intensity of the green contours suggests a significant, albeit slightly lower, density of dolphin bycatch compared to SUGN. This more dispersed pattern may indicate that SUSS fishing operations cover a broader area, potentially targeting different species or depths, which could influence the distribution and density of dolphin encounters.

Sub-Surface (SUBS) Method: Represented by blue contours, the SUBS method shows a density pattern primarily between latitudes 23.5 to 24.5 and longitudes 64.5 to 65.5. The blue contours are more spread out compared to those of SUGN and SUSS, reflecting a broader spatial distribution of sub-surface fishing efforts. The relatively lower density of dolphin bycatch weights associated with the SUBS method suggests that it may have a reduced impact on dolphins in these waters. The more dispersed blue contours imply that sub-surface fishing may encounter fewer large groups of dolphins, potentially due to different fishing depths or targeted areas.

Trawling (TRAW) Method: Shown in purple, the TRAW method displays the least concentrated density contours, with a more scattered distribution across the map. The contours for TRAW extend from latitudes 22.5 to 25.0 and longitudes 64.0 to 66.0, but with lower densities compared to other methods. The dispersed nature of the purple contours indicates that trawling results in relatively lower weights of dolphin bycatch. This scattered pattern may suggest that trawling vessels operate over larger and more varied areas, possibly adapting their routes based on fish migrations or avoiding zones with higher dolphin presence.

The spatial distribution of dolphin bycatch weights across different fishing methods underscores a central hotspot of high-density dolphin encounters within latitudes 22 to 25 and longitudes 64 to 66. The overlap of density contours from multiple fishing methods, particularly SUGN and SUSS, highlights the critical importance of this area for fishing activities but also as a high-risk zone for dolphin bycatch. These insights point to the necessity for targeted conservation measures in this region to mitigate the impact of fishing on dolphin populations.



Graph 56: The map illustrates the Spatial Distribution of Dolphin Total Weight (DTW) by Fishing Method in a specific marine region, depicting the density of dolphin bycatch weights associated with different fishing methods. The x-axis represents longitude, while the y-axis represents latitude, providing a geographic overview of where fishing activities and dolphin bycatch are most concentrated. The contours on the map are color-coded by fishing method: Surface Gillnet (SUGN), Surface/Sub-Surface (SUSS), Sub-Surface (SUBS), and Trawling (TRAW), as indicated in the legend. The intensity of the contours reflects the density of dolphin bycatch weights, with darker or more concentrated areas indicating regions where higher weights of dolphin bycatch have been recorded.

Heatmap on the iMMA

Dolphin Total Number (DTN) Distribution and Heatmap Analysis in an Important Marine Mammal Area (iMMA)

The heatmap analysis examines the distribution of DTN within a geographically defined region designated as an Important Marine Mammal Area (iMMA) (IUCN MMPATF,2021). The study area spans longitudes from approximately 58° to 72° and latitudes from about 16° to 30°, suggesting a location in a coastal or offshore zone, likely situated within the northern Indian Ocean or an adjacent sea. The shaded areas on the map represent coastal regions, providing a spatial context for interpreting the DTN distribution data (Graph 57).

