Estimating Abundance, Habitat Use, and Acoustic Characteristics of Irrawaddy Dolphins *(Orcaella brevirostris)* in Chilika Lagoon

by

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DECLARATION

I hereby declare that the work conducted under the thesis entitled **"Estimating Abundance, Habitat Use, and Acoustic Characteristics of Irrawaddy Dolphins *(Orcaella brevirostris)* in Chilika Lagoon"**, is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Master's in Wildlife Science** at the **Academy of Scientific and Innovative Research**. This research work has been carried out under the guidance and supervision of **Dr. Vishnupriya Kolipakam, Scientist-D**, and co-supervision of **Dr. Gopi G.V., Scientist-F and Ms. Gargi Roy Chowdhury, Senior Project Associate, CAMPA-Dolphin** of Wildlife Institute of India, Dehradun. The work has not formed the basis for the award of any other degree, diploma, or any other qualification. I also declare that the thesis embodies my own work, analysis, observation, understanding and the particulars given in it are true to the best of my knowledge.

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CERTIFICATE

This is to certify that the thesis by **SAKSHI** entitled **"Estimating Abundance, Habitat Use, and Acoustic Characteristics of Irrawaddy Dolphins *(Orcaella brevirostris)* in Chilika Lagoon"** is an original and independent research work submitted to the **Academy of Scientific and Innovative Research**, for the award of the degree of **Master's in Wildlife Science**.

SAKSHI has put one semester of research work embodied in this thesis under my guidance and supervision. The work presented in this thesis has not been submitted to any other University or Institute for the award of any degree, diploma or distinction.

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CERTIFICATE OF PLAGIARISM CHECK

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This study provides a comprehensive assessment of the Endangered Irrawaddy dolphin (*Orcaella brevirostris*) in Chilika Lagoon, India, through an integrated approach combining visual and acoustic surveys, environmental modelling, and prey availability analysis. Visual line-transect surveys and passive acoustic monitoring (using FPODs) were used to estimate dolphin abundance and explore patterns of habitat use. Dive-time observations revealed that calves and non-calves differ in their diving behavior, with non-calves exhibiting longer and more variable dive durations. Mark-recapture analysis produced corrected abundance estimates ranging from 24 to 32 individuals, with variation influenced by observer mismatches and brief surfacing events. To assess prey availability, catch per unit effort (CPUE) surveys were conducted at 22 sites in collaboration with local fishers. The highest CPUE values were recorded in the high salinity area (Outer channel) and low salinity area (Northern sector), indicating these areas may offer better foraging opportunities. Prey community sampling across 11 sites revealed spatial differences in species richness and evenness, with some locations dominated by a few taxa and others exhibiting high diversity. Richness estimators suggested that the true species count exceeds what was observed, indicating under-sampling in certain areas. Environmental modelling using a negative binomial generalized linear model showed that salinity had a significant negative effect on dolphin acoustic detections, while dissolved oxygen and depth were positively associated but not statistically significant. The frequency ranged from 20 kHz to 200kHz with a median frequency of 98kHz. The interclick interval ranged from 850 millisecond to 1010865 milliseconds with a median of 23605 millisecond. The histogram for ICI displayed a positively skewed distribution, consistent with irregular click trains interspersed with longer pauses. The findings highlight the importance of salinity and prey availability in shaping dolphin distribution in Chilika Lagoon. The results support targeted conservation actions such as regulating freshwater inflow, protecting productive foraging zones, and expanding acoustic monitoring efforts to improve long-term management of this vulnerable population.

1. INTRODUCTION

1.1. **Overview of Ecological Importance, and Conservation Status**

Irrawaddy dolphins (*Orcaella brevirostris*) are Endangered coastal and estuarine cetaceans patchily distributed across South and Southeast Asia, with Critically Endangered subpopulations in three rivers (Minton, 2017). Irrawaddy dolphins in Southeast Asia are patchily distributed, isolated in riverine and coastal habitats, with populations in the Ayeyarwady, Mekong, and Mahakam rivers as described by Stacey & Arnold (1999) and Reeves et al. (2008). These small, fragmented groups face heightened risks from bycatch, habitat loss, and low calf survival, which further threaten their recovery (Smith & Tun, 2007).

It is a cryptic, euryhaline species within the family Delphinidae, inhabiting nearshore coastal waters, estuaries, lagoons, lakes, and river systems. In India, it is distributed as discrete subpopulations in Chilika Lagoon, Bhitarkanika, and Gahirmatha in Odisha, where it is locally known as ‘Khera', ‘Bhuasuni Magar’,‘Bashiyya Magar’ (oil-yielding dolphin) (Sinha, 2004; Mohanty & Otta, 2008; Sutaria, 2009 and Khan, 2015). It is also found in the Hooghly River and Sundarbans in West Bengal (Smith et al., 2006; Choudhury, 2020). The Southeast Asian distribution range comprises three major river systems: the Ayeyarwady River in Myanmar, the Mahakam River in Indonesian Borneo, and the Mekong River (Baird & Beasley, 2005). The two other subpopulations inhabit marine-connected brackish water bodies: Songkhla Lagoon in Thailand (Beasley et al., 2002) and Malampaya Sound in the Philippines. The Irrawaddy dolphin is known by various local names in Southeast Asian countries, such as 'Pa kha’, 'Pesut Mahakam' or 'Ikan pesut', 'Lumba lumba', 'Pla loma hooa baht', in Lao PDR, Indonesia, Malaysia, and Thailand, respectively (Watson, 1981; Baird & Mounsouphom,1994, Sinha, 2004). Irrawaddy dolphins exhibit a diverse diet, preying on both fish and invertebrates, including shrimp, prawns, and cephalopods (Postrado et al., 2019). They primarily use a range of clicks for communication, echolocation complements their eyesight for navigation and hunting, especially in conditions where visibility is limited or when prey is hidden (Tyack, 2000). The main threat to Irrawaddy dolphins is drowning in gillnets, which causes most recorded deaths across their range. Other significant threats include habitat loss from human activities, pollution, and increased boat traffic, all of which further endanger these already vulnerable dolphins (Beasley, Kreb, & Sutaria, 2019).

The Irrawaddy dolphin plays a vital role in maintaining the ecological balance of marine ecosystems. Irrawaddy dolphins are one of only a few cetacean species that regularly live in both marine and true freshwater environments. As a flagship species, their conservation can lead to broader efforts to protect their habitats and the diverse species that share these ecosystems, raising awareness about the importance of preserving marine biodiversity (Smith et al., 1997; Smith and Hobbs, 2002; Smith and Reeves, 2000a). Their presence in specific habitats, such as estuaries and coastal waters, serves as an indicator of the health of these environments, and monitoring their populations can provide valuable insights into ecological conditions and potential threats (Baird and Beasley, 2005). As apex predators, Irrawaddy dolphins regulate prey species populations, supporting the overall health of the aquatic environment. They contribute to nutrient cycling within their habitats by distributing nutrients through foraging and excretion, promoting the growth of various marine organisms. The Irrawaddy dolphins in Chilika Lagoon have been observed cooperating with artisanal fishers, herding fish toward stationary nets, resulting in significantly higher catch per unit effort of target fish (e.g., mullet) when dolphins are present (D'Lima et al. 2014). Irrawaddy dolphins support local economies through ecotourism, incentivizing conservation efforts and promoting sustainable practices in coastal communities (D'Lima et al., 2014). However, rapid urbanization, increasing global demand for fisheries, expanding maritime transport industry, threats of entanglement in fishing gears, and habitat loss undermine dolphins' resilience, leading to the call for their conservation (Weir et al. 2011).

The species is listed under Appendix I of CITES (2005), emphasising the urgent need for conservation efforts and the highest level of international protection against trade. Within the Indian legislative framework, Section 9 of the Wild Life (Protection) Amendment Bill, 2022, which amends the Wild Life (Protection) Act, 1972 (Act No. 53 of 1972), the Irrawaddy Dolphin *(Orcaella brevirostris)* is listed under Schedule I, prohibiting hunting and enforcing strict conservation measures (Lok Sabha, 2022). Implementing a holistic approach, including all possible management practices, is imperative to ensure their survival (Acharyya et.al, 2023).

1.2. Literature Review

Earlier surveys by the Chilika Development Authority (CDA, 2013 & 2021) and researchers reported ~89 dolphins in 2003, increasing to ~146 by 2009. The population dynamics of Irrawaddy dolphins (*Orcaella brevirostris*) in Chilika Lagoon, India, have raised serious conservation concerns, as mortality records between 2003 and 2009 reveal 72 dolphin carcasses with unidentified causes of death despite no major cyclonic events during that period (Sutaria et al., 2017). This unexplained mortality highlights the need to examine ecological stressors, predator-prey interactions, and anthropogenic threats.

1.2.1. Environmental Contaminants and Their Impact

Persistent organic pollutants (POPs) pose a major threat to the Irrawaddy dolphin populations globally. In Chilika Lagoon, substantial contaminant loads have been found in dolphin tissues (Kannan et al., 2005). Organochlorine pesticides, PCBs, and PBDEs were detected, with DDT concentrations reaching as high as 10,000 ng/g lipid weight in blubber. Although PCB and PBDE levels were lower than those in other Asian coastal dolphin populations, their presence still reflects significant bioaccumulation. Exposure to such toxins has been associated with compromised immune and reproductive functions in marine mammals (Colborn & Smolen, 1996). These findings necessitate targeted action to control DDT and HCH inputs into the lagoon.

1.2.2. Predation and Habitat Overlap with Bull Sharks

In addition to pollutants, biological threats such as predation from bull sharks (*Carcharhinus leucas*) may contribute to mortality. Bull sharks migrate 5-10 km into the outer channel during dolphin gestation periods, creating habitat overlap (Muntal et al., 2011). Shark-related dolphin mortality is estimated at 1-3% annually. Given the small estimated population of 146 individuals in 2009, even limited predation events may have long-term demographic impacts. Besides, prey depletion and ecological disruption may increase vulnerability to predation, emphasizing the need for ecosystem-level conservation strategies (Khan, 2015).

1.2.3. Emergence of Fibropapilloma and Disease Prevalence

Emerging diseases are another concern. A 2014 survey of six Irrawaddy dolphin populations reported a high prevalence (13.6%) of cutaneous fibropapillomas in Chilika Lagoon (Van Bressem et al., 2014). Histology showed hyperplastic epithelial lesions with thickened collagen bundles, confirming the disease. Notably, prevalence increased from 2.8% in 2004-2006 to 13.9% in 2009–2011 ($p = 0.00078$), suggesting deteriorating environmental conditions. POP exposure, previously detected in the population (Kannan et al., 2005), may impair immunity and increase disease susceptibility (Aguilar & Borrell, 1994; Ross et al., 2000; Hall et al., 2006; Reif et al., 2009).

1.2.4. Anthropogenic Threats: Illegal Gheries, Boat Traffic, and Macrophytes

Human activity significantly impacts dolphin habitat. About 11.3% of the lagoon area is covered by illegal man-made enclosures (gheries) for prawn aquaculture, particularly near the sea mouth and Palur canal. These reduce fishable areas and obstruct migratory species. Escaped hatchery fish from damaged enclosures during storms may introduce disease and genetic contamination into the wild population (Suresh et al., 2018).

Prolific macrophyte growth, particularly in the northern and central sectors of Chilika Lagoon, degrades habitat by restricting water circulation, disrupting fish movement, and promoting localized eutrophication, leading to hypoxia and biotic stress or mortality. The invasive macrophyte *Phragmites karka* (Nala grass), covering approximately 105.1 sq. km, significantly hinders navigation and negatively impacts the lagoon's trophic functioning, underscoring the urgent need for its removal to enhance ecosystem resilience (Suresh et al., 2018; Swain et al., 2022).

Motorized boat use, particularly for fishing and tourism, is another critical threat. Fuel spills, sediment resuspension, noise, and propeller strikes disturb the lagoon's sensitive ecosystem. Dolphins are frequently injured or killed due to gear entanglement (1.8% annual mortality) and boat strikes (1.5%) (Muntal et al., 2011). Unregulated dolphin tourism has worsened these impacts, pushing the limits of sustainability (Mustika et al. (2013).

1.2.5. Population Studies of Irrawaddy dolphins

Population studies of Irrawaddy dolphins have been conducted in specific habitats, including Chilika Lagoon (since 2003) and Bhitarkanika National Park and its adjoining areas (2005-2009 and 2015). These studies have provided insights into the distribution and abundance of Irrawaddy dolphins in these areas. For example, in Chilika Lagoon, the Outer channel, Central sector, and Southern sector are primary habitats, with approximately 60% of the population in the Outer channel. In Bhitarkanika, dolphins are found in specific areas, including Nalatiapatia, Dhamara, and near-shore coastal waters, often in groups of 2-18 individuals (Khan, 2015).

