Vessel noise impacts on the acoustic behaviour of

Ganges river dolphins in the Ganga River, Bihar, India

A Summary Report

Submitted to

Shri Bharat Jyoti IFS

The Additional Principal Chief Conservator of Forests-cum-Chief Wildife Warden,

Department of Environment and Forests, Bihar state

Patna, Bihar, India

By

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(With technical inputs from Dr. Tadamichi Morisaka, Subhasis Dey,Dr. Sunil Kumar Choudhary)

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Statement and Declaration

This report is based on the Master of Science (Wildlife Biology and Conservation) thesis of Mr. Mayukh Dey, a student at the National Centre for Biological Sciences, Tata Institute of Fundamental Research, Bengaluru. The thesis is entitled "Conserving river dolphins in a changing soundscape: acoustic and behavioural responses of Ganges river dolphins to anthropogenic noise in the Ganges River, India" and comprises original research work conducted under the supervision of Dr. Jagdish Krishnaswamy during the period November 2017-April 2018. The thesis is in partial fulfilment of Mayukh Dey's M.Sc. degree.

Research Permission Details

This research was carried out in the Vikramshila Gangetic Dolphin Sanctuary (Bhagalpur) and other sites on the Ganga River, vide permit number Wildlife-688 dated 13.12.2017 with ref. letter no. NCBS/MSc/2017/BR-01/dt.30.11.2017, issued by the APCCF-cum-Chief Wildlife Warden, Bihar State, Aranya Bhawan, Patna 800114, Bihar. The permit letter provided by the authorities is enclosed.

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Acknowledgments

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Key highlights of the study

1. Proposed large-scale commercial waterway development across India's rivers has been thought to affect the Ganges river dolphin's ecology, behaviour, and habitat quality. This is the first fieldwork-based, empirical study to assess the impacts of underwater anthropogenic noise from vessel movement on endangered Ganges river dolphins in the Ganga river in Bihar.
2. The Ganges river dolphin is an endangered species, and is also the National Aquatic Animal of India. Over millions of years, this river dolphin species evolved to be almost blind, living in the murky rivers of the Indus-Ganga-Brahmaputra basins, because of which it is almost entirely dependent on high-freuency echolocation (ultrasonic clicks) for navigation, foraging, and communication. The impacts of underwater noise from anthropogenic sources on this species were poorly understood until now, a major knowledge gap now addressed by our studies.
3. The study found that motorized vessel traffic in the Ganga River significantly increased the ambient noise levels, which consistently caused shifts in acoustic responses (click rate, duration of click-trains, frequency, and loudness) of river dolphins.
4. As river flow reduced from November 2017 to March 2018 (the low-flow period or dry-season) and ambient noise levels from vessel traffic increased, river dolphin responses also changed sharply.
5. In conditions of intermittent noise exposure, dolphins tended to compensate for masking of their echolocation clicks. Under chronic and persisting noise levels, river dolphins suppressed their acoustic behaviour, possibly suggesting lost opportunities for communication and foraging.
6. In the peak dry-season (March), the impacts of noise on dolphins were aggravated by reduced river flows and reduced availability of fish prey. River dolphins are continuous emitters, and we estimated that current levels of exposure to vessel noise can impose severe energetic costs on dolphins. With doubling of ambient noise levels, metabolic costs could translate into severe cumulative stress for dolphins.
7. Our results underscore the negative impacts of vessel noise on Ganges river dolphins, and emphasize the importance of, a) reduction of vessel traffic and ambient noise emissions, b) maintaining near-natural ecological flows to buffer impacts of underwater noise, and c) mitigation of stressful impacts of vessel noise and associated activities, for the conservation of the endangered Ganges river dolphin.

Introduction

Diverse sounds are produced and processed by animals for their vital life functions such as foraging, mate selection, navigation, communication, etc., in both terrestrial and aquatic ecosystems. Animals evolved their vocal repertoires in response to their natural ambient sound environments or 'soundscapes' (Kight& Swaddle, 2011; Pijanowski et al., 2011). In the present day, human activities (e.g. industrial activities, infrastructure development, surface and water transport and traffic, etc.) have altered the natural environment by adding large amounts of anthropogenic noise. This has had deleterious effects not only on animals but also on fellow human beings (Francis & Barber 2013, Shannon et al. 2016). Noise pollution has now become a serious environmental threat, although it remains relatively less acknowledged in ecological research and conservation studies focusing on wild species (Shannon et al. 2016). In marine and freshwater ecosystems, most species are mostly dependent on sound, because of visual limitations imposed by underwater habitats (NRC, 2000; Weilgart, 2007). This is of great importance for communication and perceiving the environment, as sound travels faster in water than in air. Unwanted anthropogenic sound, i.e. noise, has the potential to have significant impacts on the health and long-term survival of aquatic species (e.g. fishes, marine mammals, esp. cetaceans, etc.).

Anthropogenic activities in aquatic systems (e.g. vessel movement, explosions, oil and gas exploration, dredging, use of sonar by the military, airguns, pile driving, etc.) have led to major surges in underwater noise (NRC, 2000). With increasing levels of anthropogenic noise in oceans and rivers, cetaceans (dolphins and whales) have become susceptible to a wide range of effects (Harwood 2001, Wright et al., 2007, Weilgart, 2007). Displacement from or avoidance of preferred habitats, propeller hits, disorientation, embolism, irregular or deeper dives, acoustic masking, elevated stress hormones, altered acoustic activity and damage to ear structures have been documented for many species of cetaceans (e.g. NRC 2000, Romano et al. 2004, Nowacek et al. 2007,Wright et al. 2007, Jensen et al. 2009, 2012; Finneran & Schlundt 2010, Gomez et al. 2016).

Most studies on effects of underwater anthropogenic noise have been conducted on marine dolphins and whales. Yet, even now, little is known about the possible effects of noise on dolphins inhabiting shallow and restricted aquatic systems like rivers and estuaries. In depth-limited river ecosystems, impacts of noise could be greater than in open-ocean environments (Trevorrow 1998, Jensen et al. 2013, Todd et al. 2015). Freshwater cetaceans such as river dolphins might therefore be highly susceptible to impacts of underwater noise. This was witnessed in the significant contribution of vessel noise and ship traffic to the recent extinction of the Chinese river dolphin or Baiji from the Yangtze River in China (Turvey 2009).

The Ganges river dolphin (*Platanista gangetica gangetica*) is an endangered freshwater cetacean (Braulik & Smith 2017) inhabiting the rivers of the Ganga-Brahmaputra basins in the Indian subcontinent. In the course of its evolution in these sediment-rich and murky waters, the Ganges river dolphin's vision regressed, making it effectively blind (Pilleri et al. 1976a, b; Sinha &Kannan 2014). This means that the species is almost entirely reliant on the use of high-frequency echolocation click sounds for navigation, communication, and foraging. Thus, any interference of anthropogenic noise in its river environment would influence its behaviour and activity. Motorised vessels plying in rivers produce noise from engine activity, propeller action, and associated effects, which can potentially interfere with the acoustic activity of the river dolphins (Kelkar 2017).

The possibility of noise impacting the river dolphins has today become a grave concern for their conservation, after the proposed industrial expansion of river waterways in India under the National Waterways Act of 2016 (Government of India 2016). Vessel navigation along a large part of the current distribution range of Ganges river dolphins is likely to see an exponential increase in the near future (Kelkar 2017). A large proportion of river flows in the Indus-Ganga-Brahmaputra basins have already been diverted for irrigation and domestic-industrial demands by existing dams and barrages (Sharma et al. 2010). As a result, due to limited water availability in rivers, waterways development plans are based on mechanized dredging of river channels to create minimum depths needed for ship passage in the low-flow season (Kelkar 2016). Dredging and projected increases in vessel traffic can together add to underwater noise pollution, but it is still not well understood whether the Ganges river dolphin can cope and survive well in the midst of these changes (Todd et al. 2015, Kelkar 2017).

Addressing this knowledge gap can help identify the main sources of risk to these dolphins and potential measures to mitigate this threat could then be explored. Given the current lack of information on effects of underwater noise on river dolphins, our study aimed to understand how increasing anthropogenic noise in the river might be affecting the vocal repertoire and behaviour of the Ganges river dolphins. This study was conducted in the Vikramshila Gangetic Dolphin Sanctuary and other sites along the Ganga River in the state of Bihar, which lie on National Waterway No. 1.

Our hypothesis was that Ganges river dolphins would alter the characteristics of their high-frequency echolocation clicks in the presence of underwater noise from vessel traffic, as compared to baseline acoustic characteristics in the absence of noise. A priori, we expected that river dolphins, being constant click emitters, will have to modify the level of their acoustic characteristics such as peak frequency, loudness, click train duration and rate of clicking when exposed to underwater noise from passing vessels.

Objectives of this study

1. To estimate impacts of motorized vessel noises on responsive acoustic behaviour of Ganges river dolphins in the Ganga River, Bihar, India
2. To identify the pathways by which underwater noise from vessels could affect dolphin energy expenditure
3. To identify linkages between changes in vessel noise relative to baselines of no anthropogenic noise, in relation to seasonal changes in river flow and fish prey availability