Observations of Dolphin Distribution

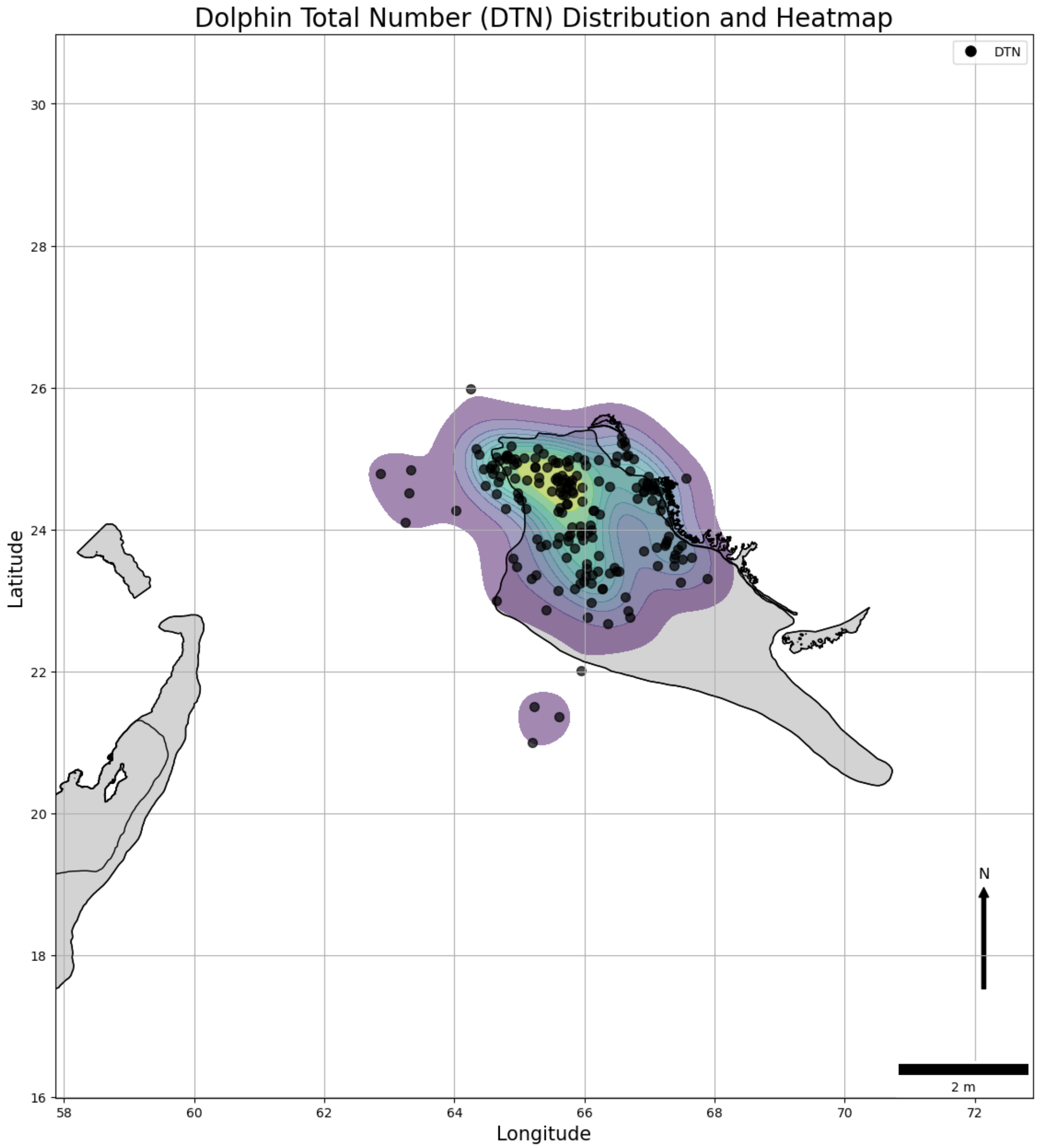
The black dots dispersed across the map represent specific locations where dolphin observations or bycatch (DTN) have been recorded. A notable clustering of these dots occurs between longitudes 64° and 68° and latitudes 22° and 26°, highlighting this area as a significant hotspot for dolphin activity. This aggregation may be influenced by factors such as habitat preferences, prey availability, or anthropogenic activities like fishing, underscoring the need for focused research and conservation measures in this region.

Insights from Kernel Density Estimation (KDE) Heatmap

The overlaid heatmap, generated using Kernel Density Estimation (KDE), provides a visual representation of areas with varying dolphin densities. The color gradient transitions from light purple, signifying lower densities, to dark purple, blue, green, and yellow, which indicate progressively higher densities. The central region, characterized by green and yellow hues, marks the areas with the highest concentration of dolphins, potentially reflecting critical habitats or zones of significant dolphin presence. Surrounding this core area, smaller regions with lower densities are also evident, suggesting broader zones of dolphin activity, albeit at a reduced intensity.

iMMA Overlay and Implications for Management

The iMMA overlay on the map delineates coastal boundaries, helping to contextualize the spatial relationship between dolphin densities and geographic features. The data indicate that dolphins are predominantly concentrated in offshore waters, relatively close to the coast but not directly adjacent to land. Understanding these spatial patterns is crucial for developing effective management strategies, such as establishing Marine Protected Areas (MPAs) or implementing fishing regulations in these waters to reduce anthropogenic impacts on dolphin populations.



Graph 57: The map illustrates the geographic distribution of DTN overlaid with a heatmap on iMMA map (IUCN MMPATF,2021)to highlight areas of varying bycatch intensity. Warmer colors (yellow and green) represent regions with higher concentrations of dolphin bycatch, while cooler colors (blue and purple) indicate lower concentrations. The heatmap provides a clear visual representation of bycatch hotspots, helping to identify key areas for conservation focus.

