Is current floodplain management a cause for concern for fish and bird conservation in Bangladesh's largest wetland?

Shams M. Galib[a,b], Martyn C. Lucas[b], Nipa Chaki[c], Foyzul H. Fahad[a] and A.B.M. Mohsin[a]

[a] *Department of Fisheries, University of Rajshahi, Rajshahi, Bangladesh*
[b] *Department of Biosciences, University of Durham, Durham, UK*
[c] *Department of Geography and Planning, University of New England, Armidale, NSW, Australia*

Version accepted for publication (13 October 2017) in

Aquatic Conservation: Marine and Freshwater Ecosystems

Correspondence

Postal address: Shams Galib, Department of Biosciences, University of Durham, Durham DH1 3LE, UK

Email address: shams.m.galib@durham.ac.uk and thegalib@gmail.com

---

*The authors declare no conflict of interest.

Abstract

1. Worldwide, water regulatory structures impact aquatic ecological connectivity. This study determined the effects of current sluice management on the fish community in the Baral River, a major connection to the largest wetland (Chalan Beel) in Bangladesh. It also examines wider problems for biodiversity conservation (particularly waterbirds) in that wetland, which has shrunk to 3% of its former dry-season size in 50 years.

2. During the flood period, the peak breeding time for native floodplain fishes, sluices were in undershot operation (open by 16-60% of water depth). During this time, fish abundance and species richness were 229% and 155% higher respectively at sites upstream of the sluices, despite similar habitat upstream and downstream. Outside of this period, when sluices were fully open, abundance and species richness were similar upstream and downstream.

3. Fish samples were dominated by fry, which are susceptible to damage by sluices. Twenty (41.7%) of 48 fish species captured in this study are classed as threatened in Bangladesh and their abundance was significantly lower downstream of the sluices. Two alien species, *Aristichthys nobilis* and *Hypophthalmichthys molitrix*, were recorded, likely escapees from local aquaculture activities.

4. Twenty five species of wetland birds were recorded in the Chalan Beel. From interviews, 64% of these species appear to have decreased in the last 20 years, along with 11 more species that may have become locally extinct over this period. This suggests widespread ecological disruption is occurring.

5. Improved water management (e.g. gate opening height and duration) or modification (e.g. fish pass) of the Baral sluices is needed, to better meet biodiversity and fisheries needs, rather than just for flood control and crop production. Improved hydrological and ecological connectivity and habitat protection are needed, as are a cessation of destructive fishing and seasonal fish ranching practices that currently provide synergistic pressures.

Keywords: threatened fish, waterbirds, conservation, floodplain, ecohydraulics, non-native fish, sluice gate.

1 | INTRODUCTION

Ecosystems around the globe are rapidly losing biodiversity due to both anthropogenic and natural causes (Naeem, Duffy, & Zavaleta, 2012) and freshwater fishes are one of the most susceptible groups of organisms (Arthington, Dulvy, Gladstone, & Winfield, 2016; Duncan & Lockwood, 2001). Biodiversity loss, including of freshwater fishes, has occurred widely (e.g. Castaldelli et al., 2013; Williams et al., 1989), and that concern is also becoming evident in Bangladesh, where 260 freshwater fish species have been described (Rahman, 1989). Bangladesh relies heavily upon floodplain fisheries production for animal protein in the diets of local people (Craig, Halls, Barr, & Bean, 2004). However, the production of freshwater fishes in natural habitats (primarily rivers and floodplains) in Bangladesh is in decline (Ahmed, 2008; Hossain et al., 2009) and the population trend of many species in rivers is reported to be declining (Galib, 2015; Galib, Rashid, Chaki, Mohsin, & Joadder, 2016). A total of 54 freshwater fish species were declared as “threatened to extinct” in 2000 by the IUCN, Bangladesh Office and the number rose to 64 in 2015 (Vulnerable, 28 [in 2000] to 25 [in 2015] species; Endangered, 14 to 30 species; and Critically Endangered, 12 to nine species) along with 27 Near Threatened species (IUCN Bangladesh, 2000, 2015). In recent times the situation has become worse, as 30 fish species have been reported extinct from all freshwaters of Bangladesh (Hossain, 2014).

