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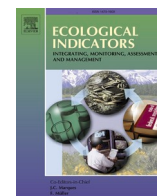


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Prioritising river stretches using multi-modelling habitat suitability of Gangetic dolphin (*Platanista gangetica*) as a flagship species for aquatic biodiversity conservation in the Ganga River Basin, India

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ABSTRACT

Globally, the river ecosystems are threatened due to human-driven exploitation and indiscriminate resource use. The rate of species loss is a magnitude higher in these ecosystems, hence, identifying conservation priority areas as refugia, using the flagship-cum-indicator species approach can aid in long-term conservation of multiple species and ensure uninterrupted functioning of ecological processes. For effective conservation planning, we derived the site occupancy and abundance of Gangetic dolphin (*Platanista gangetica*) as a flagship species in the Ganga River Basin, and modelled their distribution vis-à-vis river conditions for identifying Conservation Priority Stretches (CPS). The study incorporates the first-ever basin-wide (4635 km river) Gangetic dolphin (GD) sightings to estimate range decline, abundance, and identify CPS of select rivers in the Basin. A total of 2151 sightings of surfacing dolphins with mean encounter rate of 0.55 ± 0.09 sightings/km of the river was observed from the surveyed stretch. The GD encounter rate varied significantly across the surveyed rivers (Analysis of Variance, $F = 3.08$, $p < 0.001$). We estimated 24.37 % decline in the dolphin distribution range in the basin since 19th Century. The estimated population size of the dolphin in the Basin was $3330 \text{ individuals} \pm 620 \text{ individuals}$ (Confidence Interval 95 % = 2304–4668; Coefficient of Variance = 18.61) which varied across the river. The site occupancy and abundance were best predicted by channel depth ($\beta = 0.82 \pm 0.46$), meanders ($\beta = 0.256 \pm 0.87$) and individual rivers, whereas channel width ($\beta = 0.11 \pm 0.08$) and survey efforts influenced detection probabilities. Further, we identified 610 km (12.2 %) of river stretches as high CPS in the Basin based on the prediction probability (≥ 0.70) of GD. Protection of these stretches is likely to ensure sustained reproduction of GD and provide refugia for other threatened species of the Ganga River and its tributaries, which is under increasing anthropogenic pressure.

1. Introduction

Freshwater ecosystems such as rivers, streams and associated wetlands are an integral component of the global water cycle, flow regulation, and effective functioning of associated ecosystems (Matthews, 2016; Grantham et al., 2019). The freshwater ecosystem comprises less than 1 % of the Earth's surface yet has the most diverse habitats, species, and biodiversity (Dudgeon et al., 2006). Besides, the freshwater ecosystems represent 9.5 % of all faunal species and harbour approximately 6 % of all described species and a third of all vertebrate species globally

(Balian et al., 2007; Strayer and Dudgeon, 2010). These vital ecosystems are threatened by several human-induced factors, such as rapid infrastructure development, widespread habitat degradation, pollution, and hydrological alteration due to dams and barrages (Alizadeh et al., 2018; Alvarado et al., 2021; Kouadri et al., 2021). The upsurge in river infrastructure developments has disrupted longitudinal connectivity causing fragmentation leading to biodiversity loss and threatening ecosystem functioning (Dudgeon, 2000; Guo et al., 2019). Furthermore, the unprecedented impacts of these factors have potentially affected migration, breeding biology, habitat use pattern and has resulted in

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population isolation of many freshwater species (Strayer and Dudgeon, 2010; Boscarri et al., 2022). Additionally, rivers are vulnerable to global climate change associated uncertainties of precipitation and temperature patterns, which would worsen rivers' hydrological conditions (Schneider et al., 2013). The impact of climate change is likely to have an irreversible cascading impact on thousands of freshwater species that are currently on the verge of extinction (Vörösmarty et al., 2010). Consequently climate change impacts have drastically modified trophic interactions and altered prey species distribution, limiting the top predators' physiological and biological requirements (Learmonth et al., 2006; Wynn et al., 2007).

River systems in Asia are considered among the most dynamic and threatened ecosystems (Dudgeon, 2000, 2002), as more than half of the global human population resides in 13 % of the world's land mass (Hannah et al., 1994). The rate of biodiversity loss is a magnitude higher in tropical rivers of Asia due to escalating human demands on the river ecosystems (Guo et al., 2019). The Ganga Basin (henceforth, GB) is the largest river basin in India, which supports ~650 million people and rich aquatic biodiversity, is experiencing increased human footfall leading to population declines and range reduction of riverine biota inhibiting vital ecological processes (Nautiyal, 2010). In a nutshell, despite the high ecological significance of the GB, socio-political demands, development and religious activities, and economic feasibility have become major obstacles in developing a comprehensive and systematic conservation plan for the basin. In the current epoch of Anthropocene, biodiversity conservation has become the world's most essential shared responsibility (Sun et al., 2022). The flagship species approach can be instrumental in invoking this shared responsibility. In recent years, the flagship species approach has gained much support and acceptance as a management tool for starting point to monitor biodiversity changes and developing conservation plans (Kim et al., 2021). The flagship species are relatively large, top predators, charismatic vertebrates that can significantly promote environmental awareness (Barua et al., 2011). Consequently, flagship species are explicitly perceived as 'umbrella' species in identifying protected areas, assuming their conservation will confer appropriate protection to other species (Piatt et al., 2007; Sergio et al., 2008).

The Gangetic dolphin (*Platanista gangetica*), (henceforth, GD) was first scientifically documented in the year 1801 by Heinrich Julius Lebeck (Lebeck, 1801; Kinze, 2000). Earlier the GD was considered a sub-species of the South Asian River dolphin. However, a recent phylogenetic study revealed GD as a distinct species from the Indus River dolphin (*Platanista minor*) (Braulik et al., 2021). The GD is a top predator that influences the food chain structure, thereby plays a critical role in maintaining the vital ecological processes of the river ecosystems and serve as a potential indicator for monitoring status of river health (Gomez-Salazar et al., 2012; Turvey et al., 2012; Sinha and Kannan, 2014). Its extirpation from river systems serves as a tool to measure the extent of human footprints exploiting riverine resources (Sinha et al., 2010; Sinha and Kannan, 2014; Behera et al., 2014). Once commonly distributed in major river systems between longitudes 77° E and 89° E in India, Nepal and Bangladesh (Anderson 1879, Smith, 1993; Mohan et al., 1997), the species is now restricted to disjunct stretches of the Ganga-Brahmaputra-Barak river system in India (Wakid, 2009; Behera et al., 2014; Sinha and Kannan, 2014; Choudhury et al., 2019), Karnali, Sapta Koshi and Narayani river systems in Nepal (Shrestha, 1989; Paudel et al., 2015) and Meghna, Karnaphuli and Sangu river systems in Bangladesh (Reeves et al. 2000; Smith et al. 2006). The GD is now isolated into small groups and is under severe threat due to a wide array of factors such as flow modification, habitat degradation, prey depletion, noise pollution, poaching and net entanglement (Dey et al., 2019; Paudel and Koprowski, 2020; Kolipakam et al., 2022). Owing to these threats, the GD experienced a ~30 % decline in its population (Paudel and Koprowski, 2020) and a range reduction between the late 19th and early 21st century (Mohan, 1989; Shostell and Ruiz-García, 2010; Sinha and Kannan, 2014).

The species in the past has attracted multiple conservation efforts; the Government of India has accorded utmost protection to the species by including it in Schedule I of the Wild Life (Protection) Act, 1972, since its inception in 1972 (Sinha and Kannan, 2014). The species has been listed in the Endangered category in the International Union for Conservation of Nature Red List of Threatened Species since 1996 (Kelkar et al., 2022). To prohibit international trade, the species was enlisted in Appendix I of the Convention on International Trade in Endangered Species (CITES) and in Appendix II of the Convention on Migratory Species (CMS). To further strengthen its conservation, the Government of India has declared GD as the National Aquatic Animal of India with a clear mandate of spreading awareness among local communities to protect and conserve GD and its habitats.

Despite these efforts, the information on current distribution, abundance and factors affecting GD is limited, and information on their distribution from previous studies are from specific short stretches and in different time scales (Behera et al., 2014; Sinha and Kannan, 2014; Chowdhury et al., 2016). Hence, there is little comprehensive information on the status of the GD from its range, which is crucial for the long-term conservation of this species. Moreover, information on the extent of suitable habitats for the GD in many parts of its range in India is lacking, which hinders conservation planning. Additionally, it is paramount to configure the impacts of climate change on the distribution of the GD (Paudel and Koprowski, 2020).

In the present study, we aimed to assess the occurrence, population status, and habitat suitability of GD in GB, India, to address the following research questions (a) what is the current distribution range of GD in the basin? (b) What is the current population status of the GD in the riverscape of the GB? (c) What is the extent of occupancy of the GD in the basin? (d) What factors influence site occupancy and abundance of GD across the basin? and (e) What is the extent of best suitable areas available in the basin for the conservation of GD as an indicator species, which ultimately may improve overall river conservation in GB.

The GD and other large vertebrates such as crocodiles are the large predators found in the GB and are potential flagship species. However, the basin wide distribution of GD and its greater hydrological requirements compared to other predators in the basin makes it an ideal choice as a flagship species. It provides ample data points required for increased efficacy and to draw reliable inferences. Large-scale visual encounter survey data was employed to assess the status of GD and their site use across riverscape in the GB. We used an occupancy framework to delineate the proportion of the riverscape used by GD and evaluate how suites of environmental and anthropogenic predictors influence their site use. We then derived the abundance of GD using N-mixture models and evaluated factors influencing the abundance. We also administered a flagship-cum-indicator species based systematic conservation planning approach to identify priority stretches for effective GD conservation. The identification of conservation priority stretches of the Ganga River and its tributaries is likely to enable the policymakers and managers to develop basin-wide conservation and restoration plans. This will be in line with India's international commitment to the United Nations Decade on Ecosystem Restoration.

2. Materials and methods

2.1. Study area

The present study was conducted in the Ganga River and its major tributaries viz. Yamuna, Chambal, Ghaghra, Son, Gandak, Kosi and Rupnarayan to record the sightings of the GD (Fig. 1). The GB alone drains an area of 8,61,404 sq. km (≥ 26 %) of India's geographical area (Dwivedi et al., 2018). The GB is surrounded by the great Himalayas in the north, the Chota Nagpur plateau and Vindhya in the south, Aravalli range in the west, and the Brahmaputra Ridge in the east, which has given rise to climatic, topographical and hydrological variations (CWC, 2014). The hydrological regime also varies across seasons, with reduced

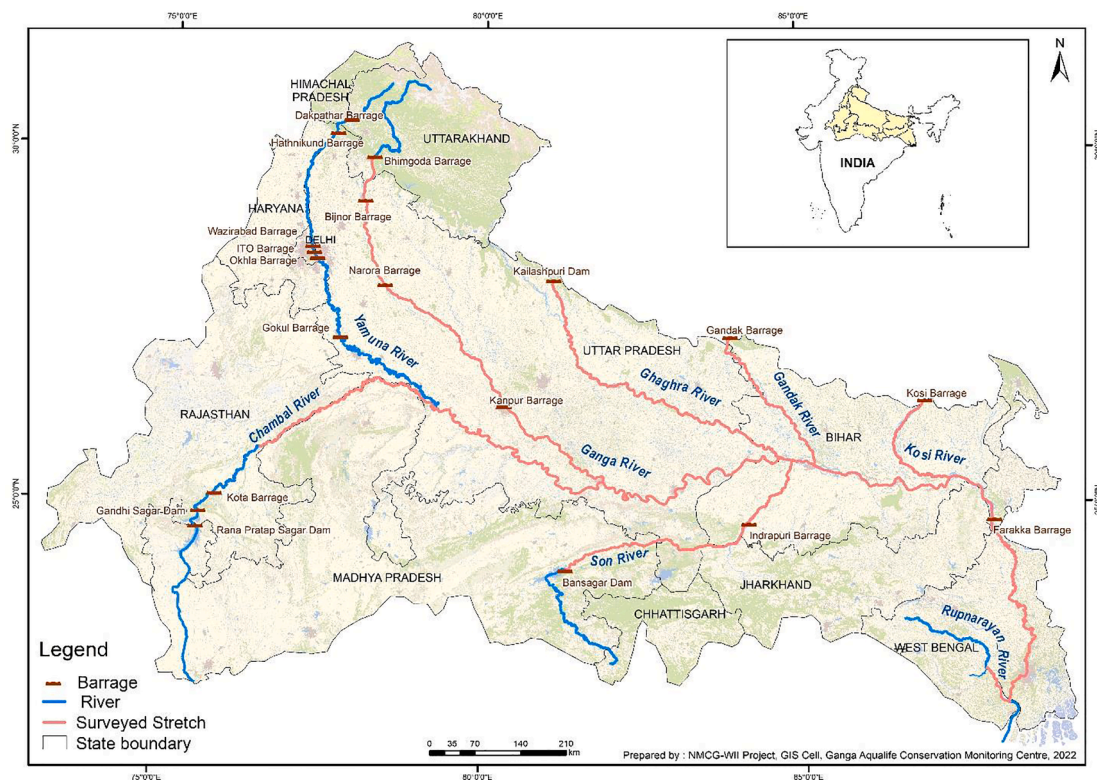


Fig. 1. Map of surveyed rivers for Gangetic dolphin in the Ganga Basin, India.

flow occurring between winter and summer and the highest river discharges recorded during the monsoon. The wide range of geomorphological and hydrological variations provides a mosaic habitat suitable for diverse flora and fauna (Hussain et al., 2020; Sonkar and Gaurav, 2020). The GB is one of the most densely populated regions of the world (>1400 individual/km²). The high human density results in higher demand of water for agriculture, industry, electricity generation and navigation. Sand mining, unplanned developmental activities and point and non-point source discharge have further degraded the river habitat including water quality (Hussain et al., 2020; Dagar et al., 2021).

