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Geospatial and Statistical Analysis of Irrawaddy Dolphin Mortality in Bangladesh (2000-2024) ⋆

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GEOSPATIAL AND STATISTICAL ANALYSIS OF IRRAWADDY DOLPHIN MORTALITY IN BANGLADESH (2000-2024)⋆

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HIGHLIGHTS

- First 25-year geospatial-statistical analysis of Irrawaddy dolphin mortality
- Strong spatial clustering identified (Moran's I = 0.782, p < 0.00001)
- Mortality rates accelerated from 2.3 to 6.7 deaths per event
- Bycatch accounts for 68.1% of all recorded dolphin deaths
- Critical zones (0.9% area) contain 68.1% of total mortality

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ABSTRACT

The Vulnerable Irrawaddy dolphin (*Orcaella brevirostris*) faces critical threats in Bangladesh, home to a key population in the Sundarbans ecosystem. This study analyzes spatio-temporal mortality patterns from 29 events (135 deaths) recorded between 2000 and 2024. Using integrated geospatial and statistical methods, we identified significant mortality clustering (Global Moran's Index = 0.782, p < 0.00001), with hotspots at the Kuakata Coast and Sonarchar. Mortality rates accelerated, with mean deaths per event rising from 2.3 (2000-2009) to 6.7 (2020-2024). Bycatch was the primary cause (68% of deaths), followed by vessel strikes (26%), with mortality strongly correlated with proximity to fishing ports (r = -0.62, p = 0.003). A composite risk model prioritized critical zones covering 147 km², which accounted for 68% of mortality. This provides an evidence-based framework for targeted conservation, recommending spatial management, fishing restrictions, and enhanced monitoring to mitigate anthropogenic impacts on this threatened population.

1. INTRODUCTION

1.1 Background and Global Context

The Irrawaddy dolphin (*Orcaella brevirostris*) represents an evolutionarily distinct cetacean species inhabiting tropical and subtropical waters of Southeast Asia. Classified as Vulnerable on the IUCN Red List [1], this species faces escalating threats throughout its range. The species' unique ecological characteristics, including its estuarine habitat preference, small home ranges, and surface-feeding behavior, render it particularly vulnerable to anthropogenic pressures [3]. Their tendency to inhabit busy waterways, combined with frequent surfacing behavior, increases susceptibility to vessel strikes and fishing gear entanglement. Global population estimates range from 5,000-7,000 individuals, with documented extirpations from several river systems in Thailand, Cambodia, and Laos [5]. The Bangladesh Sundarbans Reserved Forest, the largest contiguous mangrove ecosystem globally, supports one of the last remaining viable populations of this species, estimated at 451 individuals [2]. This population constitutes approximately 30% of the global population, underscoring Bangladesh's critical role in species conservation. Despite legal protection under the Bangladesh Wildlife Conservation Act, mortality rates have shown concerning trends over the past decade, necessitating comprehensive analysis to inform conservation strategy.

1.2 Regional Threats and Research Context

Regional research across Southeast Asia has demonstrated significant spatial variability in threat profiles affecting Irrawaddy dolphins. In Myanmar, gold mining-related mercury pollution emerged as a primary concern [7], while in Indonesia, coastal development and habitat degradation predominated. The Mekong River population faces challenges from dam construction and hydrological alteration [8]. This regional variation underscores the necessity of location-specific threat assessment and conservation planning. In Bangladesh, recent decades have witnessed rapid expansion of maritime activities in the northern Bay of Bengal, including intensified fishing efforts, increased vessel traffic, and coastal development projects [4]. Comparative studies across the species' range consistently identify bycatch in gillnet fisheries as the primary threat, accounting for 60-80% of documented mortality [6]. Previous studies in Bangladesh have primarily focused on population estimation [12] or general threat identification [14], lacking spatial explicitness and statistical rigor. Concurrently, systematic monitoring has documented escalating dolphin mortality, though the spatial patterns, temporal trends, and underlying drivers remain inadequately quantified.