Study Area

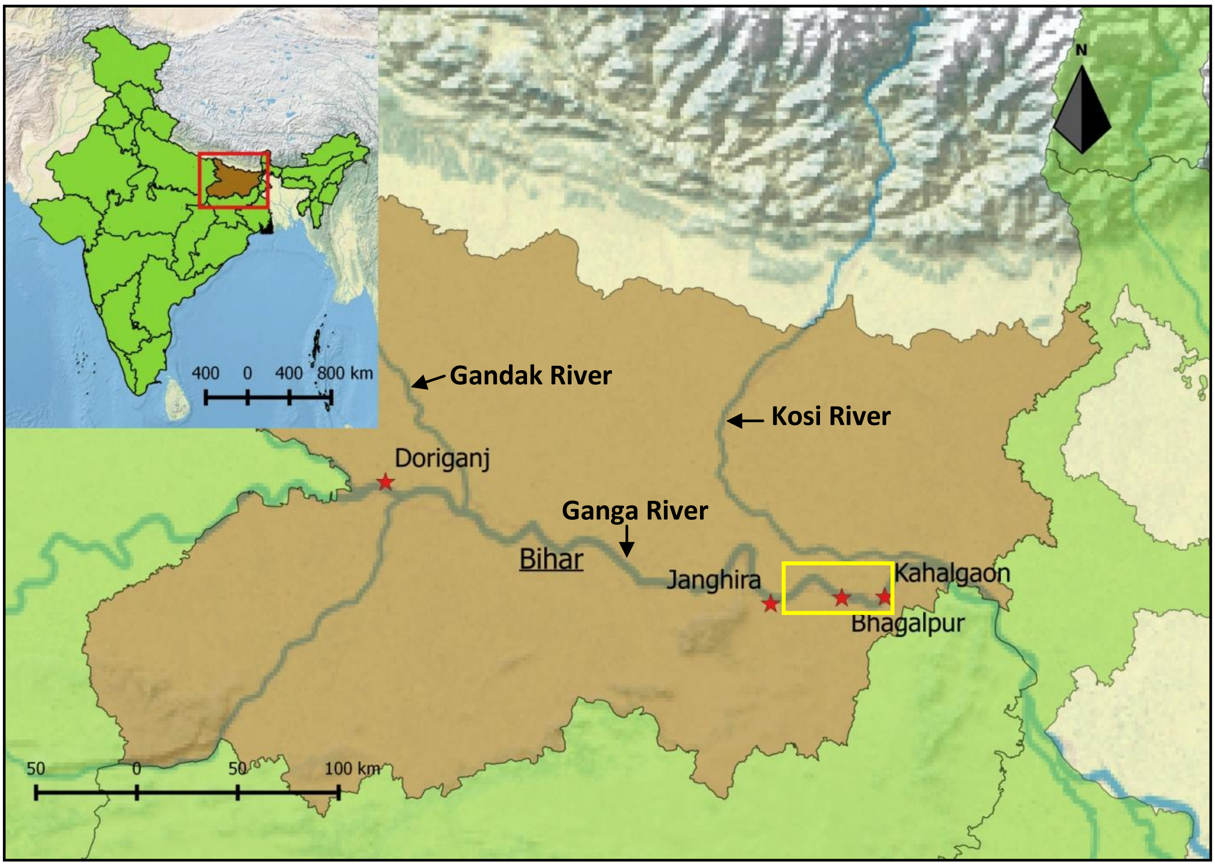
Field studies were conducted at four sites along the Ganga River in Bihar, India from November 2017 to April 2018. All sites lie along India's National Waterway No. 1 (NW-1), which was first designated in 1982 (Government of India 1982). Dredging activity and vessel traffic have been increasing on NW-1 more recently (Kelkar 2016), after the passage of the National Waterways Act in 2016 (Government of India 2016). The sites I chose for intensive studies were Kahalgaon, Bhagalpur, and Janghira (all in the Bhagalpur District of Bihar); and Doriganj (in Chapra district, Bihar). Figure 1 shows the locations of these study sites. The choice of sites in the Bhagalpur district was based on the fact that this stretch of the Ganga has probably the highest known densities of Ganges river dolphins at over 2.5-3 dolphins/km (Kelkar et al. 2010), and lately, has also witnessed increases in regular vessel traffic and river dredging (Kelkar 2016). A river stretch (currently of 70 km) from Sultanganj to Kahalgaon in Bhagalpur district was designated as the Vikramshila Gangetic Dolphin Sanctuary (VGDS) since 1991 (Choudhary et al. 2006), in which two sites, Kahalgaon and Bhagalpur, were situated.

Kahalgaon is one of the deepest stretches in the Ganges River (maximum mid-channel depths 35-40 m). There are three rocky islands in the middle of the river at Kahalgaon, and eddies and counter-current pools around the rocks are a hotspot for river dolphins (Choudhary et al. 2006), which are regularly seen in good numbers at this location. Kahalgaon has regular passage of different types of vessels (e.g. local motorized country-boats, medium-sized ferry boats, large cargo vessels, tourist ships, and hydrographic survey vessels) that move daily across and along the river.

Barari, located near the city of Bhagalpur, about 30 km upstream of Kahalgaon, was the second site within the Vikramshila Sanctuary. The river course along Barari recently shifted northwards, thereby leaving a shallow (<4 m deep), broad channel in which local motor boats could ply, but ship passage was naturally restricted. Further, due to local island formation, dredging operations to increase river depth at this site were suspended during the period of our study. Due to this, impacts of dredging-related noise and other disturbances to sediment could not be assessed.

Janghira, the third site, is located 40 km upstream of Barari. I conducted dolphin recordings to represent deep (>10 m) and quiet conditions, as I never encountered vessel passage in this channel during my sampling period (Table 1). The fourth site, Doriganj, is located approximately 300 km upstream of Barari. This site was chosen because it had both high levels of vessel noise and dolphin presence, but the river channel was shallow (<6 m). During our study period, the river flow at Doriganj was highly restricted, making it an interesting site (shallow and noisy) to compare with the other sites downstream.

Figure1. Locations of the study sites: Bhagalpur, Kahalgaon, and Janghira in the Bhagalpur district, and Doriganj in the Chapra district, along the Ganga River in Bihar. The rough extent of the Vikramshila Gangetic Dolphin Sanctuary is also indicated in the map.



Methods

For my objectives, I tested acoustic and behavioural responses to ambient vessel noise levels using two main sources of data: (1) field-based passive acoustic monitoring and recording of river dolphin clicks and vessel noise, and (2) direct observations on diving behaviour (time spent diving between surfacing events) in the presence and absence of vessels, and in relation to changing river depth. The acoustic data were used to test the hypothesis about altered acoustic activity of Ganges dolphins in response to vessel noise at different levels. We also estimated the approximate distance beyond which river dolphin clicks would be completely masked by cavitation noise produced by propellers of motorised boats (masking range). River hydrology and fisheries catch data were used as background variables in understanding the impacts of noise in interaction with changing habitat and prey availability for dolphins in their dynamic river habitat. Further, with modelling approaches, I assessed potential energetic costs of altered acoustic activity for Ganges river dolphins living in an altered soundscape with potential changes in fish prey availability. The detailed methods can be found in the thesis of Mr. Mayukh Dey enclosed with this report. A summary is provided below.

Acoustic recordings and analysis of river dolphin acoustic responses to vessel noise

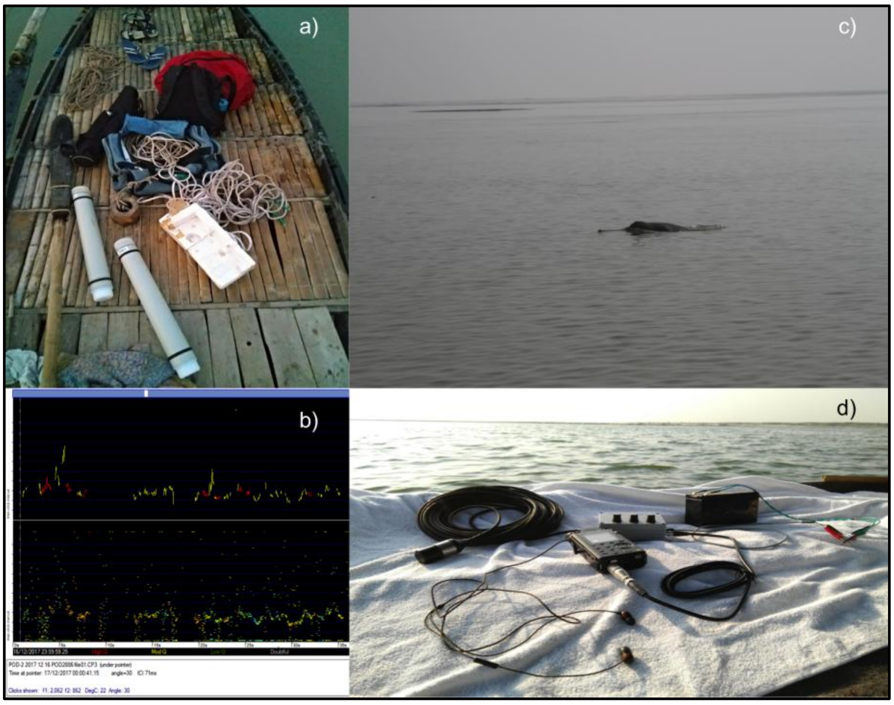
At each site, dolphin groups that were in the main-channel of the river along vessel passage routes were located by direct sightings from the river bank, GPS points of these clusters were recorded, river depth and discharge was measured, and passive acoustic monitoring devices were deployed to ensure that the coverage of acoustic recording devices consistently overlapped with local dolphin distribution. Acoustic recordings involved the use of two devices: 1) CPODs for passive acoustic monitoring of dolphin clicks, and 2) hydrophones to record and characterize sounds made by motorised vessels and dolphins (see Figure 2). CPODs (Cetacean and POrpoise Detection devices) are specialized passive acoustic loggers used to log the clicks produced by dolphins. CPODs are highly effective devices widely used in studies in whales and dolphins worldwide, and are an accepted standard method for passive acoustic monitoring (Tregenza 2014, Robbins et al. 2016). CPODs only log the sound characteristics of cetacean clicks (and do not record the actual sound), and the logged data can be directly analysed in the CPOD software to extract acoustic variables of dolphins and other sources of sound underwater.

At each site, two CPODs were simultaneously deployed using 10 kg weights suspended from small fishing boats (non-motorised) that served as mooring stations for a period of 8-24 hours per survey replicate (day), resulting in a total of 689 hours of recordings conducted over 6 months across four sites. Click-level and train level variables extracted from CPOD analyses were chosen as response variables (i.e. dolphin responses to ambient underwater noise from vessels), and included modal frequency of clicks (in kilohertz: kHz, corresponding to the peak frequency of clicks emitted by dolphins), received sound pressure level or SPL (i.e. loudness of clicks in decibels: dB), frequency range (minimum and maximum kHz in a train), clicks per train (number of clicks within a recorded train), and train duration (time length of each train of clicks in milliseconds). These variables encode important ecological information. For example, a high rate of clicks emitted per second would indicate a dolphin searching prey at close quarters, based on the basic principles of echolocation (Au 2000, Southall et al. 2007). Thus any change in the natural baseline acoustic signals of dolphins, in the presence of vessel noise/traffic, could indicate responsive changes in behaviours related to foraging, resting, or communication with other animals in the vicinity (e.g. Ng and Leung 2003, Southall et al. 2007). From earlier studies, we had the basic information that Ganges dolphins produce high-frequency, modulated, broadband clicks that can range from less than 20 kHz to more than 200 kHz (with peak frequencies between 60 and 76 kHz; Pilleri et al.1976a; Jensen et al. 2013; Kelkar et al. 2018).

Vessel noise is comprised of sounds generated from: 1) boat engines, 2) propellers (cavitation noise or the noise of bursting bubbles generated by propeller rotations), 3) noise from devices used on vessels for hydrographic surveying (e.g. SONAR), and 4) resulting reflections or aberrations in the above categories of sounds after being transmitted. Of these, source levels of engine noise are usually low in frequency (<2 kHz), whereas cavitation noise levels and ship SONAR cover the frequency range from audible to ultrasonic, thus directly interfering with dolphins' ultrasound frequencies. To record ambient noise levels from the different vessels plying on the rivers, I used a hydrophone AQH-200K (AquaSound Inc., Japan; sensitivity: -220 dB re 1 VPa; frequency response: 20 Hz–200 kHz), paired with preamplifiers and portable recorders (Aquafeeler III & RESON VP2000; KORG MR-2 & TASCAM DR-100 mk III). The hydrophone, preamplifiers, and recorders were calibrated and used for recording at all sites, where sampling was conducted in response to events of boat passage, covering a total of 125 individual boat passage events, with each boat passage event typically ranging from 2 to 5 minutes.