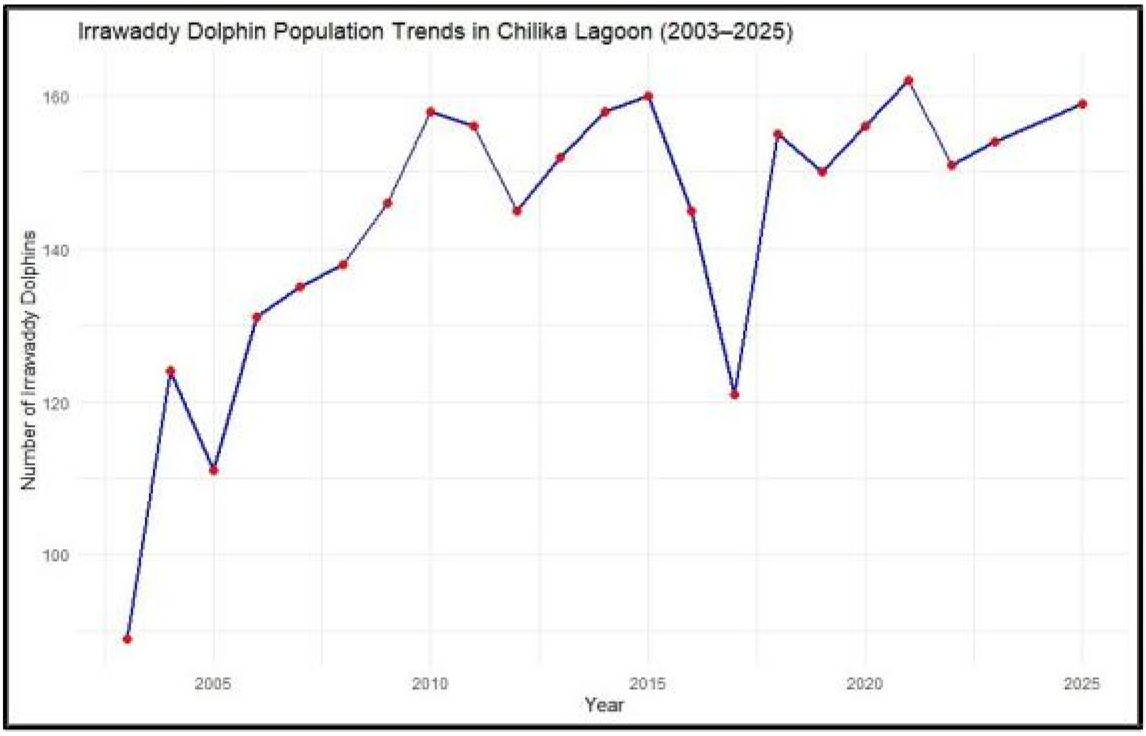

Figure 1. Compiled Irrawaddy dolphin Population Trends in Chilika Lagoon (2003-2025) from the reports of Chilika Development Authority (2013 & 2021) and The Department of Forest, Odisha (2025)

Year: Population	Year: Population	Year: Population
2003: 89	2004: 124	2005: 111
2006: 131	2007: 135	2008: 138
2009: 146	2010: 158	2011: 156
2012: 145	2013: 152	2014: 158
2015: 160	2016: 145	2017: 121
2018: 155	2019: 150	2020: 156
2021: 162	2022: 151	2023: 154
2025: 159		

Table 1: Irrawaddy dolphin Population Trends in Chilika Lagoon (2003-2025), rom the reports of Chilika Development Authority (2013 & 2021), The Department of Forest, Odisha (2025)

The quality of research is inherently tied to the methods employed, and studies on aquatic mammals, including Irrawaddy dolphins, are no exception. While research on cetaceans has experienced rapid growth in recent decades (Fumagalli, 2021), studies on Irrawaddy dolphins are surprisingly limited, with many suffering from non-replicable data and uncorrected biases. This scarcity of reliable research underscores the need for rigorous, bias-corrected studies on Irrawaddy dolphins, particularly in light of their endangered status and the unique challenges posed by their resource preferences and restricted range (Beasley, I., Kreb, D., & Sutaria, D., 2019).

Cetacean detection in line transects can be incomplete due to availability bias, where animals are underwater and undetectable, and perception bias, where animals on the surface are missed by observers (Marsh and Sinclair, 1989). Addressing these biases requires additional data collection and analysis. However, many studies have either assumed these biases are negligible or acknowledged that their estimates may be underestimated, as accounting for these biases can be complex and resource-intensive (Barlow, 2015; Gu & Swihart, 2004; Borchers et al., 2006).

Methods for estimating Irrawaddy dolphin populations, In Chilika, photo-ID mark-recapture studies estimated about 107–109 individuals (Sutaria 2009, D'Lima 2014), however the method is often challenging due to the scarcity of individuals with permanent markings. As a result, acoustic surveys have become a preferred approach (Richman et al., 2014).

Many studies have relied heavily on visual observations and direct counts, which are inherently limited by observer availability and detection constraints (Acharyya, 2020). For instance, population estimation surveys in Chilika Lagoon have been suspended due to weather conditions, highlighting the limitations of visual observations. Further, many studies have failed to correct for biases and errors, such as detection and recapture probabilities, which can lead to inaccurate population estimates.

Passive acoustic monitoring (PAM) can significantly enhance the detection of marine mammals compared to visual methods, especially in challenging environmental conditions, localizing and tracking individual animals requires high-quality, repeated signals and is subject to limitations in range estimation, particularly as the distance from the hydrophone array increases. Integrating PAM into line transect surveys allows for more comprehensive monitoring, but the ability to distinguish and assign vocalizations to individual animals remains a challenge in complex acoustic environments (Gillespie & Leaper, 2006).

Dawson et al. (2008) explored the application of smaller boats for surveys in coastal areas and rivers. When designing a line transect survey, the primary objective is to strike an optimal balance between minimizing bias and maximizing precision (Dawson et al., 2008). This is achieved by adhering to key assumptions, thereby minimizing bias and reducing variability in the component elements of the estimation calculation, including encounter rate, effective strip half-width, and mean group size.

1.3. Knowledge Gaps and Study Rationale

The proposed study aims to address the significant knowledge gaps in the current understanding of the Irrawaddy dolphin ecology and population dynamics in Chilika lagoon. Despite the conservation importance of this species, previous studies have been limited by methodological constraints, such as reliance on visual observations and direct counts, which are prone to errors and biases. Population estimates in many studies have been skewed due to uncorrected biases and errors. This study proposes to fill these knowledge gaps by employing a robust and systematic approach, incorporating acoustic surveys and advanced analytical techniques to estimate population size and utilization of its resources. By addressing the methodological limitations of previous studies, the research will integrate passive acoustic monitoring to understand the Irrawaddy dolphin's vocalizations and habitat use, while simultaneously minimizing observer bias and providing more accurate, comprehensive data on population dynamics and resource utilization (Muhamad, 2018).

1.4. Research Questions

1. What is the estimated population abundance of Irrawaddy dolphins in Chilika Lagoon, and how can a combined visual and acoustic survey approach correct for observer biases and unavailability bias?

2. What are the key environmental factors, prey resource availability, and anthropogenic threats influencing Irrawaddy dolphin habitat utilization in Chilika Lagoon?

3. What are the basic acoustic characteristics of Irrawaddy in Chilika Lagoon, as detected by F-POD (Full waveform capture porpoise detector) Passive Acoustic Monitoring (PAM) device?

1.5. Objectives:

1. To estimate the population abundance of the Irrawaddy dolphin using a combined visual and acoustic survey by establishing dive time, correcting for observer bias, and unavailability bias to ensure robust population estimates.

2. To investigate habitat utilization of Irrawaddy dolphin based on environmental factors (i.e., salinity, depth, turbidity, dissolved oxygen, electrical conductivity, flow, and temperature etc.), Prey availability, and anthropogenic threats (i.e., fishing pressure and boat traffic).

3. To understand the basic acoustic characterization of the Irrawaddy dolphins using a Passive Acoustic Monitoring (PAM) device: F-POD (Full Waveform capture porpoise detector)

2. STUDY AREA

2.1 Physical Geography

Chilika Lagoon, commonly referred to as Chilika Lake, is the largest brackish water body in Asia (Sinha, 2004). It is located along the eastern coast of India, extending across the southwest corners of Puri, Khordha, and Ganjam districts in the state of Odisha (Acharyya et al., 2023). Geographically, the lagoon is situated at 19°43′N and 85°19′E, originally covering an area of over 1165 km^2 (Figure 2). However, due to anthropogenic activities and natural sedimentation, its average area has reduced to approximately 760 km^2 (Ghosh & Pattnaik, 2005). The lagoon stretches about 65 km in length from northeast to southwest, parallel to the coastline, with an average width of 20 km. The average water depth is around 2 meters.

The western and southern margins of Chilika are flanked by the Eastern Ghat hill range, while the northern shore lies within Khordha district and the western shore within Ganjam district. Chilika Lagoon is hydrologically connected to the Bay of Bengal through several channels, with the primary water exchange occurring via lagoon mouths located in the southeastern Outer Channel. The Palur Canal, located to the south, also serves as an additional point of sea interaction. In September 2000, an artificial mouth was dredged in this sector to restore saltwater inflow, as the previous sea mouth had become choked due to siltation. To ensure continued connectivity with other parts of the lagoon and maintain a steady influx of seawater, a channel was also dredged and is regularly maintained to prevent siltation (Kim et al., 2015; Sutaria, 2009).

Freshwater input into the lagoon is primarily from tributaries of the Mahanadi River, notably the Daya, Nuna, and Bhargavi rivers, which enter the lagoon from the north. The region experiences bimodal monsoon seasons: the southwest monsoon from May to August and the northeast monsoon from November to December (Sarkar et al., 2012).

Based on Salinity and bathymetry, the lagoon is divided into four sectors namely, the southern sector, northern sector, central sector, and outer channel (Acharyya et al., 2023).

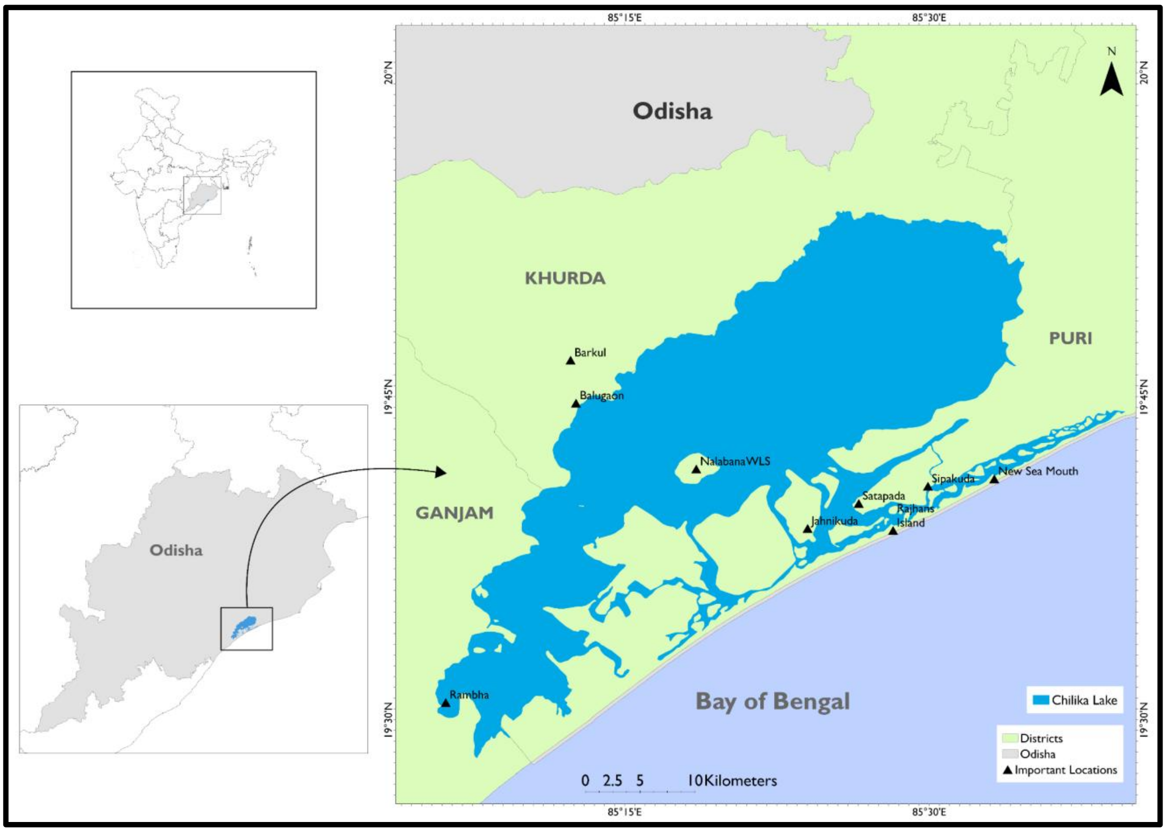

Figure 2. Map of study area in Chilika, extending across the southwest corners of Puri, Khordha, and Ganjam districts in the state of Odisha

Recognized for its rich biodiversity, Chilika Lagoon supports a unique assemblage of brackish water species and serves as a major habitat for millions of migratory waterfowl (Sarkar et al., 2012). Due to its ecological significance, it was designated as the first Indian wetland of international importance under the Ramsar Convention in 1981. The lagoon has also been classified under Category I of marine protected areas (Sarkar et al., 2012).