Dolphin Total Weight (DTW) Distribution and Heatmap Analysis in an Important Marine Mammal Area (iMMA)

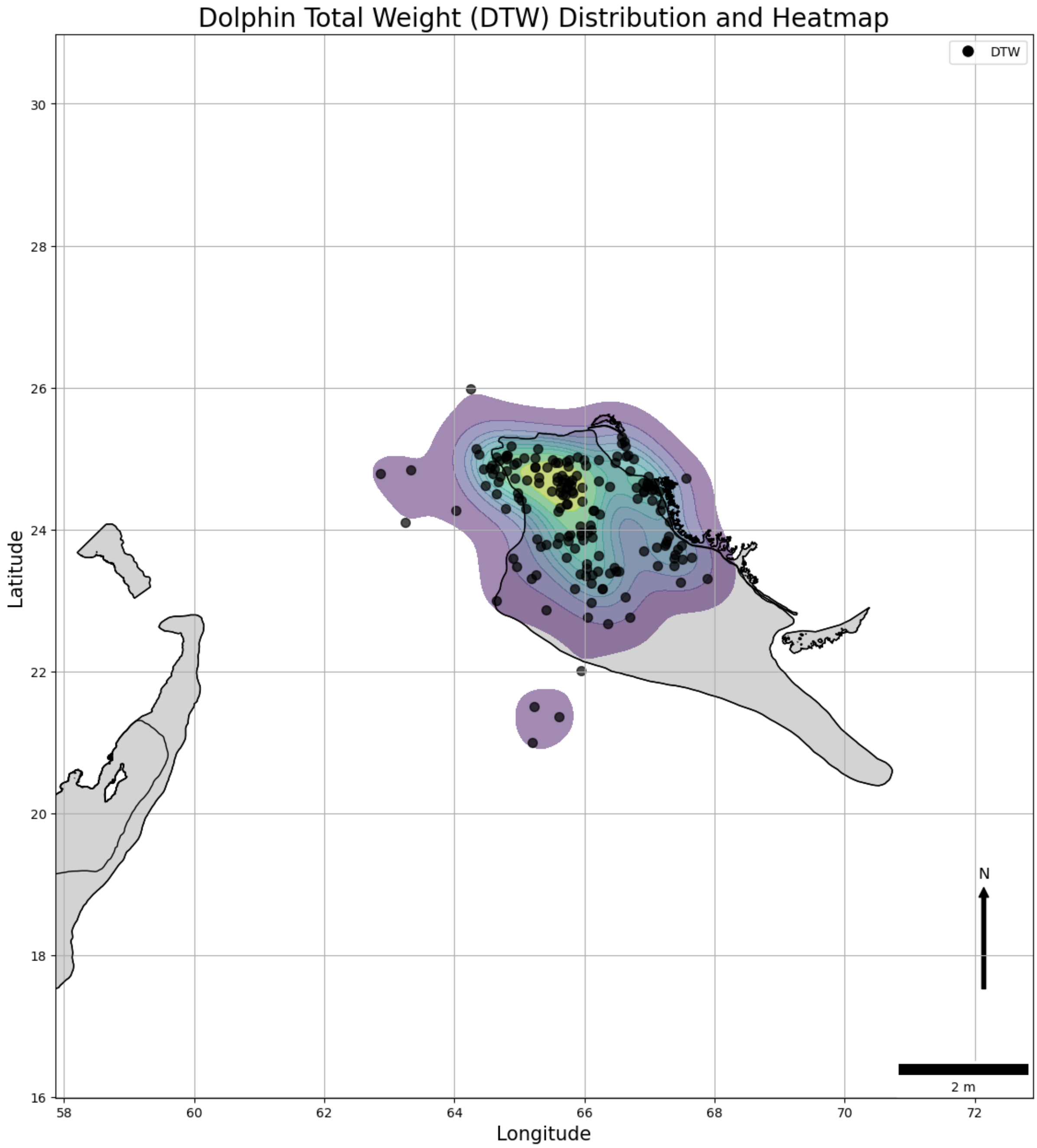
The black dots on the map indicate specific locations where data on DTW has been recorded. These points are critical for identifying areas where dolphins with higher weights are more frequently encountered. A distinct clustering of these points is observed between longitudes 64°E and 68°E and latitudes 22°N to 26°N, highlighting regions of significant dolphin activity (Graph 58).

