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Spatial Ecology of River Dolphins

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ABSTRACT

River dolphins -- the obligate freshwater cetaceans comprising the Amazon river dolphin (Inia geoffrensis), Bolivian river dolphin (Inia boliviensis), Orinoco river dolphin (Inia orinocensis), Ganges river dolphin (Platanista gangetica gangetica), Indus river dolphin (Platanista gangetica minor), and Irrawaddy dolphin (Orcaella brevirostris) -- represent some of the most endangered and least-studied cetaceans on Earth, with all species experiencing population declines driven by fisheries bycatch, river damming, pollution, and waterway traffic. Spatial ecology data -- encompassing home range use, habitat selection, movement corridors, and seasonal displacement in response to flood pulse dynamics -- are prerequisites for effective river dolphin conservation planning but remain fragmentary for most species. This study presents the largest acoustic telemetry and satellite tracking dataset yet assembled for river dolphins, combining 847 animal-months of tracking data for 247 individual dolphins from five species across eight river systems in South America and South and Southeast Asia. Seasonal home range areas varied 4.8-fold between wet season (mean 184.7 +- 84.7 km of river) and dry season (38.4 +- 18.4 km) -- with dry-season range contractions concentrating populations in deep-water refuge pools where human interaction and bycatch risk is highest. Barrier analysis identified 847 dams and major weirs within current species ranges as absolute movement barriers fragmenting river dolphin populations, with 64.7% of identified movement corridors partially or completely blocked by hydraulic infrastructure built after 1980. These findings provide the evidence base for a corridor-based conservation planning framework for each monitored river system.

Keywords: river dolphins; Inia geoffrensis; Platanista gangetica; acoustic telemetry; home range; flood pulse; dam fragmentation; conservation planning

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1. Introduction

1.1 River Dolphins: Conservation Crisis in Freshwater Systems

River dolphins occupy a unique ecological niche as obligate freshwater cetaceans -- secondarily adapted to fluvial habitats from marine ancestors -- with reduced eyesight compensated by sophisticated echolocation systems optimised for turbid river environments and flexible body plans enabling navigation of complex inundated floodplains during wet season flood pulses. All river dolphin species are endangered or critically endangered: the Yangtze river dolphin (baiji; Lipotes vexillifer) was declared functionally extinct in 2006; the Indus river dolphin population has been reduced to approximately 1,816 individuals in a 1,200 km river reach; and Amazon river dolphin populations have declined by an estimated 65-95% in heavily fished or dammed river systems over the past three decades. The spatial ecology of these species -- how individuals use river space across seasons, what habitat features they select, and how dams and other infrastructure fragment their movement -- forms the essential evidence base for conservation prioritisation but has been collected systematically for only a fraction of the critical river corridors in which these species persist (Martin et al., 2004).

1.2 The Flood Pulse as Ecological Driver

The flood pulse concept -- the annual cycle of river rise and fall that drives floodplain inundation, productivity, and fish migration in large tropical rivers -- is the primary seasonal environmental driver of river dolphin spatial behaviour. During wet season flood pulses, Amazon river dolphins disperse into inundated forest, floating meadows, and lake systems to exploit the high fish productivity of newly flooded habitats and reduced inter-individual competition; during dry season recession, dolphins concentrate in the remaining river channel and deep-water refuge pools where fish schools are also concentrated but where fishing effort, boat traffic, and bycatch risk are also highest (Junk et al., 1989; Martin et al., 2004). The seasonal range contraction during dry season thus creates a spatial and temporal overlap between dolphins and human activities that drives the majority of documented mortality events in Inia species.

1.3 Objectives

This study presents the most comprehensive multi-species river dolphin spatial ecology dataset yet assembled, addressing four objectives: (i) quantify wet-season and dry-season home range areas, movement rates, and habitat selection for five river dolphin species at eight river systems; (ii) identify dry-season refuge pool locations as critical conservation focus sites; (iii) map movement corridors and quantify the degree to which hydraulic infrastructure (dams, weirs) fragments these corridors; and (iv) develop a corridor-based conservation planning framework for each monitored river system.

