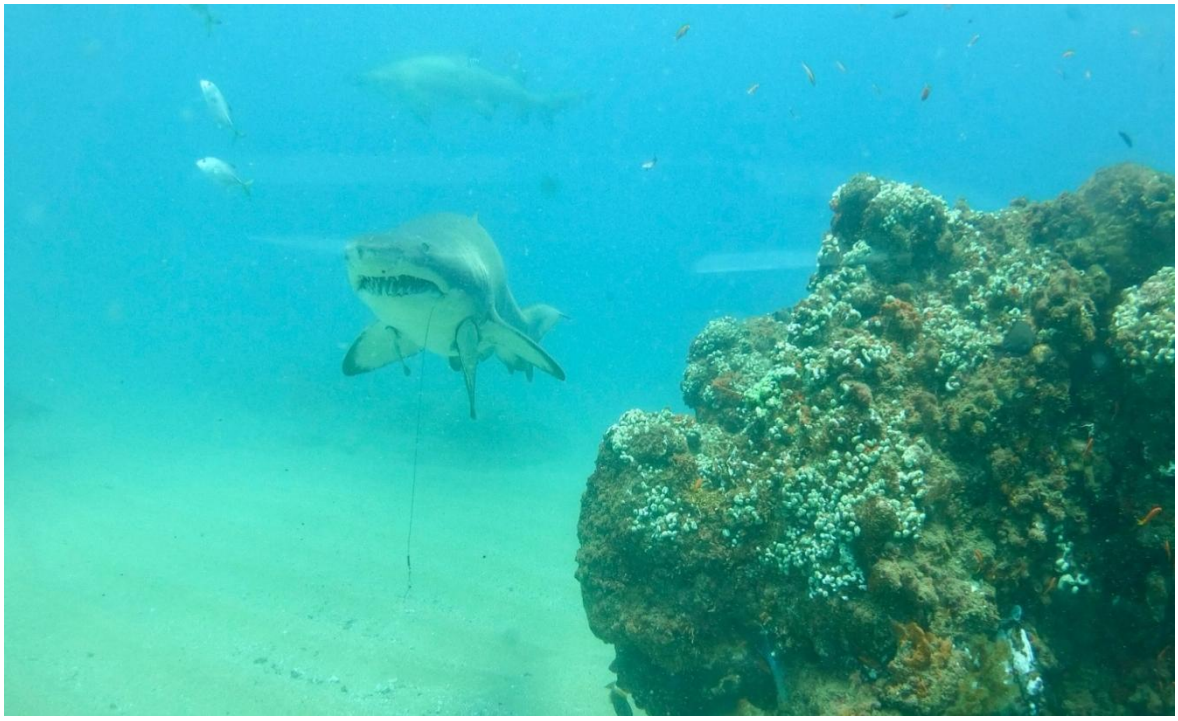
Ragged-tooth shark (Carcharias taurus) movement trends and anthropogenic impact assessment during the annual breeding migration into the iSimangaliso Wetland Park (Year 7)

2024 - 2025 Annual Research Report



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1. Executive Summary

This report presents the results of the 2024–2025 monitoring season for *Carcharias taurus* (ragged-tooth sharks) within the iSimangaliso Marine Protected Area (MPA), with a focus on long-term aggregation trends at two key sites: Raggie Reef and Quarter Mile Reef . Drawing on five years of remote video and visual census data, alongside environmental and diver activity monitoring, the report provides an integrated assessment of seasonal patterns, site-level pressures, and management needs.

Raggie Reef (RR) continued to function as a stable aggregation site, consistently hosting sharks from late October through to March. Annual aggregation intensity at RR varied significantly over the five-year period, with 2021 and 2023 standing out as peak seasons. In contrast, Quarter Mile Reef (QR) showed only short-lived, low-density pulses of shark presence, most frequently between November and early January. These differences likely reflect a combination of reef structure, exposure, and human use.

The 2024-2025 season saw continued implementation of both Underwater Visual Census (UVC) and Remote Underwater Video Stations (RUVS), resulting in nearly 155,000 images analysed and detailed daily presence data. RUVS deployments again proved essential for maintaining data continuity during periods of poor diving conditions. Environmental analyses indicated that sea surface temperature (SST), lagged by 14 days, was positively correlated with shark presence at RR, supporting the idea that seasonal warming plays a role in triggering their northward migration. No significant effects of wave height or period were observed.

Recreational diving activity at QM was high in early December, prior to reef closure being enacted, with 193 divers recorded across 38 groups. Daily dive durations often exceeded five hours, yet Code of Conduct (COC) adherence remained low, with an average compliance score of only 4.8%. No day for the duration of the monitoring recorded full compliance, and repeated non-adherence was observed during peak holiday periods. These findings point to the need for strengthened diver protocol enforcement and renewed training efforts among operators.

This report reinforces the critical value of long-term monitoring programmes in generating site-specific evidence to inform adaptive management. Continued year-round monitoring at RR is recommended, given its ecological importance and consistent shark presence. At QM, enhanced management of diving activity is urgently needed. Finally, to understand broader patterns of reef connectivity and seasonal movement, this report recommends supporting and enabling regional acoustic telemetry monitoring of tagged individuals and expanded receiver arrays beyond the MPA boundary.

Together, these actions will support more effective protection of ragged-tooth shark aggregations along South Africa's east coast and enhance the role of iSimangaliso as a leader in applied marine species conservation.

2. Background and Aim

The ragged-tooth shark (*Carcharias taurus*), also known as the sand tiger or grey nurse shark, is a slow-growing, late-maturing species with low reproductive output. It is listed as Critically Endangered on the IUCN Red List. In South Africa, a portion of its reproductive population aggregates seasonally along the subtropical east coast, where females are believed to gestate in shallow, protected reef systems over several months (Bass et al. 1975; Dicken et al. 2006). These aggregations form the foundation for long-term conservation efforts within the iSimangaliso Marine Protected Area (MPA), a UNESCO World Heritage Site recognised for its ecological and biodiversity significance.