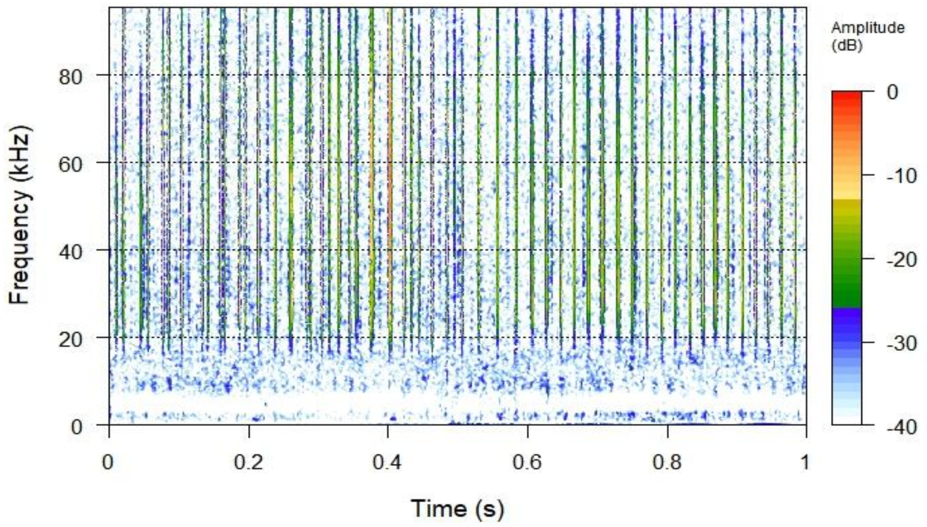
The hydrophone was deployed from the same anchored boat that was used for CPOD deployments at depths ranging from 2 to 5 meters below the water surface.When the CPOD and hydrophone recordings were on-going, I also noted down the start time, duration, and end time of vessels passing, from which intensity of vessel traffic for every hour was calculated, and the type of vessel plying was noted (see section on study area). When each individual vessel passed the hydrophone coverage area, the distance of the vessel was noted using a rangefinder along with the corresponding time in seconds displayed on the recorder. At every hour, environmental factors which were likely to affect absorption and transmission of sound, such as temperature, salinity, depth, and pH, were noted (Francois and Garrison 1982). In addition to recording cavitation noise level for passing vessels, the hydrophone system was also used to record the ambient noise level at the three different study sites. All sound recordings were analysed in the 'seewave' package (Sueur et al. 2008) in the free software R (R Core Team 2017).

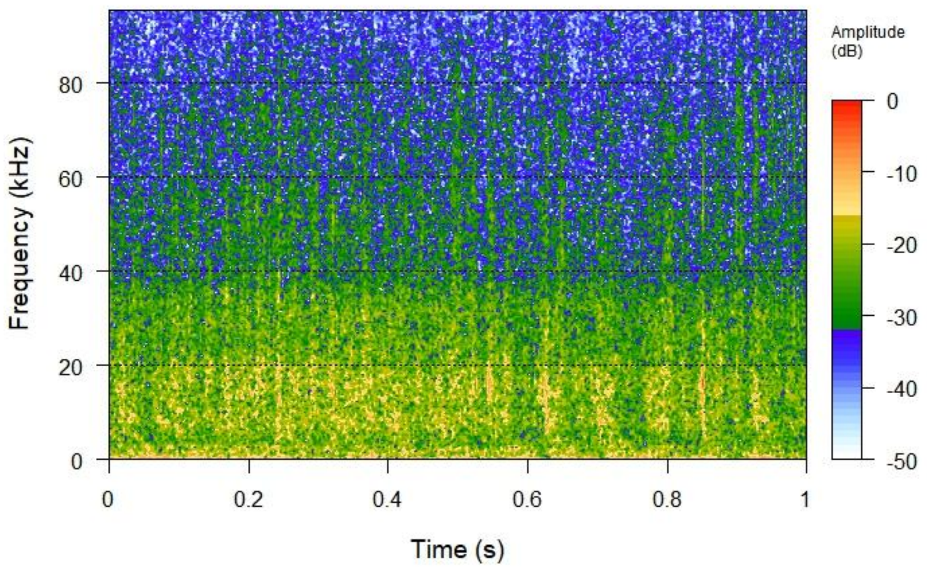
Figure 2. a) Two CPODs along with weights, ready to be deployed into the river, b) analysis of dolphin clicks in CPOD software, c) a surfacing Ganges river dolphin in the Vikramshila Sanctuary, Bihar, and d) hydrophone set used for recording river dolphin clicks, vessel noise, and ambient underwater sounds.



For data analysis, all recordings of dolphins were split into 'during' (i.e. during vessel movement) and 'pre' (i.e. before vessel movement) phases. Baseline acoustic levels of dolphins were recorded in the 'pre' phase and the magnitudes and directions of their responses in the 'during' phase were compared with the baselines. As data on number of vessels at each passage event was available, an encounter rate, i.e. boats (passing the recording station) per hour was calculated. Acoustic variables were summarized in the 'pre' and 'during' vessel phases over the months of November, December, January, and March. Example spectrograms of typical 'pre' and 'during phases with dolphin clicks and vessel noise are shown in Figure 3. Average vessel movement per hour for each recording day was plotted as well to graphically examine the relation between the observed acoustic response relative to baseline and the number of vessels moving in the recording area. We also tested the effects of different ambient vessel noise levels on five different acoustic responses (train duration, frequency range, clicks per train, modal frequency, average sound pressure level or SPL) across the three different study sites. All differences in the pre- and during- phases were interpreted statistically within and between sites.

Figure 3. Top: a spectrogram showing the echolocation clicks of a Ganges river dolphin. This recording was conducted in a relatively quiet stretch with little to no motorised vessel movement in the area. Bottom: the spectrogram below depicts the soundscape for a river dolphin when a motorised vessel passes: the cavitation noise frequency is seen up to 40 kHz and becomes relatively weaker beyond. As this makes clear, cavitation in this high-frequency range interferes with the acoustic signalling of the Ganges river dolphin.





Impacts of vessel cavitation noise and estimation of masking ranges for river dolphins

Due to their potential interference with river dolphin clicks, recording cavitation noise (Cramer and Lauterborn 1982) was an important focus of the study, rather than engine-noise or other boat-associated sounds. From data on environmental conditions (temperature, depth, etc.) the distance of the boat from the recording location, and the sound pressure level (SPL) received at the hydrophone, the sound pressure level at the source (vessel) was calculated using standard mathematical equations. The sound source levels (SSL) were then used to estimate the masking ranges of dolphins. The SSL of different vessels at frequencies ranging from 4 to 80 kHz were plotted on a graph. The audiogram (hearing sensitivity graph) of *Platanista* (from Zbinden et al., 1978), was added to indicate the minimum threshold (minimum pressure) level for dolphins to perceive different sounds. This comparison of vessel noise levels in relation to the audiogram of dolphins indicated which frequencies of sound, from what vessel types, were audible to river dolphins. For ambient noise recordings, the same data extraction approach was used, and the sound pressure levels received at the recording hydrophone were used for further analyses, since our primary interest was to record the ambient noise level at the location.

The masking range was defined as the distance beyond which acoustic signals, in this case, the high frequency clicks emitted by ‘transmitter’ dolphins, would become inaudible to other ‘receiver’ dolphins, in an environment where they are exposed to anthropogenic noise (Southall et al. 2007, Erbe et al. 2016). SSL of Ganges dolphin clicks at the known peak frequency of 74 kHz were taken from Kelkar et al. (2018) for the same study area. Masking range estimation was based on the source levels of dolphin clicks at specific frequency intervals from 20 to 80 kHz (frequencies corresponding with ambient cavitation noise). The masking range was estimated as the distance at which the source level of the dolphin clicks would decay and fall to the levels of different motorised vessel noise. This meant that if the SPL of a dolphin click at a particular frequency was below the noise levels of vessel at the same frequency, then the noise from the vessel would completely mask the dolphin click, at that frequency. Therefore, a ‘receiver’ dolphin would not be able to hear the clicks of a ‘transmitter’ dolphin and hence, the ‘transmitter’ dolphin would either have to increase its source level or both the dolphins would need to be closer to each other.

Effects of river flow and depth on acoustic responses of dolphins to noise

For each month of sampling across different sites, river depth profile and channel width were measured with cross-sectional measurements of the river channel. For discharge estimation, we followed classical procedures by employing the Manning’s equation for open channel discharge in large rivers as described by Chow (1959) and Arcement & Schneider (1984). Changes in discharge and cross-sectional characteristics of the river were estimated from November 2017 to March 2018 for Kahalgaon, to represent the decline in river flow with the progress of the dry season. Changes in river discharge were estimated at Kahalgaon from November 2017 to March 2018, as the dry-season progressed.

Differences in river discharge along a gradient of sites with different levels of vessel noise exposure were interpreted qualitatively from discharge estimates. This was done to assess the impact of depth reduction (in %, with November 2017 as baseline) in the dry-season and associated changes in ambient vessel noise levels on acoustic responses (along the gradient: from Barari (Shallow-Quiet), Doriganj (Shallow-Noisy), to Kahalgaon (Deep-Noisy).

Seasonal changes in fish prey availability

Fish catch data were obtained from logbook-based monitoring surveys conducted at the Kahalgaon fish market during the study period (Oct 2017 to March 2018). The total yield from this period was found to be proportional to fishing effort and hence catch-per-unit-effort (CPUE) was considered a simple index of prey availability. CPUE (kg of fish per fisherman per day) was calculated for species whose sizes are within the known average prey size limits of Ganges dolphins (reported by Kelkar et al., 2010; 2018), and monthly variations in CPUE were estimated.