The GB is spread across 11 Indian states and lies within five distinct biogeographic zones, viz. Himalaya (North-West Himalaya 2A and West Himalaya 2B), Semi-Arid (Punjab Plains 4A and Gujarat Rajputana 4B), Deccan Peninsula (Central Highlands 6A and Chota Nagpur Plateau 6B), Gangetic Plain (Upper Gangetic Plain 7A and Lower Gangetic Plain 7B) and Coasts (East Coast 8B) (Rodgers and Panwar, 1988; CWC, 2014). The climate of the GB varies from alpine, temperate, to sub-tropical and tropical. The annual mean precipitation ranges from 500 mm to 2500 mm, and ~80 % of the precipitation occurs between June and September (Nandargi and Shelar, 2018).

In the GB, we studied eight major rivers through literature survey and field sampling (Supplementary Fig. S1). Of these, Ganga, Yamuna, Ghaghra, Gandak and Kosi are snow fed, whereas the Chambal, Son and Rupnarayan are rain fed. The smaller tributaries such as Girwa, Sharda, Rapti and Mahananda were not surveyed due to logistical constraints even though GD were reported from these rivers. Brief description of studied rivers has been provided in the supplementary information (Supplementary Table S1).

2.2. Data collection

We surveyed 4635 km of the rivers, viz. Ganga (2070 km), Yamuna (435 km), Ghaghra (615 km), Gandak (295 km), Kosi (235 km), Chambal (405 km), Son (500 km), and Rupnarayan (80 km) for their ecological condition *vis-à-vis* occurrence of GD using boat based visual

encounter survey between 2020 and 2021 (Smith and Reeves, 2000; Sinha and Sharma, 2003a) (Fig. 1).

Each of the surveyed rivers were divided into 5 km segments referred to as Biodiversity Evaluation Unit (BEU) in ArcGIS 10.2 (ESRI, Redlands, USA). We collected information on five hydro-morphological and four anthropogenic variables at 1 km intervals, which were averaged for each BEU (Supplementary Table S2). The surveys were conducted during post-monsoon (November to February) season in daylight between 8:00 hrs to 12:00 hrs and 15:00 to 17:00 hrs using an inflatable rubber (25 hp)/country boat following thalweg (deeper part of the river) (Oliveira et al., 2017). The speed of the boat was kept constant at 6–8 km/hr to avoid missing any sightings of surfacing GD. A team of four trained observers equipped with binoculars (NIKON 8 × 42), GPS (GARMIN e-Trex 30), depth sounder (HONDEX PS7), and range finder (HAWKE Endurance LRF-1000), were stationed at the front of the boat to obtain concurrent least counts of GD sightings and associated habitat variables following Smith et al., (2006). In each team, three observers were responsible for looking for surfacing GD, and the fourth observer for recording associated habitat variables at each sighting.

Habitat parameters such as channel width (m), efforts (duration of time spent in each BEU), time (time of the day), channel depth (m), water flow (m³/sec.), river slope (degree), number of meanders (meanders/BEU), fishing intensity (active nets and boats/BEU), sand mining intensity (mining boats/BEU) as well as anthropogenic factors were recorded within each BEU (Supplementary Table S2).

2.3. Data analysis

2.3.1. Distribution and range decline

The decline in species' historical range and understanding the associated causes is central to species conservation and management. The decline is often measured through distribution or abundance changes (Gaston et al., 2000; Uzqueda et al., 2020). The use of reduction in distributional area is useful when there is no abundance data available but sufficient historical occurrence records exist (Shaffer et al.,

1998). To estimate the range decline in the GB, dolphin sighting records from recent surveys (2020 and 2021) and previous records of GD occurrences were obtained from the literature (Behera et al., 2014; Sinha and Kannan, 2014) and compared. Further, the local extinction was confirmed when it was not encountered/reported in a particular river for more than ten years' time frame (Mitra and Chowdhury, 2018). Potential hydro-morphological variables and encounter rate of GD (sightings/ km linear stretch), were evaluated for inter-river variation using Analysis of Variance (ANOVA) test (Supplementary Text S1).

2.3.2. Site occupancy and abundance

In ecological modelling, regression-based approaches such as Generalized Linear Model (Rushton et al., 2004) and Generalized Additive Models (Leathwick and Whitehead, 2001) are frequently used to evaluate species association with environmental and/or habitat variables (Guisan and Zimmermann, 2000; Rushton et al., 2004). However, these approaches do not estimate site-specific species occurrences. Unlike these approaches, models based on occupancy frameworks can produce unbiased estimates of occupancy (Ψ) and provide insights into the habitat use of a species simultaneously considering detection probabilities (p) (Mackenzie et al., 2002). The occupancy model also allows the inclusion of covariates to explain heterogeneity in both occupancy and detection probability (Mackenzie et al., 2006).

Selecting an appropriate method for population estimation is challenging, particularly for species having low detection probability, such as the GD. The occupancy models take into account detection and non-detection over multiple surveys of a sampling site to estimate detection probabilities (p) to derive unbiased estimates of occupancy (Ψ) (Mackenzie et al., 2002). Here, we used site occupancy models in maximum-likelihood frameworks to determine the probability of site use (Mackenzie et al., 2002), and the N-mixture model (Royle, 2004; Kéry and Royle, 2015) to estimate abundance (λ) of the GD in GB using spatial replicate counts while accounting for imperfect detection. *Platanista gangetica* and *Platanista minor* being identical in their external appearance, have similar physiological requirements (Smith and Braulik, 2009), and thus mean home range of the *Platanista minor* was used as a surrogate for designing the length of the sampling sites for the present study (Toosy et al., 2009). The GD is assumed to have a maximum daily movement of ~25 km given the river stretches are characterized by intermittent shallow and deep pools. Secondly, a linear river stretch of 25 km can be easily surveyed for GD detection within a day without any logistical constraints with a vessel speed of 6–8 km/ hrs. The surveyed stretch of 4635 km was split into 927 BEUs that were considered as spatial sub-units to assess the extent of site use of the GD. Five adjacent BEUs (sampling sites of 25 km) were considered as spatial replicates to accommodate it in site-occupancy and N-mixture framework (Mackenzie et al., 2002; Charbonnel et al., 2014; Searle et al., 2020). We chose a length of 25 km as the best compromise between the need to detect the presence of a species and that of having more than three spatial replicates, as recommended by Hines et al. (2010). Double counting of GD due to overnight movement from surveyed to non-surveyed segments was considered, assuming an equal probability of GD being missed due to opposite-direction movement (Braulik, 2006).

We used 156 sampling sites out of 185 as we did not record GD sightings in the surveyed stretch of the Son River, 180 km stretch of the Chambal River between Pali and Dang Basai and 70 km stretch of the Ganga River between Bhimgoda and Bijnor barrages. For deriving site occupancy, the dolphin presence/absence at each spatial unit and the covariates that may influence occupancy and detection probability were included in the analysis (Mackenzie et al., 2006). The covariates were selected based on a *priori* understanding and literature search that may influence the occurrences of GDs (Kelkar et al., 2010; Choudhary et al., 2012; Paudel et al., 2015). The detection covariates are presumed to influence the likelihood of detecting a species, given its presence at a site (p). We considered channel width, effort, and time of the surveyed day as detection covariates for both site occupancy and N-mixture

modelling, assuming these variables would influence the detection of a GD given its presence at a site. Site covariates are factors that are hypothesised to influence the probability of a species' site occupancy (ψ). The same suite of variables were selected for estimating abundance (λ) using N-mixture models (Supplementary Table S2). Each of the continuous covariates were z-standardized before analysis and categorical variables were dummy coded following Sunarto et al. (2012), Searle et al. (2020). Variables were checked for multicollinearity using Pearson's correlation test, and variables having Pearson's correlation coefficient ≥ 0.70 were excluded from the analysis following Graham (2003). Additionally, the GD count, along with covariates influencing the abundance, was included in the N-mixture modelling.

In this study, site occupancy models (MacKenzie et al., 2002) were used with detection and non-detection data using the "unmarked" package's 1.2.5 *occu()* function (Fiske and Chandler, 2011). A multi-stage modelling approach was adopted, in which covariates influencing detection probability p were run first, keeping the occupancy probability Ψ constant. Then, using multivariate occupancy models, we investigated whether environmental covariates influenced detectability (Supplementary Text S2).

The N-mixture model was performed using the *pcount()* function in "unmarked" package in R version 4.1.3 (Fiske and Chandler 2011; R Development Core Team 2022), using R Studio version 2022.02.3 (RStudio Team 2022). We fitted the N-mixture models, combining all the spatial counts data with Negative Binomial distributions (Joseph et al., 2009; Knappe et al., 2018) as it allows for modelling over dispersion data with significantly fewer true zeros in the dataset (Wenger and Freeman, 2008; Barão-Nóbrega et al., 2022). We used a numeric upper bound value for K for abundance estimates following multiple trials without affecting the model outcome (Fiske and Chandler, 2011; Kéry and Royle, 2015; Barão-Nóbrega et al., 2022). Models were ranked based on their Akaike Information Criterion (AIC) scores (Akaike, 1974; Burnham and Anderson, 2004) (Supplementary Text S3). The predictor variables associated with top-ranked univariate model were evaluated to determine GD habitat use (Ψ). We then modelled covariates hypothesised to affect detection (p), channel width, effort and time using a global model considering remaining habitat use covariates constant. A final model set was generated for all possible additive combinations of detection and site use covariates with $\Delta AICc < 2$, representing models with substantial empirical support. The goodness of fit for the most parameterized and highest-ranked models were assessed following Mackenzie and Bailey's goodness of fit test (MacKenzie and Bailey, 2004).

The AICc weights of all models in the final model set, in which the covariate appeared, were summed to assess the overall importance of the covariates (Burnham and Anderson, 2004). The sign of the covariate's beta coefficient estimates represented the direction of impact, and only if the beta coefficient's 95 % confidence interval ($\beta \pm 1.96 \times SE$) did not overlap zero, the effect of covariates was deemed significant. The predicted probability of site occupancy for each site was obtained via model averaging the final model set using the package MuMin (Bartoń, 2013). The sum of squared errors, chi-square, and freeman-tukey tests were used to evaluate the goodness of fit for the top-ranked model and the model with the most parameters in the final model set.