Irrawaddy dolphins in Chilika Lagoon exhibit a patchy distribution, with sightings concentrated in the Outer Channel, Central, and Southern sectors. Approximately 60% of the population is found in the Outer Channel, which provides deeper waters and direct access to the Bay of Bengal. High site fidelity has been documented among individuals, with over 80% consistently using specific zones within the lagoon (Sutaria, 2009). Given that Chilika hosts the largest known population of Irrawaddy dolphins in India, it was selected as the primary study site. Sampling and monitoring were strategically focused in areas of consistent dolphin presence to ensure ecological relevance and robust data collection on habitat use and acoustic behavior.

2.2 Socio-Economic Settings

The lagoon supports approximately 400,000 fishers and their families across more than 150 villages. Traditional fishing communities, including the Khatias, Keutas, Kandara, Niary, Tiaras, Kartias, Nolias, and Bengali refugees, have relied on customary fishing practices for generations (Sutaria, 2009). Fishing methods, such as Janao, Bhanao, Dian, Uthapani, and Dhaudi, are tailored to specific fish species and seasonal patterns（Pattnaik, 2007; Nayak & Berkes, 2014). The introduction of aquaculture enclosures (Gheris) and the use of fine-mesh nets, such as zero and alimi, have led to the depletion of juvenile fish stocks, threatening the sustainability of traditional fishing practices. Traditional fishing communities around Chilika Lagoon express deep concerns about the erosion of their customary fishing rights and the sustainability of their traditional practices, which are increasingly threatened by external pressures, including aquaculture expansion and policy changes favoring non-traditional fishers (Nayak, 2010).

In the early 1990s, policy reforms permitted non-fishing communities to lease lagoon areas for aquaculture, particularly shrimp farming. This shift led to the encroachment of traditional fishing grounds by non-fishers and elites, often backed by political and bureaucratic support. Traditional fishers faced displacement, loss of livelihoods, and erosion of customary rights. Despite legal interventions, including bans by the Odisha High Court and the Supreme Court, illegal aquaculture practices persist, affecting over 60% of the lagoon's fishing areas (Nayak, 2012).

Dolphin-watching has emerged as an alternative livelihood for approximately 1,000 families, with around 900 motorboats operated by community institutions. While this industry offers economic benefits, it also raises concerns about unregulated competition, misleading practices, and the impact on dolphin behavior. Tourists often report dissatisfaction due to fewer sightings (Acharyya et al., 2023). The dolphin-watching industry did not develop as part of a conservation strategy and was not managed by government agencies during its growth; it is owned by the people and has greatly helped during times of environmental change. The tourism linkage is strong from an economic perspective, but conservation outcomes from the linkage have not yet been realized (e.g., a cap on the number of boats or dolphin-watching guidelines). Traditional fishing rights and ownership are the key politics that influence all other activities in Chilika (Sutaria & Marsh, 2011).

3. METHODOLOGY

3.1. Dive Time

The dive time of a species refers to the average duration between two consecutive surfacings of an individual. To account for unavailability bias, it is necessary to determine the average dive time of Irrawaddy dolphins, ensuring that the boat moves at a steady speed to avoid counting the same individual twice.

The estimation of dive time was conducted through focal animal sampling across different age classes of Irrawaddy dolphins. Each sampling session lasted 15 minutes, during which the timing and duration of each surfacing and submergence event was recorded. A total of 50 trials were carried out for each selected individual. The study encompassed 25 individuals, comprising 16 non-calves and 9 calves. We collected 331 dive time observations. These data were analyzed to understand surfacing patterns, contributing valuable insights into their movement ecology, habitat utilization, and breath-holding capacity (Williams, 1999; Braulik et al., 2012).

3.2. Abundance Estimation

The abundance estimation of Irrawaddy dolphins in Chilika Lagoon was conducted over three consecutive days in January 2025 during the annual dolphin census organized by the Chilika Development Authority (CDA) and the Odisha Forest Department. Our team independently conducted tandem boat surveys combined with the modified capture-recapture framework, following the protocols established by Qureshi et al. (2020). A total of eighteen transects were distributed across Chilika Lagoon as per CDA protocol, out of which our team was distributed in four groups: OC6, OC4, SS1, and CS1 (Figure 3), representing diverse sectors (i.e, outer channel, southern sector and central sector).

To ensure independent detections, two boats operated simultaneously in tandem formation, maintaining a consistent distance of approximately one kilometer between them. Both vessels moved in parallel at a controlled speed of around 8 km/h. This speed was selected based on the dive-time estimates of Irrawaddy dolphins to reduce the likelihood of either double-counting the same individual or missing brief surfacings (Braulik et al., 2012).

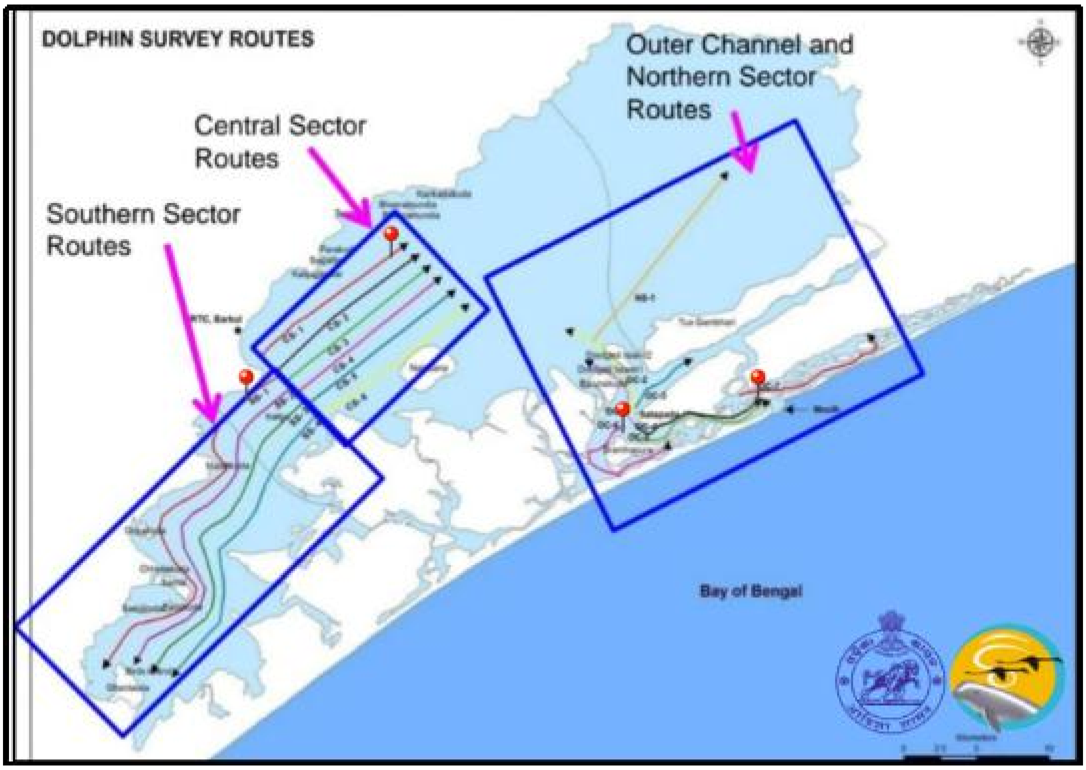

Figure 3. Map showing 18 dolphin survey transects across Chilika Lagoon, CDA (2004). Red pins mark sites (OC6, OC4, SS1, CS1) surveyed by our team across the Outer Channel, Southern, and Central sectors.

Each survey vessel was crewed by a team of three individuals: two stationed at the front, responsible for scanning left and right visual sectors (0-90° and 90-180°, respectively), with one recorder additionaly one observer the rear to cover the aft field of view and detect any missed sightings. one recorder were centrally positioned to document observations systematically. A protractor was mounted at the front observation deck with the 90-degree mark aligned with the center of the deck to ensure accurate angle measurement. Observers continuously scanned their designated sectors and relayed sighting information in real-time to the recorder.

For every dolphin sighting, the team recorded the angle and estimated distance to the animal, its presumed age class, the sighting time, boat speed, and odometer readings. GPS coordinates and compass bearings were logged. To address variability in human distance estimation, observers went through a calibration exercise before the surveys, during which they estimated the distances to known markers placed at different locations in the lagoon. These trials helped correct for ocular distance estimation bias across observers.

To supplement visual detections and account for animals that may not surface during the observation window, each boat towed a Passive Acoustic Monitoring (PAM) device, the A-tag. This device recorded dolphin echolocation clicks and enabled the detection of individuals who remained submerged during the boat's passage. The inclusion of acoustic data helped reduce availability bias and allowed for a more comprehensive and reliable estimation of population size (Braulik et al., 2012).

All collected data were analyzed using both distance sampling and a modified capture-recapture method based on the Lincoln-Peterson framework. The number of dolphins sighted independently by each boat, along with the number of matched sightings (recaptures), was used to estimate the population size following the Modified Chapman's Estimator (Anne et al., 2008; Brittain et al., 2009).

$$N\hat{} = \left(\frac{(n_p + 1)X(n_s + 1)}{m_{ps} + 1}\right) - 1$$

Where,

$N\hat{}$ = Population size estimate

n_p = The number of animals sighted by the primary observer team (1st boat)

n_s = The number of animals sighted by the secondary observer team (2nd boat)

m_{ps} = Number of animals sighted by both teams (matches or recaptures)

The probability of detection is estimated as

$$\boldsymbol{\frac{m_{ps}}{n_p} \; and \; \frac{m_{ps}}{n_s}}$$

The associated variance (Seber, 1982),

$$V = \frac{(n_p + 1)X(n_s + 1)X(n_p - m_{ps})X(n_s - m_{ps})}{(m_{ps} + 1)^2 X(\, m_{ps} + 2)}$$

The method depends on two key assumptions: (i) all dolphins surfacing within the observers' visibility range are detected by both teams, and (ii) all dolphins in the survey area surface at least once during the survey**.** The double-observer method can reduce bias (Buckland et al., 2001). The integration of acoustic and visual datasets helped strengthen the estimates, particularly for this cryptic and mobile species. This method has refined the understanding of the Irrawaddy dolphin population’s status and detectability in Chilika Lagoon.

3.3. Prey Availability and Fish Community Survey

To assess prey availability across different ecological zones of Chilika Lagoon, a Catch Per Unit Effort (CPUE) method was used. The survey spanned 22 strategically selected sites across the Outer, Central, Northern, and Southern sectors of the lagoon, representing a range of habitat types and salinity regimes relevant to Irrawaddy dolphin habitat use.

At each location, field visits were synchronized with ongoing fishing activity. Local fishers were respectfully approached to participate in a brief questionnaire survey while their fishing sessions were observed in real time. Their consent and insights provided essential context to the catch data, such as gear type, fishing method, and effort duration.

Fishing effort was primarily concentrated around traditional gill net use, which was observed at major fishing hubs such as Satapada, Sipakuda, Kalijai, Nalabana, Kankau, and Barkul. Additionally, cast nets were recorded at sites including Near Sea Mouth, Mini Kalijai, and Magarmukh, while disco nets, a type of lift net, were observed near Pathara. The duration of fishing effort per site ranged from 0.03 hours to 6 hours, depending on gear type, tidal conditions, and fisher activity.

Catch Per Unit Effort (CPUE) was calculated as the total catch (in kilograms) divided by the hours of fishing effort, providing a standardized metric of fish biomass and productivity at each site (Sparre & Venema, 1998; D'Lima, 2014). This approach allowed for categorical spatial comparisons of prey availability across lagoon sectors. For example, Satapada, Sipakuda, and Near Sea Mouth emerged as sites with the highest CPUE values (18 kg/hr, 15 kg/hr, and 13.4 kg/hr, respectively), suggesting that these areas are more productive in terms of available fish resources. In contrast, locations such as Near Pathara and Nalabana recorded markedly lower CPUE values (as low as 0.07 to 0.53 kg/hr), potentially due to reduced fish abundance or accessibility constraints imposed by vegetation or sedimentation.

Other than quantifying fish biomass, observations were made on species richness and diversity, capturing data on fish community composition and identifying the prey base of Irrawaddy dolphins. These data were used to assess regional variation in habitat quality, with particular emphasis on how prey availability may influence dolphin distribution patterns and foraging within the lagoon.

Prey availability survey provides ecological inference into spatial differences in fish abundance, gear-specific catch rates, and fisheries productivity, which were integrated into broader analyses of dolphin habitat use. As Irrawaddy dolphins are opportunistic feeders, understanding the distribution of their prey base is essential for conservation planning and management of this endangered population.