Estimation of metabolic costs to dolphins from noise exposure

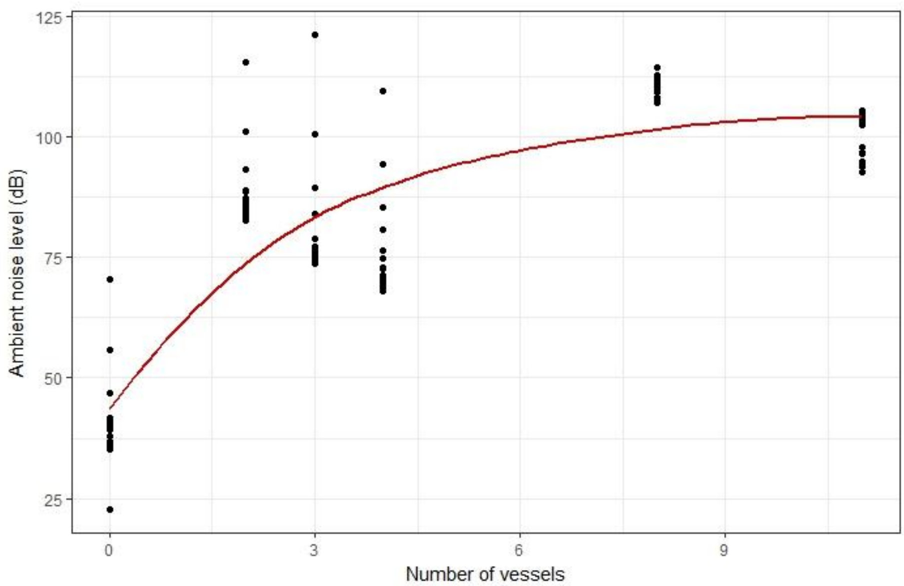
At changes in ambient noise level of 2 times of current ambient levels, and 4 times the current level, we used the data on all measured acoustic responses of dolphins to arrive at a value of "altered acoustic response" relative to natural (no-vessel) baselines. We used standardized metabolic equations (Trites et al. 1997) to estimate the energy requirement of standard-sized adult male and female Ganges river dolphins (lengths 2 to 2.5 m; Kasuya 1972) foraging and communicating in their 'natural state' (Holt et al. 2015, Noren et al. 2016). Using the estimated daily energy intake from prey consumed and data on altered acoustic responses, we estimated how much more energy a dolphin exposed to 12 hours of ambient vessel noise will need in comparison with its natural state intake. Our analysis was limited to checking whether dolphin energy intake was less or more than the predicted metabolic costs, if they fed on fish prey of sizes < 20 cm (dolphin prey size taken from Kelkar et al. 2010, 2018).

Results

Our results showed that 1) Ganges river dolphins significantly altered their echolocation clicks by increasing click-train duration, click rate, and also modulating the peak frequency and increasing the SPL of their clicks, during exposure to vessel noise, 2) shifts from baseline acoustic activity occurred only when noise was intermittent, but under constantly noisy conditions, the acoustic activity of the river dolphins fell close to baseline levels (indicating suppression of responses and lost opportunity for communication or foraging), 3) altered acoustic responses led to significant energetic costs and potential metabolic stress, and 4) impacts of vessel noise on acoustic behaviour of river dolphins were most severe in naturally shallow river channels. From November 2017 to March 2018, as the dry-season progressed, three major changes were witnessed: 1) river flow (discharge) reduced by almost 30% in this 4-month period, 2) vessel noise and traffic increased as flow reduced, and 3) fish availability also declined in the peak dry-season (March). Full results and technical details of the study can be referred to in the thesis of Mr Mayukh Dey, which is enclosed with this report. In the following points we have summarized our results with some basic data.

1. Ambient noise level increased non-linearly with increase in vessel movement (boats per hour) as the dry-season progressed. Ambient noise levels peaked at traffic intensity of four or more boats per hour (Figure 4).

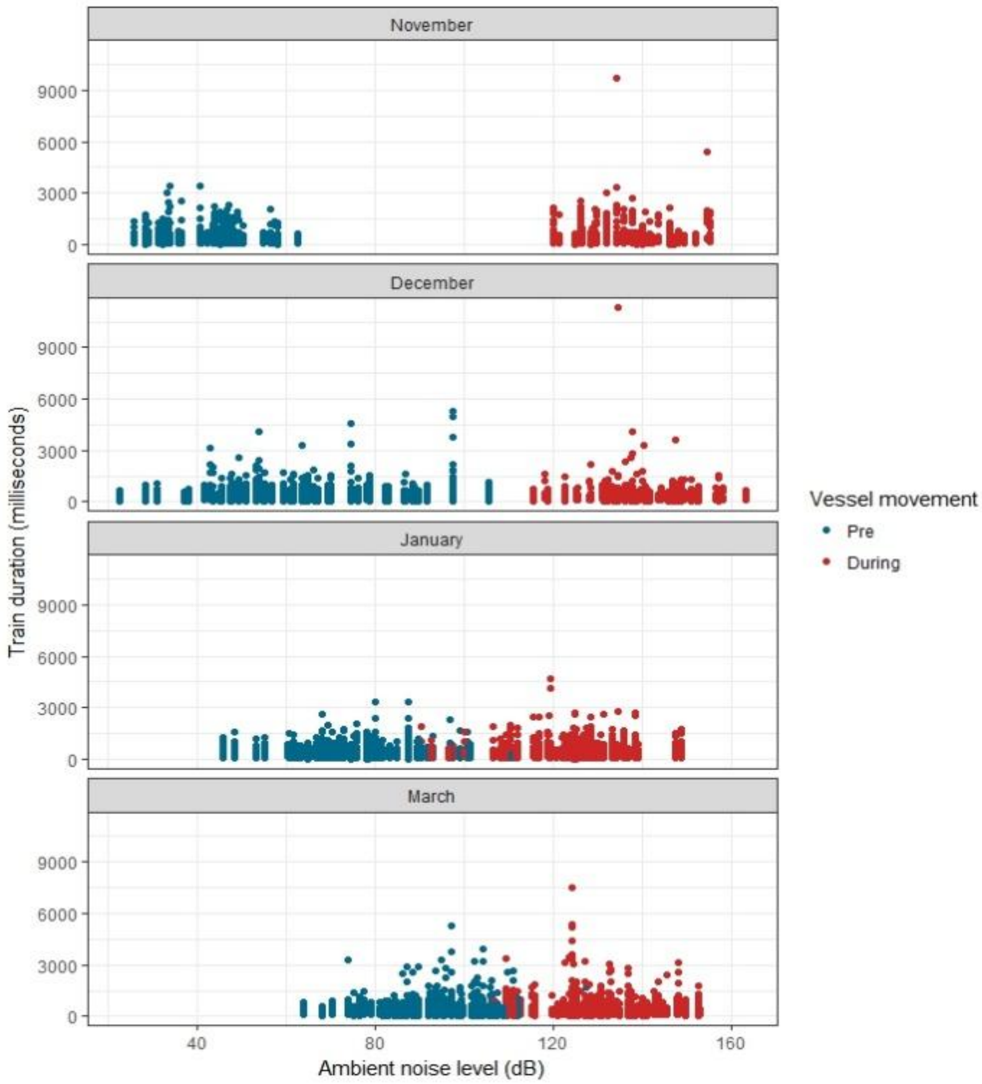
Figure 4. Increase in ambient noise level with the number of vessels passing in a river stretch.

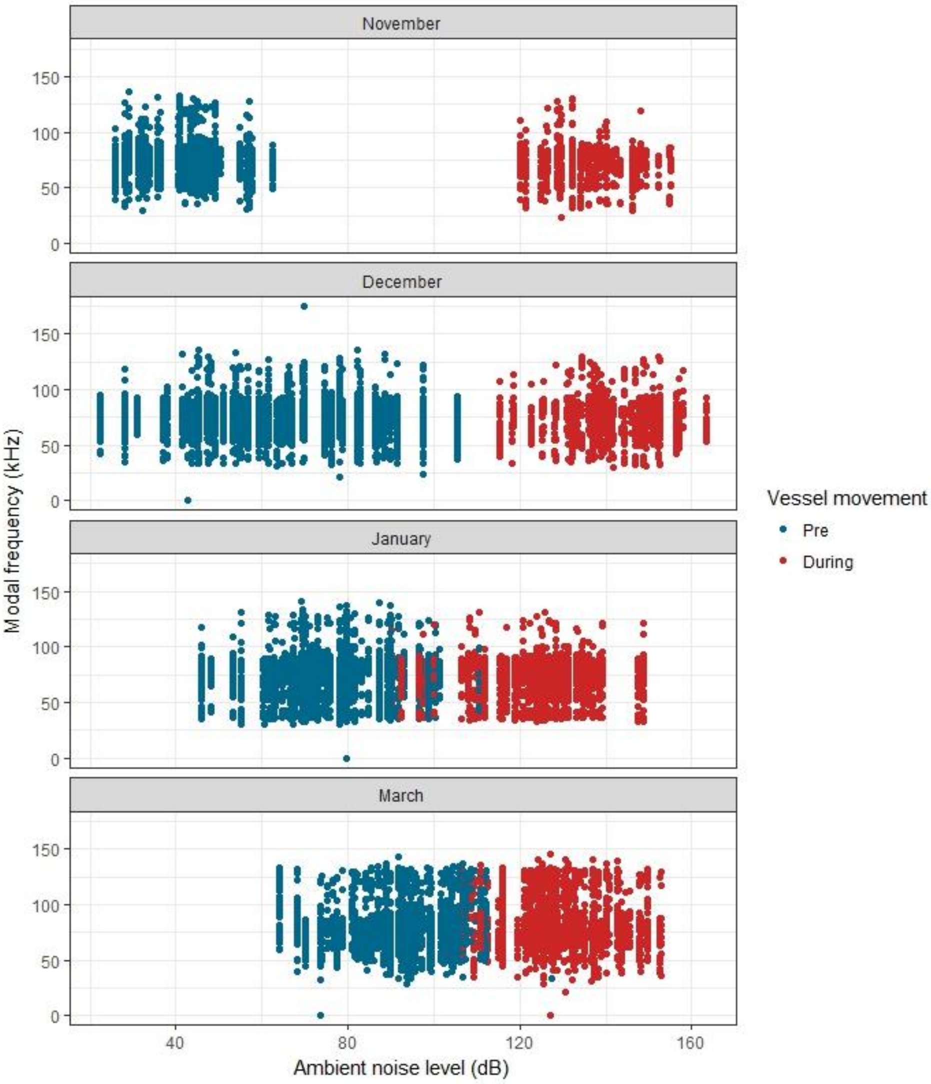


2. River dolphins significantly altered acoustic activity (changed train duration, click rate, SPL or loudness of clicks, peak frequency, and frequency range) in the presence of vessel noise, as

compared to'baseline levels'. Interestingly, the magnitude of difference between all acoustic responses in the 'pre' and 'during' phases reduced as river discharge reduced from November to March, when vessel traffic increased and led to a surge in ambient noise levels at Kahalgaon (Figure 5).

Figure 5. From November to March, as river discharge reduced and vessel noise levels increased, the magnitude of difference in acoustic characteristics of dolphinsin the 'pre' and 'during' phases reduced substantially. Here we have shown results only for dolphin train duration (milliseconds, top) and modal frequency (kHz, bottom).