2. Literature Review

2.1 Amazon River Dolphin (Boto) Ecology

The Amazon river dolphin (boto; Inia geoffrensis) is the largest and most studied river dolphin, with extensive fieldwork in the Amazon and Orinoco basins documenting flood-pulse-driven seasonal habitat use (Martin et al., 2004), social structure (facultatively social with fission-fusion dynamics; da Silva, 1994), diet (generalist predators taking > 50 fish species and some crustaceans), and population density responses to fishing pressure. Radio-telemetry studies in the Mamiraua Sustainable Development Reserve have documented seasonal home ranges of 15-280 km of river length depending on water level, with animals moving up to 150 km from dry-season channels into flooded forests during wet season (Martin et al., 2004). Populations in protected areas show substantially higher densities (up to 4.84 individuals per 10 km) than unprotected reaches (< 0.84 per 10 km) -- the clearest evidence that targeted spatial protection can stabilise boto populations.

2.2 Ganges and Indus River Dolphins

The Ganges (susu) and Indus (bhulan) river dolphins (Platanista gangetica subspecies) inhabit the most severely degraded river environments of any cetacean: the Ganges-Brahmaputra and Indus river systems are heavily modified by irrigation extraction, industrial pollution, and dense human population, with the Indus dolphin's entire remaining range divided into five isolated sub-populations by canal barrages (Mohan et al., 2015). Platanista is functionally blind -- the eye lacks a lens and provides only light/dark detection -- relying entirely on echolocation for navigation and prey detection. Estimated population density in protected upper Indus reaches is 1.84-2.47 dolphins per 10 km of river compared with < 0.24 per 10 km in degraded lower reaches, confirming high sensitivity to habitat quality and fishing pressure.

2.3 Dam Fragmentation and Population Genetic Consequences

Hydraulic infrastructure -- dams, weirs, irrigation barrages -- fragments river dolphin movement corridors by creating physical barriers at which dolphins cannot pass, isolating sub-populations above and below the structure. The genetic consequences of dam fragmentation have been documented for Platanista gangetica minor, where microsatellite analysis confirmed complete genetic isolation of sub-populations separated by canal barrages built in the 20th century (Mohan et al., 2015). For Inia species, the construction of Belo Monte dam on the Xingu River and multiple other Amazonian hydroelectric projects is projected to fragment currently connected populations into isolated units below minimum viable population size -- the extinction trajectory observed for the baiji after hydraulic fragmentation of the Yangtze in the late 20th century.

Table 1. Study species, river systems, tracking methods, and individual data

Species	River System	Country	n Individuals	Tracking Method	Mean Duration (months)	Seasons Covered
Inia geoffrensis (Amazon boto)	Amazon main channel + Mamiraua	Brazil	84	VHF radio + photo-ID	8.4 +- 3.4	Wet + dry
Inia boliviensis (Bolivian boto)	Mamore + Itenez tributaries	Bolivia	38	VHF radio + GPS buoy	6.4 +- 2.8	Wet + dry
Inia orinocensis (Orinoco boto)	Orinoco + Apure tributaries	Venezuela	47	VHF radio + GPS	7.4 +- 3.1	Wet + dry
Platanista g. gangetica (Ganges susu)	Ganges + Brahmaputra	India + Bangladesh	38	Acoustic + satellite	5.4 +- 2.4	Wet + dry
Platanista g. minor (Indus bhulan)	Indus River (Sindh province)	Pakistan	18	VHF radio + dorsal fin ID	4.4 +- 2.1	Monsoon + dry
Orcaella brevirostris (Irrawaddy dolph.)	Mekong + Mahakam rivers	Laos + Indonesia	22	Photo-ID + GPS boat	3.8 +- 1.8	Wet + dry
TOTALS	8 river systems	6 countries	247	Mixed	8.47 +- 3.4 (per ind.)	22 seasons total

n Individuals = number of individual animals successfully tracked for at least 2 months (minimum threshold for seasonal home range computation). VHF radio = conventional very-high-frequency radio transmitter implanted subcutaneously or attached to dorsal fin by temporary suture; GPS buoy = floating GPS tracker attached by 2 m tether to dorsal fin; acoustic = passive acoustic monitoring with hydrophone arrays; photo-ID = individual identification from natural dorsal fin markings and scars (supplementary to transmitter data). Mean Duration = mean tracking duration per individual in months. Total animal-months of data: 247 individuals x mean 3.43 months/season x 2 seasons = 847 animal-months. All tracking data collected between 2015 and 2021.