Within iSimangaliso, two key aggregation sites have been monitored consistently since 2019: Raggie Reef (RR), situated within the iSimangaliso Offshore Wilderness Zone (IOWZ), and Quarter Mile Reef (QM), located within the Sodwana Diving Restricted Zone (SDRZ). These sites differ markedly in both their physical structure and human use patterns. Raggie Reef is remote and undisturbed, while Quarter Mile Reef is accessible to recreational divers during specified open periods defined annually by the park authority (Sharklife, 2024; Olbers & Smith, 2019).

Long-term monitoring of ragged-tooth shark aggregations in these areas is essential to understand their spatial fidelity, phenology, and response to both environmental variability and human activity. Monitoring is conducted using Underwater Visual Census (UVC) and Remote Underwater Video Stations (RUVS)—two complementary techniques that allow for the assessment of shark abundance, aggregation intensity, and length of stay at each site (Whitmarsh et al. 2017; Sharklife, 2023). In addition, environmental parameters such as sea surface temperature (SST) and wave conditions are recorded to explore the potential drivers of shark presence and movement.

In the 2024–2025 reporting period, focus is placed on synthesising five years of aggregation data (2019–2024) alongside recreational diver monitoring conducted in 2024. This integrated approach aims to evaluate long-term trends, assess the potential impact of diver presence on shark behaviour, and inform future access protocols for high-sensitivity zones within the MPA. The results and interpretations contained in this report are intended to support evidence-based adaptive management of these aggregation sites in collaboration with the iSimangaliso Wetland Park Authority and Ezemvelo KZN Wildlife.

3. Monitoring Overview

3.1 Monitoring Sites

Long-term monitoring of ragged-tooth shark (*Carcharias taurus*) aggregations within the iSimangaliso Marine Protected Area focuses on three key sites: Raggie Reef (RR), Quarter Mile Reef (QM), and 7 Mile Reef. Of these, RR and QM are the primary sites included in this year's analysis due to their consistent monitoring coverage from 2019 to 2024.

Raggie Reef, situated within the iSimangaliso Offshore Wilderness Zone (IOWZ), is a relatively undisturbed, offshore reef known to support prolonged shark residency during summer aggregation periods. In contrast, Quarter Mile Reef, located in the Sodwana Diving Restricted Zone (SDRZ), is shallower, closer to shore, and seasonally accessible to recreational divers. These distinct reef characteristics provide valuable contrast in evaluating aggregation behaviour under varying human use and environmental exposure conditions.

7 Mile Reef, while also a historically important aggregation site, is not included in the 2024–2025 analysis due to limited data availability from the current season. Likewise, methods such as stereo-Diver Operated Video (stereo-DOVs) and photo-identification of individuals are not featured in this report, as shark densities at RR and QM were insufficient to justify the inclusion of individual-based approaches this season. These tools remain important components of the broader monitoring strategy and may be revisited in future reporting years should local aggregation strength increase or targeted studies require individual tracking.

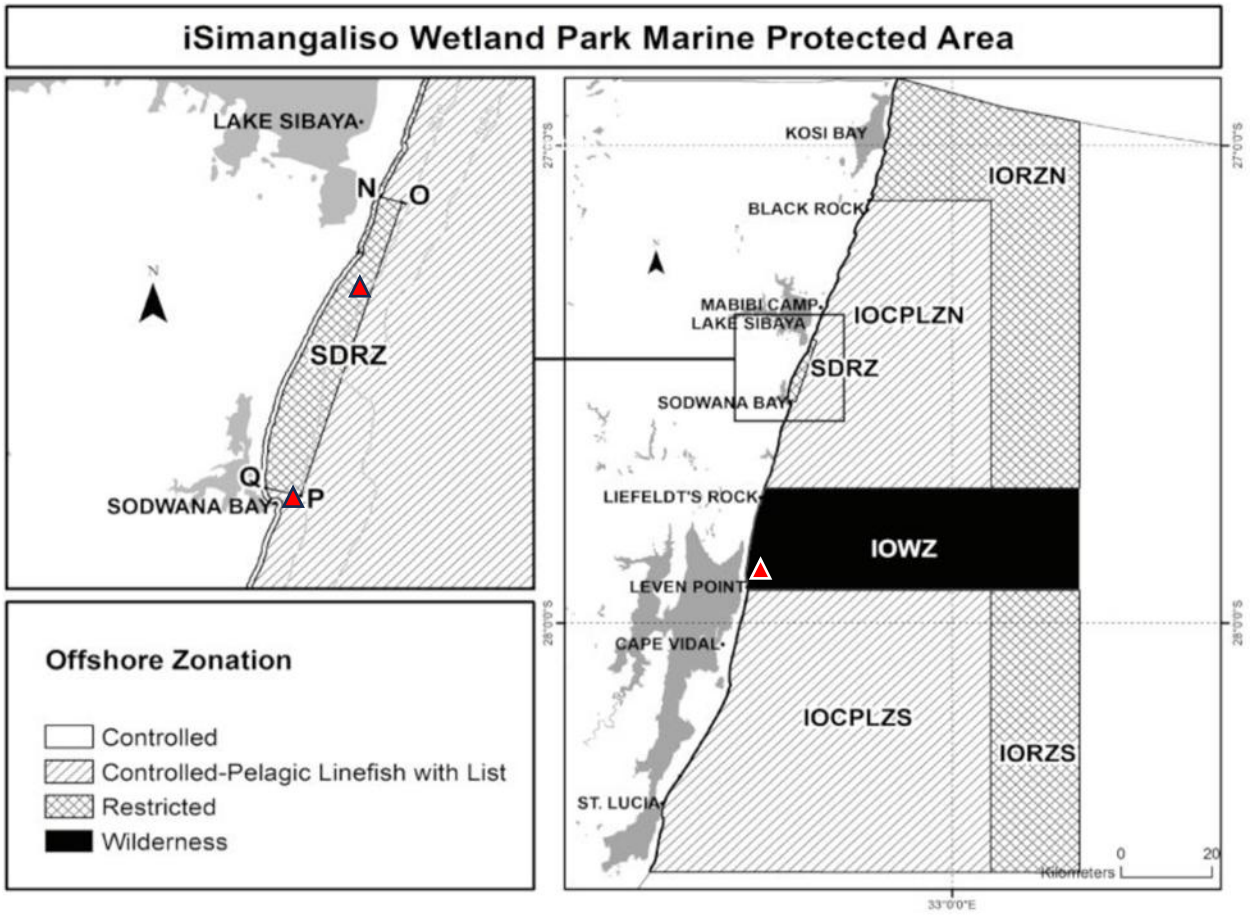

Figure 1. Map of iSimangaliso Wetland Park Marine Protected Area and (2019-2024) monitoring locations 7 Mile Reef (North SDRZ), Quarter-Mile Reef and Raggie Reef.