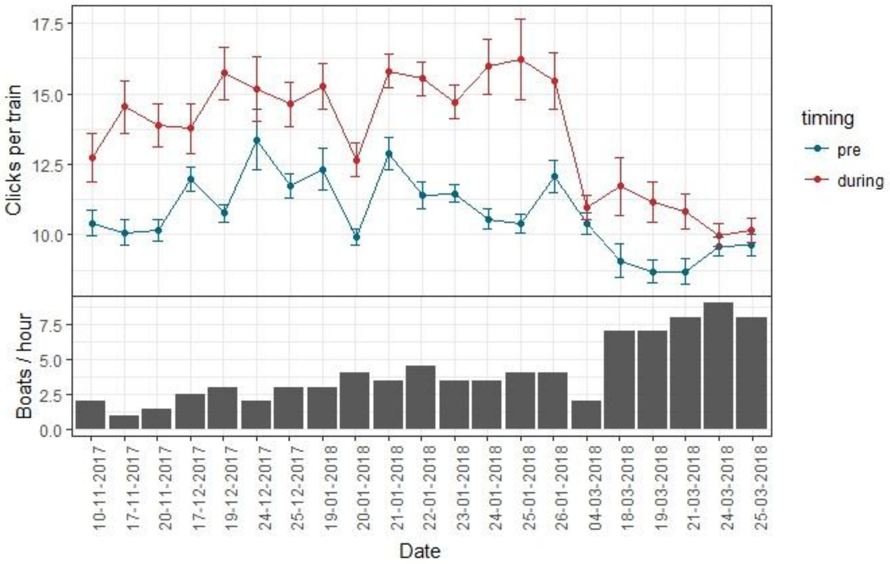


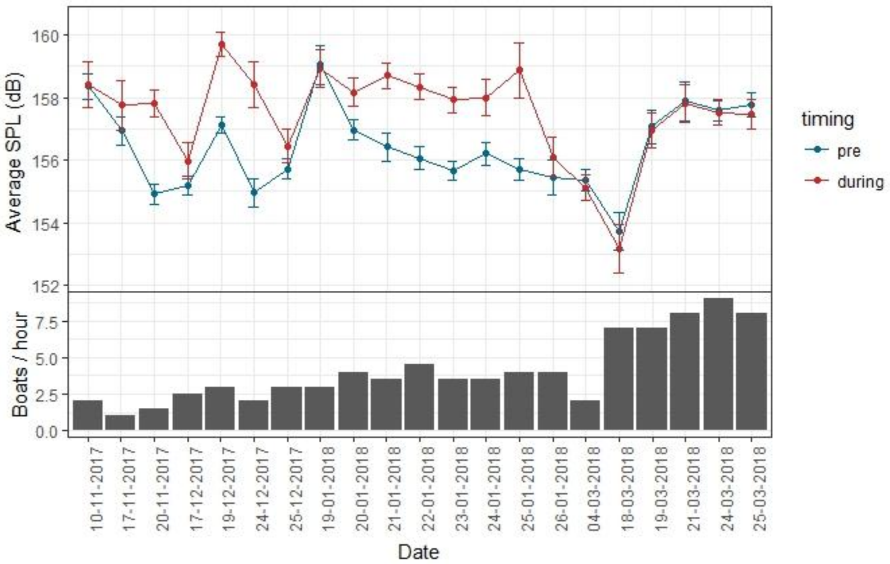


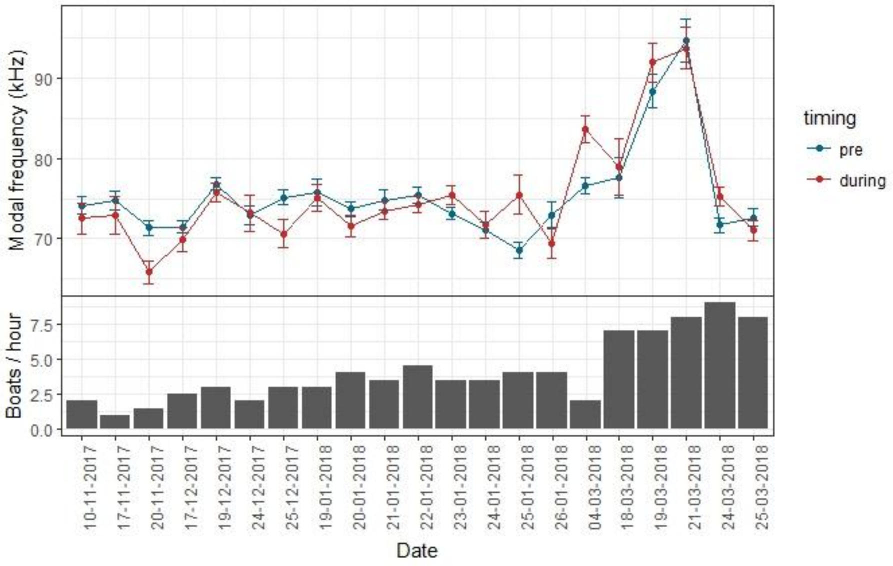
3. Time-series graphs of day-wise dolphin acoustic behaviour showed large and clearly significant, non-overlapping differences between the ‘pre’ and ‘during’ phases for three of the five acoustic responses: train duration, frequency range, and the number of clicks per train were noted, which were much higher in the ‘during’ phase than the baseline ‘pre’ phase (Figure 6). Frequency and sound pressure levels (SPL) of dolphins showed complex responses to noise. Dolphin frequency was lower than baseline in the ‘during’ phase when vessel traffic was lower, but higher in the ‘during’ phase when vessel traffic was higher – in the peak dry season (March). This indicated that dolphins might be frequency-compensating for intermittent exposure to noise and resultant masking, but suppressing click rates and even altering their frequencies at more chronic exposure levels (results similar to Papale et al. 2015). At high levels of vessel noise, baseline sound pressure level (SPL) in the ‘pre’ phase became similar to SPL in the ‘during’ phase. The difference in acoustic responses for train duration ranged from 24% in November to 6 % in March when water levels reduced and vessel traffic increased. For modal frequency, the

difference ranged from -12% in November to 8% in March. We have shown the results for click rate, sound pressure level and modal frequency of dolphins in Figure 6.

Figure 6. Time series graphs depicting clear changes in the baseline level of click rate, click loudness, and frequency of click trains of river dolphins, during vessel passage and exposure to noise. Plotted are the means and the 95% confidence interval of acoustic responses of river dolphins, and the number of boats per hour on each sampling day from November to March. The graphs depict responses of river dolphins as: clicks per train (top), average sound pressure level (SPL, middle), and modal frequency (kHz, bottom).







4. Across sites, acoustic responses of river dolphins varied substantially during exposure to vessel noise (Figure 7 shows the frequency responses to vessel noise levels across deep and shallow sites). Impacts of noise in shallow sites like Doriganj elicited the greatest degree of alteration in dolphin acoustic responses due to interacting effects of depth (<8 m at deepest point, and muddy substrate) and high levels of vessel traffic (>9 boats per hour). The river flow and depth at Doriganj was almost 1/10th of the average depth and flow at Kahalgaon during March (peak dry-season). The corresponding proportional change in acoustic responses was about twice as much in Doriganj for train duration, frequency range, and clicks per train in Doriganj as compared to these responses in Kahalgaon (which also had regular vessel noise but was a naturally deep site). Acoustic responses such as clicks per second, train duration and frequency range was almost twice as high in Doriganj as they were in Kahalgaon. Modal frequency was 8% lower and the average SPL was 5% higher in Doriganj as compared to Kahalgaon. A point to be noted here is that modal frequency and SPL are highly conserved characters and therefore, there are biological constraints on the extent modifications to these characters. Thus, it may seem like a small change from the baseline levels for modal frequency and SPL, but they require more energy to modulate as compared to altering number of clicks per second.
5. Cavitation noise (noise from bursting bubbles near the propeller) from all vessels was well within the hearing level of river dolphins. Thus it could be ascertained that noises from all motorised vessels in the river were audible to the Ganges river dolphin (Figure 8). River dolphins are most sensitive to sounds ranging from 50 kHz to 90 kHz (Zbinden et al., 1978), since the peak frequency of their echolocation clicks is also within the same range. As a result, boat SONAR, which is emitted at 50 kHz, could be extremely stressful for river dolphins in the vicinity of such boats. The lowest threshold sensitivity level of the Ganges river dolphins

observed at 10 kHz and speculated to be an adaptation that allows dolphins to hear acoustic signals produced by certain high-frequency catfish or shrimp prey (Kelkar et al. 2018). Thus even lower frequency sounds could affect the sensitivity of auditory responses of Ganges river dolphins.

6. As high frequency sounds tend to attenuate faster than low frequency sounds, the masking range of the echolocation clicks of dolphins corresponded closely with the relative loudness (sound source levels) of vessel noise. Boats with uncased engines and simple propeller design (such as ferry-boats and boulder-carrying boats) had the strongest effect of masking on the clicks of Ganges river dolphins. Clicks in Ganges dolphin serve the dual purpose of echolocation and communication unlike most other dolphins. Vessels with more efficient propeller designs had relatively lower effect on the masking range. The masking range varied from approximately 50 m to less than 600 m for these different types of vessels (Figure 9). The masking range depended on the loudness level (SSL) of the motorised vessels.
7. The overall 'altered acoustic response' was a factor denoting an increase in acoustic activity from 2.5 to 4.3 times, when the vessel noise levels increased from 1-2 times of baseline levels to over 4 times. Energy costs of exposure to chronic noise might be substantially higher than the energy gained from daily prey intake by river dolphins. Over a 12-hour exposure period, we found that a) energy costs exceeded gains by 33% when vessel noise levels doubled, and b) energy costs exceeded gains by nearly 100% when vessel noise levels quadrupled, as per our models (Figure 10). This model predicts that dolphins will hypothetically need 2 to 4 times more prey intake (8% to 16% of body weight) with doubling and quadrupling of ambient noise levels respectively (Figure 10). As dolphins cannot eat beyond their natural satiation capacity, this would mean that they would end up spending much more energy to overcome noise impacts, than they would gain by prey capture. Needless to say, increased energy costs are high and indicate a scenario of significant impacts of vessel noise on river dolphin stress levels.
8. Dry-season reduction in prey availability (in March) might not only exacerbate stress levels of Ganges river dolphins to noise, but might also make them more prone to other threats such as bycatch in fishing nets or constant movements to avoid vessel noise impacts. At higher metabolic costs, dolphins might have to spend more energy in prey searching with the use of echolocation, than they would have in natural conditions without vessel noise. Although these results are only indicative, they predict potentially serious threats from high levels of vessel traffic in the projections for near-future targets of waterways development.

Figure 7. Differences in the modal (peak) frequency of river dolphins between the 'pre' and 'during' phases for the three sampling sites, showing the mean values and 95% confidence intervals. The ambient noise levels for Kahalgaon were 110.61dB (±0.01 SE); Barari = 86.9 dB (±0.04 SE); and Doriganj = 101.54 dB (±0.01 SE).

