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Irrigation demands aggravate fishing threats to river dolphins in Nepal

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ABSTRACT

Riverine species are adapted to natural habitat changes caused by seasonal flood-pulses. However, abrupt river channel changes following flooding events intersect with social systems of land and water management (e.g. agriculture, fisheries) and in turn generate significant consequences for conservation of endangered aquatic species. We investigated tradeoffs between changing river habitat availability and exposure to fishing intensity for a small population of Ganges River dolphins *Platanista gangetica gangetica* in the Karnali basin of Nepal. A major natural flooding event in the Karnali basin in 2010 caused the river channel to shift from the Geruwa (flows through a protected area where fishing is restricted) to the Karnali channel (high fishing activity, agriculture-dominated), where dolphins moved in response. Based on our survey data (2009–2015) and long-term hydrological trends in the basin, we found that irrigation diversions since 2012 had aggravated fishing impacts on dolphins, suggesting that their new habitat had become an 'ecological trap'. Regression models showed that at low river depths, fishing intensity negatively affected dolphin abundance, but at higher depths no effect of fishing was observed. Two records of dolphin bycatch in gillnets confirmed this, as both events corresponded with periods of sudden increase in water abstraction for irrigation. Overall, dolphin distribution shifted downstream and the population declined from 11 in 2012 to 6 in 2015. Effective protection of this river dolphin population from extinction will require the Government of Nepal to prioritize ecologically adequate river flow regimes for implementing efficient irrigation schemes and adaptive fisheries regulations in the Karnali basin.

1. Introduction

Conserving freshwater animal populations is a complex challenge, given their specific ecological requirements, and the high human dependence on river and wetland ecosystems (Arthington et al., 2010; Dudgeon et al., 2006; Dudgeon, 2000). Floodplain river systems are highly dynamic and channel changes are a common feature due to seasonal flooding, precipitation, sediment deposition-erosion processes, and human alterations (Bookhagen and Burbank, 2010; Hofer and Messerli, 2006; Ward, 1998; Junk et al., 1989). Such changes provide new habitats to freshwater species that are evolutionarily adapted to hydrological cues for breeding, migration, and seasonal movements (Dudgeon et al., 2006; Lytle and Poff, 2004; Robinson et al., 2002). Owing to severe human modifications of river flow regimes (Poff and Matthews, 2013; Döll and Zhang, 2010) river channel changes can also influence the exposure of aquatic species to various anthropogenic risks (Dudgeon, 2000). In dynamic floodplain rivers, habitat conditions constantly change and intersect social systems of intensive land and water management (e.g. protected areas, forests, irrigated agriculture, etc.). As a result, freshwater species responding to habitat changes based on environmental cues might face risks that can threaten their survival and conservation in human-dominated environments (Arthington et al., 2010; Robinson et al., 2002; Ward, 1998).

The South Asian River dolphin, *Platanista gangetica*, is an endangered freshwater cetacean species that lives in the highly human-dominated Indus-Ganga-Brahmaputra basin in the Indian subcontinent. The dolphin is threatened throughout its range by declining river water availability and threats from hunting, fisheries by-catch, river pollution, etc. (Sinha and Kannan, 2014; Braulik et al., 2014; Smith and Braulik, 2012; Turvey et al., 2012). For the Gangetic subspecies, *Platanista g. gangetica*, poor dry-season flows and altered flow regimes by dams and barrages threaten their survival in upstream areas of distribution

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(Choudhary et al., 2012; Khatri et al., 2010). Riverine fisheries also result in multiple threats to dolphins, especially through accidental entanglement in gillnets (bycatch) and occasional targeted killing for use as fishing bait (Sinha and Kannan, 2014; Smith and Braulik, 2012; Bashir et al., 2012; Mansur et al., 2008). In general, fishing threats have received greater attention in conservation planning, and are typically addressed in isolation from declining flow regimes (Kelkar and Krishnaswamy, 2014). Especially for isolated small populations of Ganges river dolphins as in Nepal, a combined understanding of the multi-scale interactions between river water availability and fishing impacts is urgently required (Smith and Reeves, 2012).

The Karnali River (which is not yet dammed in Nepal) harbors a small Ganges River dolphin population in Nepal. Rivers are not well represented in Nepal's protected area network (Shrestha et al., 2010) and water availability has been strongly constrained by competing demands for irrigation, hydropower, etc. (Pradhan, 2012; Gumma et al., 2011; Smakhtin et al., 2006). These factors contribute to the significant extinction risk to river dolphins both from various anthropogenic impacts (Paudel et al., 2015a; Smith et al., 1994; Shrestha, 1989). Smith (1993), Smith et al. (1994), and Paudel et al. (2015a, 2015b) estimated 7–9 dolphins to be surviving in the Karnali River. In the plains of Nepal the Karnali bifurcates into two channels, the Karnali or Kaudiyala and Geruwa. For nomenclatural consistency we use the name Karnali for the former channel and Geruwa for the latter, following Paudel et al. (2015a). A major flooding event in 2010 led to the active channel to shift from the Geruwa (which flows through the Bardiya National Park, where fishing is restricted) to the Karnali (high levels of fishing and dominated by agriculture). Following this natural change, dolphins moved from the Geruwa to the now-deeper reaches of the Karnali channel. Further, intensive diversions of water and modernization of community-based irrigation projects began in 2012 and are ongoing, after the construction of the Chisapani irrigation intake (see Section 2.1, study area, for details). This led to continued declines in river depth in both channels till 2015, in which time fishing intensity increased. Thus, the depth cue tracked by river dolphins appears to have forced them into a deeper but more risky habitat (Karnali channel) from a relatively safer but shallow habitat (Geruwa, with better protection from fishing).