3.2 Monitoring Methods

Shark aggregation patterns were assessed using a combination of Underwater Visual Census (UVC) and Remote Underwater Video Stations (RUVS). These methods provide complementary data on abundance, spatial use, and temporal presence.

UVC surveys were conducted by trained freedivers swimming standardised transects at both reefs. During each survey, observers recorded the total number of *C. taurus* observed, using consistent protocols that standardise for time, depth, direction, and sea conditions. UVC data allow for rapid assessments of shark presence and relative abundance, particularly useful when environmental conditions are favourable for in-water work.

Figure 2. Example imagery used in monitoring ragged-tooth shark aggregations. Left: MaxN image frame from a Remote Underwater Video Station (RUVS) showing multiple *Carcharias taurus* individuals. Right: *In situ* photograph taken during a freedive-based Underwater Visual Census (UVC) survey.

RUVS are stationary, moored camera systems installed on the seafloor within known aggregation zones. These units operate autonomously, capturing images at 30-second intervals over daily deployments lasting approximately 11 hours. The method enables long-duration, non-invasive observation of shark presence in key resting areas, reducing disturbance from diver presence. Shark abundance was quantified using the MaxN metric, which records the highest number of individuals observed in a single frame each day.

Together, these methods provide robust and cross-validated measures of shark aggregation intensity and behaviour across years and reef systems. By combining diver-dependent and remote sensing approaches, the monitoring framework improves reliability in both high- and low-visibility conditions and offers continuity when fieldwork is interrupted.

3.3 Environmental Monitoring

Environmental data were collected to assess abiotic drivers potentially influencing shark presence, aggregation intensity, or observer detectability. The key variables analysed were Sea Surface Temperature (SST), wave height, and wave period.

Daily SST values were extracted for RR and QM from the NOAA Optimum Interpolation Sea Surface Temperature (OISST) v2.1 dataset. This dataset provides global, high-resolution SST estimates by integrating satellite and in situ measurements. Reef-specific data were extracted using coordinates corresponding to RUVS station deployments to ensure spatial accuracy. These values were used to assess both daily variation and seasonal trends relevant to shark aggregation timing.

Wave height and wave period data were obtained from the MeteoFrance Wave Model (MFWAM), which provides validated wave model outputs for the Western Indian Ocean. Daily maximum wave height (m) and maximum wave period (s) were analysed as potential drivers of shark detectability, UVC feasibility, and behavioural disruption. These metrics also served as indicators of diver access and operational safety during fieldwork.

Environmental variables were smoothed using a 7-day rolling average to reduce noise and better reflect biologically relevant trends. Both direct and lagged correlations between these variables and shark aggregation indices were assessed to evaluate whether environmental shifts precede observable changes in shark presence, particularly during peak aggregation periods.

4. Results

4.1 Survey Effort Summary (2024-2025 Season)

Monitoring of *Carcharias taurus* aggregations in the 2024-2025 season included both Underwater Visual Census (UVC) and Remote Underwater Video Stations (RUVS) at Quarter Mile Reef (QM) and Raggie Reef (RR). UVC surveys were conducted on a total of 59 days, with RR contributing 8 days and QM 51 days. These surveys recorded 129 sharks at RR and 56 sharks at QM, with individual survey days at QM typically yielding low counts.

RUVS monitoring stations operated over extended periods, with 56 active monitoring days at QM and 62 days at RR. Each unit captured time-lapse images at 30-second intervals for approximately 11 hours daily, resulting in an estimated 73,920 images at QM and 81,840 images at RR. (Table 1 and Table 2).

Table 1. Summary of UVC survey effort and shark observations by site during the 2024-2025 season.

Site	UVC Days	Total Sharks Observed
Quarter Mile Reef (QM)	51	56
Raggie Reef (RR)	8	129

Table 2. Summary of RUVS deployment days and estimated images analysed during the 2024-2025 season.

Site	RUVS Days	Estimated Images Analysed
Quarter Mile Reef (QM)	56	73920
Raggie Reef (RR)	62	81840

4.2 Annual Aggregation Trends at Raggie Reef (RR)and Quarter Mile Reef (QM)

Analysis of data collected between 2019 and 2024 revealed distinct interannual variation in aggregation strength at both Quarter Mile Reef (Figures 3 – 5) and Raggie Reef (Figures 6 – 8). At RR, aggregations were consistently present during the austral summer, generally beginning in late October or early November and continuing through to March or April. In particular, the years 2021-2022 and 2023-2024 exhibited the highest recorded MaxN values from RUVS data. A Kruskal–Wallis H-test confirmed that differences in annual aggregation index were statistically significant ($H = 22.61$, $p = 0.00094$), with post-hoc comparisons indicating elevated aggregation intensity in these two peak years.

At QM, aggregations were less consistent and generally lower in magnitude. Nonetheless, statistical analysis revealed that variation among years was also significant. A Kruskal–Wallis H-test of non-zero daily QM aggregation values showed a strong effect of year on the aggregation index ($H = 47.21$, $p < 0.00000002$). Aggregation intensity was highest in 2023-2024, while the 2020-2021 and 2024-2025 seasons were comparatively weak.

Aggregations at QM typically occurred in short-lived pulses between November and early January, and daily shark counts rarely exceeded five individuals. These low-density and transient events suggest that QM may function as a transitional or exploratory site, rather than a stable resting or gestation location. By contrast, the more consistent and prolonged aggregations observed at RR reinforce its ecological role as a core resting site within the iSimangaliso Marine Protected Area.