3.4. Boat Traffic Assesment

To assess the boat traffic, a combination of mobile and stationary surveys was conducted across 64 sites spanning various habitat types and use zones. Surveys were carried out exclusively during daylight hours, over multiple sessions at each site, to capture variability across time and space. Both survey approaches aimed to systematically document vessel activity and its overlap with dolphin presence across the lagoon.

At each site, the number and types of boats were recorded, with vessels broadly categorized into tourist boats, fishing boats, and passenger ferries. Simultaneously, environmental variables such as water depth and dominant habitat type were documented to assess how physical conditions may influence traffic intensity. The surveys also recorded any dolphin sightings, including time of sighting and location, to allow for later correlation analyses between vessel presence and dolphin distribution.

Each data point was geo-referenced using GPS coordinates, and both the type of survey (stationary or mobile) and survey effort (duration and timing) were logged. This standardization ensured that boat traffic data could be accurately compared across sites and sessions.

3.5. Environmental Drivers of Dolphin Presence

To investigate the environmental factors influencing Irrawaddy dolphin presence, the FPODs were deployed in selected 15 monitoring sites, distributed across the four sectors of the lagoon, representing variations in depth and salinity: the Outer Channel (6 sites), Central Sector (5 sites), Southern Sector (2 sites), and Northern Sector (2 sites). This design allowed for the inclusion of both spatial and environmental heterogeneity in assessing habitat use patterns.

FPODs were deployed at each site for a period of 3 to 5 days, based on the minimum effort threshold established in previous studies (Kolipakam et al., 2022), ensuring sufficient acoustic data to capture diel and short-term variability. All devices were submerged around 3m-4m and set up for continuous recording, enabling the detection of dolphin echolocation clicks. Upon retrieval, total deployment hours per site were calculated to account for variation in effort and to allow for standardized comparisons across locations.

The primary acoustic metric derived from the FPOD data was Detection-Positive Minutes per hour (DPM/hour), which served as a proxy for relative dolphin presence or activity at each site. This effort-corrected measure was chosen to control for differences in deployment duration and to enable consistent interpretation across habitats.

To assess the influence of environmental variables on dolphin presence, dissolved oxygen, depth, and salinity measurements were recorded at each deployment site using a depth sounder, D.O meter, and Salinity refractometer. These variables were scaled (mean-centered and standardized) to ensure comparability and avoid multicollinearity during modeling. The acoustic data (DPM/hour) were then modeled using a negative binomial Generalized Linear Model (GLM), which accounts for overdispersion, a common issue in ecological count data where variance exceeds the mean.

In addition to continuous modeling, dolphin detections were categorized into ordinal groups (low, medium, and high presence) based on DPM/hour quantiles. A chi-square test was performed to examine whether dolphin presence categories differed significantly across sectors or environmental conditions.

3.6. Passive Acoustic Characterization

To investigate the habitat use patterns of Irrawaddy dolphins and document their acoustic presence, a Passive Acoustic Monitoring (PAM) approach was employed using FPODs (Full-spectrum Porpoise Detectors) developed by Chelonia Ltd. These devices were strategically deployed at selected sites that spanned different depth and salinity profiles to assess environmental variability in dolphin occurrence.

At each treatment location, three FPODs were deployed simultaneously for a period of 3 to 5 days per unit. This deployment duration was selected based on prior research on the Ganges river dolphin (Kolipakam et al., 2022), which determined that a minimum of 72 hours is adequate to capture diel and environmental variation in habitat use. To ensure spatial independence and reduce overlap in detection ranges, FPODs within similar habitat categories were positioned at a minimum distance of 2 km from one another.

Following retrieval, data were processed using FPOD.exe software to extract detection metrics and basic acoustic characteristics such as click frequency, inter-click interval (ICI), and detection-positive minutes (DPM). These acoustic data were then standardized by effort to produce DPM per hour, which served as a proxy for relative dolphin presence at each site.

To analyze the environmental drivers influencing dolphin detections, a negative binomial generalized linear model (GLM) was implemented. This statistical approach was appropriate given the overdispersed nature of the count data (DPM/hour). The model included scaled continuous predictors: depth (m), dissolved oxygen (mg/l), and salinity (ppt), and employed a log link function to model the relationship between environmental variables and dolphin detections.

This combined methodology, integrating passive acoustic monitoring with environmental modelling, allowed for a spatially and temporally robust assessment of habitat use. It provided insights into how physicochemical parameters structure dolphin distribution across the lagoon ecosystem.

4. RESULTS & DISCUSSION

4.1. Dive Time

A total of 331 dive observations were recorded for Irrawaddy dolphins across different locations and times of day, enabling them to explore how dive duration varies with age class (calf vs. non-calf) and depth. Our preliminary analysis suggested that non-calves generally exhibited longer and more variable dive durations compared to calves.

To test whether age class significantly influenced dive time, a Welch two-sample t-test was conducted (Table 2). Non-calves had a mean dive duration of 34.12 seconds (SD = 34.57), while calves had a shorter mean duration of 26.34 seconds (SD = 30.58) (Table 2). Although the difference of approximately 7.78 seconds approached significance, the result was not statistically significant at the 0.05 level ($p = 0.061$), indicating a trend rather than a strong effect.

Age Class	Dive Duration (mean ± SD, sec)
Calf	26.34 ± 30.58
Non-Calf	34.12 ± 34.57

Table 2. Mean dive durations (± SD) of Irrawaddy dolphin calves and non-calves, showing longer average dive times in non-calves.

To further investigate this pattern and account for other predictors, linear regression models (Tables 3) were run. Model 1 included only age class as a predictor. The estimate showed that non-calves dived, on average, 7.79 seconds longer than calves, but again, this effect was marginally significant ($p = 0.0732$). The model had very low explanatory power (adjusted $R^2 = 0.008$), indicating that age alone accounted for little of the observed variation.

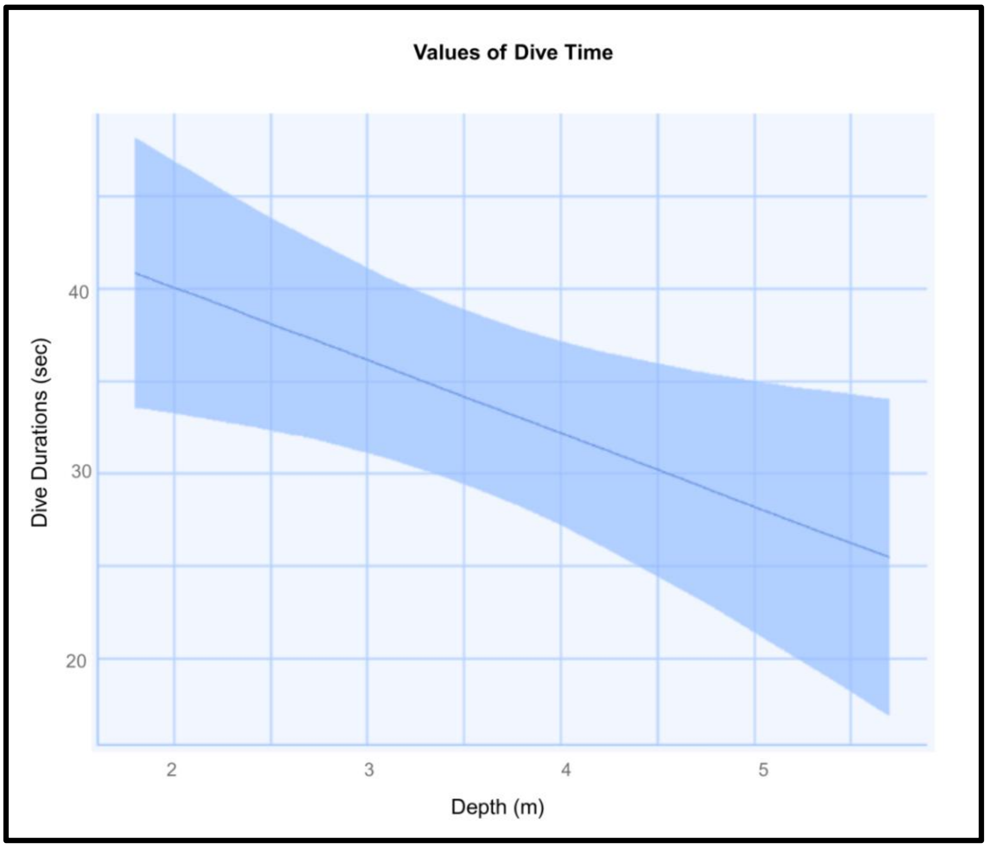

Figure 4. Relationship Between Dive Depth and Dive Duration.

Model	Predictors	Estimate	Std. Error	t-value	p-value	R² / Adj. R²	Residual SE (df)	AIC
Model 1: Linear Model	Age Class (Non-Calf vs Calf)	7.79	4.33	1.798	0.0732	0.012 / 0.008	33.4 (df = 277)	2753.5
Model 2: Linear Model	Age Class (Non-Calf vs Calf)	8.15	4.3	1.896	0.059	0.031 / 0.024	33.12 (df = 276)	2749.83
	Depth (m)	-3.95	1.66	-2.379	0.0180 *			

Table 3. Summary of linear regression models showing the effects of age class and depth on dive duration in Irrawaddy dolphins.

Model 2 incorporated dive depth as a second predictor. Depth had a significant negative relationship with dive duration (p = 0.018), suggesting that for every 1-meter increase in depth, dive time decreased by approximately 3.95 seconds. This model slightly improved fit (adjusted $R^2 = 0.024$), yet still explained a modest proportion of the variation, typical for behavioral datasets where many uncontrolled factors may influence the outcome.

The visual (Figure 4) and statistical results reveal that dive time is weakly but consistently influenced by both age and depth. Non-calves tended to dive for longer periods and with greater variability, while deeper waters were associated with shorter dive durations overall (Figure 5 & Table 4). Although the models explained only a small proportion of the variance, they offer biologically meaningful insights. Specifically, calves may perform shorter and more uniform dives due to physiological limitations or lack of experience, while older dolphins exhibit more flexible diving strategies, possibly related to foraging or navigation.

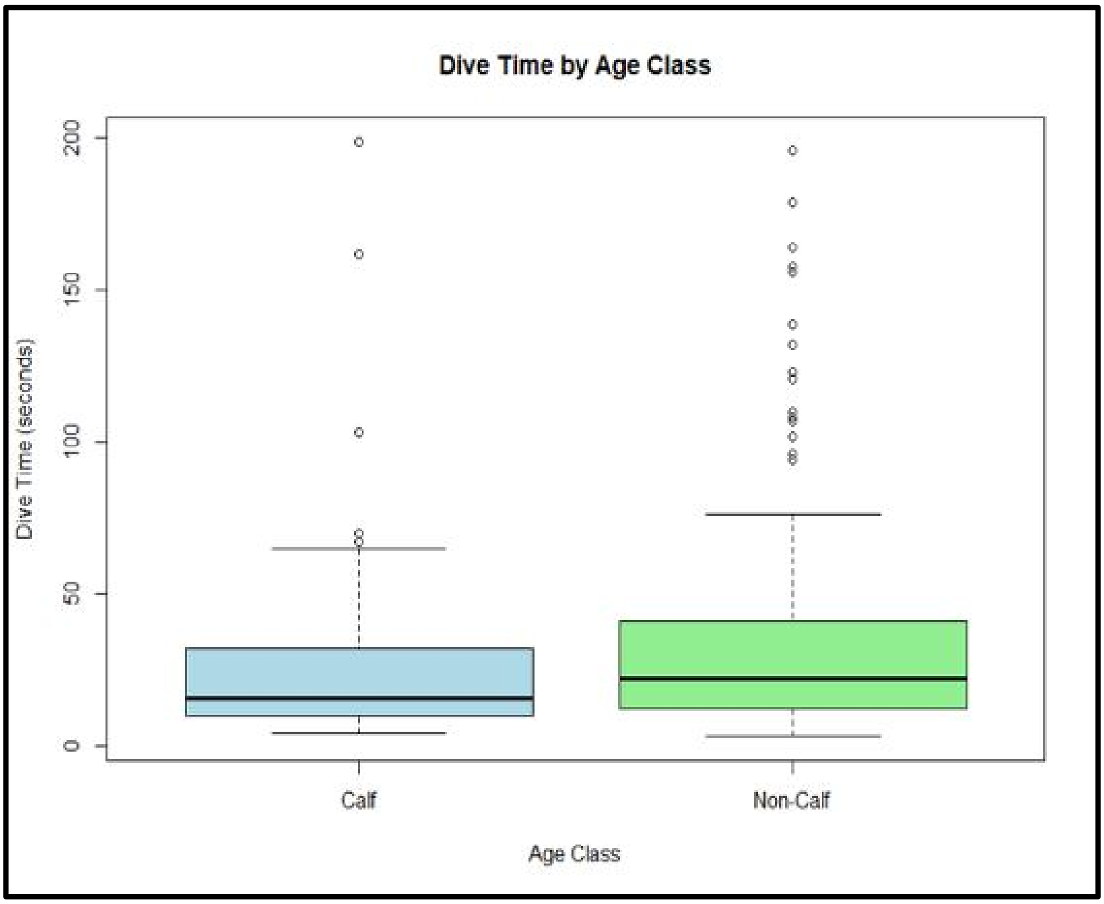

Figure 5. Boxplot showing the distribution of dive durations (in seconds) for Irrawaddy dolphin calves and non-calves. Non-calves exhibited a higher median dive time and greater variability compared to calves. Outliers are represented as individual points above the whiskers.