This ecological setting offered a great opportunity to assess dolphin responses to natural river dynamics and associated changes in habitat availability and fisheries, which we investigate in this paper. For this we use the conceptual framework of 'ecological traps' (Schlaepfer et al., 2002), that refers to circumstances wherein species first choose habitats based on evolutionarily determined responses to cues associated with habitat quality (e.g. water depth), but land up in risky situations (e.g. pollution) that might impair their survival and persistence in the novel sink habitat. Human activities often increase the mismatch between environmental cues and the evolutionary associations of animals with them such that animals are unable to correctly assess the availability of resources that can affect their fitness (Robertson et al., 2013). This idea emerged from evolutionary biology, but was soon expanded to include anthropogenic threats as proximate impacts on species' population persistence (Kristan, 2003; Schlaepfer et al., 2002). In abruptly and rapidly changing environments such as river floodplains, this concept proves useful for a better understanding of factors that create trap-like situations. This is of significance for adaptive conservation strategies (Battin, 2004) to protect endangered populations of aquatic species.

To answer the question: 'how might hydrological change and declines in river flows affect responses of dolphins to fishing pressure?' we conducted detailed analyses of river dolphin abundance and distribution in relation to changing river depth and fisheries intensity in the Karnali River. For this we analyzed river dolphin population size and distribution in the Geruwa channel (where dolphins were present in 2009) and the Karnali channel (to where dolphins shifted, and surveyed from 2012 to 2015). Fishing intensity was recorded during these time periods by compiling detailed information on the numbers and types of gears, nets and boats used. We tested whether the impacts of higher fishing pressure (e.g. bycatch risk) on river dolphins in the Karnali channel were offset by the availability of greater river depths. We contrast this with river dolphin responses to river depth and fishing intensity (fairly restricted) in the Geruwa channel before the channel shift. Finally, by integrating field survey data and long-term hydrological trends, we discuss scenarios for adaptive water allocations towards ecological flows for dolphin conservation vis-a-vis management of irrigation demand and fisheries regulations.

2. Methods

2.1. Study area

The Karnali is a perennial river that originates from the Tibetan Plateau, flows through the western part of Nepal and drains into the Ghaghara river in India, a tributary of the Ganga (Fig. 1). The eastern channel is called Geruwa (28.60°N, 81.26°E to 28.36°N 81.19° E) and the western channel the Karnali (28.64°N, 81.28° E to 28.41°N, 81.02°E), which bifurcate about 1.5 km downstream of the Chisapani Bridge (Fig. 1). This point forms the natural upstream limit for Ganges River dolphins, as upper reaches have rocky rapids and currents that dolphins avoid (Paudel et al., 2015b; Shrestha, 1989). The Karnali channel enters India at Chaugurjighat (Nepal-India border) and the Geruwa enters India at Kothiaghat, after which these channels meet upstream of the Ghaghra Barrage in India.

Of the eastern arm called the Geruwa (35 km), 25 km flows through the Bardiya National Park (BNP) boundary, where fishing is largely restricted. The remaining 10 km are outside the jurisdiction of the park authority, and subject to multiple human uses, including fisheries. Prior to 2010, the park authorities had provided fishing licenses to traditional fishermen, which allowed them to fish both within and outside the protected river stretch of the Geruwa, with strict restrictions on use of gillnet mesh size enforced by the Department of National Parks and Wildlife Conservation (DNPWC) of Nepal. This kept fishing activity in reasonable check until 2009 at much lower intensities than in 1990, as reported by Smith (1993). However, in 2010 (independent of the flood event), fishing licenses were terminated by DNPWC because a few fishermen were found to be involved in poaching of rhinoceros in the park, and hence fishing restricted to near-complete levels. After 2010, as depth reduced in the Geruwa channel outside the National Park, fishers shifted their activity to the Karnali channel, just as dolphins did after the flooding event. In contrast, the western channel of the Karnali River (Karnali channel, 46 km) flows along the boundary of the Bardiya and Kailali districts, through an irrigated agriculture landscape without any state-declared protected areas.

In the interfluve region of the Karnali and Geruwa channels, the fertile agricultural land is heavily populated with a density of 211 persons/ km^2 (<90,000 people; CBS Nepal, 2012). The average annual rainfall in the area is about 1450 mm and average annual discharge is approx.510 m^3/s (Gautam and Regmi, 2013; WECS, 2003; Upreti, 1993). Community-managed irrigation channel diversions account for a dominant proportion of river water withdrawal, especially the Chisapani irrigation intake (part of the Rani Jamara Kulariya Irrigation Project (RJKIP) constructed in 2012, at 100 m downstream of the Chisapani Bridge). A recent study by Paudel et al. (2015a) states that the river flow shifted from Geruwa to Karnali channel following the construction of the Chisapani intake. However, they appear to have missed the information, that the river course had shifted in the major flood of July–August 2010, nearly two years before the construction of the Chisapani intake, which started in 2012 (Stoutjesdijk, 2015). Hence it was the major natural flooding event in 2010 that led to the westward shift in the active flowing stream to move from the Geruwa to the Karnali channel (Table 1). Prior to 2010, the Geruwa had higher discharge and depth than the Karnali, and now it is the opposite