2.3.3. Abundance estimation using correction factor (D_{cf})

GD rely upon their surfacing, however, there is a chance of missing few individuals during the survey. Correction factor for missing/unmarked individuals is an essential precursor to estimate population figure precisely (Vu et al., 2018). Thus, correction factor (D_{cf}) was derived using detection probability extracted from published work conducted in the rivers in the Indian subcontinent and was used as an index to verify the outcome of our model-based results. The mean correction factor for GDs was derived from various studies (Supplementary Table S3). D_{cf} account for missed individuals while conducting

visual encounter surveys (Smith et al., 2006; Richman et al., 2014). The D_{cf} for GD was derived by dividing 1 by detection (p) and the corrected population estimates of GD were calculated by multiplying D_{cf} by the total number of GD sightings obtained during the visual encounter survey.

$(D_{cf}) = 1/(\hat{p})$, where (D_{cf}) is the correction factor for GD estimates and $\hat{p}$ is the detection probability.

2.3.4. Conservation priority stretches (CPS)

Scholars have identified conservation priority areas using either species or habitat, or both (Asaad et al., 2017; Maire et al., 2017). The species-based criteria include species of conservation significance, restricted-range species, biological diversity, and areas important for life history stages (e.g. Stewart et al., 2022; Banerjee et al., 2022), and habitat criteria includes unique and rare habitats, fragile and sensitive habitats, ecological integrity, and representativeness (e.g. He et al., 2018). These criteria were further categorized as five factors (habitat cover, species attribute, species richness, geographic range, and species abundance) for identification of priority areas (Assad et al., 2017). We have used flagship-cum-indicator species based approach for identification of conservation priority stretches, which essentially includes species of conservation significance, and ecological integrity criteria. These two criteria represent the four factors suggested by Assad et al. (2017), which makes our approach robust.

We used Maximum entropy (MaxEnt, version 3.4.4) models to predict the potential distribution and to identify conservation priority areas in the GB (Phillips et al., 2017). MaxEnt models are based on the principle of maximum entropy that accounts for presence-only data of rare or threatened species with environmental variables (Elith et al., 2006; Phillips et al., 2017; Clements et al., 2012; Kramer-Schadt et al., 2013) to project future distributions under global climate change impacts (Hu and Jiang, 2011) and considered as one of the efficient models for predicting species distribution models. There are many other well established species distribution modelling approaches such as Generalised Additive Models, Genetic Algorithm for Rule-set Prediction (GARP) and BIOCLIM that uses presence only data. MaxEnt has an advantage over them, as it has a higher predictive accuracy (Elith et al. 2006, Wisz et al. 2008). MaxEnt is suitable for simple as well as complex models with wide array of predictor variables. However, it can produce biases due to over-fitting of the models and influence the predictive performance when using large set of predictor variables (Phillips and Dudík, 2008).

A total of 758 presence locations of GD were used for distribution modelling. We selected 28 variables (Bioclimatic = 19, hydro-morphological = 5, and anthropologic = 4) based on *a priori* understanding of the species ecology and literature search for species distribution modelling using MaxEnt (e.g. Kelkar et al., 2010; Choudhary et al., 2012; Paudel et al., 2015). The bioclimatic layers were downloaded from WorldClim version 2 at a spatial resolution of 2.5 arc minutes ($\sim 4.5 \text{ km}^2$) (Fick and Hijmans, 2017) and resampled at 5 km^2 to have a uniform spatial resolution. Each of these variables were checked for multicollinearity, and highly correlated (Pearson correlation ≥ 0.70) variables with low ecological influences were removed from the modelling (Zuur et al., 2010).

Finally, presence location of GD, along with 16 uncorrelated ecologically meaningful variables (Bioclimatic = 7, hydro-morphological = 5, and anthropologic = 4) were used to predict the suitable habitat of the species using MaxEnt (Supplementary Table S2). Two key user-modifiable parameters influence the predictive performance of the MaxEnt, viz. feature classes and regularisation multipliers (Elith et al., 2010). These parameters were optimized to prevent model over-complexity and/or overfitting. We experimented with multiple combinations of feature classes (L = Linear, Q = Quadratic, P = Product, T = Threshold and H = Hinge) and regularization parameters (0.5, 1.0, 1.5 and 2.0). The models were ranked based on AIC to obtain the best-fit

model. The ASCII file of prediction probability was projected to ArcGIS 10.6 and reclassified to generate a probability distribution map. Potential dolphin distribution stretches (probability distribution score > 0.50) were categorised into three major conservation priority stretches, ≥ 0.70 High Conservation Priority Stretches (CPS1), 0.61–0.70 Moderate Conservation Priority Stretches (CPS2) and 0.51–0.60 Low Conservation Priority Stretches (CPS3).

3. Results

3.1. River characterization

The mean depth of the eight surveyed rivers was 3.49 m (± 0.42 , $n = 927$) and among these the Ganga River was the deepest ($5.78 \text{ m} \pm 0.27 \text{ m}$). Significant variation in mean depth was found between the rivers (ANOVA, $F = 59.88$, $p < 0.001$). The mean river width was $531.69 \text{ m} \pm 86.65 \text{ m}$, which was more than the mean width of Chambal, Son, Yamuna, Ghaghra and Gandak rivers. The mean channel width shows significant variation across studied rivers (ANOVA, $F = 74.9$, $p < 0.001$). The mean channel flow across the rivers was $531.43 \pm 86.65 \text{ m}^3/\text{s}$ and ranged between $80.31 \text{ m}^3/\text{s} \pm 102.37 \text{ m}^3/\text{s}$ (Rupnarayan River) and $762.36 \text{ m}^3/\text{s} \pm 490.45 \text{ m}^3/\text{s}$ (Ghaghra River). We observed significant difference in the mean flow between rivers (ANOVA, $F = 19.76$, $p < 0.001$). The mean number of meanders (1.34 ± 1.06 meanders/BEU) showed significant variation between rivers (ANOVA, $F = 18.72$, $p < 0.001$). The number of meanders was found to be highest in the Chambal River (1.34 ± 1.06 meanders/BEU). The mean slope (0.75 ± 0.38 degree) across the basin showed significant variation between the studied rivers (ANOVA, $F = 9.75$, $p < 0.001$). The Yamuna River was the steepest among the eight surveyed rivers (1.38 ± 2.4 degree) (Supplementary Table S4).

Our assessment suggests that in comparison to other rivers, the Chambal River is relatively disturbance free due to its protected nature. The mean fishing intensity (22.67 ± 25.70 nets/ BEU) indicated significant variation between the rivers (ANOVA, $F = 9.75$, $p < 0.001$). The fishing intensity was highest for the Rupnarayan River (72.19 ± 61.25 nets/ BEU) and lowest for the Chambal River (0.05 ± 0.21 nets/BEU). The sand mining intensity in the basin was 4.23 ± 3.24 activities (boats, tractor and earthmovers) with highest for the Yamuna River (9.64 ± 28.68) and lowest for the Chambal River (0.59 activities ± 1.47 activities). We found significant differences in the mining activities across studied rivers in the basin (ANOVA, $F = 6.038$, $p < 0.001$). The mean water extraction pumps in the GB was 0.76 ± 0.20 (pumps/ BEU) with highest in the Rupnarayan River (7.5 ± 8.37) and lowest in the Chambal River (0.05 ± 0.21) due to above stated reasons. The occurrences of water extraction pumps within rivers showed a significant variation (ANOVA, $F = 18.57$, $p < 0.001$).

3.2. Distribution and range decline

First ever description of GD range was given by Anderson (1879). In the basin, the GD used to occur between Haridwar and Ganga Sagar prior to the initiation of water resource development projects in the mainstem of the Ganga River during the 19th Century (Supplementary Fig. S2). In the present study, the occurrence of GD in the mainstem Ganga was found to be confined in two disjunct stretches (Fig. 2). The first between Bijnor barrage and Kanpur barrage, and the second one between Fatehpur and Ganga Sagar. The current occurrence of GD in the Ganga, indicates 6.51 % decline in its range, which contributes to 2.74 % decline in the GB. In the Yamuna River, the historical range was between Delhi and Prayagraj (Yamuna - Ganga confluence). During present study GD sightings were recorded downstream of Bareilly (Chambal - Yamuna Confluence) up to Prayagraj, indicating 58.57 % decline in the Yamuna, which contributes to 12.04 % decline in its entire distribution range. In the past, the GD sightings in Chambal River were recorded between Batesura and Bareilly. However, in present survey the GD distribution was

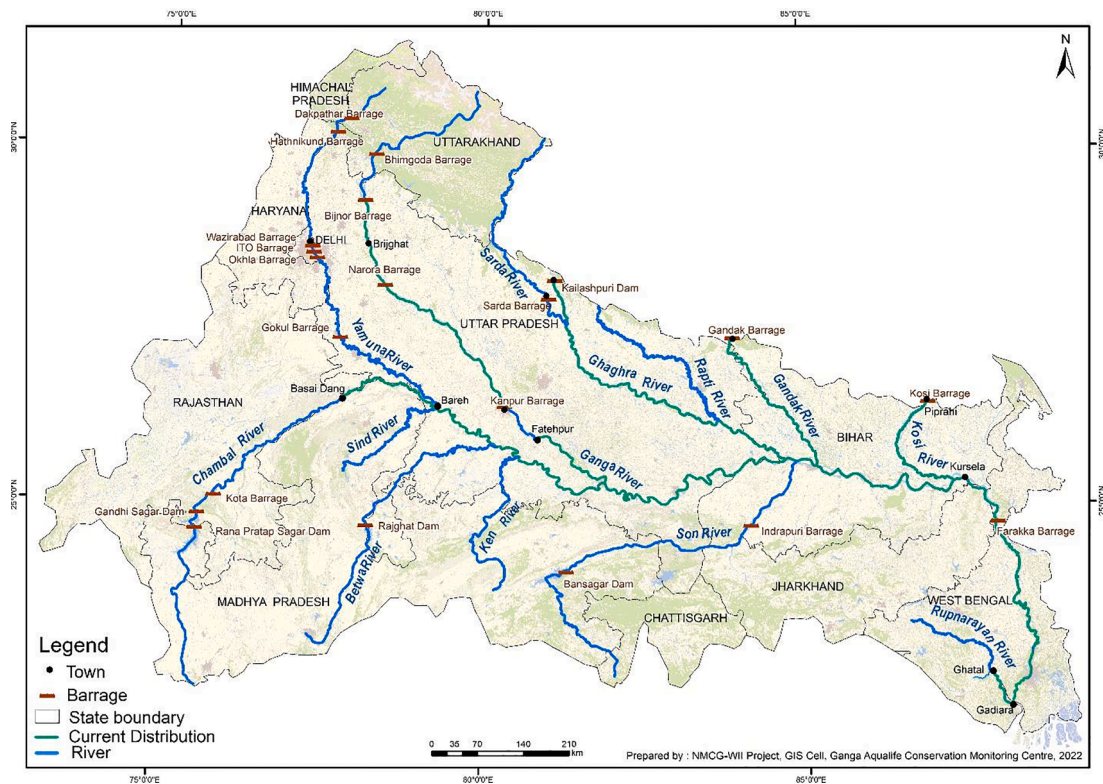


Fig. 2. Current distribution range of Gangetic dolphin in the Ganga Basin, India.

restricted between Basai Dang and Bareilly, which suggests range decline of 17.54 % in Chambal, and 0.98 % of its entire distribution range. The GD range decline in the Kosi River was 4.26 % and 0.20 % in its distribution range. The GD distribution was found to be intact in the other northern snow fed tributaries such as Ghaghra, and Gandak. In the present study we recorded no dolphin occurrences from Son River, and is

the first report of GD extirpation from entire Son River. The GD is now believed to be extirpated from Ken, Betwa, and middle stretch of Sharda rivers mainly due to reduced depth caused by water abstraction. However, in the Rupnarayan River, we observed increase in GD range, which accounted for 40 % increase from its earlier records, and 0.01 % increase in its entire range. Overall, our estimate suggest that the current