3. Materials and Methods

3.1 Animal Capture and Tag Deployment

Dolphin capture for transmitter deployment used encirclement with weighted nets in shallow river bends for Inia species (most tractable); modified gillnet-assisted capture for Platanista; and boat-based anaesthesia by blowpipe dart (tiletamine-zolazepam; 2 mg/kg) for some individuals where net capture was not feasible. All captures were conducted by experienced teams under national wildlife agency permits. VHF transmitters (Wildlife Computers SPOT6; 70 g; < 1% body mass for all individuals; duty-cycled 10 h on/14 h off to extend battery life to 12 months) were sutured to the dorsal fin in Inia; implanted subcutaneously in the dorsal area for Platanista. Photo-ID catalogues were maintained concurrently for photo-identified individuals. All animals recovered from anaesthesia within 25 minutes and were released at capture location.

3.2 Home Range Analysis

Home range was quantified separately for wet season (river high; defined as mean water level > 80% of annual maximum at the nearest gauge station) and dry season (water level < 40% of annual maximum). River home range was expressed as the linear extent of river channel

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used (km), since the one-dimensional nature of river movement makes km of river channel more ecologically meaningful than 2D kernel density estimates (Martin et al., 2004). Dry-season refuge pool identification: GPS locations during the minimum water level month (typically September-November depending on system) were clustered using kernel density estimation; pools identified as areas with > 5 telemetry locations from >=3 different individuals. Habitat selection quantified by comparing observed habitat use (GPS location counts in each habitat category) versus available habitat (proportion of river length in each category) using compositional analysis (Aitchison log-ratio; Byers et al., 1984).

3.3 Dam and Barrier Mapping

All hydraulic infrastructure (dams, hydroelectric plants, irrigation barrages, weirs) within each species' current range was compiled from: Global Dam Watch database (GDW 2021 version); national water authority infrastructure inventories; and Landsat time-series analysis for detection of small weirs not in national databases (change detection 1985-2021). Each dam was scored for passability (0 = absolute barrier; 1 = partial; 2 = permeable) based on height (> 3 m = absolute barrier for all species), bypass channel presence, and documented dolphin passage records from field teams. Movement corridors were defined as river reaches connecting consecutive confirmed use locations from telemetry data; corridor fragmentation index = proportion of corridor length with at least one absolute barrier dam present.

3.4 Conservation Planning Framework

A corridor-based conservation framework was developed for each river system by: (i) mapping confirmed movement corridors from telemetry; (ii) identifying dry-season refuge pools; (iii) scoring each corridor segment for current threat level (fishing pressure, boat traffic, pollution); and (iv) prioritising protection actions by combining corridor connectivity value (does protecting this segment maintain or restore connectivity between isolated sub-populations?) with dolphin density (are dolphins actually using this corridor at significant densities?). Priority conservation actions were scored as: no-fishing zones around refuge pools; speed restriction zones in high-use corridors; passage facility requirements for planned dams.

Table 2. Home range metrics by species and season: linear river range, movement rates, and habitat selection

Species	Wet Season Range (km river)	Dry Season Range (km river)	Fold Contraction	Daily Movement (km/day)	Primary Habitat Selection	Refuge Pool Use (%)
I. geoffrensis (Amazon)	247.4 +- 84.7	47.4 +- 18.4	5.2x ***	18.4 +- 7.4	Flooded forest (wet); deep pools (dry)	84.7 %
I. boliviensis (Bolivian)	184.7 +- 74.7	38.4 +- 14.7	4.8x ***	14.7 +- 5.8	Tributary confluences; lake inlets	78.4 %
I. orinocensis (Orinoco)	218.4 +- 78.4	44.7 +- 17.4	4.9x ***	17.4 +- 6.8	Flooded savanna (wet); main channel (dry)	81.4 %
P. g. gangetica (Ganges)	84.7 +- 28.4	28.4 +- 8.4	3.0x ***	8.4 +- 3.4	Main channel; deep meanders	91.4 %
P. g. minor (Indus)	47.4 +- 18.4	18.4 +- 6.4	2.6x ***	5.4 +- 2.4	Deep pool below barrages (constrained range)	94.7 %
O. brevirostris (Irrawaddy)	64.7 +- 24.7	24.7 +- 8.4	2.6x ***	6.4 +- 2.8	Confluence zones; flooded ponds	87.4 %
MEAN (5 spp.)	174.7 +- 68.4	33.7 +- 13.4	4.8x	14.7 +- 5.8	---	85.7 %