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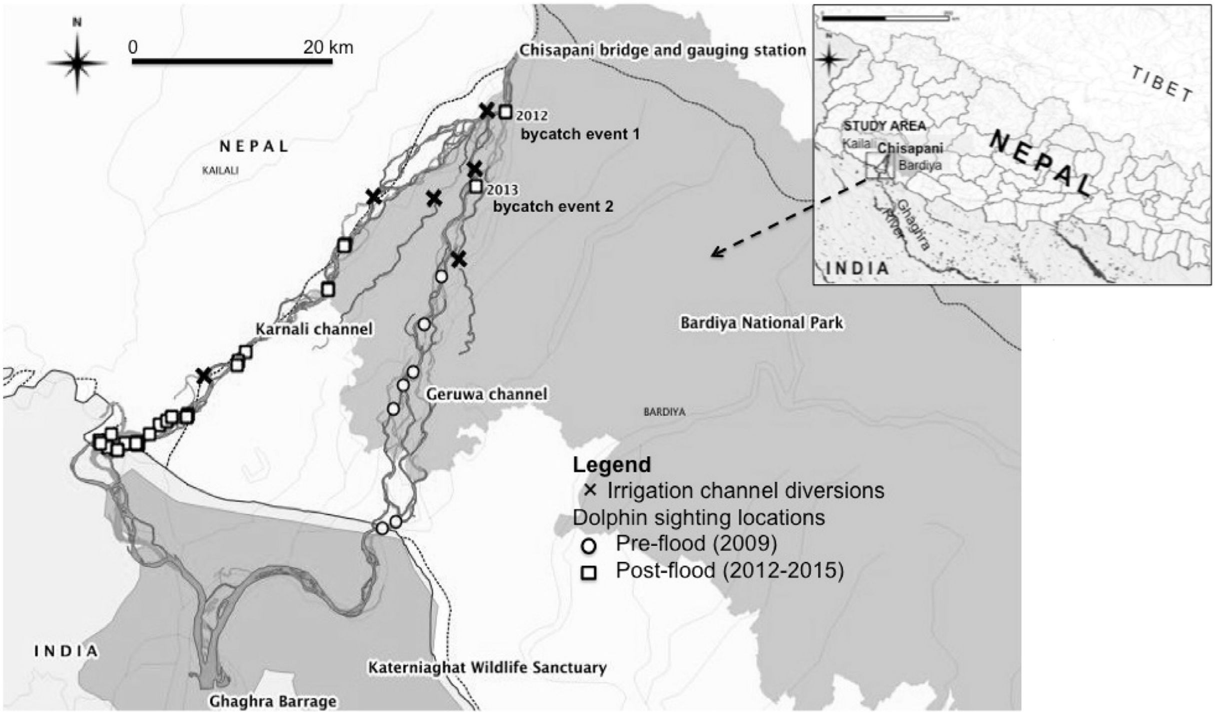

Fig. 1. Map showing the Karnali (46 km) and Geruwa river (35 km) channels in the Kailali and Bardiya districts of Nepal (inset). The study area included the river channels from the Indo-Nepal border to upstream of the Chisapani bridge. The Bardiya National Park flanks the Geruwa channel and offers some protection to river dolphins due to fishing restrictions inside its boundary. The Karnali channel flows through irrigated agricultural areas (indicated in white background). Locations of water diversions through irrigation channels are indicated. Note that the two confirmed records of dolphin bycatch (in 2012 and 2013) are in upper reaches adjacent to irrigation diversions. In the post-flood years (2012–2015), river dolphin distribution shifted to downstream locations in the Karnali channel.

(Table 1). The RJKIP and the Upper Karnali Hydropower Project (900 MW) are national priority projects of the Government of Nepal and will likely lead to large-scale water diversions in the near future.

2.2. Data collection

Data collection involved three parts: 1) surveys of river dolphins, depth profiles and fishing intensity indices in the pre-flood (2009) and post-flood (2012–2015) seasons for both the Karnali and Geruwa channels, 2) compilation of long-term data (2000–2015) on hydrological trends, especially on annual rainfall, river discharge and irrigation demand, and 3) compiling information on dolphin bycatch events, and dolphin interactions with fishing gears in both channels in relation to major water abstraction events in this period.