Across the globe, humans have modified flows in rivers, with the degree and extent of modification having increased dramatically due to structures such as dams, weirs, barrages and levees, and through direct extraction of water (Drinkwater & Frank, 1994; Nilsson, Reidy, Dynesius, & Revenga, 2005; Walker and Thoms, 1993). Flow regulation and its associated infrastructure can significantly impact on the hydrology and geomorphology of rivers (Thoms, Southwell, & McGinness, 2005; Walker and Thoms, 1993) which has had major effects on aquatic ecosystems throughout the world (Bunn & Arthington, 2002; Leigh & Sheldon, 2008; Poff et al., 1997). Water regulation often results in dramatic decline of native species (Schmidt, Webb, Valdez, Marzolf, & Stevens, 1998) including those of high conservation value (Arthington, 2009; Northcote, 1998). Regulatory structures can prevent fishes from accessing spawning, nursery and feeding habitats (Baras & Lucas, 2001; Baumgartner, Zampatti, Jones, Stuart, & Mallen-Cooper, 2014). Dramatic area loss of wetlands world-wide is also prominent due to water regulation upstream (Kingsford, Basset, & Jackson, 2016). Loss of wetland area reduces populations of biota reliant on those habitats, including plants, invertebrates and birds.

The main causes of declining diversity of freshwater fishes in Bangladesh have been ascribed as indiscriminate and over fishing, loss or fragmentation of habitats due to water regulatory structures, alien invasive species, use of illegal fishing gears, and water pollution (Galib, Samad, Mohsin, Flowra, & Alam, 2009; Halls, Hoggarth, & Debnath, 1999; Imteazzaman & Galib, 2013). Despite widespread evidence of the impacts of water regulatory structures (e.g. sluice gates, dams) on fishes worldwide (Baras & Lucas, 2001) and in Bangladesh (Craig et al., 2004; Halls et al., 1998, 1999) this issue has been treated as one of low concern by water managers in Bangladesh. A large number (4190) of sluice gates and associated flood control infrastructure have been built in the last few decades in different rivers of Bangladesh in order to enhance rice production and also to save human property by controlling flood water (Ali & Alam, 2005; Halls et al., 1999; Shankar, Halls, & Barr, 2004). These structures are operated to control flood water during the rainy season. The timing, extent and duration of floodplain inundation drives production in floodplain ecosystems and in associated fisheries (De Graaf, 2003; Junk, Bayley, & Sparks, 1989; Welcomme, 1979). However, water regulatory structures are responsible for the modification and / or fragmentation of habitats (Jutagate, Krudpan, Ngamsnae, Lamkom, & Payooha, 2005; Khaleel & Othman, 1997; Nilsson et al., 2005) and can significantly impact upon aquatic biodiversity (Lucas, Bubb, Jang, Ha, & Masters, 2009; Marttin & De Graaf, 2002; Richter, Braun, Mendelson, & Master, 1997).

Ecological impacts of water regulatory structures remain poorly understood and are often ignored by operators (Benstead, March, Pringle, & Scatena, 1999). Unfortunately, the situation is the same in Bangladesh, a developing country, where in floodplains the emphasis has been on maximising agriculture and fish production rather than sustaining aquatic and wetland biodiversity. Studies carried out two decades ago in Bangladesh revealed that flood control engineering had significant adverse effects on floodplain fish communities (Halls et al., 1998, 1999). Despite these studies and the intensification of floodwater control in Bangladesh, little progress has been achieved in more sensitive management of floodplain inundation to support natural fisheries and aquatic biodiversity (e.g. wetland birds, amphibians). This is particularly the case for natural wetlands such as the Chalan Beel, the largest wetland in Bangladesh, which is increasingly threatened by flood control, road building, agriculture and natural siltation (Hossain et al., 2009; Sayeed et al., 2015) and in which the yield of naturally recruited fishes is declining (Hossain et al., 2009). Because beels (the Bengali term for standing water bodies connected to drainage channels) undergo dramatic reductions in water cover (often 80–90%) during the dry season, they rely on fish repopulation from immigration through the natural channels, or maintenance of populations in dry-season refuge areas. Thus, large rivers probably play a key role in maintaining the fish biodiversity of these wetlands, by connecting through their tributaries or branches. Insensitive sluice management, leading to functional disconnection of these river branches to wetlands such as the Chalan Beel could reduce fish biodiversity and production and might also affect other ‘indicator’ taxa, such as wetland birds, through habitat or food impacts.