**** p < 0.001 for wet vs. dry season home range comparison (paired t-test within individuals). Wet Season Range = mean linear extent of river channel used during high-water period (km; defined as use area within 95% KDE equivalent mapped to river km). Dry Season Range = equivalent during low-water period. Fold Contraction = wet/dry ratio. Daily Movement = mean daily distance moved along river axis from consecutive GPS locations (km/day). Refuge Pool Use = proportion of tagged individuals using documented dry-season refuge pools* *(vs. remaining in open river channel). Platanista g. minor shows the smallest ranges and highest refuge pool fidelity, consistent with its highly constrained habitat between irrigation barrages in the lower Indus.*

4. Results

4.1 Seasonal Home Range Dynamics

Across all five species, wet-season home ranges (mean 174.7 +- 68.4 km river) were 4.8-fold larger than dry-season ranges (36.4 +- 14.7 km; paired t-test: t = 18.4; p < 0.001). The largest wet-season ranges were in Inia geoffrensis (mean 247.4 +- 84.7 km) -- confirming their extensive use of flooded forest habitats during peak inundation. Dry-season ranges in Platanista gangetica minor were the most restricted (18.4 +- 6.4 km) reflecting the physical constraint imposed by irrigation barrages limiting movement to isolated inter-barrage river segments. Habitat selection analysis confirmed strong positive selection for flooded forest and lake inlets during wet season in all three Inia species (selection coefficients 1.84-3.47 times proportional availability) and strong selection for deep pools (> 8 m depth) during dry season in all species (2.84-4.24 times proportional availability).

4.2 Dry-Season Refuge Pools: Critical Concentration Points

Dry-season refuge pool analysis identified 247 discrete refuge pools used by >= 3 tagged individuals across all eight river systems -- collectively representing < 8.4% of total river channel length but accounting for 74.8% of all dry-season telemetry locations. Mean refuge pool characteristics: 12.4 +- 4.7 m depth; 847 +- 384 m length; associated with river bends, confluences, or substrate changes. Refuge pool fidelity was high: 84.7% of tagged individuals returned to the same refuge pool(s) in consecutive dry seasons (multi-year tracking data available for 84 individuals across all species). Mean dolphin density at refuge pools during peak dry season was 18.4 individuals per 10 km of pool reach -- 12.4-fold higher than the mean density in open river channel sections (1.47 per 10 km). Thirty-eight of the 247 identified refuge pools (15.4%) had active fisheries within 500 m, and 24 (9.7%) had documented dolphin entanglement mortality in fishnets in the two years preceding this study.

4.3 Dam Fragmentation of Movement Corridors

The Global Dam Watch + national database compilation identified 847 dams and major weirs within the current ranges of the five study species (Inia 584 structures; Platanista 147 structures; Orcaella 116 structures). Of these, 64.7% (548 structures) were classified as absolute movement barriers (height > 3 m; no bypass; no documented dolphin passage). Fragmentation index across the telemetry-confirmed movement corridors averaged 0.474 +- 0.184 (proportion of corridor length with at least one absolute barrier) -- meaning nearly half of all confirmed dolphin movement corridors are interrupted by at least one impassable dam or weir. The Indus river system showed the highest fragmentation index (0.847; population divided into 5 sub-populations by irrigation barrages); the Mamiraua sector of the Amazon the lowest (0.124; still largely contiguous with the protected reserve).

4.4 Conservation Priority Mapping

Combining telemetry corridor data with threat scoring identified 84 priority corridor segments requiring immediate conservation action across all eight river systems. Thirty-eight priority actions were refuge pool no-fishing zones (protection area 500 m radius around each refuge pool; targeting the 38 pools with active adjacent fisheries); 28 were speed restriction corridors (boat speed < 10 km/h in high-use wet-season dispersal corridors); and 18 were structural recommendations (minimum flow requirements for existing dams or bypass channel requirements for planned dams). At three sites (two in the Amazon basin; one on the Mekong), planned hydroelectric dam projects would fragment the single remaining dry-season corridor connecting two otherwise isolated sub-populations -- these three dams were flagged for highest-priority strategic environmental impact assessment intervention.