2.2.1. Dolphin surveys

We used boat-based surveys to record Ganges River dolphins in 1-km river segments of the Karnali (length = 46 km) and Geruwa channels (35 km) from 2009 to 2015. Pre-flood data (2009) were collected with the support of the Bardiya National Park and the National Trust for Nature Conservation (NTNC). We chose a scale of 1-km channel units or segments for surveys based on Choudhary et al. (2012). All surveys were conducted along the river thalweg (centerline) parallel to shoreline contours by a motor-boat moving at 5 km per hour in the dry-season (October–December). Average boat speeds of 5 km h^{-1} helped maximize detections (dolphin surfacing) but also to avoid double counting. All observers were trained to reduce perception bias in detecting individuals and for group size estimation (Kelkar et al., 2010; Smith and Reeves, 2000). We assumed availability bias to be negligible based on observed dive-times of animals during the study period. We conducted surveys from 0900 to 1700 on clear, sunny days for the best possible sighting conditions. The survey team consisted of three observers who counted dolphins in a cone spanning 180° in the front and the sides of the boat (Smith and Reeves, 2000). Observers were capable of spotting dolphins consistently up to a distance of 300 m on both sides of the boat. This distance approximated the channel width and indicated adequate coverage of the channel area surveyed. Detection probability could not be estimated due to the low number of detections. We used the best estimates of dolphin counts recorded in each survey for analyses.

Table 1
Pre-flood (2009) and post-flood (2012–2015) comparisons of river depth, fishing intensity and Ganges River dolphin encounter-rates (.km^{-1}) in the Karnali and Geruwa channels. Mean ± SD for the three variables are provided.

Variables		Karnali	Geruwa
Depth (m)	Pre-flood	1.55 ± 0.87	2.66 ± 0.69
	Post-flood	2.29 ± 1.09	1.64 ± 0.61
Fishing intensity index	Pre-flood	0.17 ± 0.42	0.11 ± 0.32
	Post-flood	1.30 ± 1.16	0.18 ± 0.43
Dolphin encounter-rate (.km^{-1})	Pre-flood	0	0.23
	Post-flood	0.18 ± 0.47	0

2.2.2. River depth and fishing intensity data

Alongside the dolphin surveys, data recorders measured river depth at every 250 m using a depth sounder along the course of the survey boat, and the average depth (±SD) was calculated for 1 km units. Observers also recorded numbers of fishers, fishing boats active in the area, and number and types of fishing nets deployed in the river segment at every 250 m, which were summed across the 1-km dolphin sampling units. We found that the number of nets used on each boat ranged between 1 and 10 (mean = 4.46), of which the major types were nylon monofilament gillnets, multi-filament drift nets, and cast nets. Of these, gillnets and driftnets were reported to cause river dolphin mortality, but not cast nets. We calculated a weighted sum of these variables and rescaled it to a composite Fishing Intensity Index, and ranked from 0 to 4 (based on methods used by Kelkar et al. (2010)). Number of boats and gillnets deployed in the river were the major influences on the index (correlation: Spearman's *rho* = 0.98, $p < 0.0001$). The score of zero fishing intensity for a segment indicated the absence of any boats or fishing nets. Fishing effort in terms of gears and nets was about three times in magnitude of the corresponding index values (from 1 to 4).

2.2.3. Secondary data collection: long-term hydrological trends and irrigation demand

For the period from 2000 to 2014, we obtained monthly rainfall (mm) and discharge (m^3/s) data of the Chisapani hydrological station on the Karnali River, from the Department of Hydrology and Meteorology (DHM), Ministry of Science, Technology and Environment, Government of Nepal. We also conducted personal interactions with officials of the Department of Irrigation to understand their perceptions about net changes in irrigation water demand over the last 4 years. This was done to check if observed changes in river depth could be related to changing demands for water upstream of the two river channels.

2.2.4. Compilation of records of bycatch events

Information on by-catch mortality events was collected through opportunistic surveys and occasional reports from key informants, during seasonal surveys (2–3 surveys per year) regularly from 2009 to 2015 (DNPWC, 2014). We also recorded information on timings of major irrigation diversions of water from the community irrigation projects. Owing to the problematic implications for fishers in reporting even 'inadvertent' bycatch events, it is very likely that the records of bycatch events are underestimates, despite regular monitoring.

2.3. Data analysis

All analyses were conducted in the software R3.2.1 (R Development Core Team, 2014). We conducted a time-series trend analysis of the 15-year (2000–2014) monthly rainfall and discharge data from the Chisapani hydrological station (snowmelt contribution is minor in the study area (Bookhagen and Burbank, 2010)). The R package 'trend' was used for estimating Sen's slopes for annual rainfall and total annual discharge for the river. The statistical significance of the observed trends was tested with a Mann-Kendall test (Yue et al., 2002), and qualitative inferences about the causes for observed trends were drawn. Changes in river channel depth and fishing intensity were compared visually for the Karnali and Geruwa channels in the pre-flood (2009) and post-flood periods (2012–2015). We also assessed changes in the correlation between fishing intensity and river depth between these two periods, for both channels, using Spearman's rank correlation tests.

To test the effects of declining river depth and fishing intensity on river dolphins in their new habitat in the Karnali channel (compared to the earlier habitat where fishing risk was lower), we used generalized linear models (GLMs). The errors of the response variable (dolphin counts) modelled with a Zero-inflated Poisson (ZIP) distribution to account for the high proportion of zeroes (90%) in dolphin counts (Choudhary et al., 2012; Martin et al., 2005). GLMs were run with depth and fishing intensity as 1) additive, and 2) interacting effects influencing river dolphin counts. These GLMs were compared with each other using the Akaike Information Criterion (AIC) to identify the models with the best fit and parsimony (see Supplementary information, Table A1 for details). The measure of fit used was McFadden's pseudo-R^2, calculated as 1 – (log-likelihood of candidate model/log-likelihood of null model). This measure was interpreted as the overall improvement in the model over an intercept-only (no-covariate or null model; based on Williams, 2015). The analysis was separately conducted for the Karnali and Geruwa river channels only for periods when dolphins were present in those channels. For the Geruwa, analysis was based only on 2009 data. For the Karnali, we conducted year-wise analyses from 2012 to 2015, and a combined analysis with data from all four years. Year-wise analyses helped us assess the changes in the effects of river depth and fishing intensity on dolphin abundance in relation to changing irrigation water diversions that started from 2012 onwards. We also checked for the correspondence of recorded dolphin bycatch mortality cases with 1) approximate timings of seasonal water diversions for irrigation, and 2) changes in fishing intensity in the river.