Heatmap Insights on Dolphin Total Weight Distribution

The overlaid heatmap provides a visual representation of the density of dolphin total weight across the region. The color gradient transitions from light purple (representing low density) to yellow (representing high density), with the central area, particularly around the specified coordinates, exhibiting the highest concentration of dolphin biomass. This region likely represents a crucial habitat, potentially functioning as a feeding ground or a migratory route for dolphins. Surrounding areas, depicted by lighter purple hues, suggest zones where dolphins are present at lower densities or where smaller individuals predominate.

Geographical Context and Implications

The map also features a shapefile overlay delineating landmasses, which may include islands or sections of the coastline. This geographic context provides insight into the spatial relationship between dolphin distribution and terrestrial features. The data indicate that dolphins are primarily concentrated in offshore waters, relatively near the coast but not directly adjacent to it, reflecting a preference for certain marine zones. The proximity of these high-density areas to land, particularly between longitudes 64°E and 68°E, suggests that dolphins may be utilizing coastal zones, which could be vital for their conservation and management.



Graph 58: This map shows the geographic distribution of DTW with an overlaid heatmap on the iMMA map (IUCN MMPATF,2021) to highlight regions with varying bycatch weight intensity. Warmer colors (yellow and green) denote areas with higher total weights of dolphin bycatch, while cooler colors (blue and purple) indicate areas with lower bycatch weights. The heatmap provides a visual representation of areas where dolphin bycatch is most significant, guiding conservation and management efforts to reduce bycatch in critical regions.

Implications of Spatial Analysis for Marine Conservation and Management

This spatial analysis, utilizing latitude and longitude coordinates, provides critical insights for marine spatial planning, conservation prioritization, and ecological research. By pinpointing areas with high densities of DTN and DTW, management authorities can strategically design or adjust Marine Protected Areas (MPAs) to protect regions where dolphins with substantial biomass are concentrated.

Conservation efforts can then be focused on these key areas to ensure the sustainability of dolphin populations, potentially through the implementation of seasonal closures or other protective measures.

Furthermore, the relationship between dolphin weight distribution and environmental factors such as water temperature, depth, or prey availability, which vary across different latitudes and longitudes can be explored in the area. Understanding these ecological dynamics is essential for developing targeted conservation strategies to protect dolphin populations and effectively manage their habitats.

Conclusion

This study offers an in-depth analysis of dolphin bycatch in the tuna gillnet fisheries of Pakistan from 2013 to 2017, applying a comprehensive suite of spatial, temporal, and statistical methods to discern the underlying patterns and drivers of bycatch. The results underscore the critical need for targeted, evidence-based management strategies that can effectively reduce dolphin bycatch while supporting sustainable fishing practices.

Observer Engagement and Data Collection Coverage

The assessment of data collection efforts revealed considerable variability in observer engagement and contributions over the study period, coupled with a relatively limited sampling coverage (0.71% of the total fleet). This finding highlights the necessity of expanding observer programs and integrating electronic monitoring systems to enhance the representativeness and reliability of bycatch data. Further analysis of data from the crew-based observer program, involving around 75 fishers, is recommended to better capture broader bycatch patterns across the fleet and improve the robustness of management decisions.

Exploratory and Correlation Analysis

The EDA and correlation assessments indicated weak to moderate associations between DTN, DTW, and geographical coordinates, suggesting that spatial location alone does not serve as a strong predictor of bycatch rates. This underscores the importance of incorporating additional factors—such as environmental variables, fishing effort, and gear types—into predictive models to refine management approaches and enhance their effectiveness.

Temporal Dynamics and Seasonal Variability

The temporal analysis of DTN and DTW revealed distinct trends over the study period, with DTN demonstrating a relatively stable yet slightly declining trend and DTW exhibiting more pronounced inter-annual variability. Notable peaks in DTW during years such as 2015 and 2017 may reflect shifts in fishing practices, dolphin population dynamics, or environmental conditions. The seasonal and trend analyses further emphasized significant seasonal differences in DTW, particularly during spring months, suggesting the need for seasonally adaptive management measures to mitigate bycatch impacts more effectively.

Anomaly Detection and Adaptive Management

Anomaly detection and change point analyses identified critical periods where bycatch rates deviated significantly from expected patterns, indicating potential atypical fishing events or environmental shifts that could have driven these spikes. These findings underscore the need for adaptive management strategies capable of responding rapidly to such anomalies, ensuring timely interventions that mitigate unexpected surges in bycatch rates.