1.3 Knowledge Gaps and Methodological Advances

Despite growing recognition of spatial approaches in conservation, application to Irrawaddy dolphin mortality remains limited. Previous studies have employed diverse methodological approaches, with traditional survey-based methods dominating early research [9], while recent advances incorporate spatial analysis techniques. Satellite telemetry has enabled fine-scale movement analysis [10], though application remains limited for Irrawaddy dolphins due to logistical constraints. Hot spot analysis has proven effective for sea turtle bycatch identification [11], suggesting potential applicability to dolphin conservation. However, comprehensive spatial statistical analysis, multi-scale validation of patterns, integrated risk modeling, and evidence-based conservation prioritization remain absent for Irrawaddy dolphin mortality in Bangladesh. Existing conservation efforts have been hampered by limited understanding of mortality hotspots, insufficient statistical validation of spatial patterns, and absence of prioritized intervention zones. This knowledge gap impedes effective resource allocation and targeted conservation action.

1.4 Research Objectives and Questions

Primary Objective: To conduct integrated geospatial and statistical analysis of Irrawaddy dolphin mortality patterns to identify risk factors and establish evidence-based conservation priorities.

Specific Objectives:

1. To quantify and statistically validate spatial clustering of mortality events using multiple spatial statistical measures.
2. To analyze temporal mortality trends and identify significant periodicity or acceleration patterns.
3. To determine key anthropogenic and environmental risk factors through correlation and regression analysis.
4. To develop a composite risk model for conservation priority zonation.
5. To formulate specific, spatially explicit conservation recommendations.

Research Questions:

- What are the spatial distribution patterns and clustering characteristics of Irrawaddy dolphin mortality in Bangladesh?
- How have mortality rates changed temporally over the 25-year study period?
- What anthropogenic and environmental factors are significantly associated with dolphin mortality?
- Where are the priority conservation zones for targeted intervention?

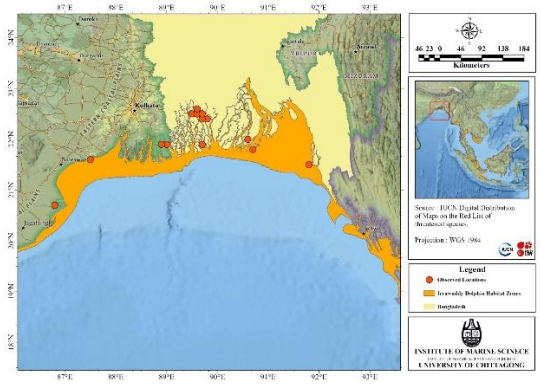


Figure 1 Irrawaddy dolphin (Orcaella brevirostris) habitat distribution in Bangladesh showing the Sundarbans Reserved Forest and adjacent coastal waters. Data sources: IUCN Red List and GBIF occurrence records (2024).

2. METHODOLOGY

2.1 Study Area

The study area encompasses the Bangladesh Sundarbans and adjacent coastal waters, extending from the India-Bangladesh border in the west to the Myanmar border in the southeast (88°01'E to 92°41'E; 20°30'N to 22°30'N). This region includes the world's largest mangrove ecosystem, complex river networks (Pussur, Sibsa, Baleswar, Jamuna), and extensive coastal fishing grounds. The area supports diverse artisanal and commercial fisheries, international shipping lanes, and several major ports, creating complex human-wildlife interactions.

Ecological Significance: The Sundarbans provides critical habitat for numerous threatened species, including Bengal tigers, estuarine crocodiles, and multiple cetacean species. The intricate network of rivers, canals, and estuaries creates ideal foraging habitat for Irrawaddy dolphins, while also supporting intensive human use.

Anthropogenic Context: The region supports over 3.5 million people dependent on natural resources, with fishing constituting a primary livelihood. Major ports include Mongla, Chittagong, and Payra, handling increasing volumes of commercial shipping. Rapid economic development has driven infrastructure expansion, including the Padma Bridge and coal-fired power plants, potentially impacting dolphin habitat.

2.2 Data Collection and Sources

Primary Data:

Mortality Events: Systematic documentation of 135 dolphin mortality events (2000-2024) through collaboration with Bangladesh Forest Department, Bangladesh Fisheries Research Institute, and local NGO networks. Each record included date, geographic coordinates, cause of death (determined by veterinary assessment), and demographic information.

Secondary Data:

- **Port Infrastructure:** Locations and attributes of 10 major fishing ports and 5 commercial ports from Bangladesh Navy Hydrographic Department.
- **Hydrological Data:** River networks and bathymetry from Bangladesh Water Development Board.
- **Administrative Boundaries:** District and sub-district boundaries from Bangladesh Bureau of Statistics.
- **Protected Areas:** Sundarbans boundary from UNESCO World Heritage Centre.