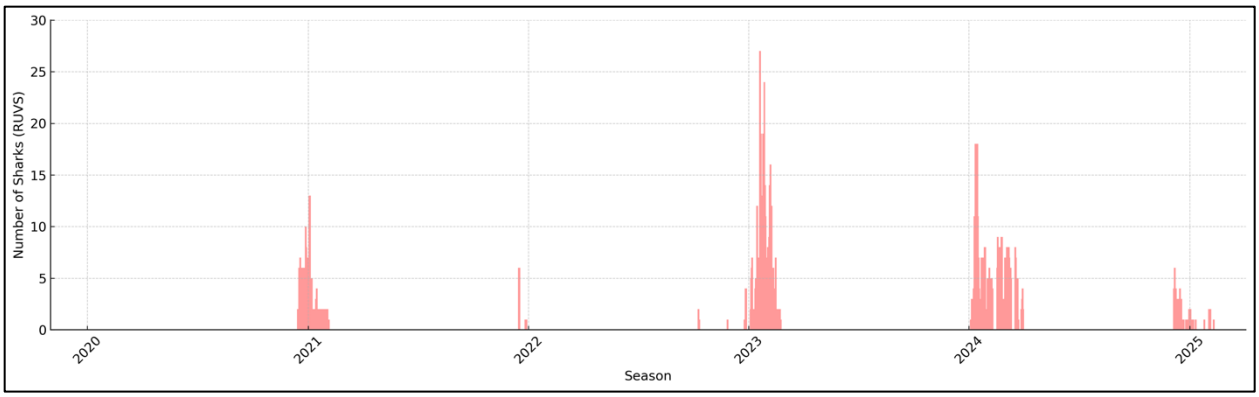

Figure 3. Number of Ragged-tooth Sharks observed using Remote Underwater Video Stations **(RUVS)** at Quarter Mile Reef.

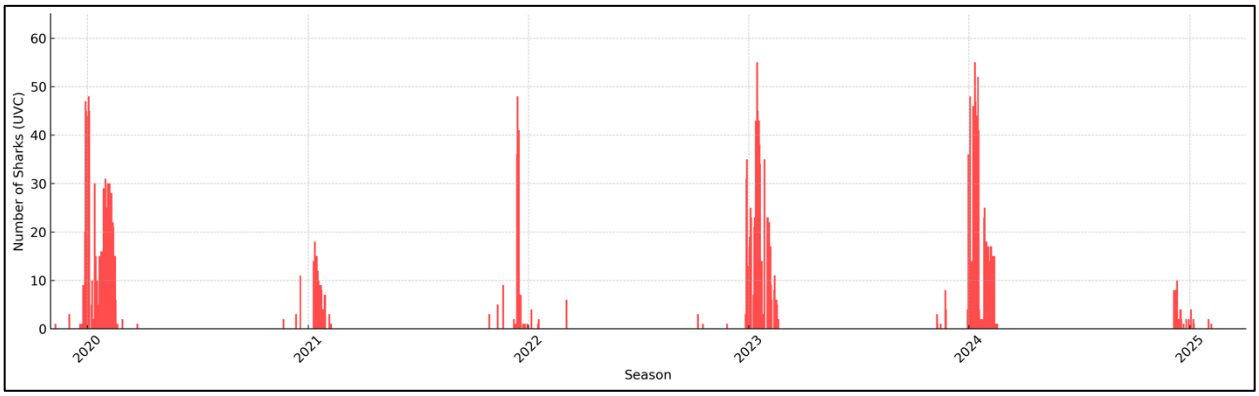

Figure 4. Number of Ragged-tooth Sharks observed using Underwater Visual Census **(UVC)** at Quarter Mile Reef.

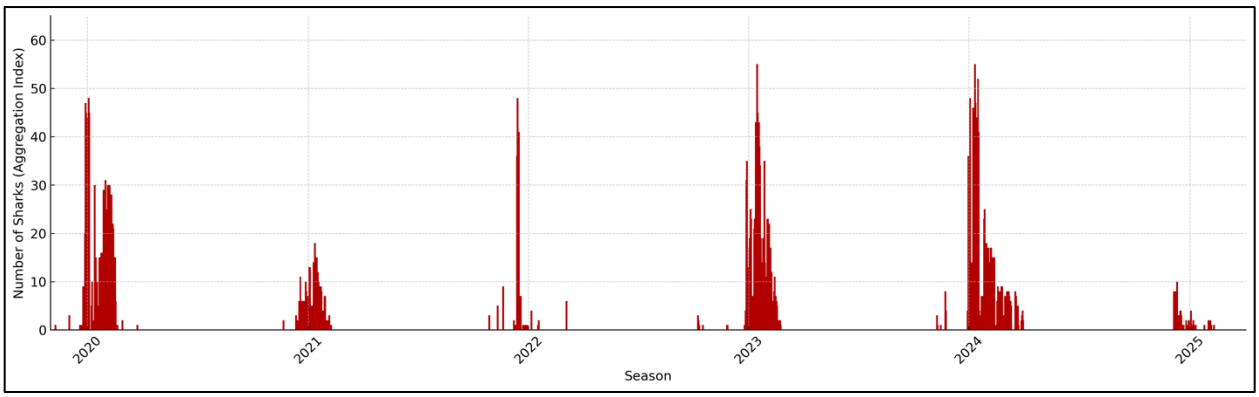

Figure 5. Aggregation index (combined **UVC and RUVS** data) of Ragged-tooth Sharks at Quarter Mile Reef.