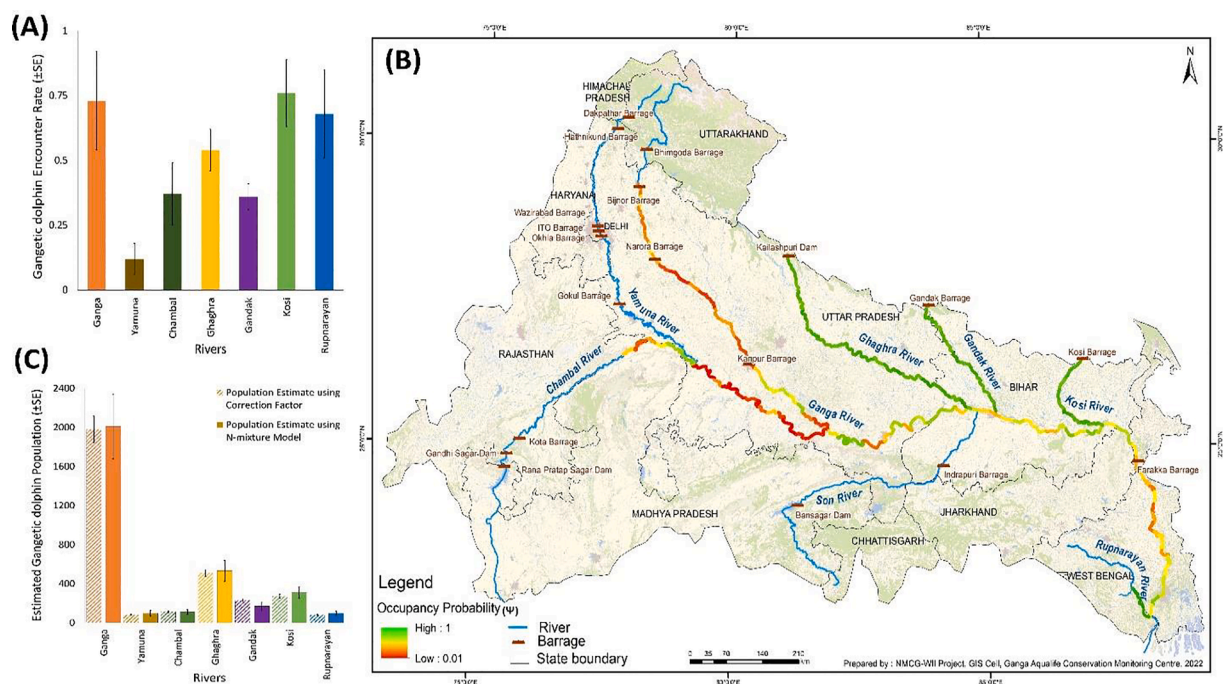


Fig. 3. (A) Encounter rate of dolphin sightings per km in eight major rivers of Ganga Basin, India, (B) Model averaged estimates of Gangetic dolphin site occupancy (Ψ), and (C) abundance estimate of Gangetic dolphin using N -mixture and correction factor (D_{CF}).

distribution range of the GD has been reduced by almost 24.37 % (1245 km) in the GB since 1878 and 7.44 % over the last two decades (Supplementary Table S5).

3.3. Encounter rate

In total, 2151 sightings of surfacing GDs were recorded in 4635 km survey stretch of eight rivers. Maximum of 1303 (60.57 %) sightings were recorded from the Ganga River followed by Ghaghra, Kosi, Gandak, Chambal, and Rupnarayan rivers, and least from the Yamuna River (Supplementary Table S6). The overall mean encounter rate was 0.51 ± 0.11 sightings/km that indicated significant variation across the surveyed rivers (ANOVA, $F = 3.08$, $p < 0.001$). We recorded the highest dolphin encounter rate in the Kosi (0.76 ± 0.13 sightings/km), followed by Ganga, Rupnarayan, Ghaghra, Chambal, Gandak and Yamuna Rivers (0.12 ± 0.06) (Fig. 3A). No dolphins were recorded from the Son River.

3.4. Factors affecting dolphin site occupancy and abundance

GD was detected in 132 out of 156 sampling units of 25 km linear stretch, accounting for a naïve occupancy of 0.85. The estimated mean detection probability was $(p) 0.60 \pm 0.03$, and the mean probability of site occupancy was $\Psi = 0.85 \pm 0.04$.

In total, 35 models, including univariate and multivariate, were generated to infer the influence of predictor variables on the detection probability (p) and site occupancy (Ψ) of the GD. The best fit model (AICc = 0.0) for site occupancy (Ψ) includes channel depth, meander and river, and for detection probability (p) includes channel width as the best predictor variable (Table 1A). Model averaged estimates revealed high GD site occupancy across the study area (Fig. 3B). The variables defining the site occupancy, viz. depth summed model weight ($\Sigma w = 1.00$), meanders ($\Sigma w = 1.00$), and individual rivers ($\Sigma w = 1.00$) were found to be positively associated with GD occurrence (Table 1B). In contrast, channel width ($\Sigma w = 1.00$) defining the detection probability showed a negative but insignificant association as beta coefficient yield overlapping zero ($\beta \pm SE = 0.11 \pm 0.08$) (Supplementary Fig. S3).

A total of 31 N-mixture models considering all possible combinations of covariates (univariate and multivariate) were generated under Negative Binomial distribution. The best fit model for abundance (λ) includes channel depth, meanders and individual rivers, and for

detection probability (p) include channel width and effort (Table 2A). Based on model-averaged parameter estimates, channel depth ($\Sigma w = 1.00$), meanders ($\Sigma w = 1.00$) and river ($\Sigma w = 1.00$) were the best predictors of the dolphin abundance (Table 2B). As seen in the site occupancy modelling, we observed a positive influence of channel depth, and meanders on GD abundance. Although parameters like individual river appeared in the final model set, the influence of it varied from river to river. Ganga, Ghaghra and Kosi had a significant positive influence on abundance, whilst the remaining had no influence (Table 2B). Channel width significantly negatively impacted detection probability ($\Sigma w = 1.00$), while effort was positively associated with the detection probability of GD in the GB ($\Sigma w = 1.00$) (Supplementary Figs. S4 and S5).

3.5. Population estimation

3.5.1. Population estimation based on N-mixture model

The overall abundance estimate of GD across the GB was 3330 ± 620 individuals (Confidence Interval (CI) = 2304–4668; Coefficient of Variance (CV) = 18.61) (Fig. 3C), the abundance was highest in Ganga River (60.36 %) with estimated 2010 ± 332 individuals (CI = 1455–2718; CV = 16.52). Of all tributaries, the Ghaghra River holds the second largest population of GD (16.01 %) with an abundance estimate of 533 ± 108 individuals (CI = 350–766; CV = 20.34) followed by the Kosi River (9.34 %) with an estimate of 311 ± 59 individuals (CI = 209–434; CV = 18.81) and Gandak River accounted for 169 ± 45 individuals (CI = 95–268; CV = 26.53). The abundance estimate for Chambal River was 111 ± 27 individuals (CI = 70–172; CV = 24.54) followed by Rupnarayan River with an estimate of 99 ± 21 individuals (CI = 64–146; CV = 20.85). The abundance estimates were least in the Yamuna River at 97 ± 28 individuals (CI = 61–164; CV = 29.33), which accounted for 2.91 % of the total estimated population in the basin (Table 3A).

3.5.2. Population estimation based on correction factors (D_{cf}) derived from other studies

The estimates of GD abundance were obtained by multiplying the mean correction factor ($D_{cf} = 1.52$) by the number of GD sightings in each river. The estimated population of GD in the GB was thus 3270 ± 229 individuals (CI = 2821–3718). The highest estimated number of GD for the Ganga River was 1981 ± 138 individuals (CI = 1709–2252). Similar to the estimate obtained using N-mixture, the Ghaghra River was estimated to have the second largest population of GD at 509 ± 36 individuals (CI = 439–579) followed by Kosi River with an estimate of 272 ± 19 individuals (CI = 235–309) and Gandak River accounted for 231 ± 16 individuals (CI = 199–263). The abundance estimate of Chambal River was 114 ± 8 individuals (CI = 98–130) followed by Rupnarayan River with an estimate of 82 ± 6 individuals (CI = 71–93). The estimated population of GD was least in the Yamuna River at 81 ± 6 individuals (CI = 70–92) (Table 3B).

3.6. Identification of conservation priority stretches (CPS)

We obtained a total of 124 models considering multiple combinations of feature classes and regularization multipliers (Supplementary Table S7). The prediction model generated using cross validation with 500 iterations had an Area Under Curve [AUC = 0.91 (SD 0.0089)] (Fig. 4A). The SDM analysis revealed that eight bioclimatic variables viz. fishing, annual mean temperature (Bio 1), channel flow, precipitation of driest quarter (Bio 17), precipitation of warmest quarter (Bio 18), precipitations of the wettest month (Bio 13), meanders, and depth had ≥ 5 % contribution in defining GD distribution under current climate conditions. The predicted potential distribution of GD showed that the contribution of fishing was maximum (18.4 %) followed by annual mean temperature (15.5 %) and channel flow (12.9 %) (Supplementary Table S8).

The species distribution obtained using MaxEnt models predicted

Table 1

Results of site occupancy model selection (A) Best model for Gangetic dolphin site occupancy (B) Parameter estimates (SE) of the final model set ($\Delta AICc < 2$) for models estimating Gangetic dolphin site occupancy.

(A) Best models for Gangetic dolphin site occupancy (Ψ)					
Model	nPars	−2*LogLike	AICc	Δ AICc	AICwt
1 Ψ (cd + me + river), p(cw)	11	467.81	957.62	0	0.66
2 Ψ (cd + me + river), p(cw + effort)	12	467.81	959.63	2	0.24

(B) Parameter estimates (SE) of the final model set					
Model	β (cd)	β (me)	β (Yamuna)	β (cw)	
1 Ψ (cd + me + river), p (cw + effort)	0.82 (0.46)	2.56 (0.87)	−3.34 (1.50)	0.11 (0.08)	
2 Ψ (cd + me + river), p (cw + effort + time)	0.82 (0.46)	1.04 (0.10)	−3.37 (1.51)	0.11 (0.08)	

Δ AIC is the relative difference in AIC values compared with the top ranked model; where AIC is Akaike's information criterion; AICwt is the Akaike weight of the model; nPars is the number of parameters; −LogLike is the negative log likelihood value; Ψ is estimated site occupancy; p is the estimated detection probability; Lambda (λ) is the abundance estimates. Cd = channel depth; me = meanders; river = individual river; cw = channel width.

Table 2

Results of *N*-mixture model selection (A) Best models for Gangetic dolphin abundance (λ) (B) Parameter estimates (SE) of the final model set (Δ AICc < 2) for models estimating Gangetic dolphin abundance.

(A) Best models for Gangetic dolphin abundance (λ)						
	Model	nPars	$-2^*LogLike$	AICc	Δ AICc	AICwt
1	$\lambda(cd + me + river), p(cw + effort)$	13	1942.35	3910.69	0	0.56
2	$\lambda(cd + me + river), p(cw + effort + time)$	14	1941.57	3911.15	0.45	0.44

(B) Parameter estimates (SE) of the final model set							
	Model	β (cd)	β (me)	β (Ganga)	β (Ghaghra)	β (Kosi)	β (cw)
1	$\lambda(cd + me + river), p(cw + effort)$	0.20(0.08)	1.03(0.10)	1.88(0.32)	1.11(0.33)	1.01(0.39)	-0.23(0.04)
2	$\lambda(cd + me + river), p(cw + effort + time)$	0.20(0.08)	1.04(0.10)	1.88(0.32)	1.11(0.33)	1.00(0.39)	-0.23(0.04)

Beta coefficients (β) shown in bold indicate significant impact on site occupancy of the model as 95 % CI $\neq$ 0 ($\beta \pm 1.96^*SE$). River which were insignificant are not included in the table. Cd = channel depth; me = meanders; river = individual river; cw = channel width.

Table 3

River wise abundance estimates of the Gangetic dolphin in the Ganga Basin (A) using *N*-mixture model (B) using Correction factor (D_{cf}).