Depth Category	Age Class	Mean Duration	SD
Deep	Calf	23.64	32.98
Shallow	Calf	28.28	28.92
Deep	Non-Calf	29.22	30.15
Shallow	Non-Calf	38.41	37.63

Table 4. Summary of dive duration by depth and age class

Overall Average= 50.59
Overall SD= 105.67

The findings provide a baseline for understanding variation in diving behavior, and suggest that depth related physiological or ecological constraints may be shaping how dolphins allocate time underwater.

4.2. Abundance Estimation

Abundance estimates for Irrawaddy dolphins in Chilika Lagoon were derived using data collected through tandem boat-based visual surveys conducted over three consecutive days: 20th, 21st, and 22nd January 2025. The Lincoln-Petersen (LP) method was applied to matched observations independently recorded by a primary and secondary boat operating in tandem, enabling the estimation of detection-corrected population sizes.

Replicate surveys along transect OC-6, a 10 km stretch in the Outer Channel, showed consistent sighting patterns. On 20th January, a direct count of 27 individuals was recorded, which was adjusted to an LP estimate of 29 dolphins (Lower Confidence Interval [LCI] = 25, Upper Confidence Interval [UCI] = 33), with a standard deviation of 2.07 and a coefficient of variation (CV) of 0.07. The second survey, conducted along the same track on 21st January, yielded a slightly lower estimate of 24 dolphins (LCI = 22, UCI = 26), with a standard deviation of 0.87 and a higher CV of 0.4, indicating tighter observer agreement. On 22nd January, the final replicate survey along OC-6 resulted in a direct count of 27 dolphins, which was corrected to an LP estimate of 32 individuals (LCI = 25, UCI = 39), with a standard deviation of 3.7 and a CV of 0.12. Across all three surveys, the encounter rate (ER) ranged from 2.4 to 3.2 dolphins per kilometer, with an average estimated abundance of approximately 29 dolphins for OC-6 (Table 6). Additional single-boat surveys were conducted on 20th January across three other transects, OC-4, CS-1, and SS-1. These surveys resulted in observed counts of 7 dolphins at OC-4, 0 at CS-1, and 6 at SS-1, suggesting spatial variation in dolphin distribution across the lagoon (Table 5). When averaged, these sites yielded approximately 9.3 dolphins per transect, although detections were far more concentrated in OC-6. The absence of sightings at CS-1 indicates that dolphin presence was limited to specific areas during the survey period.

A summary of visual sightings and LP-corrected estimates across surveys is presented in the following tables.

Transects Transect	No. of Dolphins Visual Sightings
OC 4	7
OC 6	15
CS 1	0
SS 1	6

Table 5. Dolphin sightings during single-boat surveys

Transect ID	Least count	Lincoln-Petersen estimate	LCI	UCI	ER	IndividualAvg.
OC-6 (20th Jan, 1st survey)	27	29	25	33	2.9	
OC-6 (21st Jan, 2nd survey)	24	24	22	26	2.4	
OC-6 (22nd Jan, 1st survey)	27	32	25	39	3.2	**29**

Table 6. Abundance estimates for OC-6 using the Lincoln-Petersen method

Variation in matched sightings (denoted by low m values) between observers had a notable effect on estimated precision. Surveys with fewer matched detections between the primary and secondary boats exhibited greater discrepancies between raw and corrected estimates, along with higher coefficients of variation. These mismatches likely reflect subtle differences in observer skill, rapid dolphin movement, brief surface times, or environmental conditions (e.g., glare). Such inconsistencies underscore how detectability can vary even under standardized protocols.

Correction for availability bias, which accounts for dolphins that may not have surfaced during the survey, could not be performed due to equipment malfunction and limited acoustic data. As a result, the abundance estimates presented here are uncorrected for unavailability and may represent a conservative (i.e., lower-bound) approximation of actual population size. The results indicate that Irrawaddy dolphin distribution was spatially uneven across transects during the survey period, with significantly higher abundance in the Outer Channel (OC-6) compared to other regions of the lagoon. These findings align with previous observations of dolphin site fidelity and habitat preference within Chilika Lagoon.

4.3. Prey Availability and Fish Community Survey

Analysis of prey community data revealed considerable spatial heterogeneity across the 11 primary sampling stations in Chilika Lagoon(Table 7). The summary of taxonomic richness, abundance, and diversity indices (Table 8) shows that sites such as S05, S06, S09, and S11 emerged as local biodiversity hotspots. These stations recorded high observed species richness, which was further supported by elevated values in non-parametric richness estimators: Chao-1, iChao-1, and ACE (Table 9). The discrepancy between observed and estimated species richness, particularly at sites like S05 and S06, suggests that many rare or less detectable species likely remain unsampled.

Site No.	Locations	Sector
S01	Around Nalabana	Central
S02	Magarmukh	Central
S03	Around Mini Kalijai	North
S04	Mini Kalijai	North
S05	Chandikhol	Outer
S06	Near Sea Mouth	Outer
S07	Satapada	Outer
S08	Sipakuda	Outer
S09	Near Pathara	South
S10	Rambha	South
S11	Sabulia	South

Table 7. List of Sampling Sites

Sample	Taxa (S)	Individuals	Dominance (D)	Simpson (1-D)	Diversity Status
S01	4	18	0.2614	0.7386	Moderate diversity
S02	6	18	0.1634	0.8366	High diversity
S03	3	6	0.2667	0.7333	Moderate diversity
S04	7	44	0.3298	0.6702	Lower diversity
S05	11	35	0.1244	0.8756	High diversity
S06	11	46	0.2319	0.7681	Moderate-high
S07	3	10	0.6222	0.3778	Low diversity
S08	6	44	0.5803	0.4197	Low diversity
S09	9	22	0.0996	0.9004	Very high
S10	4	10	0.2000	0.8000	High diversity
S11	7	7	0.0000	1.0000	Diverse (each individual is a different species)

Table 8. Summary of Taxa Richness, Abundance, and Diversity Indices by Sample

Estimator	Estimated Species (S)	Standard Deviation
Observed Species	46.00	N/A
Chao 2	76.76	15.43
Jackknife 1	72.36	5.6
Jackknife 2	87.99	NA
Bootstrap	57.51	NA
Chao 2 (Bootstrap Mean)	46.84	15.06

Table 9. Estimated Species Richness Using Non-Parametric Estimators

Community evenness and dominance, captured through Simpson's Index (1-D) and Dominance Index (D), provided an understanding of the prey structure. Sites S09 and S11 had very low dominance values (0.0996 and 0.0, respectively) and high Simpson's values (0.9004 and 1.0), indicating that no single species dominated the catch, reflective of balanced, healthy ecosystems. In contrast, S07 and S08 showed higher dominance values (>0.58), suggesting a more skewed species composition likely due to disturbance or environmental stress.

Evenness indices, including Pielou's Equitability (J) and the exponential evenness index (e^H/S), confirmed these trends. S11, for instance, reached perfect evenness (J = 1), indicating equal representation across taxa. However, it is important to interpret this result cautiously, as this site had a low sample size (n = 7 individuals), which can artificially inflate evenness (Krebs, 1999).

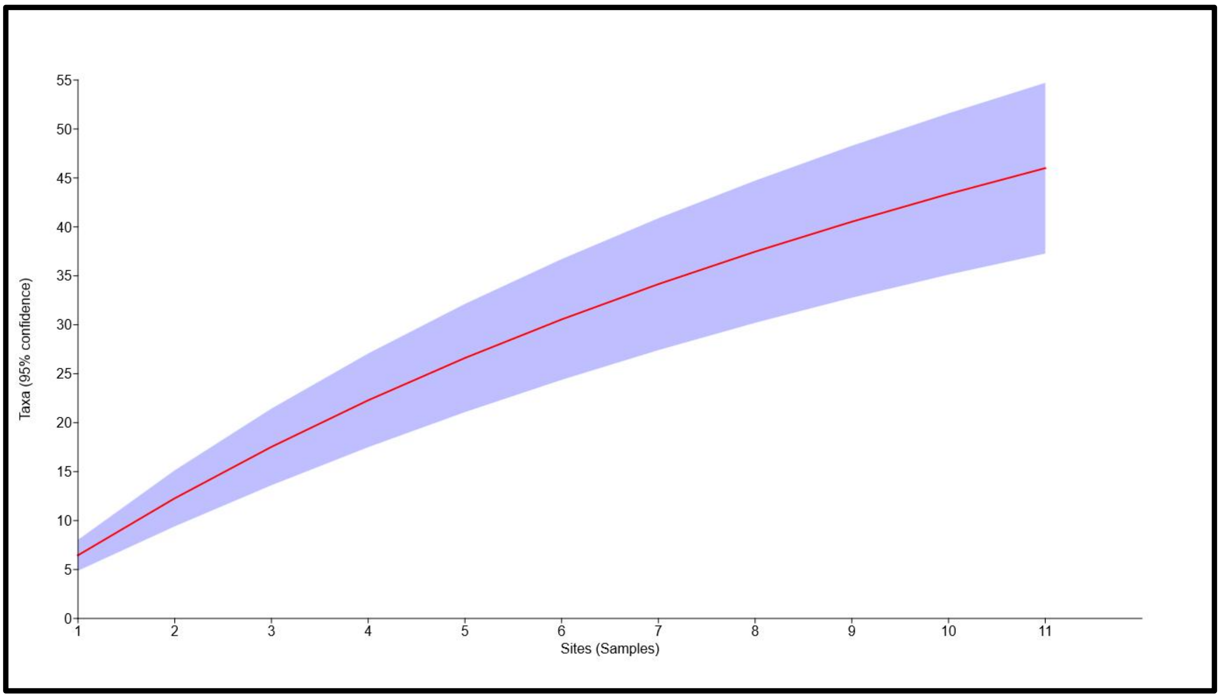

Figure 6. Sample rarefaction (Species Accumulation Curve)

Species accumulation curves provided additional evidence of sampling adequacy and richness potential. The rarefaction curve (Figure 6) shows an upward trajectory for several sites, most notably S05 and S06, indicating undersampling and suggesting that further sampling would likely uncover additional species. Non-parametric estimators such as Bootstrap, Jackknife-1 and -2, and Chao-2 placed total richness estimates between 57 and 88 species, substantially higher than the 49 species observed, supporting the conclusion that actual diversity is underestimated.

Using Bray-Curtis dissimilarity, hierarchical clustering (Figure 7) revealed distinct assemblage patterns among the sites. S01, S02, S06, and S10 clustered together, likely due to similar ecological conditions or prey profiles. Conversely, S07 emerged as an outlier, indicating a unique or degraded prey community, possibly shaped by site-specific pressures such as salinity stress, low habitat complexity, or anthropogenic activity.

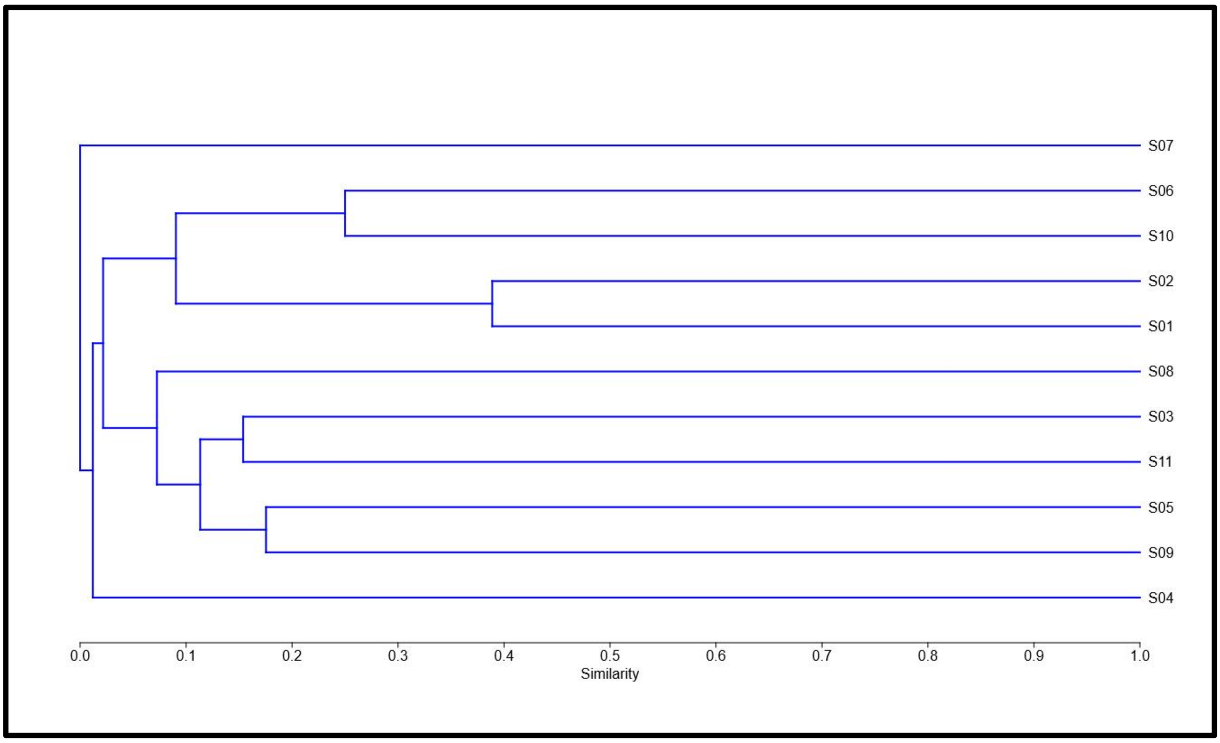

Figure 7. Hierarchical Clustering (Bray-Curtis)

These patterns collectively underscore the ecological diversity of Chilika's prey base, revealing both biologically rich and potentially degraded habitats. High-richness, balanced sites like S05 and S11 contrast sharply with simplified, dominance-driven communities like S07, offering critical insight into the heterogeneity of dolphin foraging habitats.