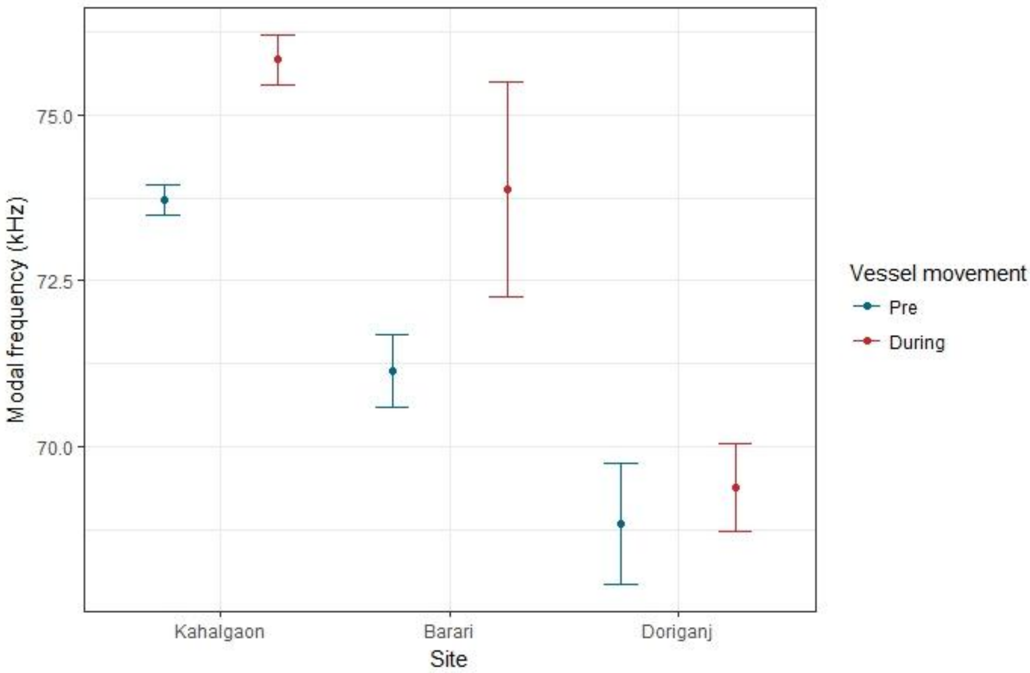


Figure 8. Modified from Zbinden et al (1978), the graph depicts the sound source level of different types of vessels at 1 kHz frequency bins, with the line in green indicating the threshold level of hearing for the Ganges river dolphin. The area shaded in green represents the inaudible zone, whereas sources having SPL above the green line would be audible to the dolphins. Further the value is from the green line, the louder it will be perceived by a dolphin. Additionally, the rise in the 50 kHz frequency range for the tourist vessel is because of on-board SONAR being active continuously.

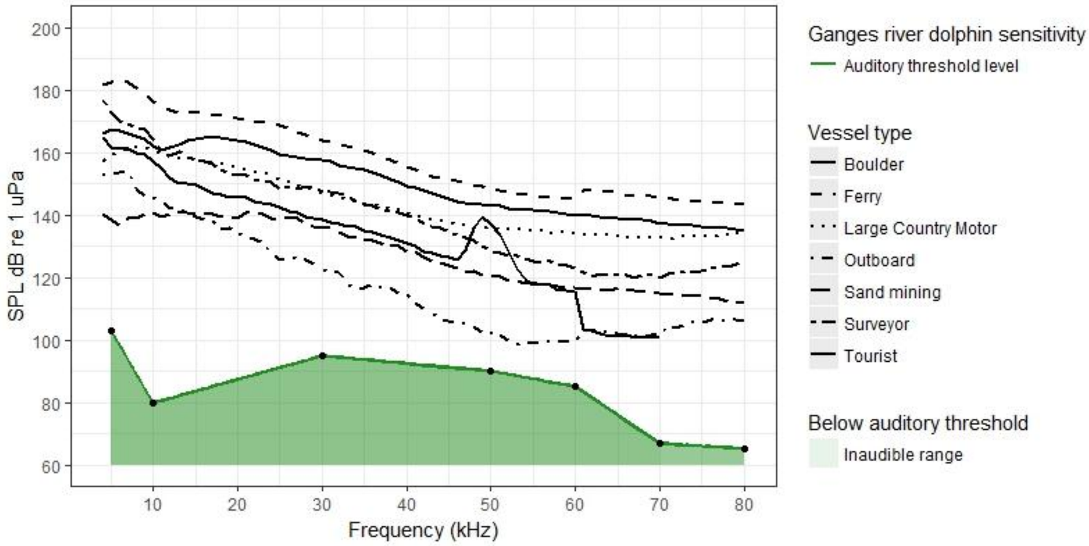


Figure 9. A comparison of the masking range of different types of vessels against one another is presented. Slow-moving vessels ('ferry', 'boulder' and 'large country motor') had the highest masking effects on Ganges river dolphin clicks, which meant that dolphins would need to be closer to one another to be able to hear a particular frequency of click. Any dolphin above the plotted lines will not be able to hear the corresponding frequency of echolocation clicks.

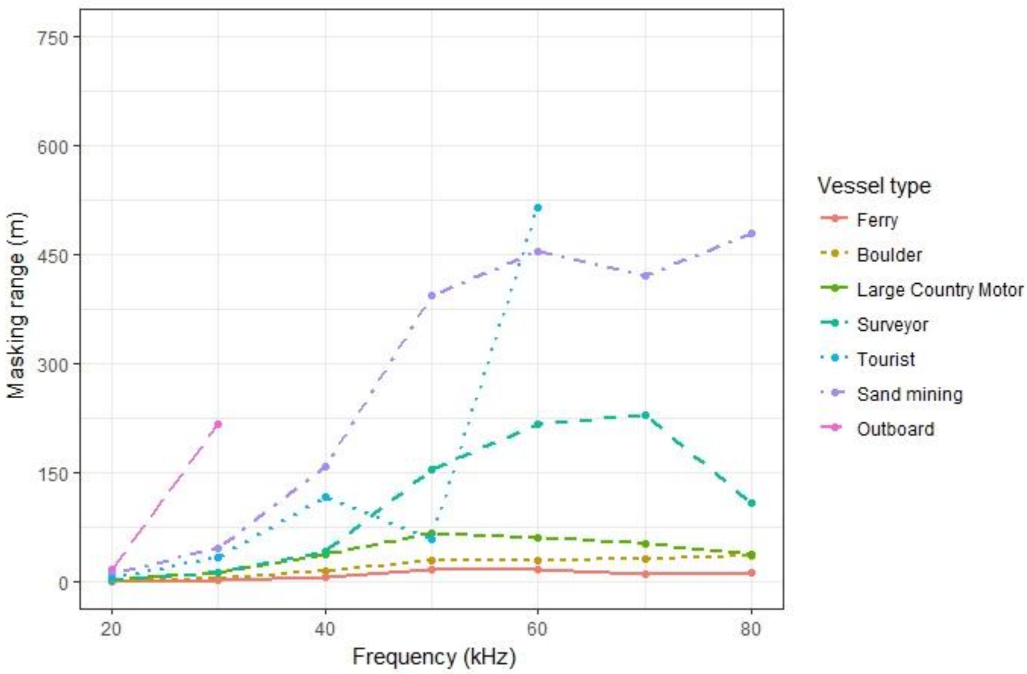
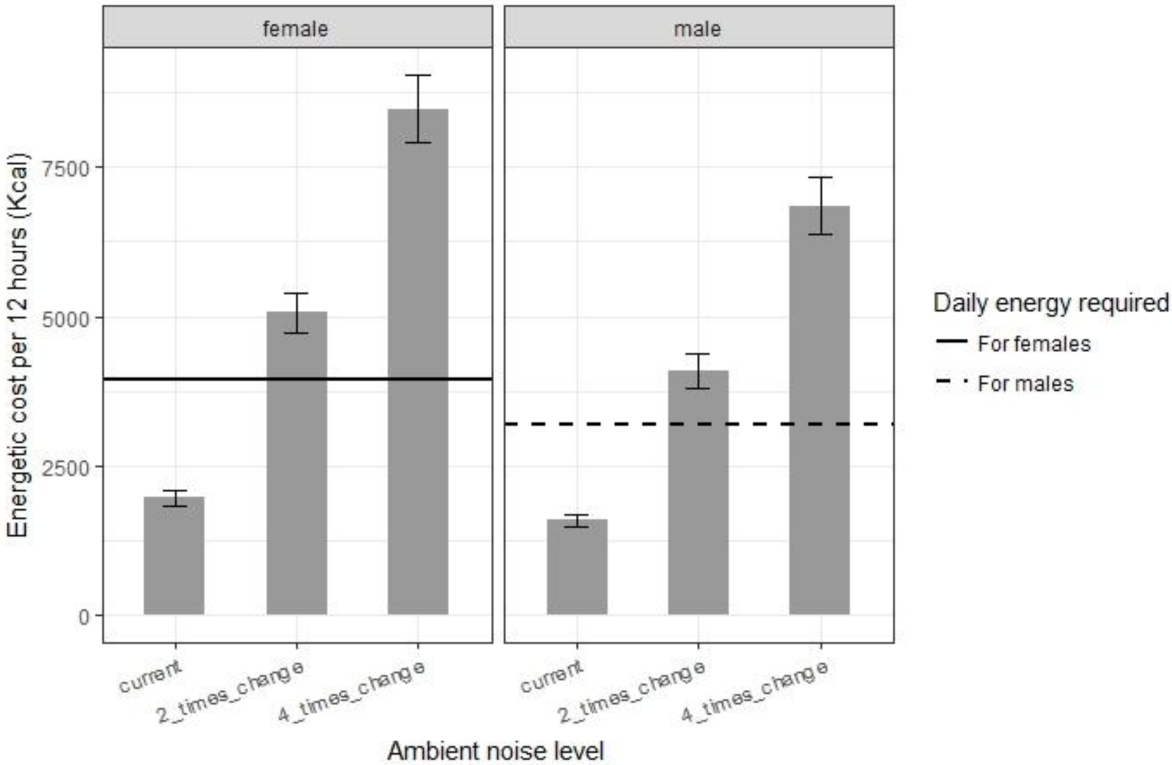


Figure 10. The increasing energetic costs of clicking in noisier conditions are given below. The horizontal lines indicate the daily prey intake in kilo calories of energy while the bar graphs indicate the energetic costs of clicking in current ambient noise level versus double and quadruple the current noise levels. At current levels, dolphins might be able to overcome metabolic stress provided prey availability is sustained. However, with increased ambient noise levels, metabolic costs of enhanced acoustic activity were much higher than energetic gains from prey intake.