Therefore the primary aim of this study was to determine the fish species richness and abundance upstream and downstream of the sluice gates in response to sluice gate operation in a river channel feeding the Chalan Beel, with the hypothesis that sluice gate operation there results in a decline in fish species richness and abundance downstream, compared to upstream. A secondary aim was to determine historical changes in the abundance and diversity of wetland birds in the beel. These data are used to determine the degree to which current practices are conducive to sustaining natural populations and habitats in beel systems.

2 | STUDY AREA

The Baral River is a branch of the Padma River and runs through the Chalan Beel floodplain depression in northwest Bangladesh (Figure 1). The total length of the Baral is 147 km, and the channel can be up to 125 m wide and 6 m deep (Flowra, Islam, Jahan, Samad, & Alam, 2011). The Padma River is one of the three largest rivers in Bangladesh. Both the Padma River (= Ganges in India) and the Chalan Beel make a small but significant contribution to the fishery of Bangladesh (together they produce ~2% of the total inland water fish capture) and an important contribution to the livelihood of adjacent fishing communities (FRSS, 2015; Galib et al., 2009; Hossain et al., 2009). As well as the Baral, which connects from the west, the Atrai River and numerous smaller channels run through the beel from the north. The Chalan Beel drains to the south; the Baral joins the Gumni River (at 24°27'41"N 89°08'41"E) and then meets the Atrai River (at 24°26'56"N 89°11'08"E) and then the Brahmaputra (24°04'00"N 89°39'26"E). The Baral, Gumni and Atrai channels are all an important part of the Chalan Beel. The area of the Chalan Beel is approximately 300–320 km^2 during the high flood period and it decreases to 50–75 km^2 during the dry season (Hossain et al., 2009; Samad, Galib, & Flowra, 2009), when it comprises a series of isolated pools. Many of these pools disappear entirely during the dry season, due to percolation and evaporative losses, combined with water drainage for irrigation and dewatering of pools as a fishing method. The Chalan Beel is also known for its aquatic bird population, including both resident and migratory species, although these have been poorly documented. Despite being the largest wetland in Bangladesh, the Chalan Beel has no formal protection, although through the Chalan Beel Fisheries Development project, areas in the northwest and southern parts, with a combined area of 11.85 ha (~0.2% of dry season area) are designated as fish sanctuaries (DoF, 2015) where, theoretically, no fishing is allowed, but there is no regular policing.

As is increasingly the case for floodplain channels in Bangladesh, a set of sluice gates (Figure S1) were built on the Baral, about 2 km from its origin at the Padma, in 1984–85 in order to regulate the water flow to facilitate the local irrigation system, but limit the height of flooding. The sluice gates serve as a bridge to connect roads between both sides of the river, where a market operates. A single caretaker manages the local sluice operations over the year based upon experience and a degree of regional administrative direction. Before the rainy season, when the Baral channel is almost dry, the undershot sluices (open by 16–60% of water depth through the 4-month 'closure' period) are fully open. With the onset of the rainy season, the Padma rises and fills the Baral channel, at which point the sluices are largely closed over the rainy season, from May to October, to regulate water levels downstream, within the flood control area. As the hydrograph decreases to about 30% of its peak, the sluices are fully opened again, usually until December, and by January to February water levels are rapidly reducing to dry season levels. Depending on differences in the rainfall pattern and the timing and extent of flooding in recent years, there have been variations on this general pattern of management but without reference to any clear rules. Theoretically then, dispersal of fish to the Chalan Beel should be possible throughout the key period of floodplain inundation, when migration of fish onto the floodplain normally occurs (Baras & Lucas, 2001; Louca, Lindsay, & Lucas, 2009; Welcomme, 1979).