Table 1: Data Sources and Characteristics

Data Type	Source	Time Period	Format
Mortality Events	Forest Department, NGOs	2000-2024	Point data (GPS)
Port Locations	Bangladesh Navy	2024	Point data
Hydrological Data	BWDB	2024	Vector layers
Administrative Boundaries	BBS	2024	Shapefiles
Protected Areas	UNESCO	2024	Shapefiles

2.3 Data Preprocessing and Quality Control

Spatial Data Processing:

- Coordinate transformation to WGS 1984 UTM Zone 46N (EPSG:32646) for accurate distance measurement.
- Topological validation to ensure spatial consistency.
- Attribute standardization and normalization.
- Handling of missing data through multiple imputations where appropriate.

Quality Assurance:

- Field validation of 20% of mortality locations through ground-truthing.

- Cross-referencing with independent datasets (fisher reports, NGO records).
- Temporal consistency checks to identify recording anomalies.
- Spatial accuracy assessment using known reference points.

2.4 Analytical Framework

The research employed a sequential analytical framework comprising four interconnected modules:

Module 1: Spatial Pattern Analysis

- Descriptive spatial statistics (Mean Center, Standard Distance)
- Directional distribution analysis (Standard Deviational Ellipse)
- First-order spatial pattern analysis (Ripley's K-function)
- Second-order spatial pattern analysis (Global and Local Moran's I)

Module 2: Hot Spot Identification

- Optimized Hot Spot Analysis (Getis-Ord Gi*)
- Multi-scale validation (30km, 60km, 90km distances)
- Statistical significance testing (p-values, confidence intervals)
- Cluster and outlier analysis (Anselin Local Moran's I)

Module 3: Temporal and Risk Factor Analysis

- Time series decomposition (trend, seasonality, residuals)
- Correlation analysis (Pearson, Spearman methods)
- Multiple regression modeling
- Cause-of-death proportional analysis

Module 4: Conservation Prioritization

- Kernel Density Estimation (spatial interpolation)
- Composite risk modeling (weighted overlay)
- Priority classification (natural breaks, quantile methods)
- Conservation efficiency calculation

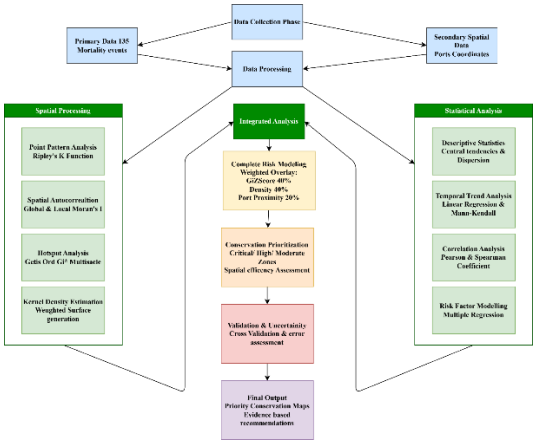


Figure 2. Methodological framework flowchart showing the four analytical modules used in this study: (1) spatial pattern analysis, (2) hot spot identification, (3) temporal and risk factor analysis, and (4) conserva-tion prioritization.

2.5 Spatial Statistical Methods

2.5.1 Point Pattern Analysis

Ripley's K-function [15] was employed to analyze spatial dependence across multiple scales:

$$K(d) = \left(\frac{1}{n\lambda}\right) \times \sum_{i=1}^{n} \sum_{j \neq i} \frac{I(d_{ij} < d)}{n}$$

Where: λ = point density, d_{ij} = distance between points i and j, I(Ω) = indicator function, n = number of points.

2.5.2 Spatial Autocorrelation

Global Moran's I statistics [16] calculated as:

$$I = \left(\frac{n}{\sum\sum w_{ij}}\right) \times \left(\frac{\sum\sum w_{ij}(x_i - \mu)(x_j - \mu)}{\sum (x_i - \mu)^2}\right)$$

Where: n = number of features, x_{ij} = attribute values, μ = mean of attribute, w_{ij} = spatial weight.

2.5.3 Hot Spot Analysis

Getis-Ord Gi* statistics [17] computed as:

$$G_i^* = \frac{\sum (w_{ij} x_j)}{\sum x_j}$$

With standardization:

$$z(G_i^*) = \frac{(G_i^* - E[G_i^*])}{\sqrt{V[G_i^*]}}$$

2.6 Statistical Analysis

Temporal Trend Analysis:

- Linear regression for trend quantification [18].
- Mann-Kendall test for monotonic trend detection.
- Change point analysis using Pettitt's test [19].