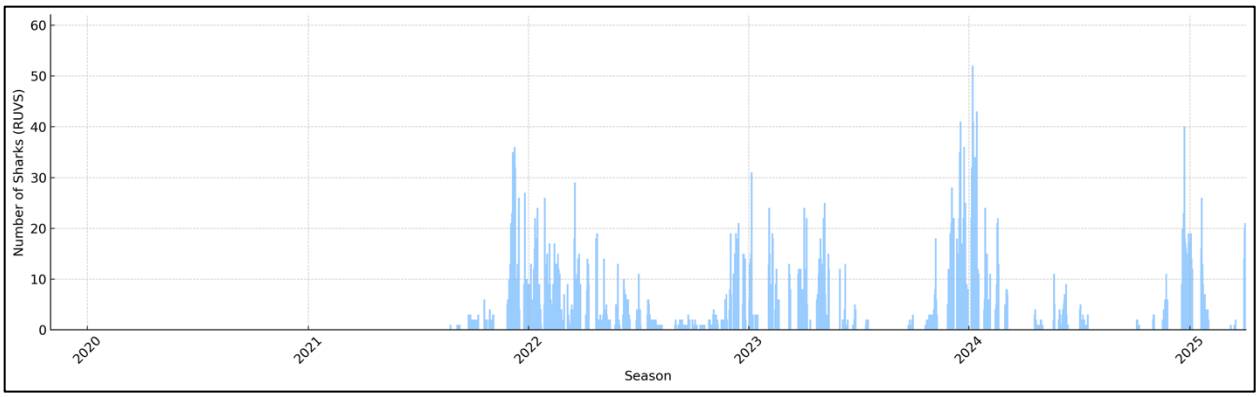

Figure 6. Number of Ragged-tooth Sharks observed using Remote Underwater Video Stations **(RUVS)** at Raggie Reef. (No RUV in place in 2019 -2020)

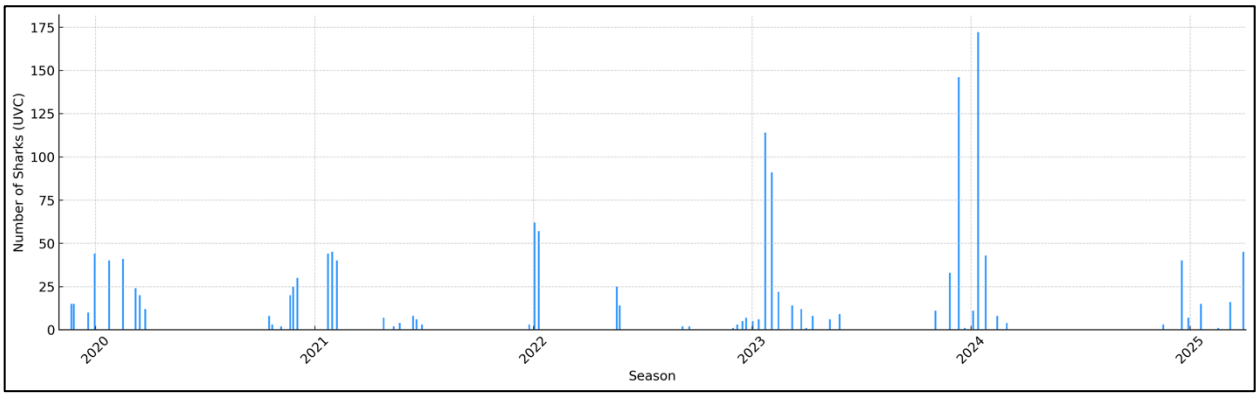

Figure 7. Number of Ragged-tooth Sharks observed using Underwater Visual Census **(UVC)** at Raggie Reef.

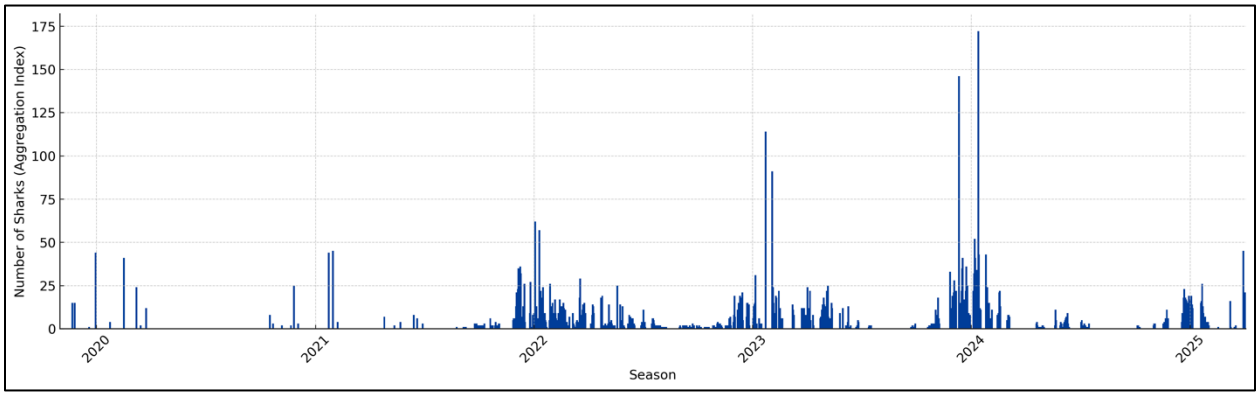

Figure 8. Aggregation index (combined **UVC and RUVS** data) of Ragged-tooth Sharks at Raggie Reef.

4.3 Comparison Between Sites

Comparison of aggregation patterns between RR and QM highlights marked differences in their respective ecological functions. Raggie Reef consistently supported higher daily shark counts and more sustained aggregation events. MaxN values at RR frequently exceeded ten individuals per day during the peak season, with sharks often observed across several consecutive weeks. These patterns are consistent with the reef's structural complexity, offshore location, and reduced human disturbance, which together offer conditions conducive to long-term occupancy by aggregating sharks.

In contrast, Quarter Mile Reef exhibited only sporadic aggregation events of short duration and limited size. Shark presence at QM was brief and discontinuous, and the site rarely hosted more than a few individuals per day. Its shallower bathymetry, greater exposure to swell, and periodic access by recreational divers likely reduce its suitability as a primary aggregation site.

A Mann–Whitney U test comparing daily MaxN values across both sites (pooled across all years) confirmed that RR hosted significantly higher aggregations than QM ($U = 2894.0$, $p < 0.001$). These findings are consistent with previous reports and provide further evidence supporting the prioritisation of RR for long-term monitoring and protective management.

4.4 Environmental Drivers of Aggregation

Sea surface temperature was examined as a potential driver of aggregation dynamics using site-specific daily values obtained from the NOAA OISST v2.1 dataset (Figure 9). A paired t-test comparing SST values at RR and QM across the same sampling periods showed that RR was consistently, though marginally, warmer than QM ($t = 2.49$, $p = 0.013$). While the absolute difference in mean temperature was small, the pattern was statistically robust and may reflect consistent thermal variation between the two sites.