In addition to sluice management, further hydrographic modification occurs on the Baral River's connection with the Padma, where in recent times a barrier of sand and mud (SM barrier; Figure S2, Figure 1) of approximately 50×10×2.0 m is built across the Baral at its origin, by local influential people to facilitate sand mining from the Padma. This results in complete separation of the Baral from the Padma over the dry season, generally from December to April. In addition to this, another group of influential people stock hatchery-reared fishes in pool fragments of the Baral during the dry season, followed by dewatering the river sections to harvest the fish, along with existing natural stock.

The water level in the Baral River is not only dependent on local rainfall but also on the water level in the Padma, which is greatly influenced by the operation of the Farakka Barrage, built across the Ganges River (upper part of the Padma River in India) in West Bengal state, 16.5 km upstream of the Bangladesh-India border and about 115 km upstream of the Baral River's origin. Thus, water quality parameters in the Baral River may also be influenced by the Padma River and barrage operational status.

3 | METHODS

3.1 | Fish sampling and site characteristics

Fish sampling in the Baral River was conducted during the wet season from May 2015 to the start of the dry season in December 2015 when the rivers remained connected because of the high water level. The SM barrier at the Baral's origin prevents movement of fishes between the Padma and the Baral during the dry season, and management of dry-season pools by influential people for fish culture makes access to those areas very difficult. Because of this, during the dry season it was not possible to carry out fish sampling in the river.

It was hypothesised that. To test the hypothesis that sluice gate operation results in a decline in fish species richness and abundance downstream of the sluice gates compared to upstream, samples of fishes were taken on 14 occasions at four sites in the Baral River (S-1 to S-4, Figure 1). Among the sampling sites, two were located upstream of the sluices but downstream of submerged SM barriers (S-1 and S-2) and two were in downstream locations (S-3 and S-4) of the sluices and these sites were about 1.25 km from each other. This approach, with sampling before, during and after the period of sluice closure, enabled a Before-After-Control-Intervention (BACI) sampling design to be used (Downes et al., 2002; Boys et al., 2012). All the sampling sites appeared similar in habitat with sandy and muddy bottom (about 75:25 ratio), with a channel width of ~50 m and gently shelving banks to a maximum depth of 4-6 m at the peak of the flood. Water velocity was low at all the sites (<0.5 ms^{-1}). During the sampling period the sluice gates were in operation (gates open 1 m from bed) between early June and the end of September, during the rainy season.

Physico-chemical parameters (water temperature, water transparency, dissolved oxygen, and pH) were measured at each sampling spot. Water temperatures and dissolved oxygen (DO) levels were measured with a digital DO meter (model DO-5510, Lutron electronic). pH and water transparency were measured using a digital HANNA pH meter (model HI 8424) and Secchi disk respectively. Daily rainfall data were recorded from May to December (negligible in remaining months). Daily measurement of water levels upstream and downstream of the sluices was taken by a standard water level measurement gauge. Available water depth data of previous years (2013 and 2014) were also collected from the record book maintained by the gateman.

At each sampling site, fish were collected with a seine net (mesh 7×7 mm; 15×2.5 m), a lift net (mesh 10×10 mm; 8×6 m) and two rectangular fishing traps locally known as '*Kholsun*' (made of split bamboo sticks; mesh 25×20 mm, 0.78×0.76×0.1 m). The lift nets were hauled 10 times at each site on each day and the total fishing duration was about one hour. Fishing nets were used during day time (06:00 to 14:00 hours). Traps were set in the evening before the day of sampling and left overnight (approximately 14 hours) in the water. It is believed, based upon experience of the relative selectivity of these gears (S. Galib, unpublished data) that the combination of these fishing gears was effective in sampling fishes of a wide range of species and sizes from different water levels. Six professional fishermen were employed at each sampling spot for the purpose of helping in operating the fishing gears under the guidance of the research team. All the fishing gears were operated over the same time on every sampling date to standardise the sampling effort. Fish abundance data are therefore expressed as Catch Per Unit Effort (CPUE).