Discussion

Our study has established that, with increasing vessel traffic and noise, resulting acoustic responses can change dramatically, leading to potentially severe metabolic costs to river dolphins in the Ganga River. Vessel noise impacts would have the highest risk for resident river dolphins in the low-flow dry-season, when river depths are the lowest. With vessel traffic increasing during the dry-season, reduction in dry-season flow due to human abstraction in addition to natural flow recession will make dolphins more vulnerable to other indirect threats (Choudhary et al. 2012). The impacts are likely to be further intensified in drought years when discharge and depth in the river is at very low levels. In combination with reduced fish availability, these stresses would become detrimental to river dolphin survival in the Ganga River waterway. Measures such as dredging used to artificially deepen river channels, can contribute to additional stress in river dolphins due to noise and river sediment disturbance. River dolphins in their natural habitat need a combination of deep and shallow river segments (for resting, feeding, and other activities; Kelkar et al. 2010, Sinha & Kannan 2014). So artificial deepening of habitat might only worsen the pre-existing impacts of noise, and do nothing to ameliorate noise impacts, as is wrongly assumed by current impact assessment studies.

The study makes a significant scientific contribution to inform important debates regarding the impact of waterways on the riverine biota. Given the current plans of infrastructural development on the National Waterway No. 1 on the Ganga River, the fear that ambient noise levels could increase to ecologically damaging levels might actually be realised, according to the findings. Although the study did not quantify the ecological and water quality impacts of dredging and other associated waterway development activities, their cumulative impact along with underwater noise might seriously affect dolphin individuals and populations, especially those inhabiting shallower stretches of the river. River dolphins occur throughout the Ganga in Bihar, and not only in the Vikramshila Sanctuary. This entire population is expected to suffer the impacts of increased vessel noise in the near future.

Recently, India’s Inland Waterways Authority, and associated central government agencies under the Ministry of Water Resources, River Development, and Ganga Rejuvenation (Government of India), appear to have acknowledged concerns surrounding the potential ecological consequences of these projects, and might even initiate studies on the Ganges river dolphin, which is India’s National Aquatic Animal, and hence a high conservation priority too. The upcoming Bihar river dolphin survey (planned in Nov-Dec 2018) can also use the study’s information to maintain observations on vessel traffic across the stretch of the Ganga from Buxar to Manihari in Bihar. This can help us understand the extent of exposure of river dolphins to vessel noise in the river within Bihar.

The findings of our study provide an empirical basis for conservation of the endangered Ganges river dolphin in this context, and also can help to identify measures to regulate or manage water transport in the Ganga River at levels where threats to the survival of this species can be minimized. The study provides a combined understanding of impacts of underwater noise from different vessel traffic levels under conditions of declining river discharge, and declines in prey availability. It thus contributes to rigorous scientific knowledge for use by future range-wide studies of waterway impacts on river biodiversity in India. This knowledge may thus contribute to conservation of river dolphins in India through avoidance and mitigation strategies.

In the dry-season (especially from November-April), the risk of river dolphin bycatch and mortality in fishing nets is the highest. Thus, in extreme scenarios of underwater noise exposure, bycatch risk might also increase due to fatigue in Ganges dolphins, as seen from the significant metabolic costs experienced by dolphins. At certain times of the year, therefore, dolphins might be at greater risk from underwater noise and vessel traffic. Along NW-1, impacts of vessel noise will also vary spatially. It is known that after Patna, Ganga river flow improves due to the inflow contributions from tributaries such as the Gandak, Son, Burhi Gandak, Kosi, and Mahananda rivers (Choudhary et al. 2012). Thus the impacts of vessel noise upstream and downstream of Patna may be different, as shown in the greater impacts seen at Doriganj, as compared to those at Kahalgaon. These results stress the need for maintaining near-natural and adequate 'ecological flows' for river dolphins in river reaches to buffer against impacts of increase in vessel noise, by improving barrage releases both into the Ganga river and its tributaries (and not by practices such as dredging that do not address the real problem of poor flow in the Ganga river). Vessel noise reduction, in this new scenario, should be made a necessary target. In fact, acoustic criteria must be incorporated and the definition of 'ecological flows', as currently understood, can be broadened for endangered species such as Ganges river dolphins. Our study provides some leads in this regard, by identifying thresholds in terms of both vessel traffic and river discharge that might substantially alter the 'quality' of habitats needed for the continued survival of river dolphins.

With the current rapid push for commercial waterway development on the NW-1, major projected increases in cargo transportation are on the horizon (EQMS India Pvt. Ltd. 2016). While waterways may arguably be beneficial for cheap transportation, their negative ecological impacts must be acknowledged and addressed urgently. Recent debates both within the government and in civil society have categorically questioned the assumption that waterways are environmentally friendly in a universal sense. Multiple lines of evidence across the world have been highlighting the damaging and potentially irreversible environmental impacts of the industrial waterways development. In this context, the findings of our study provide a solid empirical basis for conservation of the endangered Ganges river dolphin, which can help to identify measures to regulate or manage water transport in the Ganga River at levels where threats to the survival of this species can be minimized. We propose some recommendations based on the current need for continued generation of rigorous scientific knowledge and monitoring of the range-wide impacts of waterways on river biodiversity in India. The recommendations also suggest specific avoidance and mitigation strategies to prevent irreparable damages to the already endangered river dolphin populations in the Ganga.

Recommendations

1. Acute and chronic impacts of vessel noise on Ganges river dolphins, as our study shows, are a matter of serious concern for the immediate wellbeing and survival of Ganges river dolphins living in the Ganga River (National Waterway No. 1, or NW-1). In light of these new and empirically robust results, strict regulations on vessel traffic on the Ganga River, monitoring and reduction of underwater noise levels, and continuous assessmentsof the impacts of waterways development in Bihar's rivers is an urgent need.
2. The Department of Environment & Forests, Bihar, is the state agency responsible for the protection of the endangered Ganges river dolphin, which is also the National Aquatic Animal of India, and a Schedule I species as per India's Wildlife (Protection) Act, 1972. The species occurs throughout the extent of the NW-1 in India (Allahabad to Haldia, 1620 km), and is not restricted to protected areas such as the Vikramshila Gangetic Dolphin Sanctuary (a 65 km stretch of the Ganga in Bhagalpur district of Bihar). Our study results establish that impending development of industrial waterways is a major threat to the species, because vessel noise and associated changes to the river dolphin's 'sound environment' are likely to alter their natural behaviour and induce persistent stress in dolphin populations. These effects can impinge significantly on river dolphin survival. We recommend that the authorities concerned should work with the government towards meaningful reduction of vessel traffic and associated threats in light of our findings.
3. Our results provide a baseline for future research studies, surveys, or impact assessment studies on this issue. In fact, this is the first independent study by any agency on the impacts of vessel noise on the Ganges river dolphin, which is based on rigorous fieldwork and advanced statistical analysis of actual sound recordings of the species. So far, none of the existing impact assessments (e.g. EQMS India Pvt. Ltd. 2016) based their findings on acoustic data recorded directly from the species. Instead they assumed parameters of marine dolphins for their assessments. As we have shown, the acoustic repertoire and behaviour of the Ganges river dolphin is rather different from marine species. The former lives in shallow

riverine habitats and the impacts of vessel noise are likely to be much higher for this species as compared to marine species. Hence, thestatements from earlier reports about impacts of vessel noise on river dolphins need to be critically revisited.

4. Our study has only focused on impacts of vessel noise on river dolphins. At present, therefore, they only partly indicate the impacts of waterways development on the Ganges river dolphin. For a more complete understanding, it is deemed critical to undertake studies on impacts of river bottom maintenance dredging and studies on direct and indirect threats from vessels (e.g. mortality from propeller hits or bycatch, health impacts due to changes in sediment and water quality). In this context, the limited but important observations of our study on masking range, vessel engine and propeller technology, and speed and timing of operations need to be considered in future regulations to limit noise impacts.
5. The Ganga River is the largest and naturally deepest river holding the highest population of Ganges river dolphins in South Asia. In spite of this, the impacts of vessel noise on river dolphins are significant. In the case of shallower tributaries of the Ganga in Bihar, such as the Gandak, Kosi, etc., waterways have been already proposed. But impacts of waterways on dolphin populations in these smaller rivers might be even worse than what we have reported in case of the Ganga. We recommend the Bihar state government to consider such impacts predicted by our study, while plans for waterways on these tributaries are discussed.

Selected References

1. Arcement, G. J., & Schneider, V. R. (1984). *Guide for selecting Manning's roughness coefficients for natural channels and flood plains*. United States Geological Survey Report No. FHWA-TS-84-204, for the Federal Highway Administration, USA, p. 72.
2. Au, W. W. (2000). Echolocation in dolphins. In:*Hearing by whales and dolphins* (pp. 364-408). Springer, New York, NY.
3. Braulik, G.T. & Smith, B.D. (2017). *Platanista gangetica*. The IUCN Red List of Threatened Species 2017: e.T41758A50383612. http://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T41758A50383612.en. Downloaded on 14 July 2018.
4. 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*(2), 189-197.
5. Choudhary, S.K., 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. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 22, 11–25.
6. Chow, V.T. (1959) Open-channel hydraulics: New York, McGraw-Hill, 680 p.
7. Cramer, E., &Lauterborn, W. (1982). Acoustic cavitation noise spectra. In *Mechanics and Physics of Bubbles in Liquids* (pp. 209-214). Springer, Dordrecht.
8. EQMS India Pvt. Ltd. (2016). Environmental and Social Impact Assessment Report, Environmental Management Plan And Resettlement Action Plan For Capacity Augmentation Of National Waterway.1‖ Between Haldia And Allahabad (Jal MargVikas Project). Draft Cumulative Impact Assessment Report For National Waterways-1, New Delhi, India, 456 pp.
9. Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., &Dooling, R. (2016). Communication masking in marine mammals: A review and research strategy. *Marine pollution bulletin*, *103*, 15-38.
10. Finneran, J. J., &Schlundt, C. E. (2010). Frequency-dependent and longitudinal changes in noise-induced hearing loss in a bottlenose dolphin (Tursiopstruncatus). *The Journal of the Acoustical Society of America*, *128*(2), 567-570.
11. Francis, C. D., & Barber, J. R. (2013). A framework for understanding noise impacts on wildlife: an urgent conservation priority. *Frontiers in Ecology and the Environment*, *11*(6), 305-313.
12. Francois, R. E., & Garrison, G. R. (1982). Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. *The Journal of the Acoustical Society of America*, *72*(6), 1879-1890.
13. Gomez, C., Lawson, J. W., Wright, A. J., Buren, A. D., Tollit, D., & Lesage, V. (2016). A systematic review on the behavioural responses of wild marine mammals to noise: the disparity between science and policy. *Canadian Journal of Zoology*, *94*(12), 801-819.
14. Government of India. (1982). National Waterway (Allahabad-Haldia Stretch of the Ganga-Bhagirathi-Hooghly River) Act (No. 49 of 1982). October 18, 1982.