(A) Abundance estimate using <i>N</i> -mixture					
River	Surveyed length (km)	Mean $\pm$ SE	95 % CI-lower	95 % CI-upper	CV
Ganga	2070	2009.76 $\pm$ 332.04	1454.95	2718.18	16.52
Yamuna	435	97.14 $\pm$ 28.49	60.98	164.05	29.33
Chambal	405	110.86 $\pm$ 27.2	70	172	24.54
Ghaghra	615	532.83 $\pm$ 108.38	349.95	766.03	20.34
Gandak	295	169.02 $\pm$ 44.84	94.98	268	26.53
Kosi	235	311.38 $\pm$ 58.56	209	434.05	18.81
Rupnarayan	80	99.48 $\pm$ 20.74	64	146	20.85
Ganga Basin	4135	3330 $\pm$ 620	2304	4668	18.61

(B) Abundance using correction factor (D_{cf})					
River	Surveyed length (km)	Observed sightings	Population estimates $D_{cf} = 1.52 \pm SE$	95 % CI-lower	95 % CI-upper
Ganga	2070	1303	1981 $\pm$ 138.49	1709.12	2252.00
Yamuna	435	53	81 $\pm$ 5.63	69.52	91.60
Chambal	405	75	114 $\pm$ 7.98	98.38	129.62
Ghaghra	615	335	509 $\pm$ 35.61	439.41	578.99
Gandak	295	152	231 $\pm$ 16.16	199.38	262.70
Kosi	235	179	272 $\pm$ 19.03	234.79	309.37
Rupnarayan	80	54	82 $\pm$ 5.74	70.83	93.33
Ganga Basin	4135	2151	3270 $\pm$ 228.62	2821.43	3717.61

~5000 km of river stretch including historic and current distribution range of the GD (Supplementary Table S5). Of the total predicted distribution, 2040 km (40.8 %) of stretch was found suitable (probability distribution score $\geq$ 0.50) for GD in the GB (Table 4). Identification and classification of priority stretches based on potential distribution map of the GD revealed that 12.2 % (610 km) of the river stretches fall under High Conservation Priority Stretch (CPS1) (>0.70), 14.3 % (715 km) under Moderate Conservation Priority Stretch (CPS2) (0.61–0.70) and 14.3 % (715 km) under Low Conservation Priority Stretch (CPS3) (0.51–0.60). The majority of the CPS1 was confined between the Ganga-

Yamuna and Ganga-Kosi confluences (Fig. 4B), while the remaining CPS1 was located in the tributaries. Among the rivers that showed suitable habitat, the Ganga River had the largest contiguous, highly suitable river segment of 200 km in the basin representing 6.5 % of total available stretch. CPS2 and CPS3 were interspersed with CPS1 of the Ganga River and its tributaries (Fig. 4C and 4D).

4. Discussion

Rivers are dynamic systems that vary with changes in flow regimes, which regulate intricate hydro-morphological processes (Zeiringer et al., 2018). Species occurring in these habitats are highly reliant on established patterns of habitat dynamics maintained by the natural hydrologic regime and their biology is closely linked with seasonal change in the hydrological regime (Poff et al., 1997; Thorp et al., 2006). However, anthropogenic stressors have disrupted the natural hydrological cycle resulting in biodiversity loss and interrupted vital ecological processes in these ecosystems (Dudgeon et al., 2006; Strayer and Dudgeon, 2010; Alizadeh et al., 2018). These underlying effects make maintaining critical ecological processes in these threatened ecosystems challenging. Studies have highlighted the importance of dedicated geographical areas identified through comprehensive scientific methods in maintaining biodiversity and ecological functioning (Belote and Wilson, 2020). In the present study the GD sighting was used to derive their distribution patterns, abundance, *vis-à-vis* influence of hydrological, anthropogenic and climatic factors and prioritise conservation for long-term survival of the aquatic species and functioning of riverine ecological process.

The distribution pattern of GD in the Basin revealed a decline in its range since 1878. The observed sightings of GD showed clustered distribution and relatively high sightings in lower stretches of the rivers where mean depth, confluences, river constrictions and meanders were significantly high (Sinha & Kannan, 2014; Choudhury et al., 2019). The low sightings of GD in the upper stretches of the river was attributed to small cross-sectional area with high degree of channel bifurcation and comparatively low flow with shallow depth. The encounter rate also varied across the study area with several stretches showing an increase while others showed a decline. The difference in hydrological regimes of surveyed rivers due to their nature of origin and course through different biogeographic zones and terrain types would have resulted in variation in GD occurrence across the basin.

The reduction in distribution range, specifically in the upstream of the river, is likely due to the structural barriers, which alters the hydrological regime and disrupts lateral connectivity. Additionally, water development projects such as dams, barrages and embankments are likely to interrupt dolphin movement and result into fragmented populations. The impact of anthropogenic activities such as fishing, in-stream mining and heavy vessel movement also led to disruption of

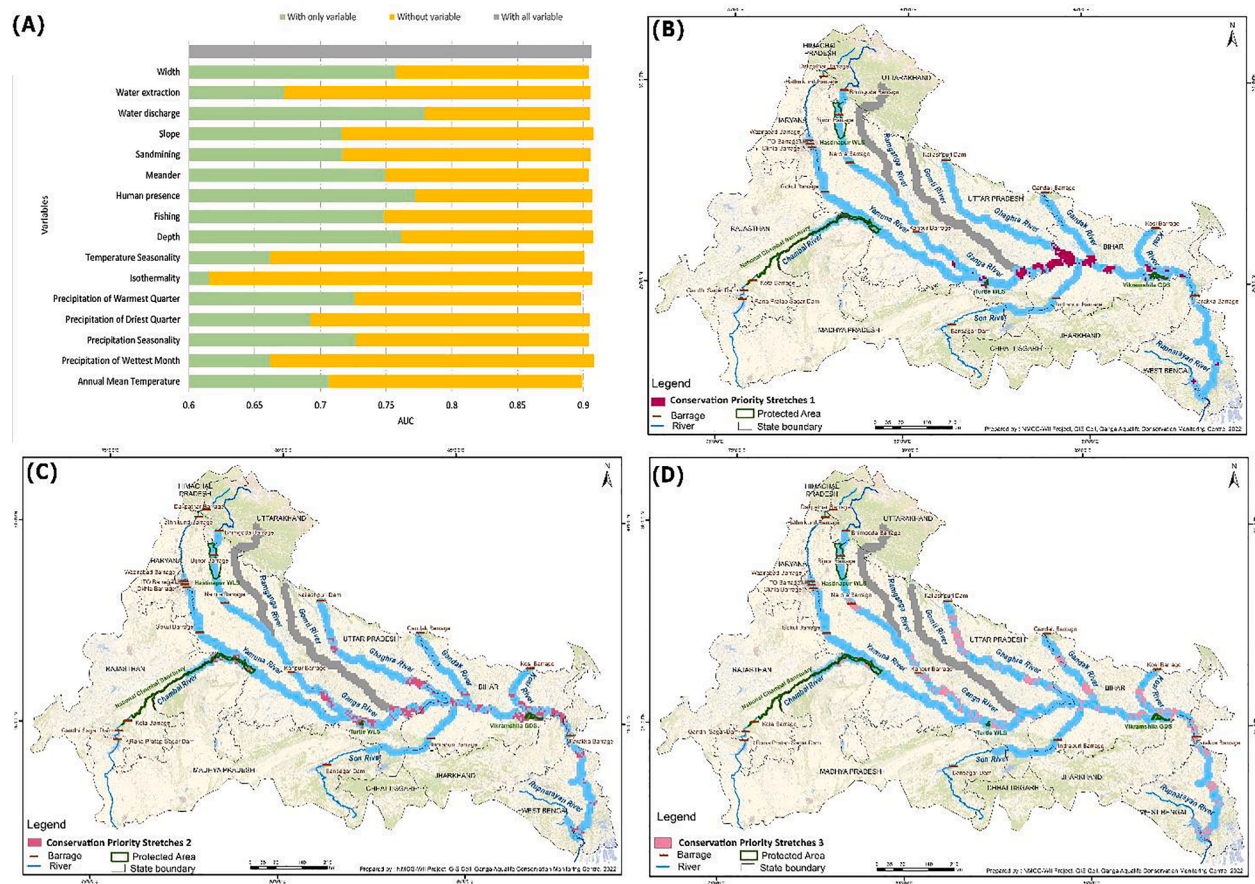


Fig. 4. Identification of Conservation priority river stretches in the Ganga Basin, (A) Jackknife test using AUC on test data, (B) Conservation Priority Stretches 1, (C) Conservation Priority Stretches 2, (D) Conservation Priority Stretches 3.

Table 4
Length of identified priority river stretches in Ganga Basin for conservation. The values in parentheses are the percentage (%) of priority river stretches for each category.

River	Total length (km)	Surveyed length (km)	High Priority Stretches (CPS1) (km)	Moderate Priority Stretches (CPS2) (km)	Low Priority Stretches (CPS3) (km)
Ganga	2525	2070	325 (6.5)	435 (8.7)	310 (6.2)
Yamuna	1435	435	20 (0.4)	50 (1.0)	45 (0.9)
Chambal	960	405	85 (1.7)	60 (1.2)	50 (1.0)
Ghaghra	1123	615	85 (1.7)	55 (1.1)	150 (3.0)
Son	784	500	5 (0.1)	5 (0.1)	20 (0.4)
Gandak	775	295	5 (0.1)	35 (0.7)	75 (1.5)
Kosi	729	235	70 (1.4)	45 (0.9)	45 (0.9)
Rupnarayan	280	80	15 (0.3)	30 (0.6)	20 (0.4)
Total	8346	4635	610 (12.2)	715 (14.3)	715 (14.3)

connectivity between tributaries and the mainstem river (Aggarwal et al., 2020; Paudel and Koprowski, 2020; Samad et al., 2022). The lower stretches of the river, due to the hydrological complexities particularly availability of higher mean depth, confluences, meanders, unbraided channel and possibly low impacts of dams and barrages are suitable for GD presence (Sinha and Sharma, 2003b; Choudhary et al., 2006; Kelkar et al., 2010; Behera et al., 2013; Mazumder et al., 2014). Consistent with the findings of Kelkar et al., (2010), Bashir et al., (2012), Paudel et al., (2015), the site occupancy and N-mixture models revealed a positive association of GD site occupancy and abundance with channel depth, meanders, and river type, particularly in mainstem Ganga and snow-fed tributaries such as Ghaghra, Gandak and Kosi

ivers. (Tables 1B and 2B). Findings of Kelkar et al. (2010) explained that a high occurrence of GD occurred at > 5.2 m depth, and also emphasized that a contiguous series of deep pools with high prey availability are suitable for providing ample space for dolphin movement. Owing to the physiological needs of the GD, the deep pools, meanders and confluence tend to provide ample foraging opportunities, predator avoidance and escape from entrapment in shallow pools (Kelkar et al., 2010; Bashir et al., 2010; Khanal et al., 2016; Choudhury et al., 2019; Paudel et al., 2021). The deep pools are good fish habitat, thus have high fish abundance (Smith et al., 1998; Zhou et al., 2022), which results in increased foraging ability of GD by reducing foraging time and degree of metabolic investment. The deep pools provide the highest possible usable area for GD due to presence of higher cross-sectional area, and depth (Braulik et al., 2012; Paudel et al., 2021). Low-velocity in the deep pools favour efficient diving for prey capture and predator avoidance, if necessary. Further, the significance of deep pools increases particularly during the low-water season when suitable habitat shrinks manifolds compared to the high-water season (Braulik et al., 2012; Paudel et al., 2021; Samad et al., 2022; Sharma et al., 2022) and GD tend to occupy and congregate in these deeper areas for their survival (Bashir et al., 2010; Kelkar et al., 2010). N-mixture models have been applied to a wide range of wildlife species ranging from invertebrates to large mammals (Paudel et al., 2015; Kidwai et al., 2019; Manica et al., 2019; Searle et al., 2020; Than et al. 2020; Barão-Nóbrega et al., 2022), that explicitly allow for assessing abundance estimates and detection probability from a repeated count data of unmarked individuals (Kéry and Royle, 2015; Bötsch et al., 2020). N-mixture model is cost effective and widely used to estimate the abundance of population from count data with both spatial and temporal replications while accounting for imperfect detection

(Royle, 2004; Joseph et al., 2009). There are many alternative sampling methods exist for obtaining estimates of abundance such as capture-recapture, distance and multiple-observer sampling; however the N-mixture model is comparatively cost-effective and requires minimum effort for data collection and does not require individuals to be identified (Dennis et al., 2015). Nonetheless, N-mixture model is particularly promising for wildlife studies because it has the potential to produce estimates that are comparable to those obtained by intensive surveys such as capture-mark-recapture approaches.