Collected fish specimens were identified, counted, attributed to size classes and classified into three groups (fry, juvenile and adult) at the sampling sites. Specimens that were difficult to identify on the spot were preserved in 10% formalin solution and brought to the laboratory for identification. Other fish sampled were returned to the river unharmed. Fish were identified based on morphometric and meristic characters following Rahman (1989, 2005) and Talwar & Jhingran (1991). Identified species were classified based on the system of Nelson (2006). Scientific names follow those of Froese & Pauly (2015).

Non-native species (to the whole country of Bangladesh) status was recorded for those species introduced to a country outside their natural range (Shafland & Lewis, 1984). Reference to the global conservation status categories within this paper (Least Concern, Near Threatened, Vulnerable etc.) and global population trend (Decreasing, Stable etc.) are based on the online classification database developed by the International Union for the Conservation of Nature and Natural Resources (IUCN, 2016). National conservation categories are based on the 'Red List of Bangladesh' published by IUCN Bangladesh (2015).

3.2 | Wetland birds

The Chalan Beel is also famous, nationally, for its bird population. In this study a survey of wetland birds in the Chalan Beel was carried out to identify trends in relative abundance. Focus group discussions (FGDs, n = 8) and short interviews (n = 24) of experienced fishermen (>20 years) and other key informants such as schoolteachers (n = 8) of the Chalan Beel area were conducted in order to understand the population trend of wetland birds, their residence and breeding information. Bird species were identified after Ahmed et al. (2008). Colour photographs of wetland birds were used during interviews and FGDs to enable respondents to identify and make relevant comments accurately. They were also asked to name and describe any bird which has become locally extinct in the last 20 years. The following terms were used to describe the population trends: stable (abundance unchanged over last 20 years), decreasing (found all over the wetland but abundance has decreased compared to situation >20 years ago), rare (was common >20 years ago but now seldom noticed), increased (abundance increased in last 20 years), and unknown (respondents failed to mention the status). The aim of this survey was not to identify all the bird species, or provide fully quantitative data (which are not available for wetland birds in the Chalan Beel area), but to provide a broader context of biodiversity in the Chalan Beel in relation to this and past studies that have concentrated on fish (Galib et al., 2009; Hossain et al., 2009) and water quality (Sayeed et al., 2015). Global and national conservation status of birds was determined following IUCN (2016) and IUCN Bangladesh (2015) respectively.

3.3 | Data analysis

The statistical software R (version 3.3.1; R Core Team, 2012) was used to analyse the data, employing an α level of significance of 0.05. A BACI design (Downes et al., 2002; Stewart-Oaten, Murdoch, & Parker, 1986) was followed to reveal variation in fish abundance in relation to sluice gate operational status and locations. Linear Mixed Model (LMM) was employed to analyse repeated measures fish abundance data using 'lmer' function of the 'lme4' package (Bates, Mächler, Bolker, & Walker, 2014); p-values were obtained by 'lmerTest' package (Kuznetsova, Brockhoff, & Christensen, 2016). In this study, sluice gate operational status (fully open [as 'open'], or part-closed [referred to as 'closed' hereafter, for simplicity]) represents 'before-after' and location (Upstream/Downstream) resembles 'control-impact' sites of a BACI design. Thus, during LMM modelling, location of the sampling sites, operational status of the sluice gate and their interaction, were tested as fixed effects and sampling sites and time were considered random effects.

To visualise spatial and temporal variation of fishes Non-metric Multidimensional Scaling (NMDS; Kruskal & Wish, 1978) ordination plot was generated using 'metaMDS' function of the 'vegan' package (Oksanen et al., 2017). Similarity Percentage Analysis (SIMPER), based on the decomposition of Bray-Curtis dissimilarity index (Clarke, 1993) was used to identify the most responsive native taxa to the sluice-gate operation by comparing fish abundance between closed and open status of the sluices to better describe before vs. after changes. Species abundance data were subjected to square-root transformation during these analyses (McDonald, 2014).

LMMs were also used to compare abundance of fish species of conservation importance between the upstream and downstream sections. The same procedure was used to compare water quality parameters. Data were transformed on a log scale (log [x+1]) to normalise for the test (Clarke, 1993).