Spatial Clustering and Hotspot Identification

Clustering and heatmap analyses, employing techniques such as K-means, DBSCAN, and GMM, identified distinct geographical clusters of dolphin bycatch. High-density clusters, particularly between latitudes 24° to 25° and longitudes 65° to 66°, highlight these areas as bycatch hotspots requiring focused management actions, such as time-area closures or the establishment of Blue Corridors to safeguard dolphin migratory routes.

Fishing Methods and Bycatch Rates

Spatial-temporal analysis of different fishing methods revealed that Sub-Surface fishing methods result in lower dolphin bycatch densities compared to Surface Gillnets. This supports the promotion of SUBS fishing as a best practice in high-risk areas and underscores the importance of gear modifications and incentive programs to encourage the adoption of dolphin-friendly fishing techniques across the fleet.

Overlap with Important Marine Mammal Areas (iMMAs)

Heatmap analyses of iMMAs revealed substantial overlap between high bycatch zones and iMMAs, emphasizing the need for spatial management interventions, such as regulated access or time-area closures, within these critical conservation areas to mitigate bycatch risks and protect vulnerable marine mammal populations.

Advanced Predictive Modeling and Spatial Targeting

The regression analysis and predictive modeling efforts showed limited explanatory power for DTN and DTW based solely on geographic coordinates, reinforcing the need for more sophisticated models that incorporate a broader array of environmental and operational variables. Advanced temporal analyses and forecasting models, such as Prophet and BSTS, demonstrated considerable potential in predicting bycatch trends and informing adaptive management strategies.

Spatial Autocorrelation and Implications for Management

Spatial autocorrelation analysis revealed significant clustering for DTW but not for DTN, suggesting that while dolphin bycatch numbers are randomly distributed, specific areas are more prone to the capture of larger dolphins. This finding indicates the necessity for spatially targeted management measures aimed at reducing the capture of larger, potentially more vulnerable individuals.

Overall, this study provides a robust foundation for developing adaptive, spatially targeted management strategies to mitigate dolphin bycatch in Pakistan's tuna gillnet fisheries. By integrating diverse data sources, advanced predictive modeling, and multi-stakeholder collaboration, fisheries managers can develop more nuanced policies that balance conservation objectives with the socio-economic needs of fishing communities, ensuring the long-term sustainability of marine ecosystems in the Northern Arabian Sea.

Recommendations

The analysis of dolphin bycatch in the tuna gillnet fisheries of Pakistan from 2013 to 2017 has revealed significant spatial patterns and hotspots across various fishing methods and geographic regions. The following recommendations outline targeted, adaptive, and effective management strategies that integrate spatial findings, species conservation approaches, and enhanced data utilization to mitigate dolphin bycatch while supporting sustainable fishing practices.

Expand Monitoring and Enhance Observer Data Utilization

To collect comprehensive bycatch data, it is critical to expand observer coverage on more vessels, as current sampling encompasses only 0.71% of the total fleet. With approximately 75 fishers participating in the crew-based observer program for tuna gillnet fisheries, a more in-depth analysis of the data collected by these observers is essential for identifying broader patterns and refining bycatch management strategies. Additionally, deploying advanced electronic monitoring (EM) systems, such as AI-based cameras and real-time data processing, on vessels operating in high-risk areas—particularly between latitudes 24° to 25° and longitudes 64° to 66°—would improve monitoring accuracy and facilitate more effective enforcement of regulations to mitigate dolphin bycatch.

Establish Real-Time Monitoring Systems and Adaptive Management

Developing a real-time bycatch monitoring platform that integrates data from electronic monitoring systems, observer reports, and self-reports from fishermen is crucial for effective management. This platform would allow for dynamic management adjustments, such as temporary closures or gear modifications, in response to bycatch spikes. Incorporating environmental variables (e.g., sea surface temperature, currents) into predictive models can further enhance adaptive management, making it more responsive to changing environmental and fishing conditions.