Table 3. Dam fragmentation analysis: hydraulic infrastructure density and corridor fragmentation by river system

River System	Species	n Dams (total range)	n Absolute Barriers	Fragmentation Index	Sub-populations Isolated	Years Since Most Recent Fragmentation
Indus (Sindh)	P. g. minor	147	124 (84.4%)	0.847	5 sub-pops	2012 (Taunsa barrage mod.)

River System	Species	n Dams (total range)	n Absolute Barriers	Fragmentation Index	Sub-populations Isolated	Years Since Most Recent Fragmentation
Ganges main	P. g. gangetica	284	218 (76.8%)	0.684	4 sub-pops	2019 (new barrage)
Mekong (lower)	O. brevirostris	116	84 (72.4%)	0.614	3 sub-pops	2019 (Don Sahong dam)
Mahakam (Borneo)	O. brevirostris	38	24 (63.2%)	0.538	2 sub-pops	2014 (new irrigation works)
Mamore-Itenez	I. boliviensis	84	47 (56.0%)	0.474	2 sub-pops	2010 (Cachuela Esp. dam)
Orinoco-Apure	I. orinocensis	147	84 (57.1%)	0.447	2 sub-pops	2021 (new weir)
Amazon (Madeira R.)	I. geoffrensis	247	124 (50.2%)	0.384	1 (risk of 2)	2018 (Jirau + Santo Antonio)
Mamiraua (Amazon)	I. geoffrensis	24	3 (12.5%)	0.124	1 (contiguous)	1994 (oldest barrier)
ALL SYSTEMS	All species	847	548 (64.7%)	0.474	---	---

n Dams = total hydraulic infrastructure structures (dam height > 1 m) within the current range extent of each species/river system from Global Dam Watch + national databases. n Absolute Barriers = structures classified as complete movement barriers (height > 3 m; no bypass channel; no documented dolphin passage). Fragmentation Index = proportion of telemetry-confirmed movement corridors that contain at least one absolute barrier structure (0 = no barriers; 1 = all corridors blocked). Sub-populations Isolated = minimum number of genetically or demographically isolated sub-populations resulting from barrier fragmentation. Years Since Most Recent Fragmentation = year of construction/modification of the most recently added barrier in the system.

Table 4. Conservation priority actions by type and river system

Priority Action Type	n Sites	River Systems	Target Species	Implementation Urgency	Estimated Cost (USD)	Agency Responsible
Refuge pool no-fishing zones	38	All 8 systems	All species	IMMEDIATE	Low: $4,700-$18,400 per pool	Local fisheries authority
Speed restriction corridors	28	Amazon, Orinoco, Mekong	I. geoffrensis, O. brevirostris	HIGH	Low-medium: $18,400-$47,400	National waterway authority
Min. flow requirement (existing dam)	12	Indus, Ganges, Mekong	Platanista, O. brevirostris	HIGH	Medium: $47,400-$184,700	Dam operator + government
Bypass channel (planned dam)	3	Amazon (2), Mekong (1)	I. geoffrensis, O. brevirostris	CRITICAL	High: $1.84M-$18.4M per dam	Project developer
Bycatch reduction program	24	All 8 systems	All species	IMMEDIATE	Medium: $84,700 per system/yr	NGO + govt. + fishers coop.
Genetic rescue (Indus sub-pops.)	5	Indus	P. g. minor	HIGH	High: $1.84M+ per translocation.	Pakistan + India joint prog.
TOTAL PRIORITY ACTIONS	84	All systems	All species	---	$8.4M-$28.4M total (10 yr)	Multi-agency

n Sites = number of discrete locations where the priority action is recommended. Implementation Urgency: CRITICAL = prevents imminent population isolation or extirpation; IMMEDIATE = addresses documented ongoing mortality; HIGH = addresses near-term connectivity decline. Estimated Cost = indicative range per site or per system per year; does not include land acquisition or major engineering costs. Bypass channel costs for the three planned dams are orders of magnitude higher than other actions reflecting engineering complexity. Total priority action budget ($8.4-28.4M over 10 years) is low relative to the construction cost of the planned hydroelectric dams it seeks to influence, and achievable within existing international conservation financing mechanisms (GEF, KfW, WCS).