3. Results

3.1. Hydrological trends in the Karnali basin: significance of current irrigation demand

There were no significant trends in the annual rainfall and river discharge in the last 15 years from 2000 to 2014 (Fig. 2a, b), and confidence intervals (CI) for Sen's slope included zero for rainfall (Sen's slope = −12.03; CI−94.17 to 80.62) and for discharge (Sen's slope = 143.75; CI −261.8 to 332.1). We found a complete switch in the river channel depth from the pre-flood to the post-flood event (in 2010). In the Karnali channel, river depth (mean ± SD) increased from 1.55 ± 0.87 m to 2.29 ± 1.09 m, but in the Geruwa channel a reverse trend was found, from 2.66 ± 0.69 m to 1.64 ± 0.61 m (Table 1, Fig. 3a,b). We recorded consistently declining river depth in both the Karnali and Geruwa channels after 2012 (Fig. 3a,b). Since the discharge and rainfall showed no clear trend for the Chisapani station, the observed declines in river depth across the Karnali and Geruwa were speculated to be mainly due to diversion of water by the irrigation project below Chisapani (see Fig. 1). Accounts by government officials supported the fact that increases in irrigation demand from the Karnali at Chisapani had caused the decline in river depth.

3.2. Changes in fishing intensity

In the Karnali channel, fishing intensity showed an increase (Fig. 3c) from 2012 to 2015, but fishing restrictions implemented by the Bardiya National Park authorities on 25 km of the Geruwa were evident in that no changes in fishing intensity were observed (Fig. 3d). Importantly, after 2012, fishing intensity increased but river depth progressively declined in the Karnali channel. As a result, we found that the correlation between these variables was not significant from 2012 to 2015 (Spearman's rho = −0.02, $p = 0.75$), indicating potential risks to dolphins from fishing effort in both shallow and deep areas of the channel. In contrast, significant positive correlation (Spearman's rho = 0.33, $p = 0.03$) was estimated between fishing intensity and depth for both channels in 2009, indicating that fishing was restricted to deeper habitats prior to the channel shift and subsequent impacts of irrigation diversion.

3.3. Dolphin responses to river depth and fishing intensity

River dolphin distribution appears to have switched from the Geruwa in 2009 to the Karnali channel post-flood 2012–2015 (Table 1), barring one dead individual found in the Geruwa (2013). Our surveys did not record a single live dolphin in the Geruwa channel from 2012 to 2015 (Table 1). Zero-inflated regression models showed that depth had the most consistent and positive influence on dolphin counts (slopes of models ranged from 0.9 to 1.8; Table 2). Depth thresholds of at least 2 m were required for dolphins to persist in river channel segments. Year-wise regression analyses for the Karnali channel from 2012 to 2015 showed that in 2012, no significant effect of fishing intensity was found, except at low river depths (interaction effect: −0.54 (SE 0.28); Table 2). However, after 2012 (when irrigation water diversions were increased after modernizing the existing projects), fishing impacts on dolphin abundance became significantly negative (e.g. slope = −0.89 (SE = 0.38) in 2014; Table 2). When the same analysis was conducted for all years together, it revealed that impacts of fishing were the most negative at lower river depths, but by themselves fishing impacts were not significant (Table 2).

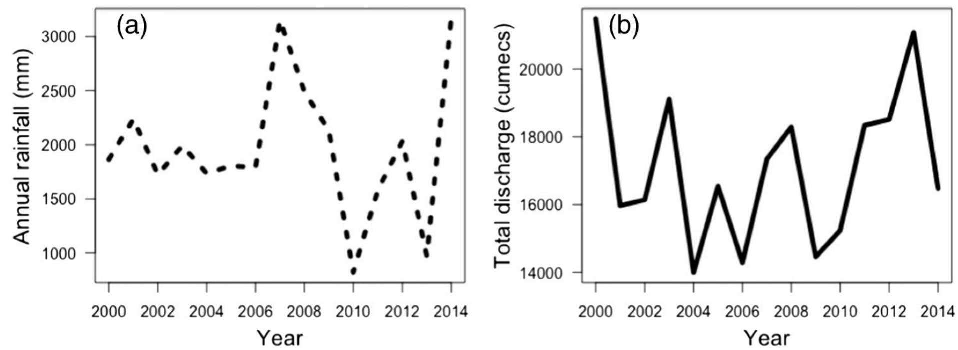

Fig. 2. Annual rainfall in mm (a) and river discharge in m^3/s (b) trends in the Karnali River at Chisapani were not significant over the last 15 years.