Spearman correlation analysis indicated that same-day SST was not significantly correlated with aggregation index at either site. However, when SST was tested with time lags of 7, 14, and 21 days, clearer relationships emerged. At RR, SST lagged by 14 days and was positively correlated with shark aggregation ($\rho = 0.210$, $p = 0.026$), suggesting that sustained warming trends may act as a proximal environmental cue for the arrival of gestating females during their northward migration along South Africa's east coast. This seasonal movement is thought to be timed with increasing coastal temperatures and improved thermal conditions for embryo development. The correlation supports the hypothesis that ragged-tooth sharks respond not to short-term thermal fluctuations, but to broader thermal gradients and climatic signals that align with the onset of their summer residency phase in the subtropical waters of the iSimangaliso MPA.

Wave height and period were evaluated using hindcast data from the MeteoFrance MFWAM model (Figure 10). No statistically significant correlations were found between these variables and the aggregation index at either site (all $p > 0.1$). Nevertheless, wave conditions were observed to influence monitoring logistics and diver access. At QM, UVC surveys were frequently

suspended during periods of high swell (>2 m), while RUVS continued to operate uninterrupted, albeit with reduced visibility. Although sea state did not emerge as a direct ecological driver in this analysis, its operational implications and potential indirect effects on shark behaviour remain relevant for ongoing monitoring and management.

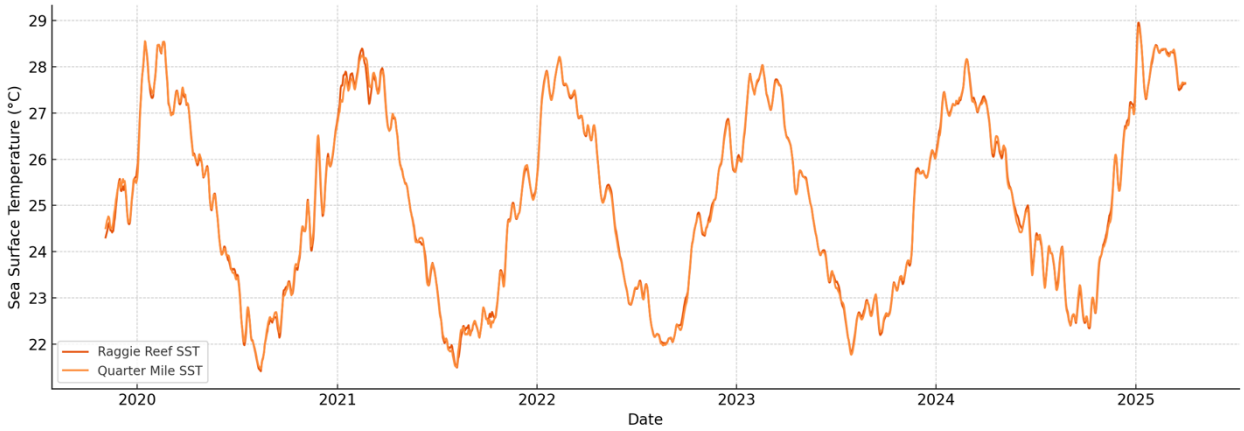

Figure 9. Daily sea surface temperature (SST) at both monitoring sites from November 2019 to April 2025, smoothed using a 7-day rolling average.

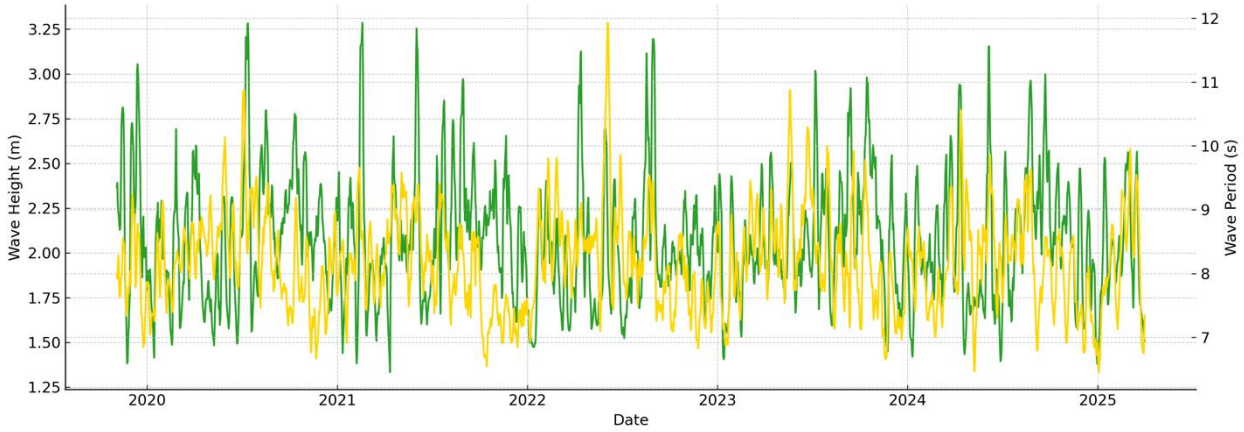

Figure 10. Daily maximum wave height (m) and wave period (s) from November 2019 to April 2025, shown as 7-day rolling averages.

4.5 Recreational Diving Activity and Code of Conduct Adherence (2024-2025)

Quarter Mile Reef, situated within the Sodwana Diving Restricted Zone (SDRZ), remains accessible to recreational divers during the ragged-tooth shark aggregation season under regulated conditions, set annually by Ezemvelo and the iSimangaliso Wetland Park Authority. In the 2024-2025 season, diver presence was monitored daily to evaluate dive pressure and assess adherence to the species-specific Code of Conduct (COC) (Table 3 & Figures 11 -14).

During the elapsed time period taken to close the reef, after the recommendation by Ezemvelo, a total of 38 dive groups were recorded, comprising 193 individual divers. The number of divers per day varied considerably, with an average of approximately 32 divers per day and a peak of 53 divers recorded on the busiest day. Daily diving activity typically extended across several hours, with many days exceeding five hours of site use. Dive day duration, recorded from first diver entry to final exit, consistently reflected extended periods of in-water presence at the site.