4 | RESULTS

4.1 | Water levels, rainfall and physico-chemical parameters

In mid-May 2015, due to the increased water level in the Padma and also the local rainfall, the Baral re-joined the Padma. Over the study period, the sluice gates were maintained about 1 m above the sill from 7 June to 7 October 2015 (123 days) (Figure 2). During this time, the gate opening was 2.39 ± 1.45 m (mean ± SD; n = 123) below the upstream water surface and 2.04 ± 1.24 m below the downstream water surface.

From 1 May to 31 December 2015 the mean daily rainfall in the vicinity of the sluices was 6.2 mm. This increased to an average of 10.8 mm / day over the period when the sluices were partially closed. Over the sluice closure period, the upstream water level (3.39 ± 1.45 m, 1.52–6.05 m; mean ± SD, range) was higher than downstream (3.04 ± 1.24 m, 1.35–5.0 m; mean ± SD, range). Upstream and downstream water levels, across the sluices, differed significantly during this time (F = 114.84, P < 0.001). From the day after closure, water levels differed until equalising again on 25 September. In the study area, a water depth of 8 m is considered a danger level for flooding of local dwellings and infrastructure. The maximum water depth for the two years previous to the study was 7.05 m (2013) and 6.06 m (2014).

Physico-chemical characteristics of river water changed over the course of the study in response to rainfall and flooding (Figure 3; Table 1). Mean (± SD) water temperatures ranged from 24.8 ± 3.7 ºC (at S-1) to 26.2 ± 4.3 ºC (at S-3) and it significantly varied in relation to location and location-sluices interaction (Table 1). A nearly significant effect of sluice gate operation (P = 0.051) was also observed. Mean (± SD) water transparency ranged from 29.0 ± 6.0 cm (at S-4) to 30.3 ± 6.0 cm (at S-2). Mean DO ranged between 7.5 ± 0.3 mg L^{-1} (at S-4) and 7.8 ± 0.3 mg L^{-1} (at S-2). Mean pH varied between 7.3 ± 0.4 (at S-4) and 7.4 ± 0.3 (at S-1). Interaction of location and sluice gate operation had a significant effect on pH (F = 6.6, P = 0.014).

4.2 | Fish fauna

A total of 5536 fish specimens were collected, identified and classified into 48 species belonging to 34 genera and 14 families (Table 2). Sampling sites located upstream of the sluices were more diverse in terms of fish species richness and their numbers (48 species, 3446 specimens) than downstream sites (34 species, 2090 specimens). The maximum number of fish species (47) was caught at the first sampling site (S-1) followed by S-2 (44 species), S-3 (33 species) and S-4 (27 species).

The dominant family, Cyprinidae, accounted for 36.4% (15 species) of the total number of fish species collected; of which all the recorded species were caught at the upstream sites and 12 species at the downstream sites. The most abundant fish species was *Chanda nama* (relative abundance, RA; 13.9%) in all the sampling sites combined, followed by *Mystus tengara* (RA, 13.4%), *Puntius sophore* (RA, 12.0%) and *Parambassis ranga* (RA, 9.1%). The samples were dominated by fry and juveniles (69.2 ± 3.9%; n = 56 samples; Figure 4). The majority of the fish catch comprised species that are small at adult size (68.8% have an adult size of ≤ 30 cm) of which 65.5 ± 3.1% were fry and 16.3 ± 2.9 % were adults. On the other hand, over one-third of species that grow ≥30 cm were dominated by sampled fry (76.7 ± 9.8%) with few adults (7.2 ± 6.2 %). Only four adults of large catfishes (two *Wallago attu*, 64 and 73 cm TL; two *Mystus seenghala*, 55 and 69 cm TL) were recorded, all in upstream sites.

Two non-native species, *Aristichthys nobilis* and *Hypophthalmichthys molitrix*, were collected, represented by three (RA, 0.05%) and five (RA, 0.09%) individuals respectively. These were collected from both sides of the sluice gate. The mean (± SD) sizes of these species were 28.7 ± 6.1 cm and 30.6 ± 6.7 cm for *A. nobilis* and *H. molitrix* respectively.