Promote Sustainable Fishing Practices

Encouraging the adoption of Sub-Surface (SUBS) fishing methods, which have demonstrated lower bycatch densities, is essential for reducing dolphin interactions. Promoting the use of SUBS, especially in high-density areas between latitudes 23.5° to 24.5° and longitudes 64.5° to 65.5°, over Surface Gillnets, can significantly lower dolphin bycatch rates. To support this transition, incentives such as subsidies or grants for fishermen to adopt modified gear types, including deeper-set gillnets and exclusion devices, should be provided. These incentives should target high-risk zones where Surface Gillnet and Surface/Sub-Surface fishing methods overlap, such as between latitudes 24.0° to 25.0° and longitudes 64.0° to 66.0°. Additionally, comprehensive training programs on safe handling and release techniques for dolphins and other megafauna, including Endangered, Threatened, and Protected (ETP) species, should be implemented to minimize mortality and enhance post-release survival rates.

Implement Dynamic Closures and Strengthen iMMAs Protection

Dynamic time-area closures are essential for reducing bycatch in identified high-density zones. The spatial analysis has pinpointed the region between latitudes 24° to 25° and longitudes 65° to 66° as a high-density dolphin bycatch area, where implementing dynamic closures, particularly during peak fishing periods, could significantly lower bycatch rates. Additionally, the overlap between high bycatch zones and iMMAs necessitates stricter management within these areas. Establishing time-area closures or regulated access within iMMAs, as developed by the IUCN for dolphin conservation, is crucial for balancing conservation goals with fishing activities. Management actions should prioritize areas identified by spatial analysis, such as between latitudes 24.5° to 25.0° and longitudes 64.5° to 66.5°.

Develop Blue Corridors and Regulate Vessel Traffic

The development of Blue Corridors represents an innovative strategy to balance marine conservation with sustainable fishing practices. These corridors should be established along routes with moderate to low bycatch densities, such as between latitudes 24° to 25° and longitudes 64° to 66°, to provide safe migratory pathways for dolphins while minimizing bycatch risks. Furthermore, regulating fishing vessel traffic in high bycatch zones through speed restrictions, designated lanes, and fishing-free zones between latitudes 24.5° to 25.0° and longitudes 65.0° to 66.5° can help reduce the risk of dolphin bycatch and minimize habitat disturbance. These measures should be adaptive, based on real-time monitoring data, to optimize both dolphin conservation and fishing activities. A multitaxa species conservation approach is recommended, focusing not only on dolphins but also on other vulnerable species such as sea turtles, sharks, and seabirds, to ensure holistic ecosystem-based management.

Strengthen Policy Frameworks and Stakeholder Collaboration

Updating and enforcing bycatch mitigation policies is essential for reducing dolphin bycatch. New regulations should mandate the use of bycatch reduction devices (BRDs) in areas with high overlap between fishing activity and dolphin presence, particularly for Surface Gillnet operations in high-risk areas like latitudes 23.5° to 25.0° and longitudes 64.5° to 66.0°. Engaging local fishing communities, conservation organizations, and government agencies in co-management frameworks can help ensure the effective implementation of bycatch reduction strategies. Collaborative decision-making and stakeholder engagement are crucial for improving compliance and achieving conservation objectives.

Invest in Bycatch Mitigation Research and Development

Investing in research and development is vital for advancing bycatch mitigation technologies. Research should focus on developing and testing innovative fishing gear, such as exclusion devices or acoustic deterrents, tailored for high-risk zones between latitudes 24° to 25° and longitudes 64° to 66°. Encouraging pilot programs to test these solutions in collaboration with local fishermen can provide practical insights into their effectiveness and inform future policy decisions. Additionally, incorporating environmental and ecological data into bycatch management is essential. Integrating factors such as ocean currents and prey availability into management models can improve the prediction of high bycatch areas and guide more targeted interventions.

Build Awareness and Capacity

Conducting targeted awareness campaigns and capacity-building initiatives is vital to support these recommendations. Awareness campaigns should focus on the ecological and economic impacts of dolphin bycatch and promote sustainable fishing practices, particularly in high-risk zones. These campaigns can emphasize the benefits of adopting lower-impact methods, such as Sub-Surface (SUBS) fishing, to encourage widespread adoption. Building capacity for fisheries managers and enforcement officers through enhanced training in adaptive management, electronic monitoring, and enforcement will further support the effective implementation of bycatch reduction measures.

Acknowledgement

We express our deepest gratitude to the fishermen from the tuna gillnet fisheries who participated in this study. Their invaluable cooperation in providing their time, expertise, and data on dolphin bycatch during their fishing operations was crucial to the success of this research. We acknowledge their dedication to enhancing the understanding of bycatch dynamics, which forms the foundation of this study.

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Appendix