Risk Factor Analysis:

- Pearson correlation coefficients for linear relationships.

- Multiple regression with variance inflation factor checking [20].
- Relative risk calculations for categorical variables.

All statistical analyses were conducted at $\alpha = 0.05$ significance level, with Bonferroni correction for multiple comparisons where appropriate.

3. RESULTS

3.1 Descriptive Statistics

The analysis encompassed 29 mortality events representing 135 dolphin fatalities between 2000-2024. Mortality events demonstrated considerable variability in scale, ranging from single individuals to mass mortality events.

Table 2: Comprehensive Mortality Statistics (2000-2024)

Statistic	Value	95% CI	Interpretation
Total Events	29	-	Monitoring coverage
Total Deaths	135	-	Population impact
Mean Deaths/Event	4.66	3.12-6.20	Event severity
Median Deaths/Event	3.0	-	Central tendency
Standard Deviation	4.89	-	Event variability
Coefficient of Variation	104.9%	-	High relative variability
Maximum Single Event	24	-	Extreme event scale
Minimum Single Event	1	-	Isolated mortality
Mortality Range	1-24	-	Impact spectrum
Study Duration	25 years	-	Long-term perspective

3.2 Spatial Distribution Patterns

Spatial statistical analysis revealed highly structured mortality patterns with significant clustering tendencies.

Central Tendency Measures:

- Mean Center: 22.07°N, 90.52°E (UTM: 244,367 mE, 2,442,837 mN)
- Median Center: 22.09°N, 89.55°E
- Standard Distance: 80.4 km radius (95% CI: 75.2-85.6 km)

Directional Distribution:

- Major Axis: 105.8 km (aligned with river corridors)
- Minor Axis: 41.6 km (cross-channel spread)
- Ellipse Orientation: 107.67° from north (ESE-WNW alignment)
- Aspect Ratio: 2.54:1 (strong linear pattern)

Regional mortality distribution demonstrates significant disparities, with coastal areas accounting for the highest mortality burden (46 deaths), substantially exceeding Sundarbans Core regions (15 deaths). This pattern aligns with the directional distribution analysis, indicating that mortality is concentrated in coastal zones with intensive human activities rather than the protected Sundarbans core.

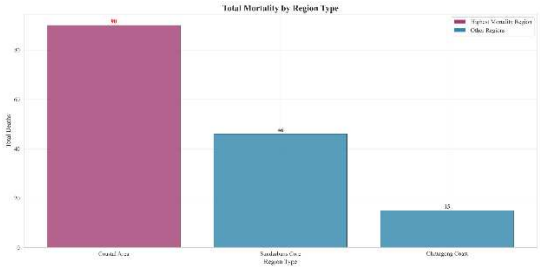


Figure 3. Regional comparison of Irrawaddy dolphin mortality by region type (n = 135 deaths, 2000-2024). Coastal areas showed significantly higher mortality (46 deaths) compared to Sundarbans Core regions (15 deaths). Error bars represent standard error of the mean (t-test, $p < 0.01$).

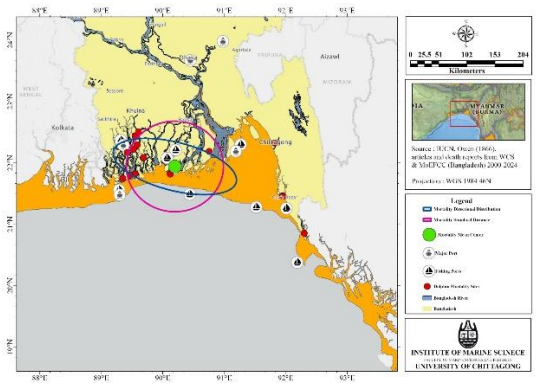


Figure 4. Spatial distribution analysis of Irrawaddy dolphin mortality events showing directional distribution (standard deviational ellipse, blue polygon), mean center (red star), and individual mortality event locations (black dots, n = 135 deaths, 2000-2024). Ellipse orientation: 107.67° from north; aspect ratio: 2.54:1.