Previous studies were conducted in different time scales and were subjected to disjunct pockets. The available studies utilizing similar methodology were either conducted in small segments of high GD occurring stretch (Paudel et al., 2015) or for different species, rivers or terrestrial systems with varied geomorphological characteristics (Barão-Nóbrega et al., 2022; Than et al., 2020; Searle et al., 2020). Hence direct comparison of efficacy of N-mixture model in riverine system is not feasible as the present study is the first ever comprehensive survey conducted in the major rivers of the GB which is beyond the scale of comparison to earlier studies (e.g. Paudel et al., 2015; Than et al., 2020).

The findings of N-mixture model also revealed that channel depth, meanders and river type act as a crucial factor in determining GD abundance, which is evident from the fact that lower segments of the river are laden with deep pools and have more meanders. Channel width and efforts were considered as covariates of detection as it was quite obvious from the fact that increase in channel width resulted in decreasing detection of GD as it disrupts visual efficiency of the observer. Under such conditions, efforts of the observer team to detect individuals would be considered for optimizing detection.

This is the first study from India that employed the N-mixture models in large riverscapes to assess the abundance of GD and one of the first to do so for a flagship species in freshwater systems. Presumably, we can argue that the N-mixture framework applied to heterogeneous datasets offers a flexible approach for abundance estimates when ecological conditions are conducive for optimizing detectability, and provided reliable and insightful abundance estimates of GD and its detection across the study site. Earlier, the approach had been successfully employed to obtain abundance estimates of GD in the Karnali River of Nepal (Paudel et al., 2015). We also compared the estimates of GD derived from the N-mixture models with the correction factors (D_{cf}) extracted from published literature while accounting for imperfect detection. Both the approaches resulted in similar estimates as the probability of detection (p) was 0.66 and 0.65 for correction factor and N-mixture model, respectively. The mean population estimates of the individual rivers followed similar pattern as derived using correction factors for the GD. However, the abundance estimates of GD generated using N-mixture models cannot be exclusively interpreted as absolute abundance, as individuals whose home range spans multiple sites would have been accounted for multiple times within their home range (Link et al., 2018; Nakashima, 2020). Nevertheless, it can be safely said that the derived abundance of GD using correction factors (D_{cf}) (Fig. 3B) as an indices and the population estimates derived from N-mixture model make appropriate inferences about abundance across the riverscapes.

We believe that the N-mixture model, as compared to the conventional direct count method, would yield reliable abundance estimates for the heterogeneous detection population like GD that spend most of their time underwater. The N-mixture model is regarded as most suitable framework for estimating abundance (λ) and detectability (p) of unmarked individuals, which describes count data (sightings) replicated in time and space. Our analysis demonstrates that sighting-based occupancy modelling can be employed to monitor top predator's habitat use across large riverscapes such as GB (Bashir et al., 2012; Paudel et al., 2015). Findings of occupancy surveys and its insights can therefore be supplemented to mark-recapture surveys that yield robust population estimates at finer scales. However, the present work proposes robust survey designs combining visual and acoustic framework to yield reliable population estimates of GD where the acoustic survey will aid in

underwater missing animals (Richman et al., 2014). This approach would greatly enhance the detection probability of GD; hence, reliable estimates can be used to formulate strategies for conserving viable populations along its distribution range, including GB.

In our study, the predicted probability distribution used for prioritisation of conservation stretches was supported by high AUC (0.91 ± 0.0089). We highlight the potential bioclimatic variables governing GD distribution under the current climate change scenario and modelled probable high distribution stretches for prioritisation. Several identified priority stretches fall within the delineated boundaries of the Protected Areas (PAs) such as the Turtle Sanctuary, the Vikramshila Gangetic Dolphin Sanctuary and the National Chambal Sanctuary. The highest priority for conservation should focus on the stretches that are currently outside the PA network and are suitable for dolphins. These stretches were mostly confined in around the confluence of tributaries with the mainstem Ganga River. In the wake of growing demand for river resources and increasing threats to the freshwater ecosystem, it is crucial to protect these CPS to prevent habitat degradation and species loss. Societal reliance on the services provided by vast expanses of river stretches complicate management interventions, particularly those aimed at offsetting human footprints on riverine ecosystem (Pracheil et al., 2013). The identified river stretches with high biodiversity value in the Basin give an opportunity for targeted conservation actions and provide options to conserve the optimal stretches of the river for the continued flow of ecosystem services. This may serve as a blueprint for biodiversity conservation while preserving the societal benefits without de-linking the natural resources and human ecological requirements (Wang et al., 2015).

5. Conclusions

The GB is one of the largest and most densely populated regions of the world that supports more than 25,000 floral and faunal species and serves as a lifeline for over 650 million people (Dwivedi et al., 2018; Hussain et al., 2020). Over the past decades, population growth, agricultural and industrial expansion have led to the over-exploitation of riverine resources leading to its fragmentation. The inadequate water management policies to address the extensive use of water for irrigation, industry, and public supply have emerged as obstinate challenges for river conservation. Furthermore, the future climate change scenarios encompassing melting headwater glaciers, and changes in rainfall patterns have triggered extreme events and altered drought and flooding cycles that threaten the natural flow regime of the rivers. These adversely affect the species diversity of the basin, which are either currently endangered or are likely to become endangered in the foreseeable future. The riverine impoundments and reservoir-induced habitat fragmentation restrict connectivity in the aquatic system and impede natural migration of the aquatic fauna resulting in spatially and genetically fragmented populations. Conservation prioritisation of river stretches has been advocated to counter the impact of negative factors, and enable the riverine ecological process and functioning.

The first ever comprehensive surveys conducted in all major rivers in the GB covering a length of 4635 km revealed that the basin holds ~65 % of the total population of the GD. We also identified a 610 km river stretch, accounting for 12.2 % of the GB as a high conservation priority stretch (CPS1) for the conservation of the GD and other riverine associated species. The sub-optimal stretches between the CPSs need to be restored to enhance the connectivity and improve ecological functioning within the basin. Conservation of these stretches will provide a safety net against the cascading ecological and socio-economic impacts of climate change.

The assessment of large river habitats and estimation of the abundance of cryptic species within a vast stretch of linear system is a challenge for field ecologists. To overcome this limitation and challenge, a survey protocol for field observation and data recording was developed after thorough review of published literature and pilot survey. This

protocol was then followed by the multiple survey teams, deployed across the GB. In future, the population estimation of Gangetic dolphin in the GB can be further validated using the capture-mark-recapture framework, which can elucidate the loss of information due to under or over-estimates occurring due to false-negative or false-positive counts of the species, respectively (Barker et al., 2018). Further, spatio-temporal variation in the GD sightings can be estimated using a dynamic version of the N-mixture modelling approach using multi-season data, and multi-species-based ensemble modelling can be applied for delineating CPS in a river system.

CRedit authorship contribution statement

Goura Chandra Das: Data curation, Formal analysis, Software, Writing – original draft. **Surya Prasad Sharma:** Data curation, Formal analysis, Writing – original draft. **Sk Zeeshan Ali:** Data curation, Formal analysis, Visualization. **Saurav Gawan:** Data curation. **Aftab Alam Usmani:** Data curation. **Arkojyoti Sarkar:** Data curation. **Suyash Katdare:** Data curation. **Ajay Rawat:** Data curation. **Pichaimuthu Gangaimaran:** Data curation. **Ashish Kumar Panda:** Data curation. **Umang Agnihotri:** Data curation. **Aishwarya Ramachandran:** Visualization. **Srijani Guha:** Visualization. **Shivani Barthwal:** Supervision, Writing – review & editing. **Jeyaraj Antony Johnson:** Supervision, Writing – review & editing. **Ruchi Badola:** Conceptualization, Funding acquisition, Project administration, Supervision, Methodology, Writing – review & editing. **Syed Ainul Hussain:** Conceptualization, Funding acquisition, Project administration, Supervision, Methodology, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

- Aggarwal, D., Kumar, N., Dutta, V., 2020. Impact on endangered Gangetic dolphins due to construction of waterways on the river Ganga, India: an overview. *Environ. Sustain.* 3, 123–138.
- Akaike H., 1974. A new look at the statistical model identification. *IEEE Trans. Autom. Control* 19, 716–723. <https://doi.org/10.1109/TAC.1974.1100705>.
- Alizadeh, M.J., Kavianpour, M.R., Danesh, M., Adolf, J., Shamshirband, S., Chau, K.W., 2018. Effect of river flow on the quality of estuarine and coastal waters using machine learning models. *Eng. Appl. Comput. Fluid Mech.* 12, 810–823.
- Alvarado, R., Tillaguango, B., Dagar, V., Ahmad, M., Isik, C., Méndez, P., Toledo, E., 2021. Ecological footprint, economic complexity and natural resources rents in Latin America: empirical evidence using quantile regressions. *J. Cleaner Prod.* 318, 128585.
- Anderson, J., 1879. Anatomical and zoological researches: Comprising accounts of the zoological results of the tico expeditions to tcester Yunnan in 1868 and 1875, and a monograph of the two cetacean genera, *Platanista* and *Orcaella*. Bernard Quaritch. IaI. R.
- Asaad, I., Lundquist, C.J., Erdmann, M.V., Costello, M.J., 2017. Ecological criteria to identify areas for biodiversity conservation. *Biol. Conserv.* 213, 309–316.
- Balian, E.V., Segers, H., Martens, K., Lévêque, C., 2007. The freshwater animal diversity assessment: an overview of the results. *Freshw. Anim. Divers. Assess.* 627–637.
- Banerjee, A.K., Feng, H., Lin, Y., Liang, X., Wang, J., Huang, Y., 2022. Setting the priorities straight-Species distribution models assist to prioritize conservation targets for the mangroves. *Sci. Total Environ.* 806, 150937.
- Barão-Nóbrega, J.A.L., González-Jaurégui, M., Jehle, R., 2022. N-mixture models provide informative crocodile (*Crocodylus moreletii*) abundance estimates in dynamic environments. *PeerJ* 10, 12906.
- Barker, R.J., Schofield, M.R., Link, W.A., Sauer, J.R., 2018. On the reliability of N-mixture models for count data. *Biometrics* 74, 369–377.
- Bartoń, K., 2013. R package “MuMin”: Multi-model inference (Version X).
- Barua, M., Root-Bernstein, M., Ladle, R.J., Jepson, P., 2011. Defining flagship uses is critical for flagship selection: a critique of the IUCN climate change flagship fleet. *Ambio* 40, 431–435.
- Bashir, T., Khan, A., Gautam, P., Behera, S.K., 2010. Abundance and prey availability assessment of Ganges river dolphin (*Platanista gangetica gangetica*) in a stretch of upper Ganges River, India. *Aquat. Mammals* 36, 19.
- Bashir, T., Khan, A., Behera, S.K., Gautam, P., 2012. Factors determining occupancy of Gangetic dolphin (*Platanista gangetica gangetica*) during differing river discharges in the upper Gangetic, India. *Mammalia* 76, 417–426.
- Behera, S.K., Singh, H., Sagar, V., 2013. Status of Gangetic dolphin (*Platanista gangetica gangetica*) in the Ganga River basin, India: A review. *Aquat. Ecosyst. Health Manage.* 16, 425–432.
- Behera, S.K., Singh, H., Sagar, V., 2014. Indicator species (Gharial and Dolphin) of riverine ecosystem: an exploratory of River Ganga. In: *Our National River Ganga*. Springer, Cham, pp. 121–141.
- Belote, R.T., Wilson, M.B., 2020. Delineating greater ecosystems around protected areas to guide conservation. *Conserv. Sci. Pract.* 2, 196.
- Boscari, E., Wu, J., Jiang, T., Zhang, S., Cattelan, S., Wang, C., et al., 2022. The last giants of the Yangtze River: A multidisciplinary picture of what remains of the endemic Chinese sturgeon. *Sci. Total Environ.* 843, 157011.
- Bötsch, Y., Jenni, L., Kéry, M., 2020. Field evaluation of abundance estimates under binomial and multinomial N-mixture models. *Ibis* 162, 902–910.
- Braulik, G.T., 2006. Status assessment of the Indus River dolphin, *Platanista gangetica minor*, March–April 2001. *Biol. Conserv.* 129, 579–590.
- Braulik, G.T., Archer, I., Khan, F., Imran, U., Sinha, M., Jefferson, R.K., et al., 2021. Taxonomic revision of the South Asian River dolphins (*Platanista*): Indus and Ganges River dolphins are separate species. *Mar. Mammal Sci.* 37, 1022–1059.
- Braulik, G.T., Reichert, A.P., Ehsan, T., Khan, S., Northridge, S.P., Alexander, et al., 2012. Habitat use by a freshwater dolphin in the low-water season. *Aquat. Conserv. Mar. Freshwater Ecosyst.* 22, 533–546.
- Burnham, K.P., Anderson, D.R., 2004. Model selection: understanding AIC and multimodel inference, with contrasts to BIC. *Sociol. Methods Res.* 33, 261–304.
- Charbonnel, A., d’Amico, F., Besnard, A., Blanc, F., Buisson, L., Némot, M., et al., 2014. Spatial replicates as an alternative to temporal replicates for occupancy modelling when surveys are based on linear features of the landscape. *J. Appl. Ecol.* 51, 1425–1433.
- Choudhary, S., Dey, S., Dey, S., Sagar, V., Nair, T., Kelkar, N., 2012. River dolphin distribution in regulated river systems: implications for dry-season flow regimes in the Gangetic basin. *Aquat. Conserv. Mar. Freshwater Ecosyst.* 22, 11–25.
- Choudhary, S.K., Smith, B.D., Dey, S., Dey, S., Prakash, S., 2006. Conservation and biomonitoring in the Vikramshila Gangetic dolphin sanctuary, Bihar. *India. Oryx* 40, 189–197.
- Choudhury, N.B., Mazumder, M.K., Chakravarty, H., Choudhury, A.S., Boro, F., Choudhury, I.B., 2019. The endangered Ganges river dolphin heads towards local extinction in the Barak river system of Assam, India: A plea for conservation. *Mamm. Biol.* 95, 102–111.
- Chowdhury, M.R., Mitra, S., Sen, S., 2016. On the Behaviour, abundance, habitat use and potential threats of the Gangetic Dolphin *Platanista gangetica* in southern West Bengal, India. *J. Threat. Taxa* 8, 9131–9137.
- Clements, G.R., Rayan, D.M., Aziz, S.A., Kawanishi, K., Traeholt, C., Magintan, D., Yazi, M.F.A., Tingley, R., 2012. Predicting the distribution of the Asian tapir in Peninsular Malaysia using maximum entropy modeling. *Integr. Zool.* 7, 400–406.
- CWC, 2014. Ganga Basin. Ministry of Water Resources, Government of India, Central Water Commission, New Delhi <https://indiawris.gov.in/downloads/Ganga%20Basin.pdf>.