15. Government of India. (2016). National Waterways Act (No. 17 of 2016). Registered No. Dl—(N) 04/0007/2003—16. March 26, 2016,15 p.
16. Harwood J. 2001. Marine mammals and their environment in the twenty-first century.*Journal of Mammalogy*,82, 630–640.
17. Holt, M. M., Noren, D. P., Dunkin, R. C., & Williams, T. M. (2015). Vocal performance affects metabolic rate in dolphins: implications for animals communicating in noisy environments. *Journal of Experimental Biology*, *218*(11), 1647-1654.
18. Jensen, F. H., Bejder, L., Wahlberg, M., Soto, N. A., Johnson, M., & Madsen, P. T. (2009). Vessel noise effects on delphinid communication. *Marine Ecology Progress Series*, *395*, 161-175.
19. Jensen, F. H., Beedholm, K., Wahlberg, M., Bejder, L., & Madsen, P. T. (2012). Estimated communication range and energetic cost of bottlenose dolphin whistles in a tropical habitat. *The Journal of the Acoustical Society of America*, *131*(1), 582-592.
20. Jensen, F. H., Rocco, A., Mansur, R. M., Smith, B. D., Janik, V. M., & Madsen, P. T. (2013). Clicking in shallow rivers: short-range echolocation of Irrawaddy and Ganges River dolphins in a shallow, acoustically complex habitat. *PloS One*, *8*(4), e59284.
21. Kasuya, T. (1972). Some informations on the growth of the Ganges dolphin with a comment on the Indus dolphin. *Scientific Reports of the Whales Research Institute*, *24,* 87-108.
22. Kelkar, N. (2016) Digging Our Rivers‘ Graves? A summary analysis of the ecological impacts of the National Waterways Bill (2015). Dams, Rivers, and People Newsletter, South Asia Network for Dams, Rivers, and People (SANDRP), 14, 1-2, p. 1-6.
23. Kelkar, N. (2017). A river dolphin's ear-view of India's waterways development plans. Sanctuary Asia, Vol. XXXVII No. 4, 58-61. February 2017.
24. Kelkar, N., Dey, S., Deshpande, K., Choudhary, S.K., Dey, S., &Morisaka, T. (2018). Foraging and feeding ecology of Platanista gangetica: an integrative review. Mammal Review, 48, 194-208.
25. Kelkar, N., Krishnaswamy, J., Choudhary, S. & Sutaria, D. (2010) Coexistence of fisheries with river dolphin conservation. *Conservation Biology,* 24, 1130–1140.
26. Kight, C. R., & Swaddle, J. P. (2011). How and why environmental noise impacts animals: an integrative, mechanistic review. *Ecology letters*, *14*(10), 1052-1061.
27. Ng, S. L., & Leung, S. (2003). Behavioral response of Indo-Pacific humpback dolphin (Sousa chinensis) to vessel traffic. *Marine Environmental Research*, *56*(5), 555-567.
28. Noren, D. P., Holt, M. M., Dunkin, R. C., & Williams, T. M. (2013). The metabolic cost of communicative sound production in bottlenose dolphins (Tursiopstruncatus). *Journal of Experimental Biology*, *216*(9), 1624-1629.
29. Nowacek, D. P., Thorne, L. H., Johnston, D. W., & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammal Review*, *37*(2), 81-115.
30. NRC (National Research Council). (2000). *Marine mammals and low-frequency sound: Progress since 1994*. National Academies Press.

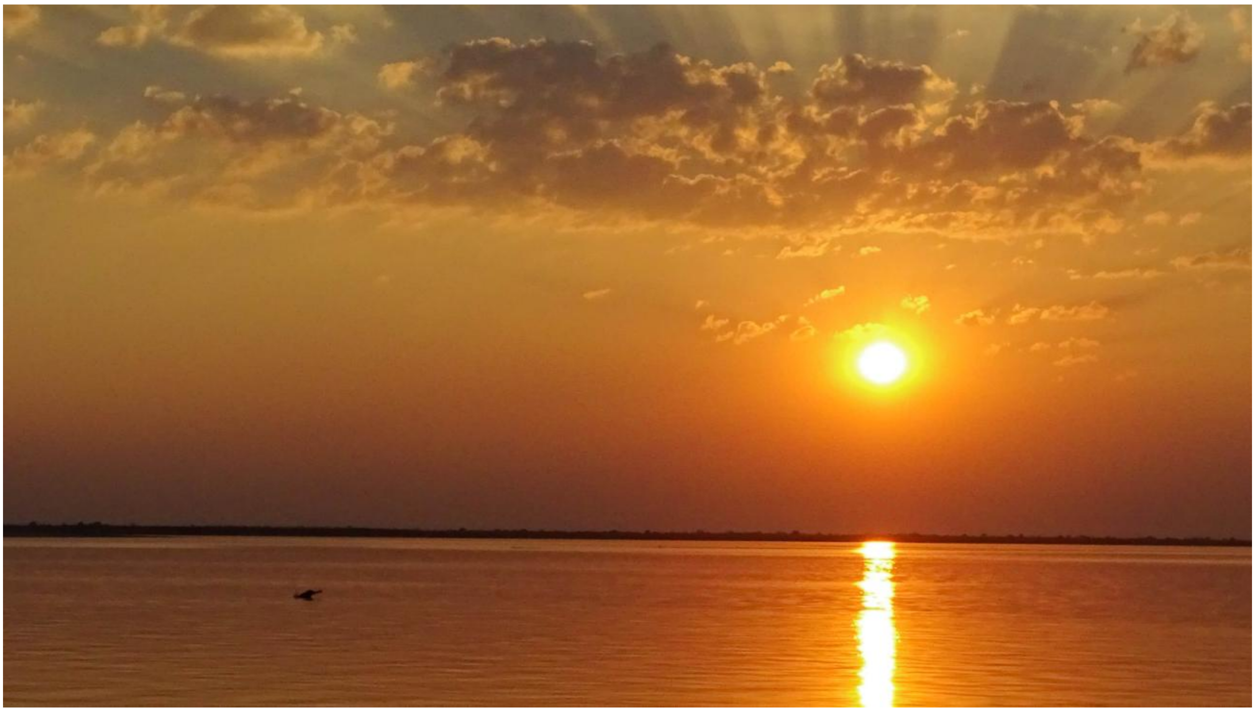
31. Papale, E., Gamba, M., Perez-Gil, M., Martin, V. M., &Giacoma, C. (2015). Dolphins adjust species-specific frequency parameters to compensate for increasing background noise. *PloS one*, *10*(4), e0121711.
32. Pijanowski, B. C., Farina, A., Gage, S. H., Dumyahn, S. L., & Krause, B. L. (2011). What is soundscape ecology? An introduction and overview of an emerging new science. *Landscape ecology*, *26*(9), 1213-1232.
33. Pilleri, G., Zbinden, K., Gihr, M., & Kraus, C. (1976a). Sonar clicks, directionality of the emission field and echolocating behaviour of the Indus dolphin (Platanista indi, Blyth, 1859). *Investigations on Cetacea. Brain Anatomy Institute, Berne, Switzerland*, 13-43.
34. Pilleri G, Gihr M, Purves PE, Zbinden K, Kraus C (1976b) On the behaviour, bioacoustics and functional morphology of the Indus River dolphin (Platanista indi Blyth, 1859). Investigations on Cetacea 6:11–141.
35. R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.
36. Robbins, J. R., Brandecker, A., Cronin, M., Jessopp, M., McAllen, R., &Culloch, R. (2016). Handling dolphin detections from C-PODs, with the development of acoustic parameters for verification and the exploration of species identification possibilities. *Bioacoustics*, *25*(2), 99-110.
37. Romano, T. A., Keogh, M. J., Kelly, C., Feng, P., Berk, L., Schlundt, C. E., &Finneran, J. J. (2004). Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. *Canadian Journal of Fisheries and Aquatic Sciences*, *61*(7), 1124-1134.
38. Shannon, G., McKenna, M. F., Angeloni, L. M., Crooks, K. R., Fristrup, K. M., Brown, E., & McFarland, S. (2016). A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews*, *91*(4), 982-1005.
39. Sharma, B., Amarasinghe, U., Xueliang, C., de Condappa, D., Shah, T., Mukherji, A., &Xenarios, S. (2010). The Indus and the Ganga: river basins under extreme pressure. *Water International*, *35*(5), 493-521.
40. Sinha, R. K., &Kannan, K. (2014). Ganges River dolphin: an overview of biology, ecology, and conservation status in India. *Ambio*, *43*(8), 1029-1046.
41. Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene Jr, C. R., & Richardson, W. J. (2007). Marine mammal noise-exposure criteria: initial scientific recommendations. *Bioacoustics*, *17*(1-3), 273-275.
42. Sueur, J., Aubin, T., &Simonis, C. (2008). Seewave, a free modular tool for sound analysis and synthesis. *Bioacoustics*, *18*(2), 213-226.

43. Todd V.L.G., Todd I.B., Gardiner J.C., Morrin E.C.N., Macpherson N.A., Dimarzio N.A., Thomsen F. (2015). A review of impacts of marine dredging activities on marine mammals. ICES Journal of Marine Science 72:328–340.
44. Tregenza, N. (2014). CPOD.exe: a guide for users. *United Kingdom*.
45. Trevorrow, M. V. (1998). Boundary scattering limitations to fish detection in shallow waters. *Fisheries Research*, *35*(1-2), 127-135.
46. Trites, A. W., Christensen, V., & Pauly, D. (1997). Competition between fisheries and marine mammals for prey and primary production in the Pacific Ocean. *Journal of Northwest Atlantic Fishery Science*.
47. Turvey, S. (2009). *Witness to extinction: how we failed to save the Yangtze River dolphin*. Oxford University Press, USA.
48. Weilgart, L. S. (2007). The impacts of anthropogenic ocean noise on cetaceans and implications for management. *Canadian Journal of Zoology*, *85*(11), 1091-1116.
49. Wright, A. J., Soto, N. A., Baldwin, A. L., Bateson, M., Beale, C. M., Clark, C., & Hatch, L. T. (2007). Do marine mammals experience stress related to anthropogenic noise?. *International Journal of Comparative Psychology*, *20*(2).
50. Zbinden, K., Kraus, C., &Pilleri, G. (1978). Auditory response of Platanista indi (Blyth, 1859). *Invest. Cetacea*, *9*, 41-64.

Appendices

A CPOD being deployed from a moored fishing boat in Barari with weights attached. The device logs dolphin clicks but does not record their sound.

The hydrophone set used to record dolphin sounds and noise from motorised vessels in the river.



A Ganges river dolphin is seen surfacing for a breath of air at Kahalgaon.

A collage of various vessels plying on the river. A) local country-motor, B) rowing boat, C) non-mechanised fishing boats, D) Dredging vessel, E) Reduced water levels during dry season, F) Large barges ferrying up the river, G & H) Tourist vessels that have active SONAR on board, I) Barge ferrying people and vehicles across the river. Picture credits: Nachiket Kelkar and Subhasis Dey.