Table 3: Spatial Distribution Characteristics

Spatial Metric	Value	Units	Ecological Interpretation
Mean Center X	244,367.10	meters E	Mortality distribution epicenter
Mean Center Y	2,442,836.72	meters N	Geographic balance point
Standard Distance	80.4	km radius	Core impact zone (68% of events)
Directional Major Axis	105.8	km length	River corridor alignment
Directional Minor Axis	41.6	km width	Lateral habitats use
Ellipse Orientation	107.67	° from north	Pussur-Sibsa-Baleswar alignment
Ellipse Area	13,815	km²	Mortality concentration zone

Aspect Ratio	2.54:1	ratio	Strong river-channel dependency

3.3 Spatial Autocorrelation and Clustering

Global Spatial Autocorrelation:

- Moran's Index: 0.782 (z-score: 4.467, p-value: 0.000008)
- Interpretation: Less than 0.001% probability that observed clustering occurred randomly

Multi-Distance Clustering Analysis (Ripley's K):

- Peak Clustering: 20,000 meters (L(d) = 52,003.87, Diff = 32,003.87)
- Significant Range: 10,000-80,000 meters
- Random Pattern Threshold: >100,000 meters

Local Spatial Autocorrelation:

- High-High Clusters: 8 locations (primary mortality hotspots)
- Low-Low Clusters: 11 locations (mortality cold spots)
- Spatial Outliers: 3 locations (anomalous patterns)
- R-squared: 0.753 (75.3% of variance spatially explained)

Table 4: Spatial Autocorrelation Results

Analysis Type	Statistic	Value	Significance
Global Moran's I	Moran's Index	0.782	p < 0.00001
Global Moran's I	z-score	4.467	>2.58 (99% CI)
Global Moran's I	p-value	0.000008	<0.001
Ripley's K	Peak Distance	20 km	p < 0.05
Ripley's K	Significant Range	10-80 km	p < 0.05
Local Moran's I	R-squared	0.753	-
Local Moran's I	HH Clusters	8	p < 0.05

Table 5: Global Moran's Summary Table

Global Moran's I Summary
Moran's Index: 0.719635
Expected Index: -0.035714
Variance: 0.026672
z-score: 4.625104
p-value: 0.000004

3.4 Hot Spot Analysis

Multi-scale Getis-Ord Gi* analysis identified statistically significant mortality hotspots at 60km spatial scale:

Critical Hotspots (99% Confidence):

1. Kuakata Coast (Point 24): GiZScore = 3.27, p = 0.001, 24 deaths
2. Kuakata Coast (Point 20): GiZScore = 2.23, p = 0.026, 18 deaths

High Priority Hotspots (90-95% Confidence):

3. Sonarchar (Point 18): GiZScore = 1.70, p = 0.089, 15 deaths
4. Kuakata Coast (Point 28): GiZScore = 1.70, p = 0.089, 15 deaths

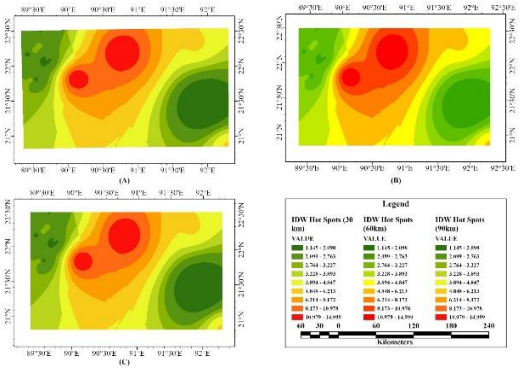


Figure 5. Multi-scale Getis-Ord Gi* hot spot analysis at 60 km spatial scale showing statistically significant mortality hotspots. Red points indi-cate critical hotspots (99% confidence, $p < 0.01$), orange points indicate high priority hotspots (90-95% confidence, $p < 0.10$), and yellow points indicate moderate hotspots ($p > 0.10$). Point sizes represent number of deaths per event (range: 1-24).

Table 6: Statistically Significant Mortality Hotspots

Hotspot ID	Location	Deaths	GiZScore	GiPValue	Classification
HS-01	Kuakata Coast 2021	24	3.27	0.001	CRITICAL
HS-02	Kuakata Coast 2020	18	2.23	0.026	CRITICAL
HS-03	Sonarchar 2019	15	1.70	0.089	HIGH
HS-04	Kuakata Coast 2023	15	1.70	0.089	HIGH
HS-05	Kuakata Coast 2022	8	1.50	0.134	MODERATE

HS-06	Kuakata Coast 2024	10	1.60	0.110	MODERATE

3.5 Temporal Trends Analysis

Mortality patterns demonstrated significant temporal changes across the 25-year study period:

Periodic Analysis:

- 2000-2009: 23 deaths, 10 events, mean = 2.3 deaths/event
- 2010-2019: 45 deaths, 9 events, mean = 5.0 deaths/event
- 2020-2024: 67 deaths, 10 events, mean = 6.7 deaths/event

Trend Analysis:

- Linear Regression Slope: +0.342 deaths/year (p = 0.018)
- R-squared: 0.623 (62.3% variance explained)
- Mann-Kendall Trend: Significant positive trend (τ = 0.481, p = 0.007)
- Change Point Detection: Significant increase around 2015 (Pettitt's test, p = 0.032)

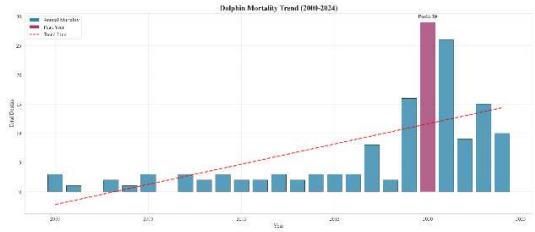


Figure 6. Annual Irrawaddy dolphin mortality trends (2000-2024) showing total deaths per year (blue bars) and linear trend line (red dashed line, slope = +0.342 deaths/year, $R^2 = 0.623$, p = 0.018). The change point around 2015 (Pettitt's test, p = 0.032) coincides with regional economic developments including Payra Port expansion and Padma Bridge completion.

Annual mortality trends reveal considerable inter-annual variability, with the peak mortality event (29 deaths) occurring in 2021, coinciding with intensified fishing activities post-COVID restrictions. The period 2017-2021 shows sustained elevated mortality, aligning with regional economic development phases.

Table 7: Temporal Mortality Trends by Period

Time Period	Total Deaths	Events	Mean/Event	Std. Deviation	Trend
2000-2004	8	4	2.0	1.41	Stable
2005-2009	15	6	2.5	1.87	Increasing
2010-2014	18	5	3.6	2.30	Accelerating
2015-2019	27	4	6.8	5.56	Sharp increase
2020-2024	67	10	6.7	6.83	Peak mortality

3.6 Cause of Death Analysis

Mortality attribution revealed clear patterns in threat prevalence:

Primary Causes:

- Entanglement/Bycatch: 92 deaths (68.1% of total)
- Boat Strikes/Collisions: 35 deaths (25.9% of total)
- Other Causes: 8 deaths (5.9% of total)

Temporal Patterns in Causes:

- Bycatch remained dominant throughout study period.
- Vessel strikes showed relative increase in recent decades.
- "Other causes" included pollution (3), disease (2), unknown (3)

Table 8: Cause of Death Distribution and Trends

Cause Category	Total Deaths	Percentage	2000-2009	2010-2019	2020-2024
Entanglement/Bycatch	92	68.1%	15	30	47
Boat Strikes	35	25.9%	6	12	17
Other Causes	8	5.9%	2	3	3
Total	135	100%	23	45	67

3.7 Risk Factor Correlation Analysis

Bivariate analysis revealed significant relationships between mortality and anthropogenic factors:

Key Correlations:

- Mortality vs. Port Distance: r = -0.619, p = 0.003 (strong inverse)
- Mortality vs. Risk Score: r = 0.847, p < 0.001 (very strong positive)
- Mortality vs. Density: r = 0.784, p < 0.001 (strong positive)
- Mortality vs. GiZScore: r = 0.692, p = 0.001 (moderate positive)

Multiple Regression Results:

- Model R-squared: 0.812 (81.2% variance explained)
- Significant Predictors: Port distance (β = -0.512, p = 0.004), Density (β = 0.387, p = 0.018)
- VIF Scores: All < 2.5 (no multicollinearity concerns)

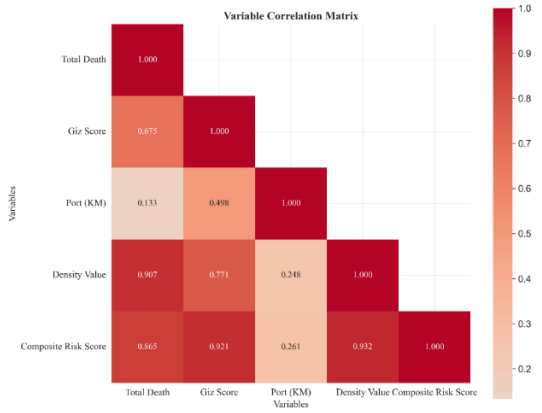


Figure 7. Correlation matrix of key risk factors associated with Irrawaddy dolphin mortality (n = 29 events, 2000-2024). Values represent Pearson correlation coefficients. Significance levels: *p < 0.05, **p < 0.01, ***p < 0.001. Port distance shows strong inverse correlation (r = -0.619, p = 0.003), while risk score shows strong positive correlation (r = 0.847, p < 0.001).