- Dagar, V., Khan, M.K., Alvarado, R., Usman, M., Zakari, A., Rehman, A., et al., 2021. Variations in technical efficiency of farmers with distinct land size across agro-climatic zones: Evidence from India. *J. Cleaner Prod.* 315, 128109.
- Dennis, E.B., Morgan, B.J., Ridout, M.S., 2015. Computational aspects of N-mixture models. *Biometrics* 71, 237–246.
- Dey, M., Krishnaswamy, J., Morisaka, T., Kelkar, N., 2019. Interacting effects of vessel noise and shallow river depth elevate metabolic stress in Ganges river dolphins. *Sci. Rep.* 9, 1–13. <https://doi.org/10.1038/s41598-019-51664-1>.
- Dudgeon, D., 2000. Large-scale hydrological changes in tropical Asia: prospects for riverine biodiversity: the construction of large dams will have an impact on the biodiversity of tropical Asian rivers and their associated wetlands. *Bioscience* 50, 793–806.
- Dudgeon, D., 2002. The most endangered ecosystems in the world? Conservation of riverine biodiversity in Asia. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*. 28, 59–68.
- Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C., et al., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. *Biol. Rev.* 81, 163–182.
- Dwivedi, S., Mishra, S., Tripathi, R.D., 2018. Ganga water pollution: a potential health threat to inhabitants of Ganga basin. *Environ. Int.* 117, 327–338.
- Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., et al., 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* 29, 129–151.
- Elith, J., Kearney, M., Phillips, S., 2010. The art of modelling range-shifting species. *Methods Ecol. Evol.* 1, 330–342.
- Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37, 4302–4315. <https://doi.org/10.1002/joc.5086>.
- Fiske, I., Chandler, R., 2011. Unmarked: an R package for fitting hierarchical models of wildlife occurrence and abundance. *J. Stat. Softw.* 43, 1–23.
- Fürstenau Oliveira, J.S., Georgiadis, G., Campello, S., Brandão, R.A., Ciuti, S., 2017. Improving river dolphin monitoring using aerial surveys. *Ecosphere* 8, 1912.
- Gaston, K.J., Blackburn, T.M., Greenwood, J.J., Gregory, R.D., Quinn, R.M., Lawton, J. H., 2000. Abundance–occupancy relationships. *J. Appl. Ecol.* 37, 39–59.
- Gomez-Salazar, C., Coll, M., Whitehead, H., 2012. River dolphins as indicators of ecosystem degradation in large tropical rivers. *Ecol. Ind.* 23, 19–26.
- Graham, M.H., 2003. Confronting multicollinearity in ecological multiple regression. *Ecology* 84, 2809–2815.
- Grantham, T.E., Matthews, J.H., Bledsoe, B.P., 2019. Shifting currents: Managing freshwater systems for ecological resilience in a changing climate. *Water Secur.* 8, 100049.
- Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. *Ecol. Model.* 135, 147–186.
- Guo, D., Lintern, A., Webb, J.A., Ryu, D., Liu, S., Bende-Michl, U., et al., 2019. Key factors affecting temporal variability in stream water quality. *Water Resour. Res.* 55, 112–129.
- Hannah, L., Lohse, D., Hutchinson, C., Carr, J.L., Lankarani, A., 1994. A preliminary inventory of human disturbance of world ecosystems. *Ambio* 246–250.
- He, J., Huang, J., Liu, D., Wang, H., Li, C., 2018. Updating the habitat conservation institution by prioritizing important connectivity and resilience providers outside. *Ecol. Ind.* 88, 219–231.
- Hines, J.E., Nichols, J.D., Royle, J.A., MacKenzie, D.I., Gopalaswamy, A.M., Kumar, N.S., Karanth, K.U., 2010. Tigers on trails: occupancy modeling for cluster sampling. *Ecol. Appl.* 20, 1456–1466.
- Hu, J., Jiang, Z., 2011. Climate change hastens the conservation urgency of an endangered ungulate. *PLoS ONE* 6, 22873.
- Hussain, S.A., Irengbam, M., Barthwal, S., Dasgupta, N., Badola, R., 2020. Conservation planning for the Ganga River: a policy conundrum. *Landscape Res.* 45, 984–999. <https://doi.org/10.1080/01426397.2020.1808959>.
- Joseph, L.N., Elkin, C., Martin, T.G., Possingham, H.P., 2009. Modeling abundance using N-mixture models: the importance of considering ecological mechanisms. *Ecol. Appl.* 19, 631–642.
- Kelkar, N., Smith, B.D., Alom, M.Z., Dey, S., Paudel, S., Braulik, G.T., 2022. *Platanista gangetica*. The IUCN Red List of Threatened Species 2022: e.T41756A50383346.
- Kelkar, N., Krishnaswamy, J., Choudhary, S., Sutar, D., 2010. Coexistence of fisheries with river dolphin conservation. *Conserv. Biol.* 2, 1130–1140.
- Kéry, M., Royle, J.A., 2015. *Applied Hierarchical Modeling in Ecology: Analysis of Distribution, Abundance and Species Richness in R and BUGS*. Academic Press, Elsevier, Amsterdam.
- Khanal, G., Suryawanshi, K.R., Awasthi, K.D., Dhakal, M., Subedi, N., Nath, D., et al., 2016. Irrigation demands aggravate fishing threats to river dolphins in Nepal. *Biol. Conserv.* 204, 386–393.
- Kidwai, Z., Jimenez, J., Louw, C.J., Nel, H.P., Marshal, J.P., 2019. Using N-mixture models to estimate abundance and temporal trends of black rhinoceros (*Diceros bicornis* L.) populations from aerial counts. *Global Ecol. Conserv.* 19, e00687.
- Kim, J.H., Park, S., Kim, S.H., Lee, E.J., 2021. Identifying high-priority conservation areas for endangered waterbirds using a flagship species in the Korean DMZ. *Ecol. Eng.* 159, 106080.
- Kinze, C.C., 2000. Rehabilitation of *Platanista gangetica* (Lebeck, 1801) as the valid scientific name of the Ganges dolphin. *Zoologische Mededelingen* 74, 193–203.
- Knape, J., Arlt, D., Barraquand, F., Berg, Å., Chevalier, M., Pärt, T., et al., 2018. Sensitivity of binomial N-mixture models to overdispersion: The importance of assessing model fit. *Methods Ecol. Evol.* 9, 2102–2114.
- Kolipakam, V., Jacob, M., Gayathri, A., Deori, S., Sarma, H., Tasfia, S.T., Rokade, A., Negi, R., Wakid, A., Qureshi, Q., 2022. Pingers are effective in reducing net entanglement of river dolphins. *Sci. Rep.* 12, 1–14. <https://doi.org/10.1038/s41598-022-12670-y>.
- Kouadri, S., Elbeltagi, A., Islam, A.R.M., Kateb, S., 2021. Performance of machine learning methods in predicting water quality index based on irregular data set: application on Illizi region (Algerian southeast). *Appl. Water Sci.* 11, 1–20.
- Kramer-Schadt, S., Niedballa, J., Pilgrim, J.D., Schröder, B., Lindenborn, J., Reinfelder, V., et al., 2013. The importance of correcting for sampling bias in MaxEnt species distribution models. *Divers. Distrib.* 19, 1366–1379.
- Learmonth, J.A., MacLeod, C.D., Santos, M.B., Pierce, G.J., Crick, H.Q.P., Robinson, R.A., 2006. Potential effects of climate change on marine mammals. *Oceanogr. Mar. Biol.* 44, 431.
- Leathwick, J.R., Whitehead, D., 2001. Soil and atmospheric water deficits and the distributions of New Zealand's indigenous tree species. *Funct. Ecol.* 15, 233–242.
- Lebeck, H.J., 1801. *Delphinus gangeticus* beschrieben von Heinrich Julius Lebeck zu Trankenanbar. Der Gesellschaft naturforschender Freunde zu Berlin Neue Schriften. 3. Wittenberg, pp. 280–282.
- Link, W.A., Schofield, M.R., Barker, R.J., Sauer, J.R., 2018. On the robustness of N-mixture models. *Ecology* 99, 1547–1551.
- MacKenzie, D.I., Bailey, L.L., 2004. Assessing the fit of site-occupancy models. *J. Agric. Biol. Environ. Stat.* 9, 300–318.
- MacKenzie, D.I., Nichols, J.D., G.B., Lachman, S., Droege, J.A., Royle, C.A., Langtimm, J., 2002. Estimating site occupancy rates when detection probabilities are less than one. *Ecology* 83, 2248–2255.
- MacKenzie, D.I., Nichols, J.D., Royle, J.A., Pollock, K.H., Bailey, L.A., Hines, J.E., 2006. *Occupancy modeling and estimation*. Academic, San Diego, CA.
- Maire, A., Laffaille, P., Maire, J.F., Buisson, L., 2017. Identification of priority areas for the conservation of stream fish assemblages: implications for river management in France. 33, 524–537.
- Manica, M., Caputo, B., Screti, A., Filipponi, F., Rosà, R., Solimini, A., et al., 2019. Applying the N-mixture model approach to estimate mosquito population absolute abundance from monitoring data. *J. Appl. Ecol.* 56, 2225–2235.
- Matthews, N., 2016. People and fresh water ecosystems: pressures, responses and resilience. *Aquat. Procedia* 6, 99–105.
- Mazumder, M.K., Boro, F., Barbhuiya, B., Singha, U., 2014. A study of the winter congregation sites of the Gangetic River Dolphin in southern Assam, India, with reference to conservation. *Global Ecol. Conserv.* 2, 359–366.
- Mitra, S., Chowdhury, M.R., 2018. Possible range decline of Ganges River Dolphin *Platanista gangetica* (Mammalia: Cetartiodactyla: *Platanistidae*) in Indian Sundarban. *J. Threat. Taxa* 10, 12738–12748.
- Mohan, R.S.R., Dey, S.C., Bairagi, S.P., Roy, S., 1997. On a survey of the Ganges River dolphin *Platanista gangetica* of Bramaputra River, Assam. *J. Bombay Nat. Hist. Soc.* 94, 483–495.
- Mohan, R.L., 1989. Conservation and management of the Ganges river dolphin, *Platanista gangetica*. India. In *Biology and Conservation of the River Dolphins. Occasional Papers of the IUCN Species Survival Commission*, 64–69.
- Nakashima, Y., 2020. Potentiality and limitations of N-mixture and Royle-Nichols models to estimate animal abundance based on noninstantaneous point surveys. *Popul. Ecol.* 62, 151–157.
- Nandargi, S.S., Shelar, A., 2018. Rainfall and flood studies of the Ganga River Basin in India. *Ann. Geogr. Stud.* 1, 34–50.
- Nautiyal, P., 2010. Food chains of Ganga River ecosystems in the Himalayas. *Aquat. Ecosyst. Health Manage.* 13, 362–373.
- Paudel, S., Koprowski, J.L., 2020. Factors affecting the persistence of endangered Ganges River dolphins (*Platanista gangetica gangetica*). *Ecol. Evol.* 10, 3138–3148.
- Paudel, S., Timilsina, Y.P., Lewis, J., Ingersoll, T., Jnawali, S.R., 2015. Population status and habitat occupancy of endangered river dolphins in the Karnali River system of Nepal during low water season. *Mar. Mammal Sci.* 31, 707–719.
- Paudel, S., Koprowski, J.L., Thakuri, U., Karki, A., 2021. In-stream habitat availability for river dolphins in response to flow: Use of ecological integrity to manage river flows. *PLoS ONE* 16, e0241099.
- Phillips, S.J., Dudík, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 31, 161–175.
- Phillips, S.J., Anderson, R.P., Dudík, M., Schapire, R.E., Blair, M.E., 2017. Opening the black box: An open-source release of Maxent. *Ecography* 40, 887–893.
- Piatt, J.F., Harding, A.M., Shultz, M., Speckman, S.G., Van Pelt, T.I., Drew, G.S., et al., 2007. Seabirds as indicators of marine food supplies: Cairns revisited. *Mar. Ecol. Prog. Ser.* 352, 221–234.
- Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegard, K.L., Richter, B.D., et al., 1997. The natural flow regime. *Bioscience* 47, 769–784.
- Pracheil, B.M., McIntyre, P.B., Lyons, J.D., 2013. Enhancing conservation of large-river biodiversity by accounting for tributaries. *Front. Ecol. Environ.* 11, 124–128.
- R Development Core Team., 2022. R: a language and environment for statistical computing. The R Foundation for Statistical Computing, Vienna. Available at <http://www.R-project.org/>.
- Reeves, R.R., Smith, B.D., Kasuya, T. (Eds.), 2000. *Biology and Conservation of Freshwater Cetaceans in Asia 1–164*. IUCN, Gland, Switzerland.
- Richman, N.I., Gibbons, J.M., Turvey, S.T., Akamatsu, T., Ahmed, B., Mahabub, E., et al., 2014. To see or not to see: investigating detectability of Ganges River dolphins using a combined visual-acoustic survey. *PLoS ONE* 9, e96811.
- Rodgers, W. A., Panwar, H. S. 1988. Planning a wildlife protected area network in India. A Report Prepared for the Department of Environment, Forest & Wildlife. Government of India. Dehradun: Wildlife Institute of India.
- Royle, J.A., 2004. N-mixture models for estimating population size from spatially replicated counts. *Biometrics* 60, 108–115.
- RStudio Team., 2022. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA <http://www.rstudio.com/>.