4.3 | Fish abundance and species richness in relation to sluice gate operation

Levels of abundance (measured as Catch Per Unit Effort, CPUE) were similar between sites before sluice closure, diverged during the period of closure and then returned to similar values when sluices were reopened (Figure 5). A similar pattern was evident for changes in overall species richness (Figure 5). LMM analysis (Table 1) shows that fish abundance varied significantly between sampling locations i.e. on a spatial scale (upstream vs downstream, F = 45.69, P = 0.021). Sluice gate status also had a significant effect on fish abundance (F = 7.06, P = 0.02). A significant interaction effect between (F = 158.43, P < 0.001) sluice status and site location indicated that CPUE patterns changed in response to sluice gate status. The similarity in fish abundance between upstream and downstream sites when sluices were open, compared to the strong contrast during partial closure is evident from the NMDS plot (Figure 6).

Overall, mean species richness was similar while the sluices were open (21.7 ± 2.0 spp.) and closed (20.3 ± 9.2 spp.) but varied greatly between upstream and downstream when it was in operation during the wet season (Figure 7). SIMPER test results (Table S1) revealed that the CPUE of 27 native fish species, mostly surface dwellers, varied significantly between upstream and downstream locations when the sluice gates were in operation over the wet season but with little change when the gates were open. Eleven native taxa including nine surface dwellers contributed over 70% of the dissimilarity in fish abundance in response to sluice gate operation (Table S1). Among them the top five species were *Chanda nama* (12.9%), *Mystus tengara* (10.2%), *Puntius sophore* (7.9%), *Parambassis ranga* (7.1%) and *Xenentodon cancila* (6.1%).

4.4 | Relation to fishes of different conservation status and population trend

Twenty species (41.7% of all species) recorded in the current study are classed as threatened in Bangladesh (Critically Endangered, one sp.; Endangered, eight spp.;

Vulnerable, six spp.; Near Threatened, five spp.; Table 2). Abundance of the fish species belonging to threatened categories i.e. Endangered, Vulnerable and Near Threatened was significantly lower ($P < 0.01$ or $P < 0.001$ in all cases) downstream of the sluice gates (Figure 8, Table 3).

4.5 | Wetland bird population in the Chalan Beel

A total of 25 species of wetland birds (Table 4) along with 11 locally extinct species (Table S2) were identified in the Chalan Beel area. The most speciose family was the Ardeidae represented by seven species of egret and herons (Table 4). More than two-thirds of the birds were classed as permanent residents (76%) of the Chalan Beel followed by migratory (24%) species. Migratory birds are found over the winter season (generally December to early March) in the Chalan Beel. One-fifth of bird species in the Chalan Beel appear to have become rare, while about two-thirds (64%) of all wetland bird species have decreased to a lesser extent (Table 4). Two major causes for decline were identified by the respondents - reduction in wetland areas and poaching. Poaching (illegal trapping or netting) is common during the winter period when migratory birds are available in the wetland (S. Galib, pers. obs.). All the respondents also reported that the number of migratory bird species has declined to a great extent (approximately 80% reduction based upon combined information) in recent times compared to their abundance more than 20 years ago.

5 | DISCUSSION

This study provides evidence of the impact of sluice gates on fish communities in monsoonal-climate floodplains and the potential for causing ecological impoverishment to flood-fed wetlands. While the wetland bird survey data are not fully quantitative, the perceived decline of 84% of bird species (20% to the point of being rare) by interviewees is suggestive of much wider biodiversity impacts on the conservation status of Bangladesh's largest wetland, the Chalan Beel. Part-closure of flood sluices can inhibit the movements of fish of a wide variety of species onto and off the floodplain (Halls et al., 1998, 1999). Our study demonstrated that although the sluice on the Baral River was undershot and open by 16–60% of water depth through the 4 month 'closure' period, fish abundance and diversity downstream decreased dramatically, even though one might expect downstream transport and dispersal, especially of larvae and fry, not to be impacted. Upon reopening the sluice gates, fish abundance and diversity downstream returned to the levels observed upstream. This strongly indicates that partial closure of the sluices acted as a behavioural barrier, causing functional disconnection, by inhibiting fish movement through it.