3.4. Declines in dolphin abundance, bycatch events, and timing of water diversions

Our findings were vindicated by the observed downstream shift in river dolphin distribution in response to declining river depths that we observed from 2012 to 2015 (Fig. 4a). We also recorded a population decline from about 11 dolphins in 2012 to 6 in 2015, in the Karnali River (Fig. 4b). We confirmed two cases of by-catch mortality of one dolphin in gillnets in the upper reaches of the Karnali (2012) and one in the Geruwa channel (2013). Fishers did not perceive competition with dolphins for fish, and both by-catch events were accidental. Their locations were close to irrigation diversion channels. The April 2012 event corresponded strongly with sudden reduction in river discharge after rapid diversion of water for irrigating summer crops, following the modernization of community irrigation projects. The 2013 case was also correlated with a sudden fall in river discharge from November to December. These events confirm the causes of decline of the small population over the last 4 years, as bycatch mortality would likely have caused even more deaths than those recorded by us.

4. Discussion

A major flooding event in the Karnali River led to a complete shift in the distribution of Ganges River dolphins from the Geruwa, (with protection from fishing), to the Karnali channel (with deeper water but also greater fishing intensity). The post-flood movement to the Karnali channel likely became an 'ecological trap' for the river dolphin population where former adaptive preferences actually became maladaptive given the combined impacts of irrigation and fisheries bycatch risk. Regression models of dolphin abundance indicated that dolphins tracked river depths, but the interaction of reducing depth and simultaneously increasing fishing pressure negatively affected river dolphin persistence in the Karnali channel. Two observed cases confirmed that bycatch risk for dolphins would increase especially at times of poor water availability

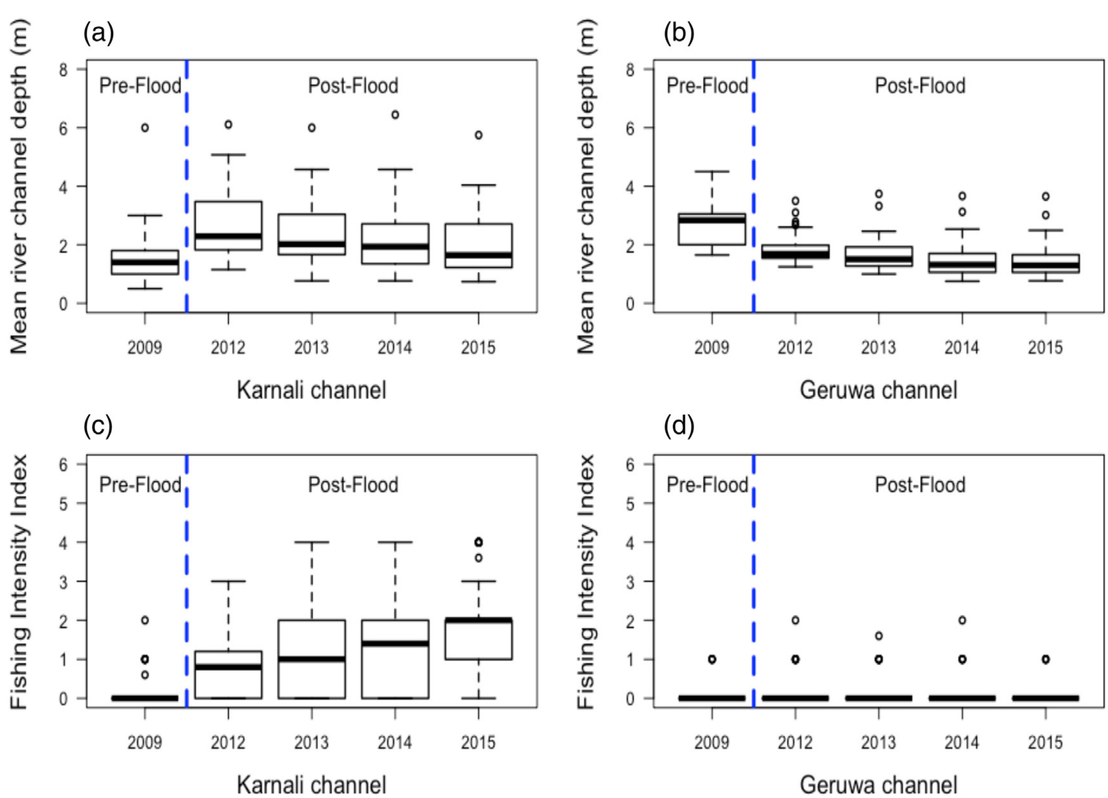

Fig. 3. Pre- and post-flood changes in mean river thalweg depth (a & b) and fishing intensity (c & d) in the Karnali and Geruwa river channels respectively from 2009 to 2015. Note the shift in river depth profile from the Geruwa to Karnali channel caused by the flooding event (also see Table 1). However, declines in water depths in both rivers have been continuing due to increasing irrigation demand. Fishing intensity has increased in Karnali channel post-flood, but has not changed in the Geruwa channel.