- Rushton, S.P., Ormerod, S.J., Kerby, G., 2004. New paradigms for modelling species distributions? *J. Appl. Ecol.* 41, 193–200.
- Samad, I., Kelkar, N., Krishnaswamy, J., 2022. Life at the borderline: Responses of Ganges river dolphins to dry-season flow regulation of river and canal habitats by the Farakka barrage. *Aquat. Conserv. Mar. Freshwater Ecosyst.* 32, 294–308.
- Schneider, C., Laizé, C.L.R., Acreman, M.C., Flörke, M., 2013. How will climate change modify river flow regimes in Europe? *Hydrol. Earth Syst. Sci.* 17, 325–339.
- Searle, C.E., Bauer, D.T., Kesch, M.K., Hunt, J.E., Mandisodza-Chikerema, R., Flyman, M. V., et al., 2020. Drivers of leopard (*Panthera pardus*) habitat use and relative abundance in Africa's largest transfrontier conservation area. *Biol. Conserv.* 248, 108649.
- Sergio, F., Caro, T., Brown, D., Clucas, B., Hunter, J., Ketchum, et al., 2008. Top predators as conservation tools: ecological rationale, assumptions, and efficacy. *Annu. Rev. Ecol. Evol. Syst.* 1–19.
- Shaffer, H.B., Fisher, R.N., Davidson, C., 1998. The role of natural history collections in documenting species declines. *Trends Ecol. Evol.* 13, 27–30.
- Sharma, A., Baruah, A., Mangukiyi, N., Hinge, G., Bharali, B., 2022. Evaluation of Gangetic dolphin habitat suitability under hydroclimatic changes using a coupled hydrological-hydrodynamic approach. *Ecol. Inf.* 69, 101639.
- Shostell, J.M., Ruiz-García, M., 2010. An introduction to river dolphin species. *Biology, Evolution and Conservation of River Dolphins*. Editors: Manuel Ruiz-García and Joseph Shostell. Nova Science Publishers, Inc. New York. 1–28.
- Shrestha, T.K., 1989. Biology, status and conservation of the Ganges River dolphin, *Platanista gangetica*. *Nepal. Biol. Conserv.* 66, 159–169.
- Sinha, R.K., Kannan, K., 2014. Ganges River dolphin: an overview of biology, ecology, and conservation status in India. *Ambio* 43, 1029–1046.
- Sinha, R.K., Sharma, G., 2003a. Current status of the Ganges river dolphin, *Platanista gangetica* in the rivers Kosi and Son, Bihar, India. *J. Bombay Nat. Hist. Soc.* 100, 27–37.
- Sinha, R.K., Sharma, G., 2003b. Faunal diversity of the River Sarda, Uttar Pradesh, India. *Journal of Ecophysiology. Occup. Health* 3, 103–116.
- Sinha, R.K., Verma, S.K., Singh, L., 2010. Population status and conservation of the Ganges River dolphin (*Platanista gangetica gangetica*) in the Indian subcontinent. In: *Biology, Evolution and Conservation of River Dolphins Within South America and Asia*. Nova Science Publishers, Inc., pp. 419–444.
- Smith, B.D., 1993. Status and conservation of the Ganges River dolphin *Platanista gangetica* in the Karnali River, Nepal. *Biol. Conserv.* 66, 159–169.
- Smith, B.D., Aminul Haque, A.K.M., Shakhawat Hossain, M., Khan, A., 1998. River dolphins in Bangladesh: conservation and the effects of water development. *Environ. Manage.* 22, 323–335.
- Smith, B.D., Braulik, G.T., 2009. Susu and Bhulan: *Platanista gangetica gangetica* and *P. g. minor*. In *Encyclopedia of Marine Mammals*. Academic Press, 1135–1139.
- B.D. Smith R.R. Reeves Survey methods for population assessment of Asian River dolphins R.R. Reeves B.D. Smith T. Kasuya *Biology and conservation of freshwater cetaceans in Asia. Occasional Paper of the IUCN Species Survival Commission No. 23* 2000 IUCN, Gland, Switzerland 97 115.
- Smith, B.D., Braulik, G., Strindberg, S., Ahmed, B., Mansur, R., 2006. Abundance of Irrawaddy dolphins (*Orcaella brevirostris*) and Ganges river dolphins (*Platanista gangetica gangetica*) estimated using concurrent counts made by independent teams in waterways of the Sundarbans mangrove forest in Bangladesh. *Mar. Mammal Sci.* 2, 527–547.
- Sonkar, G.K., Gaurav, K., 2020. Assessing the impact of large barrages on habitat of the Ganga River dolphin. *River Res. Appl.* 36, 1916–1931.
- Stewart, B.A., Ford, B.M., Benson, J.A., 2022. Using species distribution modelling to identify 'coldspots' for conservation of freshwater fishes under a changing climate. *Aquat. Conserv. Mar. Freshwater Ecosyst.* 32, 576–590.
- Strayer, D.L., Dudgeon, D., 2010. Freshwater biodiversity conservation: recent progress and future challenges. *J. N. Am. Benthol. Soc.* 29, 344–358.
- Sun, Z., Behrens, P., Tukker, A., Bruckner, M., Schere, L., 2022. Shared and environmentally just responsibility for global biodiversity loss. *Ecol. Econ.* 194, 107339.
- Sunarto, S., Kelly, M.J., Parakkasi, K., Klenzendorf, S., Septayuda, E., Kurniawan, H., 2012. Tigers need cover: Multi-scale occupancy study of the big cat in Sumatran forest and plantation landscapes. *PLoS ONE* 7, 30859.
- Than, K.Z., Strine, C.T., Sritongchuay, T., Zaw, Z., Hughes, A.C., 2020. Estimating population status and site occupancy of saltwater crocodiles *Crocodylus porosus* in the Ayeyarwady delta, Myanmar: Inferences from spatial modeling techniques. *Global Ecol. Conserv.* 24, 1206.
- Thorp, J.H., Thoms, M.C., Delong, M.D., 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. *River Res. Appl.* 22, 123–147.
- Toosy, A.H., Khan, U., Mahmood, R., Bhagat, H.B., 2009. First tagging with a radio-transmitter of a rescued Indus River dolphin near Sukkur barrage, Pakistan. *Wildlife Middle East* 3, 6.
- Turvey, S.T., Risley, C.L., Barrett, L.A., Yujiang, H., Ding, W., 2012. River dolphins can act as population trend indicators in degraded freshwater systems. *PLoS ONE* 7, 37902.
- Uzqueda, A., Burnett, S., Bertola, L.V., Hoskin, C.J., 2020. Quantifying range decline and remaining populations of the large marsupial carnivore of Australia's tropical rainforest. *J. Mammal.* 101, 1021–1034.
- Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., et al., 2010. Global threats to human water security and river biodiversity. *Nature* 467, 555–561.
- Vu, T.T., Tran, L.M., Nguyen, M.D., Van Tran, D., Ta, N.T., 2018. Improving the estimation of calling probability and correction factors in gibbon monitoring using the auditory point count method. *Int. J. Primatol.* 39, 222–236.
- Wakid, A., 2009. Status and distribution of the endangered Gangetic dolphin (*Platanista gangetica gangetica*) in the Brahmaputra River within India in 2005. *Curr. Sci.* 1143–1151.
- Wang, Y., Sun, M., Wang, R., Lou, F., 2015. Promoting regional sustainability by eco-province construction in China: A critical assessment. *Ecol. Ind.* 51, 127–138.
- Wenger, S.J., Freeman, M.C., 2008. Estimating species occurrence, abundance, and detection probability using zero-inflated distributions. *Ecology* 89, 2953–2959.
- Wis, M.S., Hijmans, R.J., Li, J., Peterson, A.T., Graham, C.H., Guisan, A., NCEAS Predicting Species Distributions Working Group, 2008. Effects of sample size on the performance of species distribution models. *Diversity and distributions*. 14, 763–773.
- Wynn, R.B., Josey, S.A., Martin, A.P., Johns, D.G., Yésou, P., 2007. Climate-driven range expansion of a critically endangered top predator in northeast Atlantic waters. *Biol. Lett.* 3, 529–532.
- Zeiringer, B., Seliger, C., Greimel, F., Schmutz, S., 2018. River hydrology, flow alteration, and environmental flow. *Riverine Ecosyst. Manage.* 67–89.
- Zhou, H., Yu, C., Guo, Q., Zheng, Y., Hou, X., 2022. Spatial suitability evaluation of spawning reach revealing the location preference for fish producing drifting eggs. *Front. Mar. Sci.* 1713.
- Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* 1, 3–14.