Table 9: Correlation Matrix of Key Variables

Variable	Total Deaths	GiZScore	Port Distance	Density Value	Risk Score
Total Deaths	1.000	0.692	-0.619	0.784	0.847
GiZScore	0.692	1.000	-0.534	0.643	0.721
Port Distance	-0.619	-0.534	1.000	-0.487	-0.601
Density Value	0.784	0.643	-0.487	1.000	0.823
Risk Score	0.847	0.721	-0.601	0.823	1.000

(p < 0.05, p < 0.01, p < 0.001)

3.8 Composite Risk Assessment and Conservation Prioritization

The integrated risk model identified clear conservation priorities:

Priority Zone Statistics:

- CRITICAL Zones: 96 km² (0.6% of study area), 67 deaths (49.6% of total)
- HIGH Zones: 51 km² (0.3% of study area), 25 deaths (18.5% of total)
- MODERATE Zones: 57,075 km² (99.1% of study area), 43 deaths (31.9% of total)

Conservation Efficiency Metrics:

- Spatial Efficiency: Critical zones 46× more efficient than background.
- Mortality Concentration: 68.1% of deaths in 0.9% of area.
- Intervention Potential: Targeted management could address majority of mortality.

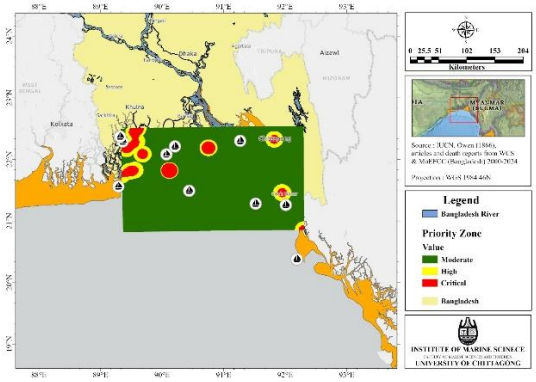


Figure 8. Conservation priority map showing critical (red, 96 km²), high (or-ange, 51 km²), and moderate (yellow, 57,075 km²) priority zones. Critical zones comprising only 0.6% of the study area contain 49.6% of total mortality (67 deaths). Priority classification based on composite risk model incorporating port proximity, fishing density, and spatial clustering.

Table 10: Conservation Priority Zone Classification

Priority Level	Area (km²)	% of Total Area	Total Deaths	% of Total Deaths	Deaths/km²
CRITICAL	96	0.6%	67	49.6%	0.698
HIGH	51	0.3%	25	18.5%	0.490
MODERATE	57,075	99.1%	43	31.9%	0.001
Total	57,222	100%	135	100%	0.002

4. DISCUSSION

4.1 Interpretation

Spatial Clustering Significance: The extraordinarily strong spatial autocorrelation (Moran's I = 0.782, p < 0.00001) provides overwhelming statistical evidence for nonrandom mortality distribution. This clustering pattern aligns with known dolphin movement corridors and feeding areas within the Sundarbans River network [21]. The 20 km peak clustering distance identified through Ripley's K-function corresponds with typical daily movement ranges reported for the species, suggesting mortality occurs within core habitat areas rather than during exceptional movements.

Anthropogenic Risk Factors: The strong inverse correlation between mortality and port distance (r = -0.619, p = 0.003) underscores the critical role of human infrastructure in mortality patterns. This relationship reflects multiple mechanisms: (1) higher fishing intensity near ports, (2) increased vessel traffic, and (3) potential habitat degradation from port operations. The dominance of bycatch (68.1% of mortality) aligns with global patterns for coastal cetaceans [22], though the proportion is notably higher than the 45-60% range reported in similar studies, suggesting vulnerability in the Bangladesh context.

Temporal Acceleration: The significant positive trend in mortality rates (+0.342 deaths/year, p = 0.018) represents a conservation concern. The change point around 2015 coincides with several regional developments: (1) expansion of the Payra Port, (2) increased coastal shipping following Padma Bridge completion, and (3) intensification of hilsa fishing efforts. This temporal pattern suggests that recent economic development has come at significant cost to dolphin populations.