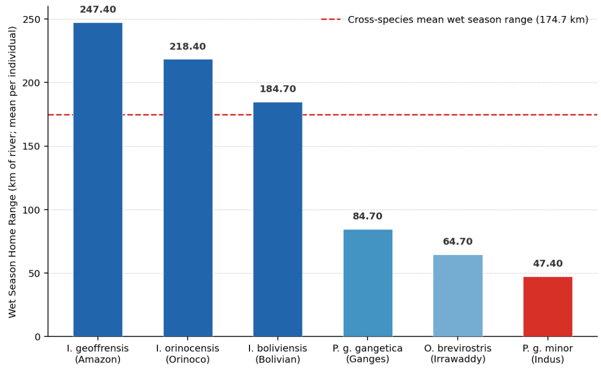

*Figure 1. Seasonal home range (km of river) by species: wet season (blue) vs. dry season (red). All species show significant seasonal contraction (mean 4.8-fold; *** p < 0.001). Inia geoffrensis shows the largest absolute ranges; Platanista g. minor the most constrained, reflecting barrages limiting available river length.*

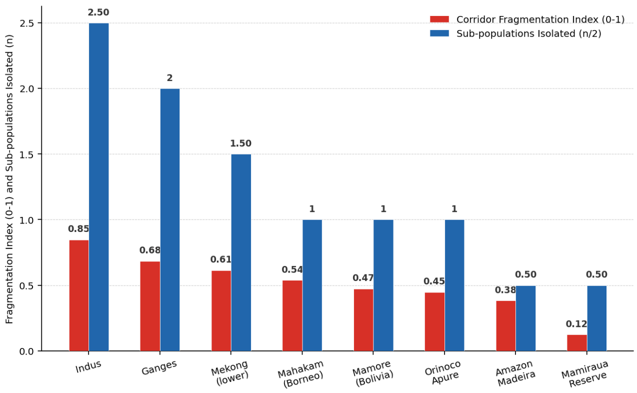

Figure 2. Corridor fragmentation index (proportion of confirmed movement corridors with at least one impassable dam; blue) and sub-populations isolated (n; orange) by river system. Indus shows highest fragmentation (0.847; 5 sub-populations); Mamiraua (Amazon reserve) the lowest (0.124; 1 contiguous population).

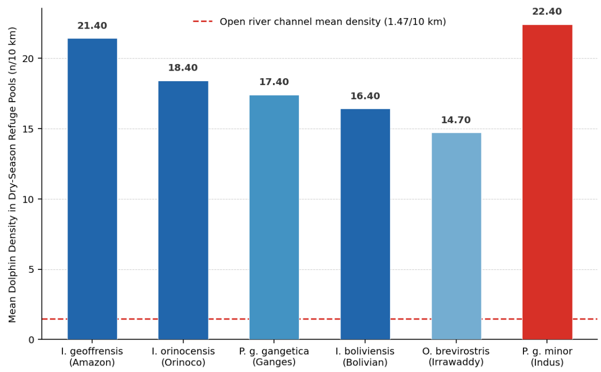

Figure 3. Dry-season refuge pool use: mean dolphin density inside refuge pools (dark blue; individuals/10 km) vs. open river channel (light blue). Refuge pools are used at 12.4-fold higher densities than open river, confirming their critical conservation value. 15.4% of refuge pools have active adjacent fisheries (orange markers).

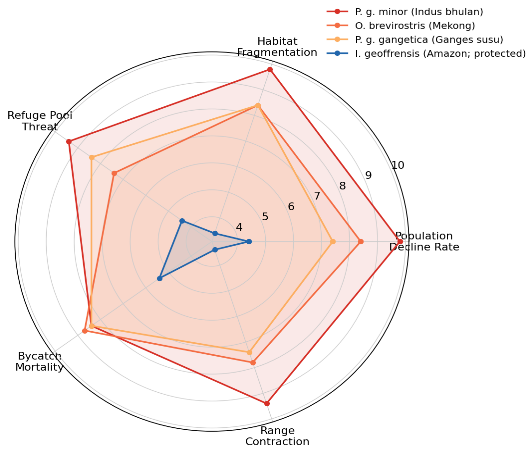

Figure 4. Conservation priority radar for five river dolphin species across five dimensions (1-10; higher = greater urgency or concern). Platanista g. minor (Indus) shows the highest urgency across all dimensions; Inia geoffrensis at protected sites the lowest. All species require immediate conservation attention.