Adherence to the ragged-tooth shark Code of Conduct (COC) was generally low throughout the season. The average daily compliance score was 4.8%, and no days achieved full adherence (100%). The lowest recorded adherence was 0%, which occurred on multiple days, particularly during periods of high visitor volume in December. These figures reflect a pattern of persistent non-compliance and highlights the need for COC materials and prior awareness initiatives. Examples of both non-compliance and adherence to the Code of Conduct were captured in RUVS imagery and are included for reference in *Appendix Figure A1 and A2*.

Instances of non-compliance included overlapping dive groups at the aggregation site, observation durations that exceeded recommended limits, and close proximity to resting sharks. While the impact of these interactions on shark behaviour was not assessed in this report, the consistency of low compliance highlights a continued need for more effective communication of guidelines and stronger enforcement mechanisms during peak diving periods.

Table 3. Summary of recreational diving activity and Code of Conduct (COC) adherence at Quarter Mile Reef during December 2024. Data include the number of dive groups, total divers, dive day duration, and percentage of adherence to the COC.

Date	Number of Dive Groups	Total Daily Divers	Dive Day Duration (Hours)	Code of Conduct Adherence (%)
12/17/24	7	34	6:35	29
12/18/24	10	53	6:36	0
12/19/24	2	7	1:49	0
12/20/24	6	40	3:48	0
12/21/24	8	26	5:04	0
12/22/24	5	33	2:52	0

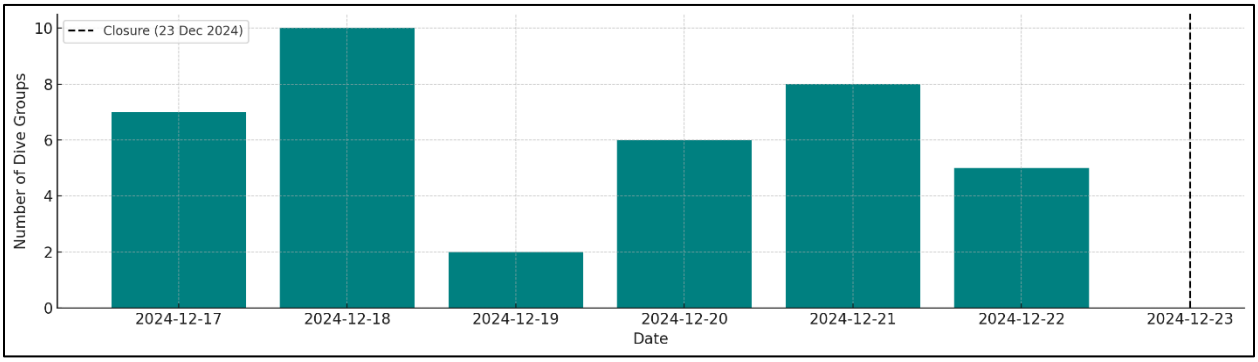

Figure 11. Daily number of dive groups recorded at Quarter Mile Reef during the 2024-2025 season. The vertical line indicates the seasonal closure date (23 December 2024).

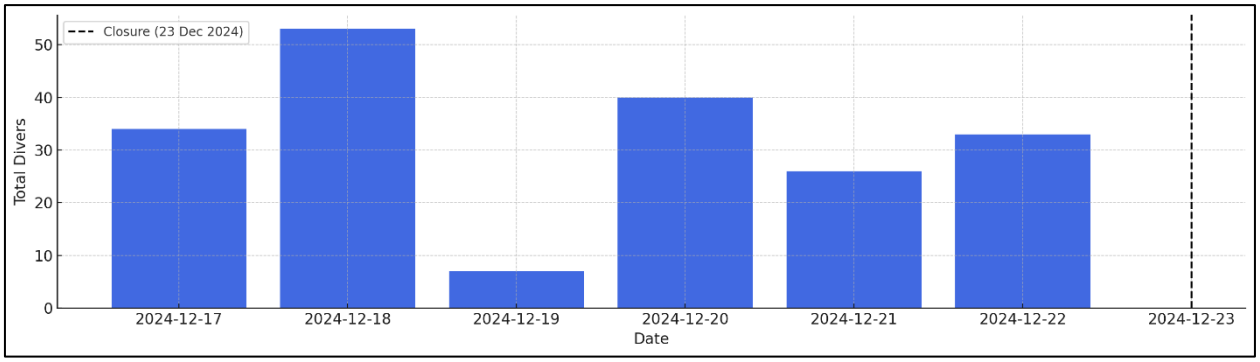

Figure 12. Total number of individual divers per day at Quarter Mile Reef during the 2024-2025 season.

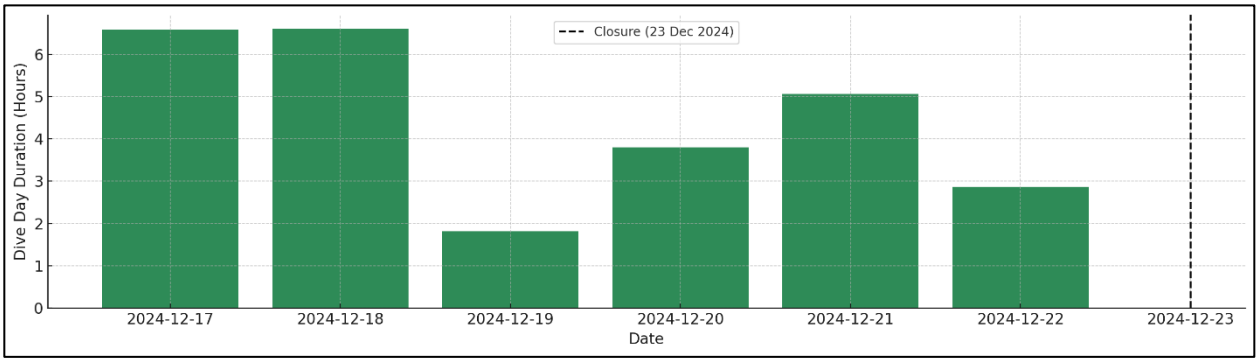

Figure 13. Dive day duration (hours) at Quarter Mile Reef during the 2024 season, measured from first diver entry to last diver exit.