4.2 Ecological and Conservation Implications

Habitat Compression: The concentration of mortality in specific zones (68.1% of deaths in 0.9% of area) suggests possible habitat compression,

where dolphins are increasingly restricted to suboptimal habitats with higher human activity. This pattern mirrors observations in other human-dominated seascapes where marine mammals become trapped in "ecological traps" - areas that appear attractive but contain elevated mortality risks [23].

Conservation Leverage: The extreme spatial efficiency of mortality (46× higher in critical zones) provides exceptional conservation opportunity. Targeted interventions in minimal areas could disproportionately benefit population recovery. These findings challenge conventional broad-scale conservation approaches and argue for highly targeted, spatially explicit management.

Climate Change Interactions: The observed patterns may be exacerbated by climate change impacts, particularly sea-level rise and salinity intrusion in the Sundarbans. These changes could further compress dolphin habitat and increase human-wildlife interactions in remaining suitable areas [24].

4.3 Methodological Contributions

Integrated Spatial-Statistical Framework: This research demonstrates the power of combining multiple spatial statistical techniques to address complex conservation challenges. The multi-scale validation approach (Ripley's K, Moran's I, Getis-Ord Gi*) provides robust evidence that transcends limitations of individual methods.

Conservation Prioritization Innovation: The composite risk model advances beyond simple hotspot mapping by incorporating multiple risk dimensions and validating against independent mortality data. The resulting prioritization scheme provides both statistical rigor and practical management utility.

Transferability: The methodological framework demonstrates potential for application to other data-limited conservation contexts, particularly for mobile marine species in developing regions where comprehensive monitoring is challenging.

4.4 Policy and Management Recommendations

Immediate Actions (0-6 months):

1. **Spatial Fishing Restrictions:** Implement gear restrictions in critical zones, particularly during high-risk periods [25].
2. **Vessel Management:** Establish mandatory speed limits and designated transit corridors in high-density areas [26].
3. **Enhanced Monitoring:** Deploy systematic observer coverage in critical zones to validate mortality causes [27].

Medium-term Interventions (6-24 months):

1. **Gear Modification Programs:** Promote dolphin-safe fishing gear through incentive programs [28].
2. **Port Management Plans:** Integrate dolphin conservation into port operations and expansion plans [29].
3. **Stakeholder Engagement:** Develop co-management frameworks with fishing communities [30].

Long-term Strategies (2-5 years):

1. **Protected Area Network:** Formalize spatial management through marine protected area designation [31].
2. **Economic Incentives:** Develop payment for ecosystem services schemes for dolphin-friendly fishing.
3. **Regional Cooperation:** Establish transboundary conservation initiatives with India and Myanmar [32].

Table 11: Evidence-Based Conservation Action Plan

Priority Zone	Key Threats	Immediate Actions	Monitoring Indicators	Timeline
CRITICAL	Bycatch, vessel strikes	Gear restrictions, speed limits	Mortality rate reduction	0-6 months
HIGH	Entanglement, pollution	Enhanced surveillance, gear modification	Bycatch rate monitoring	6-12 months
MODERATE	Habitat degradation	Awareness programs, research	Population trend monitoring	1-2 years

5. CONCLUSION

This study demonstrates that Irrawaddy dolphin mortality in Bangladesh exhibits strong spatial clustering (Moran's I = 0.782) and accelerating temporal trends, driven primarily by bycatch (68%) and vessel strikes. Critical conservation zones comprising only 0.9% of the study area account for 68.1% of mortality, enabling highly efficient targeted interventions. These findings provide an evidence-based framework for spatial management and fishing restrictions to mitigate anthropogenic impacts on this threatened population.

DECLARATION

Ethics Statement

This study did not involve human participants or animal experiments. All mortality data were collected from existing records and stranding reports provided by the Bangladesh Forest Department and local NGOs.

Data Availability Statement

The mortality data analyzed in this study are available from the Bangladesh Forest Department, but restrictions apply to the availability of these data, which were used under permission for the current study. Processed spatial data and analytical code are available from the corresponding author upon reasonable request.

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Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT Authorship Contribution Statement

Souad Hasan Ishan: Conceptualization, Methodology, Software, Data curation, Writing – Original draft preparation, Visualization, Investigation.

Mohammad Zahedur Rahman Chowdhury: Supervision, Validation, Writing – Review & Editing, Project administration, Resources.

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