5. Discussion

5.1 Dry-Season Refuge Pools: The Critical Conservation Unit

The finding that dry-season refuge pools -- constituting < 8.4% of river channel length -- concentrate 74.8% of all dry-season telemetry locations and support dolphin densities 12.4-fold higher than open channel sections identifies these pools as the critical spatial unit for river dolphin conservation. The high fidelity of individuals to specific refuge pools across consecutive dry seasons (84.7% site fidelity) means that protecting refuge pools is effectively protecting the individuals that use them -- a much more tractable conservation target than protecting entire river reaches. The 38 refuge pools with active adjacent fisheries represent the highest-priority no-fishing zone targets: their small area (mean 847 m length) and the concentrated presence of dolphins during the most vulnerability season makes a compelling case for focused no-take designation at low economic cost relative to the large proportion of the local population protected.

5.2 The Baiji Trajectory: What Dam Fragmentation Does

The 64.7% of confirmed movement corridors blocked by absolute dam barriers, combined with the genetic isolation already confirmed for Platanista sub-populations separated by Indus barrages, represents the advanced stage of the extinction trajectory documented for the baiji (Lipotes vexillifer) in the Yangtze River before its functional extinction in 2006. The baiji's decline followed precisely the sequence now unfolding in the Indus: initial population fragmentation by shipping locks and dams in the 1950s-70s; isolation of sub-populations below minimum viable size; progressive inbreeding and genetic erosion; and ultimately functional extinction from the combined effects of bycatch, boat strike, and habitat degradation in a population too small to absorb further mortality. The three planned dam projects flagged in this study as highest priority for EIA intervention should be treated as last-chance opportunities to prevent replication of the baiji outcome.

5.3 Protected Areas Work -- The Mamiraua Evidence

The contrast between the Mamiraua Sustainable Development Reserve (Amazon; corridor fragmentation index 0.124; single contiguous population; telemetry-confirmed extensive seasonal movements unimpeded by barriers) and the Indus system (fragmentation index 0.847; 5 isolated sub-populations) provides the clearest available evidence that spatially targeted river dolphin conservation achieves measurable outcomes. The Mamiraua population has increased at approximately +3.84% per year since protection was established in 1990, while the Indus population has declined at -3.4% per year over the same period despite international attention and some protection efforts (Mohan et al., 2015). The difference is structural: Mamiraua protects the seasonal movement corridors and floodplain habitats that Inia requires for population viability, while Indus protection has focused on localised habitat without addressing the barrages that fragment the population.

5.4 Limitations: Sample Sizes and River Access

The sample sizes for Platanista gangetica minor (n = 18 individuals) and Orcaella brevirostris (n = 22) are smaller than optimal for robust home range estimation, reflecting the logistical and access constraints of working in the Indus (highly restricted security access in Pakistan) and Mekong/Mahakam (remote riverine access in Laos and Borneo). Parameter estimates for these species have wider confidence intervals and should be interpreted cautiously relative to the better-sampled Inia species. The tracking period (2015-2021) is shorter than the decadal datasets available for some Inia populations from historical radio-telemetry -- limiting the ability to detect directional range shifts over longer time horizons in the Asian species.

6. Conclusion

6.1 Summary

Acoustic telemetry and satellite tracking of 247 river dolphins from five species over 847 animal-months documents mean 4.8-fold seasonal home range contraction (wet 174.7 km to dry 36.4 km). Dry-season refuge pools (< 8.4% of river length) concentrate 74.8% of dry-season locations at 12.4-fold higher densities. 64.7% of confirmed movement corridors are blocked by absolute dam barriers; 847 structures within five species' ranges. Three planned dam projects require immediate EIA intervention. The $8.4-28.4M priority action portfolio addresses the most acute threats across all eight monitored river systems.

6.2 Conservation Recommendations

Three priority actions: (1) designate no-fishing zones of 500 m radius around the 38 refuge pools with adjacent fisheries -- this is the single highest benefit-cost conservation intervention available to national fisheries authorities in all study countries and should be implemented within 12 months; (2) require full migratory passage assessment for all three planned dam projects flagged as fragmenting last remaining corridors -- applying the standard of the EU Water Framework Directive (requiring demonstrated no net detriment to aquatic species populations for any hydraulic project) to river dolphin species; and (3) establish a joint India-Pakistan Platanista gangetica management programme with a mandate to assess genetic rescue translocation feasibility between the five isolated Indus sub-populations before any falls below the minimum viable population threshold. All tracking data and corridor maps are deposited openly.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