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Table 2
Zero-inflated generalized linear models (ZIP GLMs) showing year-to-year changes in dolphin responses to river depth and fishing intensity for 1) Geruwa (2009), 2) Karnali (2012–2015), and Karnali channel (all years). Intercepts for count model and zero-inflated model are not included here, and only the selected best model summaries are shown (see methods for details). McFadden's pseudo-R^2 was used as a measure of model fit over and above intercept-only models. River depth was the strongest and most consistent predictor of dolphin abundance. In the Karnali, fishing impacts were significant in 2012 only when river depths were low. After the intensification of irrigation in 2012, the impact of fishing threats on dolphin abundance became significantly negative. Asterisks indicate significance levels.

River	Year	Effect size Mean (SE), p-value		Interaction River depth × fishing intensity	Model fit (McFadden's pseudo-R^2)	Remarks
		River depth	Fishing intensity			
Geruwa	2009+	1.78 (0.46), $p < 0.001^{***}$	–	–	0.35	Fishing intensity was low, no effect observed
Karnali	2012^	1.48 (0.41), $p < 0.001^{***}$	1.79 (1.14) $^{\text{Not significant (NS)}}$	−0.54 (0.28), $p = 0.05^{*}$	0.33	Fishing by itself had no effect, but effect was negative when river depth was low
	2013	0.91 (0.29), $p < 0.001^{***}$	−0.71 (0.38), $p = 0.06^{\#}$	–	0.25	Lower effect of depth than in 2012, but negative
	2014	1.02 (0.31), $p < 0.001^{***}$	−0.89 (0.38), $p = 0.018^{*}$	–	0.42	effect of fishing intensity on dolphin counts observed
	2015	1.15 (0.36), $p < 0.001^{***}$	−0.63 (0.31), $p = 0.04^{*}$	–	0.35	
	All years	1.33 (0.22), $p < 0.001^{***}$	0.65 (0.46)$^{\text{NS}}$	−0.31 (0.12), $p < 0.001^{***}$	0.34	Effects of fishing intensity on dolphin abundance were most severe at low depths

+2009: Dolphins present only in the Geruwa River prior to the 2010 flooding event.
^2012: Modernization of community irrigation projects and construction of Chisapani irrigation intake, reductions in river depth from 2012 onwards.
p-value < 0.1.

(as compared to better river depth). This does not mean that gillnets and driftnets will not entangle dolphins if water levels are maintained above a certain depth, but the correlation of known mortality with water diversion timings is clearly cause for serious concern in future conservation planning and strict regulation of gillnet usage in fisheries. Yet, reducing fishing impacts without mitigating the constraints imposed by low river discharge might still be of limited value. Effective river dolphin conservation will need to focus attention on planning fishing net/gear regulations in sync with the maintenance of adequate river flow regimes (Braulik et al., 2014; Choudhary et al., 2012; Smith et al., 2009).

In the Geruwa channel, despite existing protection from fishing, reduction in river depth below a threshold of about 2 m still led to complete emigration of dolphins. This also highlights the limitation of local-scale protected areas in averting basin-scale reductions in water availability that affects the conservation of river dolphins in intensively human-used riverscapes. Further, a difficult challenge is to maintain adequate ecological flows for dolphins without major compromises on agricultural and fisheries production levels for sustaining local people's wellbeing. Like dolphins, many fish species critically depend on ecological flow regimes for breeding, growth, and migration triggers (Cowx, 2008; Bunn and Arthington, 2002; Welcomme, 1985). In Nepal, a large population of river fishers is also finding it difficult to cope with dry-season water availability, siltation and pollution impacts (Paudel et al., 2016). Hence, maintaining adequate river water is also critical for sustaining fishery-based livelihoods, in ways that do not affect