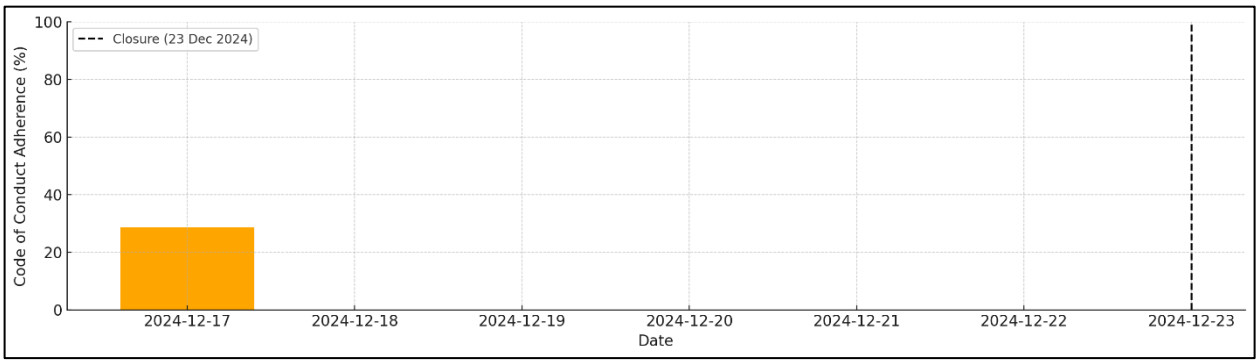

Figure 14. Daily adherence (%) to the ragged-tooth shark Code of Conduct at Quarter Mile Reef in 2024.

5. Management Interpretation and Recommendations

The results presented in this report offer a valuable longitudinal perspective on the dynamics of ragged-tooth shark aggregations within the iSimangaliso Marine Protected Area. Over five seasons of continuous monitoring, clear patterns have emerged: Raggie Reef stands out as a stable and consistently used aggregation site, while Quarter Mile Reef is characterised as a more exposed location that functions as a lower-density core site, with sharks exhibiting prolonged seasonal occupancy only when undisturbed. These distinctions underscore the importance of site-specific management, especially where sensitive habitats coincide with recreational diving activity.

The continuation of this monitoring programme—despite logistical, financial, and environmental constraints—demonstrates the significant effort required to build long-term datasets capable of detecting subtle ecological signals and informing meaningful conservation action. The use of complementary methods such as RUVS and UVC, combined with environmental and human-use monitoring, has enabled robust and repeatable assessments of seasonal patterns and pressures. Maintaining and expanding this level of monitoring at RR, in particular, is vital, given its persistent use by gestating females and its current protection within the iSimangaliso Offshore Wilderness Zone.

At Quarter Mile Reef, the low but consistent lack of adherence to the Code of Conduct (COC) in 2024-2025 presents a clear management challenge. Given the ongoing use of QM during sensitive aggregation windows, it is recommended that diver protocol enforcement be strengthened through a combination of targeted training for operators, increased signage at launch and briefing points, and formal penalties for repeated or egregious non-compliance. Importantly, such interventions must be supported by clear communication of the ecological rationale for the COC and the consequences of its breach. It should be noted that the COC and annual dive leader training—originally adopted in 2003—served as an effective mechanism for many years. This precedent underscores that the tools for compliance already exist and should be reinstated with renewed commitment.

Looking forward, continued site-based monitoring must be complemented by an expanded focus on reef-scale and regional connectivity. While this report has focused on *in-situ* aggregation patterns at RR and QM, the long-term conservation of *Carcharias taurus* in South Africa will require an understanding of how individuals move between aggregation areas both within and beyond the boundaries of the MPA. The seasonal arrival of sharks at Raggie Reef, and the apparent short-lived visits to Quarter Mile Reef, raise important questions about movement pathways, habitat use, and site fidelity across the broader coastline.

To address these knowledge gaps, it is recommended that movement-specific studies be initiated or expanded, using acoustic telemetry infrastructure (e.g. passive receiver arrays) and the tagging of individuals at sites outside the protected area. These data will be critical to assess functional connectivity between reefs in northern KwaZulu-Natal, along the broader east coast, and potentially between aggregation and pupping grounds. This work would complement and extend the current monitoring framework and directly support regional and national conservation objectives.

In summary, the findings presented here reinforce the value of site-level protection, the continued need for year-round monitoring, and the importance of integrated research strategies that connect local patterns with broader ecological processes. As pressures on marine species and protected areas increase, long-term, multi-method monitoring—combined with focused enforcement and regionally coordinated science—will remain essential to adaptive management and the persistence of this vulnerable species.

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Appendix

Appendix Figure A1.
Representative Remote Underwater Video Station (RUVS) frames captured at Quarter Mile Reef during the 2024 season.

Examples of diver non-compliance with the ragged-tooth shark Code of Conduct, groups are well inside the buffer zone.

Examples of divers showing appropriate positioning and buffer boundary adherence.

Appendix Document A2.

Ragged-tooth Shark Diving Code of Conduct (2025). Issued by the iSimangaliso Wetland Park Authority and Ezemvelo KZN Wildlife. This document outlines behavioural guidelines for recreational divers near aggregating *Carcharias taurus* individuals within the iSimangaliso MPA.

iSimangaliso Wetland Park | iSimangaliso Marine Protected Area | Ezemvelo KZN Wildlife

Ragged-tooth Shark Diving - Code of Conduct

Please adhere to the following code of conduct when encountering ragged-tooth sharks within the iSimangaliso Marine Protected Area.

- Keep 5m away from ragged-tooth sharks at all times
- Keep your movements to a minimum
- Stay together as a group, don't surround the sharks
- Don't descend onto the sharks or into their rest areas
- Don't swim under any overhangs or into caves where the sharks are resting
- Never swim after the sharks if they move off

Notice: 1/4 Mile Reef

Please stay outside of the 5m buffer area around this reef when sharks are present.