Catch Per Unit Effort (CPUE), calculated as total fish catch (in kilograms) per hour of fishing, served as a key proxy for prey biomass. Regional analysis revealed clear differences in productivity (Figure 8). The Northern and Outer sectors recorded the highest mean CPUE, followed by the Central sector with moderate values. The Southern sector, in contrast, consistently yielded low CPUE, less productive habitats.

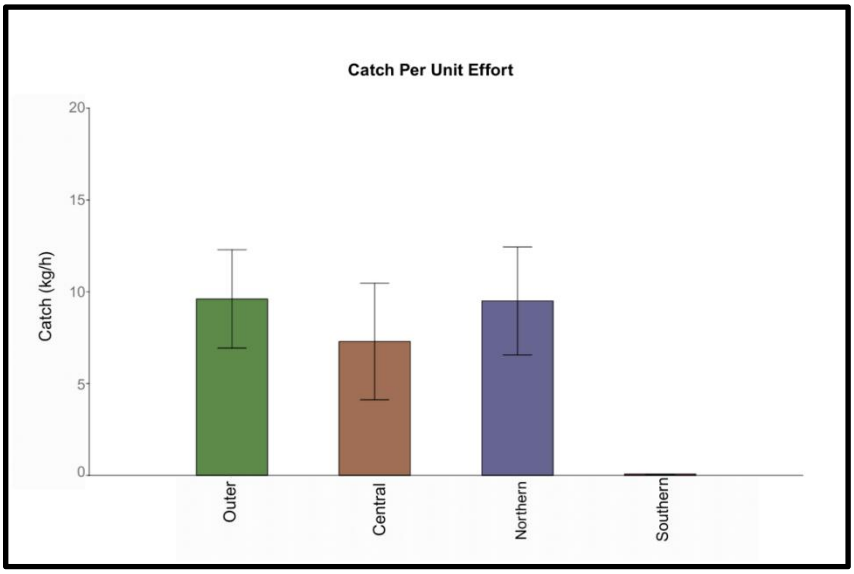

Figure 8. Mean catch per unit effort (CPUE, kg/h) across the four regions

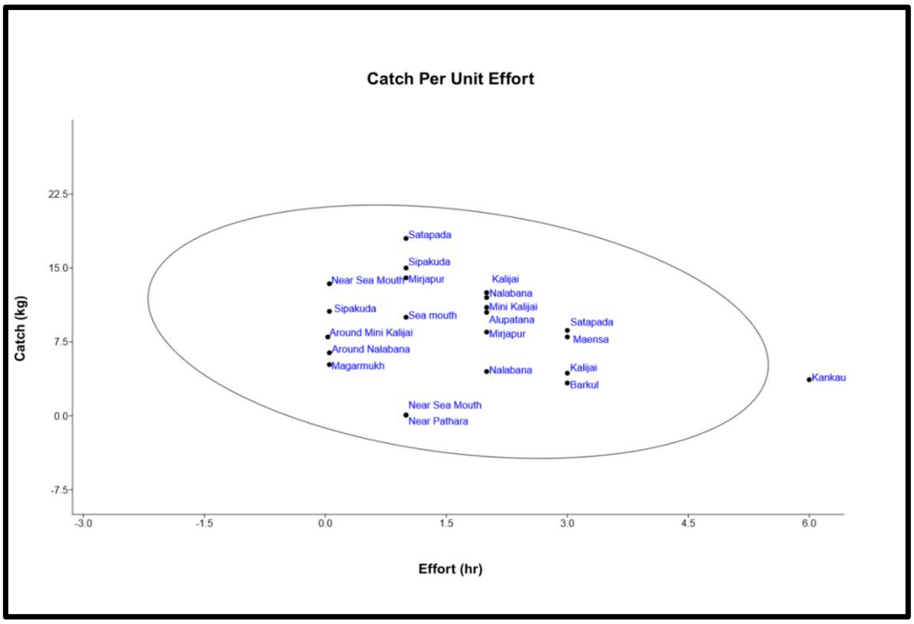

Figure 9. Scatter plot showing catch per unit effort (CPUE) across various fishing locations. Each point represents a specific site, plotted by effort (hours) on the x-axis and total catch (kg) on the y-axis. The ellipse indicates the general clustering of sites, with most locations showing moderate effort and catch, while a point (e.g., Kankau) stands out as outliers with higher effort.

A more detailed view of individual sites is provided here (Figure 10), which plots fishing effort (x-axis) against total catch (y-axis). Locations such as Satapada, Sipakuda, and Near Sea Mouth stood out with high CPUE relative to moderate effort, suggesting favorable environmental conditions or high prey density. Conversely, Kankau exhibited high fishing effort but low returns, indicative of resource depletion, overfishing, degraded habitats, or low sample size. sites, with most locations showing moderate effort and catch, while a point (e.g., Kankau) stands out as an outlier with higher effort.

Site Group	Sites Included
High CPUE, Low Effort	Satapada, Sipakuda, Near Sea Mouth, Mirjapur
Moderate CPUE & Effort	Kalijai, Nalabana, Alupatana, Mini Kalijai, Maensa
Low CPUE, High Effort	Kankau, Barkul, Kalijai (second point)
Low CPUE, Low Effort	Near Pathara, Near Sea Mouth (low CPUE variant), Nalabana (low CPUE point)

Table 10. Site Groups Based on CPUE and Fishing Effort

The sites (Table 10) based on fishing intensity and productivity. An inverse relationship was observed between effort and catch at several locations, an expected trend in overexploited fisheries, where increasing effort leads to diminishing returns. Error bars on regional CPUE (Figure 8) further showed that the Southern sector had the highest variability, hinting at inconsistent resource availability and possible ecological stress.

The prey availability results reflect substantial spatial variability in both prey composition and biomass across Chilika Lagoon. While sites such as S05, S06, S09, and S11 are identified as biodiversity-rich zones with high evenness and balanced prey structures, other areas like S07 and Kankau exhibit signs of simplification and stress, likely linked to environmental or anthropogenic factors. These differences are critical in shaping dolphin habitat use, emphasizing the importance of maintaining prey-rich, diverse zones for the conservation of Irrawaddy dolphins.

4.4. Influence of Boast Traffic

To investigate whether boat traffic influenced dolphin presence across survey sites in Chilika Lagoon, a generalized linear model (GLM) was employed (Table 11). The model included the number of tourist boats and scaled depth as predictor variables, with dolphin sightings as the response variable.

Predictor	Estimate	Std. Error	z value	p-value	Interpretation
Intercept	-0.767	0.294	-2.613	0.00896	Significant
No. of Touris t Boats	0.003	0.056	0.056	0.955	Not significant
Scaled Depth (ft)	-0.182	0.283	-0.643	0.520	Not significant

Table11. Generalized linear model results for dolphin sightings as a function of boat traffic and depth

As shown in Table 11, the intercept was statistically significant ($p = 0.00896$), indicating a baseline level of dolphin sightings when all predictors are at their mean (zero on a scaled axis). However, neither of the two main predictors showed a statistically significant effect. The number of tourist boats had a negligible estimate (0.003) and an extremely high *p*-value (0.955), indicating no measurable influence on dolphin presence. Similarly, scaled water depth was also not significantly associated with dolphin sightings ($p = 0.520$), suggesting that within the range of sampled depths, dolphins did not preferentially occupy deeper or shallower areas.

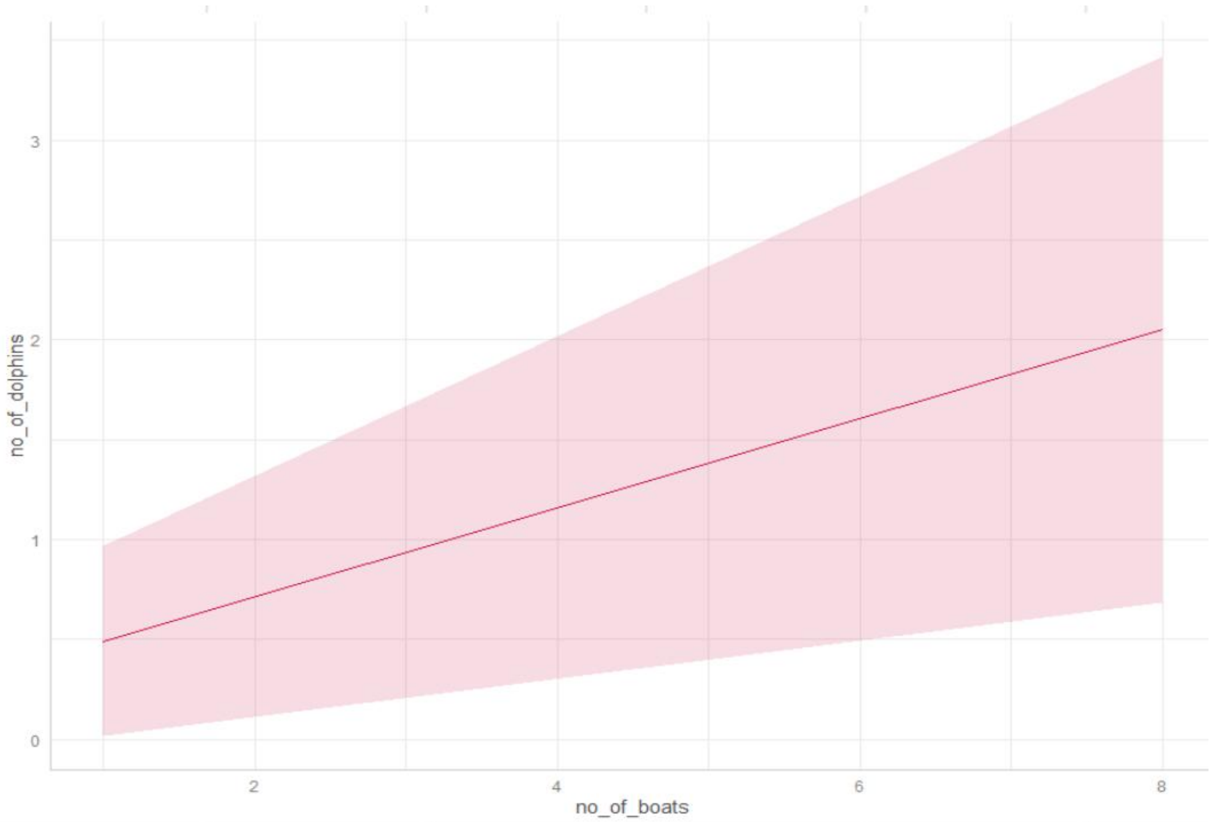

Figure 10. Effect of tourist boat numbers and depth on dolphin presence across 64 sites in Chilika Lagoon. Shade represent 95% confidence intervals.

These results collectively suggest that dolphin occurrence was not significantly influenced by either the intensity of tourist boat activity or local depth conditions across the surveyed locations. One possible explanation is that Irrawaddy dolphins in Chilika may exhibit a degree of habituation to frequent boat traffic, particularly in areas like the Outer Channel, where tourism and fishing activity are longstanding. Alternatively, other unmeasured factors, such as prey availability, ambient noise levels, or time of day, may play a more important role in shaping dolphin distribution.

While these findings do not indicate a strong statistical relationship between vessel traffic and dolphin presence, the lack of significance does not necessarily imply the absence of ecological impact. It may reflect either temporal mismatch (e.g., dolphins avoiding boats outside survey windows), non-linear responses, or threshold effects not captured in this model (Figure 10). Future studies using acoustic behavior, fine-scale tracking, or longer time-series data may help clarify whether more subtle behavioral changes occur in response to boat presence.