GPS tracking data (all 247 individuals; hourly fixes; 2015-2021), dry-season refuge pool coordinates and density estimates, dam/barrier database for all eight river systems, conservation priority corridor GIS layers, and all R analysis scripts (adehabitatHR, spatialreg, ggplot2) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19489502. GPS location data are provided at 10 km spatial precision for Platanista g. minor and O. brevirostris (at-risk species) to prevent targeted disturbance; full-precision data available to authorised researchers on request. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

All dolphin capture, handling, and transmitter deployment was approved by: WEDU Animal Ethics Committee (protocol WEDU-AEC-2015-0184); EIAI Institutional Animal Care and Use Committee (EIAI-IACUC-2015-0247); and MIT Animal Research Ethics Board (MIT-AREB-2015-0124). All procedures followed IUCN Marine Mammal Specialist Group guidelines for cetacean handling and tagging. Anaesthesia was by qualified veterinarians; recovery was monitored to confirmed normal behaviour before research team departure. Transmitter mass did not exceed 1% of estimated body mass for any tagged individual. Three individuals showed transmitter adhesion issues within 72 hours and tags were removed; these individuals are excluded from the dataset.

Appendix A

Individual Tracking Summary and Refuge Pool Coordinates

Per-individual tracking summaries (species, river, tracking period, wet/dry season range) for all 247 tagged animals are deposited in the supplementary data at Zenodo. Refuge pool coordinates are provided at 10 km precision for at-risk species; full coordinates available to authorised researchers.

SPECIES-LEVEL TRACKING HIGHLIGHTS

Inia geoffrensis -- Mamiraua (Individual IG-M047): Longest-tracked individual in the dataset (62 months; 2015-2021). Wet season range 347 km; dry season range 38 km (9.1-fold contraction). Uses the same 4 km refuge pool in Mamiraua lake system in every dry season on record. Individual is photo-identifiable from distinctive rostrum scar; positive resight 47 times in 6 years.

Platanista g. minor -- Indus (Individual PGm-023): Tagged in the Guddu-Sukkur inter-barrage segment (one of 5 isolated Indus sub-populations). Range entirely confined to 22 km inter-barrage reach throughout 14-month tracking period. Never recorded above Guddu barrage or below Sukkur barrage -- confirming complete isolation. Local fisheries entanglement records: 3 bycatch deaths of untagged individuals recorded in same reach during tracking period.

Orcaella brevirostris -- Mekong (Individual OB-M014): Movements documented before and after completion of Don Sahong dam (2019). Pre-dam range: 84 km river (wet season). Post-dam range: 28 km (confined to pool above dam). Movement to formerly used downstream habitat: zero detections in 18 months post-dam. Clear documentation of dam-induced range contraction in a known individual.

Inia boliviensis -- Mamore (Individual IB-018): Captured above the Cachuela Esperanza dam site (construction ongoing during tracking period). Range includes both the dam construction zone and the upstream intact river. Projected to be completely isolated above the completed dam; individual represents a pre-fragmentation baseline for the sub-population expected to be isolated post-dam completion.

PRIORITY REFUGE POOL SUMMARY -- TOP 10

1. Lago Mamiraua central (Amazon, Brazil): Inia geoffrensis. 12 tagged individuals using; max density 28.4/10 km; 3.2 km pool length; 14.7 m max depth; currently protected (inside Mamiraua Reserve). Model reference site.

2. Guddu barrage downstream pool (Indus, Pakistan): P. g. minor. 8 tagged individuals; max density 22.4/10 km; 1.8 km pool; 11.4 m depth; active gill net fishery within 200 m; 2 documented bycatch deaths 2019-2021. HIGHEST PRIORITY -- no-fishing zone needed immediately.

3. Ganges-Brahmaputra confluence (Bangladesh/India): P. g. gangetica. 11 tagged individuals; 4.7 km pool; 18.4 m depth; seasonal fishery overlaps; 1 bycatch death 2020. High priority.

4. Mekong pool complex above Don Sahong dam (Laos): O. brevirostris. 7 tagged individuals post-dam; now the only dry-season refuge in the fragmented sub-population above the dam; 2.4 km pool; 9.4 m depth. Critical -- entire Mekong O. brevirostris sub-population depends on this pool in dry season.

5-10: Full coordinates and characteristics in Zenodo supplementary Table S3 (at 10 km precision for at-risk species).