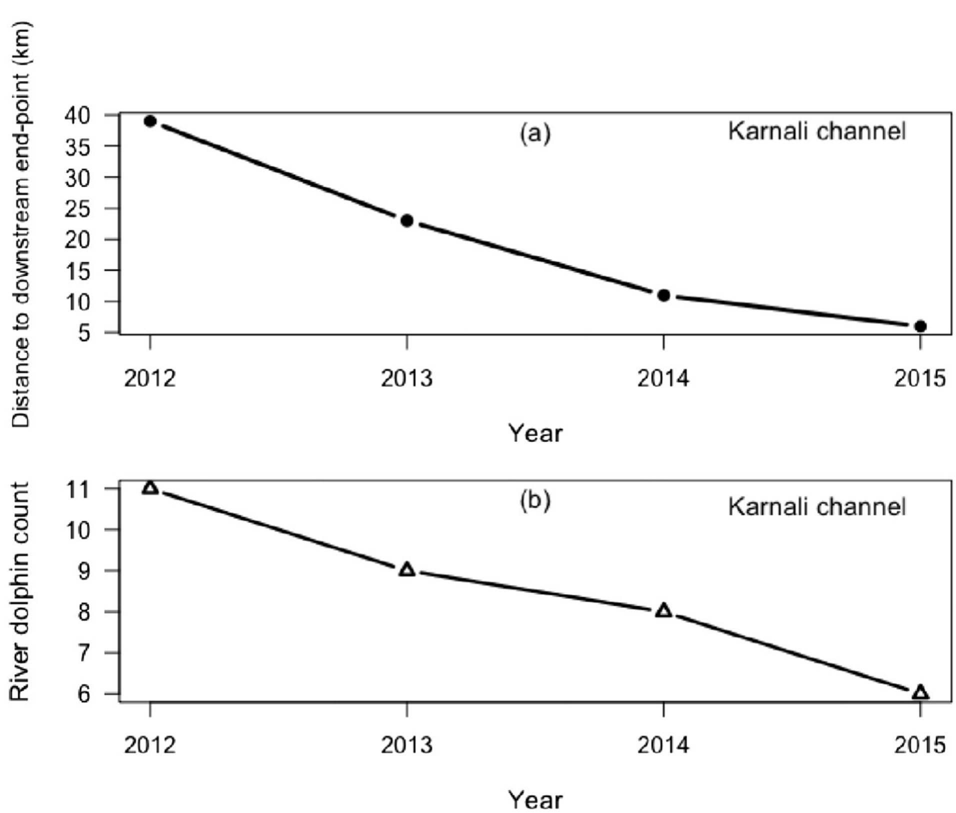

Fig. 4. a) Evidence for shift in Ganges River dolphin distribution with declining river depth post-2010, and b) decline in river dolphin population abundance in the Karnali channel.

food security and do not threaten dolphins (Kelkar and Krishnaswamy, 2014).

Our field observations show that water depth reduction was most pronounced in river segments connecting deep pool habitats. Deep pools are usually productive fishing grounds both for fisheries and dolphins (Kelkar et al., 2010; Smith et al., 1998, 2009). Severing of connectivity between pools appears to have resulted from the combined pressures of irrigation diversions and excessive groundwater extraction by tube-wells and pumps in the floodplain (Atapattu and Kodituwakku, 2009; Ambast et al., 2006; Hannah et al., 2005). Reduction in the water table can decrease the capacity of groundwater returns to river discharge and to base-flow contribution in the dry-season (Gautam and Regmi, 2013; Ambast et al., 2006). Upstream range declines of Ganges river dolphins have been attributed to altered and poor dry-season flow regimes (Choudhary et al., 2012), and for Indus river dolphins (*Platanista gangetica minor*), downstream attrition (i.e. movement below barrages but limited ability to return upstream) (Braulik et al., 2014) has been reported. For the Karnali, the existing demands for irrigation, upstream bycatch mortality, and the presence of the Ghaghra Barrage downstream might result in such impacts in the near future. This is especially critical for the Karnali to support the refuges for *Platanista* that persist as small populations within Nepal today. Other studies have suggested that declining river dolphin population trends correlate with degrading habitat (Huang et al., 2012; Turvey et al., 2010). Managing irrigation demand without affecting 'longitudinal connectivity' (Ward and Stanford, 1995) for dolphin habitats even in undammed river reaches needs to be a priority task for the Government of Nepal.

Instream declines in water availability raise the question of how much irrigation water must be diverted and how much must be maintained in the river to ensure dolphin persistence, and viable fisheries, with minimal or zero impact on dolphins. In general, the challenge of distributing water optimally across the agriculture and fishery sectors requires realistic scenario building exercises (e.g. Pradhan, 2012; Atapattu and Kodituwakku, 2009; Lancker and Nijkamp, 2000), to which our results contribute. If river dolphins are to be protected in their new habitat in the Karnali channel, fisheries regulations must be brought in along with estimation of the amount of discharge needed to maintain depths above 2.5–3 m for safer passage, and relatively lower bycatch risk to dolphins, but also not compromising agricultural production (Gumma et al., 2011; WWF-Nepal, 2006; Smakhtin et al., 2006). In Nepal, existing irrigation projects are mainly based on continued community involvement and monitoring (CIP-Nepal, 2015; Cifdaloz et al., 2010; Howarth and Pant, 1987). This can provide opportunities to facilitate dialogue with downstream fishing communities on co-management of water resources (Paudel et al., 2016; Shrestha and Pant, 2012).

Catchment-scale irrigation demands need to be managed even in undammed rivers, where they might still have considerable influence on continuity of ecological flow regimes (Hannah et al., 2005). Ecological and efficient irrigation water management needs to feature in the planning of impending irrigation projects (e.g. the Nepal Government's ambitious Rani Jamara Kulariya Project). Diverted irrigation water might also generate excesses based on cropping and land-use management that could be controlled at the source level. Alternative scenarios for dolphin conservation in the Karnali also need to include the possibility of returning requisite flows to existing protection zones along the Geruwa channel, where fishing pressure is already low. This might also potentially benefit terrestrial charismatic megafauna such as tigers, rhinoceroses, and elephants in the dry season. This scenario requires consideration given the degree of flow alterations possible in the future. On the Indian side, the Geruwa channel flows through the Katerniaghat Wildlife Sanctuary, and is well connected downstream with the Ghaghara River, wherein the two channels converge again. Through this paper we also wish to emphasize that closer coordination is needed among government agencies (e.g. environment, fisheries, and irrigation departments) not just within Nepal but also at a trans-boundary level. Given the future scenarios of irrigation development in the upstream areas in Nepal, a trans-boundary conservation plan between Nepal and India is essential for river biodiversity conservation. Our paper makes a relevant contribution towards conservation planning in this area by identifying mechanisms through which current irrigation demands and declining flows in Nepal's rivers directly aggravate fisheries' threats to the few river dolphins that persist in the Karnali River today. Prioritizing action towards securing ecological flows for both efficient agricultural/fisheries production and the conservation of endangered biodiversity will be key to averting dolphin extinctions in Nepal.

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