4.5. Environmental Drivers of Dolphin Presence

To examine environmental variables influencing Irrawaddy dolphin presence in the Lagoon, the relationships between salinity, dissolved oxygen (DO), and catch per unit effort (CPUE) using a chi-square test based on categorized dolphin detections (low, medium, high) across the 15 acoustic monitoring sites were tested. The results of this analysis are summarized in Table 12.

Environmental Variable	Test Statistic (χ^2)	Degrees of Freedom (df)	p-value	Significance
Salinity	10.914	4	0.02754	Significant
Dissolved Oxygen (DO)	7.000	4	0.1359	Not significant
Catch Per Unit Effort (CPUE)	5.556	4	0.2349	Not significant

Table 12. Chi-square test results for environmental variables influencing dolphin presence across 15 sites.

Here, salinity has emerged as the only significant predictor of dolphin presence, with a chi-square value of 10.914 (p = 0.02754), indicating that the spatial distribution of acoustic detections varied meaningfully across different salinity regimes. This result suggests that Irrawaddy dolphins are more likely to occupy areas with specific salinity conditions, possibly reflecting physiological preferences or prey availability associated with brackish water zones.

In contrast, both dissolved oxygen (p = 0.1359) and catch per unit effort (p = 0.2349) showed no significant relationship with dolphin detections. This implies that, within the range of values observed during the study period, these factors were not major drivers of habitat use by dolphins. However, their ecological importance can't be ruled out and may vary seasonally or interact with other unmeasured variables.

Although not included in the present statistical model, field observations indicated that increased boat traffic, particularly in heavily trafficked tourist routes, was associated with the displacement of dolphins from preferred areas (Dharmaraj, 2021). Even if it is not directly captured in the present dataset. Future studies incorporating fine-scale boat traffic metrics may help clarify this relationship.

4.6. Acoustic Characterization

Acoustic data collected from FPOD deployments gave a total of 73,336 echolocation clicks, which were analyzed to understand the spectral and temporal characteristics of Irrawaddy dolphin vocalizations in Chilika Lagoon. Two primary variables were extracted and analyzed: click frequency (in kilohertz) and interclick interval (ICI) (in microseconds). These parameters were analyzed both overall and across different habitat types to assess potential habitat-specific patterns.

The distribution of click frequency showed a unimodal pattern, ranging from 20 kHz to 200 kHz, with a mean frequency of 87.28 kHz and a median of 98 kHz (Table 13). The histogram (Figure 15) reveals a right-skewed distribution, indicating that most dolphin clicks were concentrated in the higher end of the frequency range, with a noticeable cluster around 98-114 kHz. These spectral characteristics are consistent with known odontocete echolocation patterns and suggest that Irrawaddy dolphins in Chilika primarily utilize high-frequency clicks for navigation and foraging.

Inter-click intervals (ICI) were more variable. The ICIs ranged from 850 microseconds to over 1,010,865 microseconds, with a mean of 25,649 µs and a median of 23,605 µs. The histogram of ICIs (Figure 14) displayed a positively skewed distribution, with the majority of click trains having short intervals (<100 ms), but several instances extending far beyond this range. Such variability in ICI values may indicate different click train functions—short ICIs are typically associated with echolocation, while longer intervals may relate to exploration or communication behavior. Log-transformed ICI values further supported this pattern by normalizing the skew and revealing underlying behavioral structure.

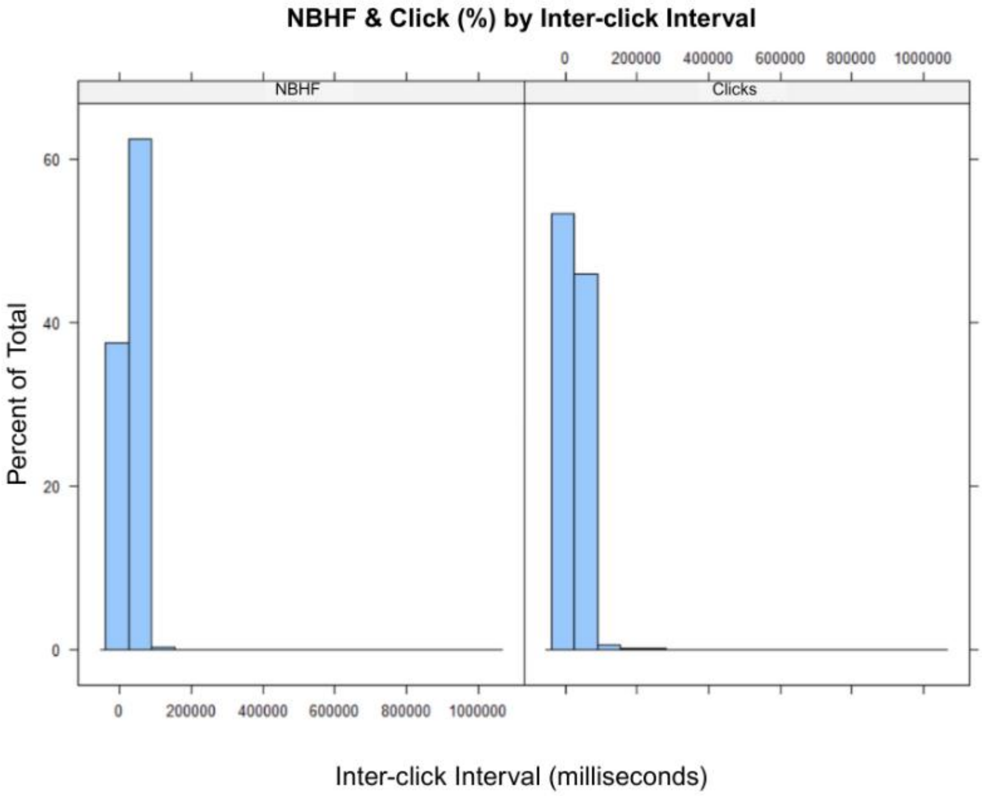

Figure 11. Histogram of NBHF & Click(%) of Inter- click Interval

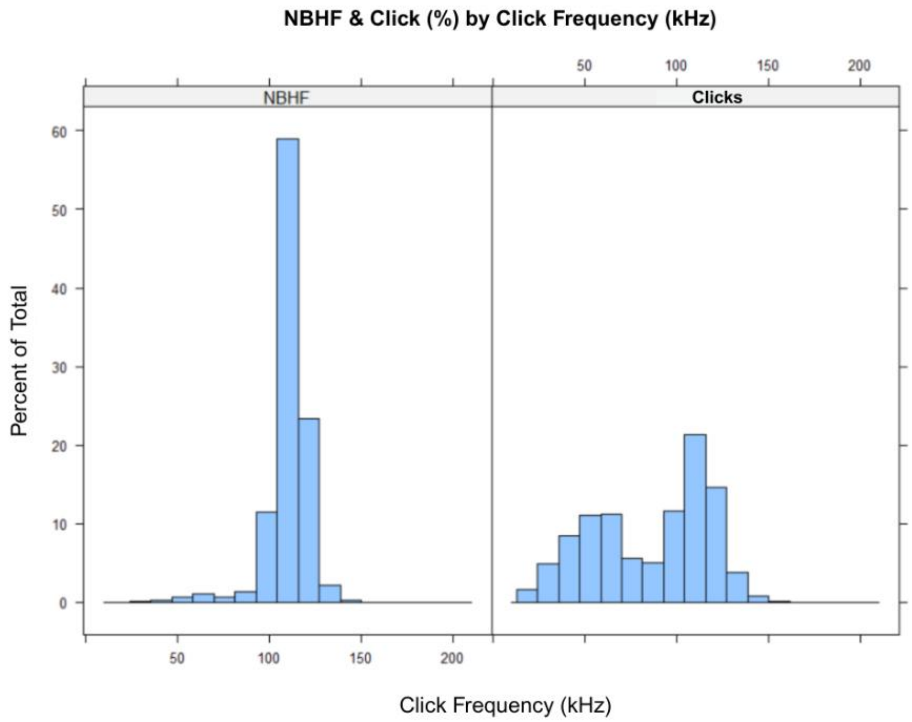

Figure 12. Histogram of NBHF & Click(%) of Click Frequency (kHz)

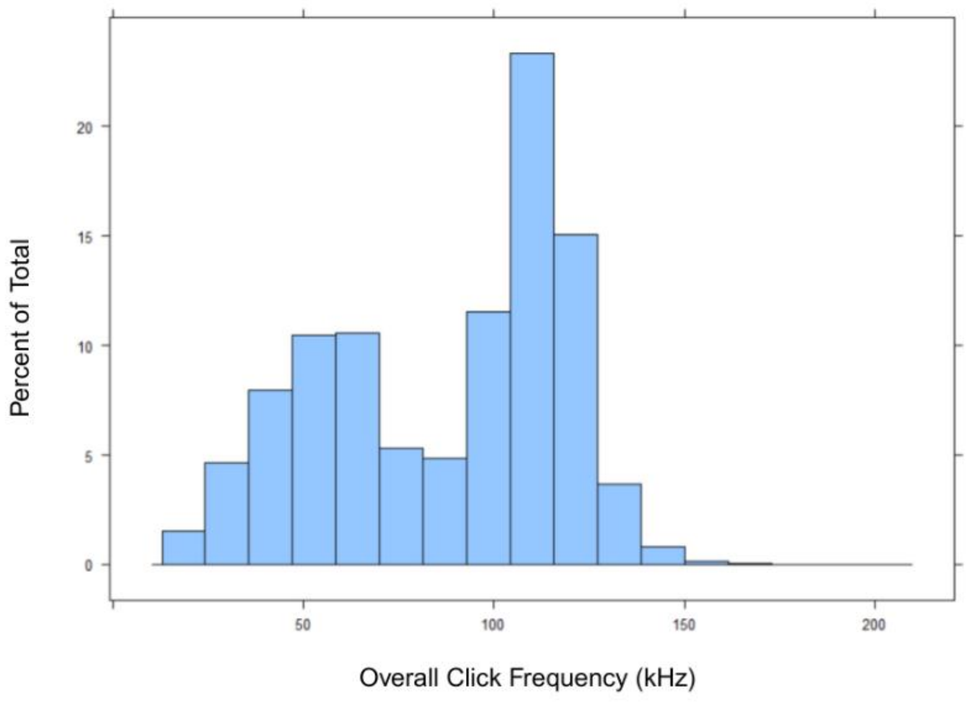

Figure 13. Histogram of Overall Click Frequency (kHz)

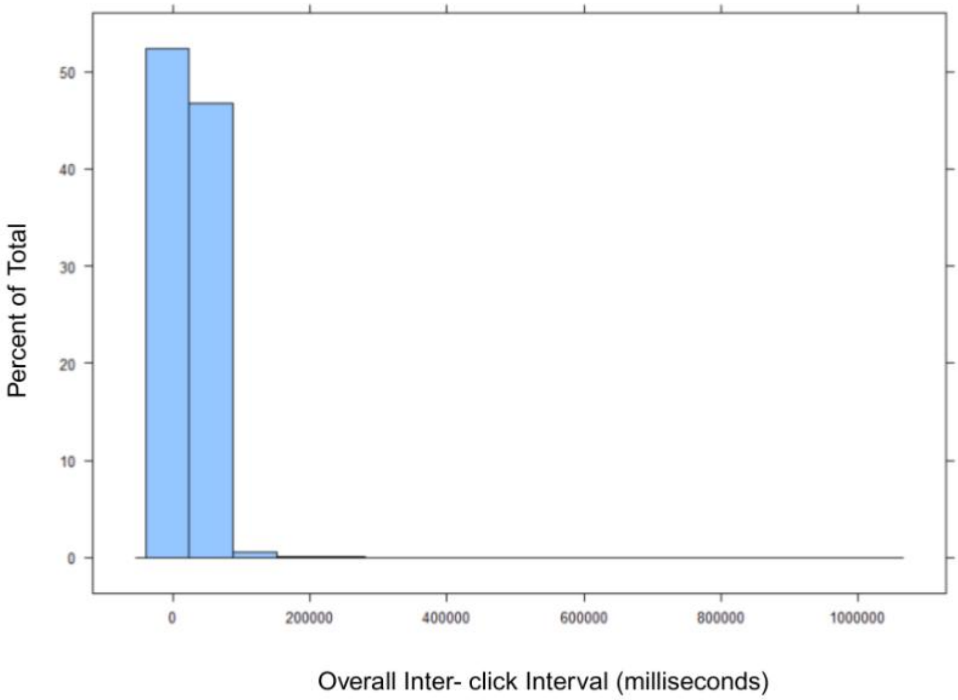

Figure 14. Histogram Overall Inter- click Interval

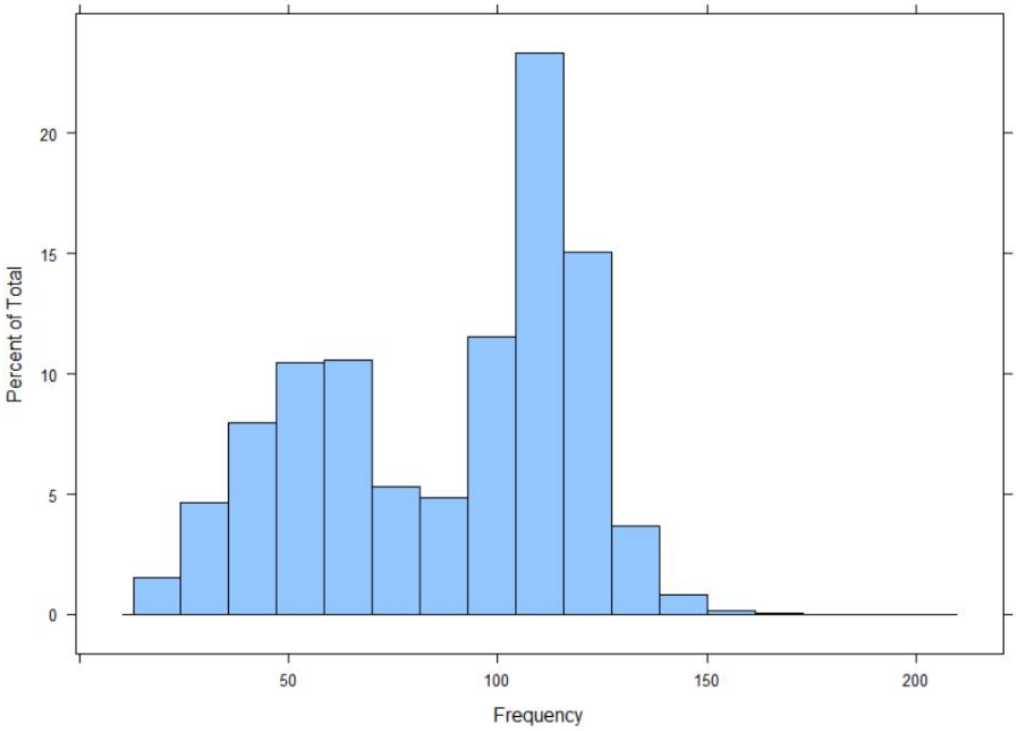

Figure 15. Histogram of Frequency (kHz)

Variable	Min	1st Quartile	Median	Mean	3rd Quartile	Max
Frequency (kHz)	20	59	98	87.28	114	200
ICI (microseconds)	850	11,458	23,605	25,649	35,465	10,10,865

Table 13. Summary of dolphin click characteristics (n = 73,336)

In addition to the overall characterization, acoustic parameters were analyzed across six habitat types: along islands, rocky hills, deeper pools, new sea mouth, open water, and seagrass beds (Table 14). Dolphins recorded in deeper pools produced the highest mean click frequencies (≈110.86 kHz) and exhibited relatively stable ICIs (≈23.7 ms), suggesting focused echolocation activity in deeper water. Conversely, habitats like seagrass beds and the new sea mouth showed greater variability in both click frequency and ICI, with standard deviations exceeding 60 ms and 20 kHz, respectively. These broader ranges likely reflect a diversity of behavioral contexts or movement patterns in more open or variable habitats.

Habitat	Inter Click Interval (milliseconds)	Frequency (kHz)
Along Island	14.13 ± 33.96	92.96 ± 26.76
Along rocky hill	31.48 ± 30.44	97.52 ± 26.48
Deeper pools	23.70 ± 8.28	110.86 ± 9.31
New Sea Mouth	44.70 ± 0.95	103.00 ± 23.86
Open Water	25.92 ± 19.13	86.74 ± 32.12
Sea grass bed	38.32 ± 69.95	77.58 ± 28.52

Table 14. Habitat-wise variation in dolphin click parameters

The results show that dolphins appear to exhibit habitat-specific acoustic behaviors. In environments like deeper pools and rocky edges, click characteristics are more consistent, suggesting targeted echolocation in known territories. In contrast, more dynamic or open environments, such as seagrass beds and the sea mouth, display greater variability, potentially reflecting exploratory behavior, multiple individuals, or a mixture of communication and echolocation clicks.

The acoustic results provide a baseline dataset for Irrawaddy dolphin click parameters in Chilika Lagoon, and also demonstrate the potential of PAM to infer behavior and habitat use. The consistent spectral profile and variable temporal click structure suggest a mix of functional click types influenced by environmental context. These findings have important implications for refining automated detection algorithms and for interpreting future long-term acoustic monitoring efforts in estuarine dolphin populations.

5. CONCLUSION

Estimating dolphin populations within a scientific framework is essential for monitoring trends over time and for evaluating the effectiveness of conservation actions. This study highlights the importance of methodological consistency in population assessments. Differences in observer perception and timing led to significant variation in dolphin counts, even within the same location and time frame. Such discrepancies underscore the need to establish a standardized, replicable framework for dolphin population monitoring that corrects for biases in detection and availability. Without such rigor, it becomes difficult to compare estimates across years or regions, which is critical for tracking long-term trends in small, vulnerable populations like that of the Irrawaddy dolphin in Chilika Lagoon.

In terms of habitat use, the findings suggest that environmental parameters, particularly salinity play a key role in shaping dolphin distribution. A significant negative relationship between salinity and dolphin detections indicates that increasing salinity, likely driven by reduced freshwater inflow or hydrological changes, could pose a threat to these estuarine-adapted cetaceans. However, more data across seasons and locations are needed to better understand this relationship and to identify thresholds beyond which habitat quality may deteriorate. Similarly, while this study provides foundational insights into the basic acoustic characteristics of Irrawaddy dolphin Narrow Band High Frequency (NBHF) and clicks, further research is needed to understand how they use different frequency bands across behavioral contexts. As boat traffic continues to grow in Chilika, it is increasingly important to determine whether the acoustic spectrum used by vessels overlaps with the dolphins' communication and echolocation bands, potentially leading to masking or disturbance.

Understanding diel (day-night) patterns of dolphin activity could also help identify quiet windows for conservation.

Looking forward, there is a clear need to establish a broader, range-wide monitoring framework that combines standardized dolphin population assessments with concurrent habitat data collection. This should involve repeated sampling across specific time windows and incorporate metrics such as salinity, depth, prey availability, and anthropogenic activity. Such an approach would not only allow comparison across years but also provide early warnings of ecological changes that may influence dolphin presence or behavior. In addition, further work is needed to understand how Irrawaddy dolphins are responding to ongoing environmental changes, whether through altered movement patterns, shifts in foraging behavior, or changes in reproductive success.

The sustainability of human activities in Chilika must be carefully considered. Many communities around the lagoon depend on fishing for their livelihoods, yet the extraction of fish resources may impact dolphin prey availability and, by extension, their foraging success. Future studies should aim to quantify the overlap between dolphin foraging areas and fishing zones, assess whether current levels of extraction are sustainable, and explore opportunities for co-management that support both biodiversity conservation and community well-being.

6. ANNEXURE

Order	Family	Species	Common Name	IUCN Status
Myliobatiformes	Dasyatidae	*Brevitrygon cf. imbricata* (Bloch & Schneider 1801)	Laccadive Whipray	VU
Elopiformes	Elopidae	*Elops machnata* (Fabricius 1775)	Tenpounder	LC
Anguilliformes	Ophichthidae	*Pisodonophis boro* (Hamilton 1822)	Rice-paddy eel	LC
Clupeiformes	Engraulidae	*Thryssa setriostris* (Broussonet 1782)	Longjaw Thryssa	LC
	Clupeidae	*Nematalosa nasus* (Bloch 1795)	Bloch's Gizzard Shad	LC
	Pristigasteridae	*Opisthopterus tardoore* (Cuvier 1829)	Long-finned herring, Tardoore	LC
	Dorosomatidae	*Hilsa kelee* (Cuvier 1829)	Keele Shad	LC
Cypriniformes	Cyprinidae	*Puntius sophore (*Hamilton 1822)	Pool barb	LC
		Pethia ticto (Hamilton 1822)	Tic-tac-toe barb	LC
Siluriformes	Plotosidae	*Plotosus canius* Hamilton 1822	Grey eel-catfish	LC
	Bagridae	*Mystus gulio* (Hamilton 1822)	Long-whiskered catfish	LC
	Ariidae	*Arius arius* (Hamilton 1822)	Threadfin Sea Catfish	LC
Gobiiformes	Eleotridae	*Eleotris fusca* (Bloch & Schneider 1801)	Dusky sleeper	LC
	Gobiidae	*Glossogobius giuris* (Hamilton 1822)	Tank goby	LC
Syngnathiformes	Syngnathidae	*Ichthyocampus carce*?	Pipe fish	CR
Scombriformes	Scombridae	*Rastrelliger kanagurta* (Cuvier 1816)	Indian mackerel	LC
	Trichiuridae	*Trichiurus lepturus* Linnaeus 1758	Largehead Hairtail, Cutlassfish	LC
Anabantiformes	Channidae	*Channa striata* (Bloch 1793)	Striped snakehead	LC
Carangiformes	Polynemidae	*Eleutheronema tetradactylum* (Shaw 1804)	Indian Salmon	NE
	Paralichthyidae	*Pseudorhombus triocellatus* (Bloch and Schneider 1801)	Ringed Flounder	DD
	Soleidae	*Brachirus annularis* Fowler 1934	Indian Zebra Sole	NE
	Cynoglossidae	*Cynoglossus puncticeps* (Richardson 1846)	Speckled tongue sole	NE
	Carangidae	*Caranax ignobilis* (Forsskål 1775)	Brassy Trevally	LC

Atheriniformes	Atherinidae	*Doboatherina duodecimalis* (Valenciennes 1835)	Tropical Silverside	NE
Beloniformes	Belonidae	*Strongylura strongylura* (van Hasselt 1823)	Spottail needlefish	LC
	Hemiramphidae	*Hemiramphus far* (Fabricius 1775)	Black-barred halfbeak	NE
		Hyporhamphus limbatus (Valenciennes 1847)	Congaturi halfbeak	LC
Cyprinodontiformes	Aplocheilidae	*Aplocheilus panchax* (Hamilton 1822)	Blue panchax	LC
Cichliformes	Cichlidae	*Etroplus suratensis* (Bloch 1790)	Green chromide	LC
Mugiliformes	Ambassidae	*Ambassis macracanthus* (Bleeker 1849)	Estuarine glass perchlet	DD
	Mugilidae	*Moolgarda cunnesius* (Valenciennes 1836)	Longarm mullet	NE
		Moolgarda tade (Fabricius 1775)	Tade grey mullet	DD
		Mugil cephalus (Linnaeus 1758)	Flathead grey mullet	LC
Perciformes	Epinephelidae	*Epinephelus coioides* (Hamilton 1822)	Orange spotted grouper	NT
	Platycephalidae	*Platycephalus indicus (*Linnaeus 1758)	Bartail flathead	DD
	Synanceiidae	*Inimicus sp.*	Stingfish, goblinfish	LC
Centrachiformes	Terapontidae	*Terapon jarbua* (Fabricius 1775)	Jarbua terapon	LC
Acanthuriformes	Gerreidae	*Gerres phaiya* Iwatsuki & Heemstra 2001	Strong-spined silver-biddy	NE
	Sillaginidae	*Sillago sihama* (Fabricius 1775)	Silver sillago	LC
	Sciaenidae	*Johnius borneensis* (Bleeker 1851)	Croaker, Drum	LC
	Haemulidae	*Pomadasys kaakan* (Cuvier 1830)	Barred javelin	LC
	Lobotidae	*Lobotes surinamensis* (Bloch 1790)	Tripletail	LC
	Leiognathidae	*Nuchequula nuchalis* (Temminck & Schlegel 1845)	Spotnape Ponyfish	NE
		Deveximentum insidiator (Bloch 1787)	Pugnose Ponyfish	DD
	Sparidae	*Rhabdosargus sarba* (Gmelin 1789)	Stumpnose	VU
	Siganidae	*Siganus vermiculatus* (Valenciennes 1835)	Vermiculated spinefoot	LC
	Scatophagidae	*Scatophagus argus* (Linnaeus 1766)	Spotted scat	LC

Tetraodontiformes	Triacanthidae	*Tricanthus nieuhofii* Bleeker 1851	Silver Tripod	NE
	Tetraodontidae	*Takifugu oblongus* (Bloch 1786)	Oblong blowfish	LC

Table 15. Fish diversity identified during the prey availability survey

Figure 16. An Irrawaddy dolphin (*Orcaella brevirostris*) observed spy-hopping in Chilika Lagoon during early morning hours. Spy-hopping, where the dolphin vertically raises its head above the water surface, is often associated with environmental scanning or social behavior.

Figure 17. A pod of Irrawaddy dolphins (*Orcaella brevirostris*) swimming in close association in Chilika Lagoon.

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