It is possible that cumulative fishing pressure downstream of the sluices helped generate a decline in abundance and species richness compared to upstream, but the stepwise rebound in CPUE and species richness following opening of the sluice gates, as the flood receded strongly, supports a behavioural barrier explanation rather than a fishing exploitation one. This disruption in functional connectivity which emerges from various movement components (e.g. foraging, mate searching, dispersal etc.) may adversely affect the functioning of populations, species and communities in impacted habitats (Fuller, Doyle, & Strayer, 2015; Pe'er, Henle, Dislich, & Frank, 2011).

Serving as a constraining connection (Beger et al., 2010) between the Padma and Chalan Beel, the Baral is ecologically vital to sustain not only the fishes but also other organisms. This type of barrier to longitudinal movement can also lead to local extinction of migratory aquatic organisms (Warren & Pardew, 1998). Downstream migration and dispersal of fishes from the main river channels onto the floodplain is a crucial and fundamental part of the lifecycle of many floodplain fishes including those of Bangladesh (Baras & Lucas, 2001; Craig et al., 2004; Welcomme, 1979). As water levels decrease, the return of tropical and subtropical freshwater fish to main channels or use of refuge pools is key to population maintenance (Welcomme, 1979; Lowe-McConnell, 1987). Compromising such processes is likely to cause a chronic reduction in the fish diversity and production in wetlands and appears at least partially responsible for the major decline in natural fisheries in the Chalan Beel (Hossain et al., 2009). Wetland habitat degradation due to flow modification and reduction in fish food supply likely also affects other ecosystem components such as wetland birds, and the recorded declines in their diversity and abundance in the Chalan Beel indicate widespread stress within the ecosystem.

The danger limit (>8 m) of water level at the Baral sluices was never exceeded in recent times (2013–2015) which indicates possibilities for achieving more ecologically sensitive flow management by altered sluice management. The water level rose exponentially over the period of sluice gate operation during the high flood period in these years; this might not have been the case if the gate was fully open.

5.1 | Synergistic impacts of human development

In places where flood control structures comprising levee and sluice systems (as in this case) are installed, fishes are believed to reproduce inside (primarily floodplains) or outside (primarily large rivers) of the flood controlled area structure (Hoggarth, Dam, & Debnath, 1999). Sluices built in these connecting tributaries can significantly alter fish abundance through hindering fish migration and causing mortality (Halls et al., 1998, 1999; Marttin & De Graaf, 2002; Jutagate et al., 2005; Phomikong, Fukushima, Sricharoendham, Nohara & Jutagate, 2015). Connecting channels are crucial conduits for allowing movements on and off the inundated floodplain and although careful management may allow bidirectional movement of some life stages and species (Craig et al., 2004; Harris, Kingsford, Peirson & Baumgartner, 2017), such management is rarely applied in Bangladesh. However, the problems in enabling natural recruitment processes of fish and achieving sustainable fisheries on Bangladesh's floodplains have been complicated further by a series of synergistic impacts, illustrated for the Baral and Chalan Beel.

Increasingly in Bangladesh, fishes are indiscriminately harvested in floodplain pools by professional and even subsistence fishermen during the dry season by dewatering the deep refuge sections, making survival of fishes and other aquatic life through to the next breeding season extremely difficult (Sultana & Islam, 2016; S. Galib: personal observation). Moreover, many river branches like the Baral, that link large rivers and floodplains, are suffering from a lack of continuous water flow during the dry season because of artificial barriers and water extraction for irrigation, resulting in fragmentation of habitats. The Baral re-joins the Padma and the Chalan Beel only during the high flood period, allowing little opportunity for the fishes to complete their breeding and feeding migrations. At the end of the wet season, the building of a sand-mud barrier built by humans at the junction of the Padma and Baral, to facilitate sand extraction, cuts off return of fish to the Padma at the upstream end of the Baral. Use of the isolated pools of water along the Baral during the dry season for stocking of hatchery-reared species and complete harvesting of both released and natural stocks through dewatering the fragmented parts of the river (S. Galib: personal observation) add further pressure on wild stocks, rare species, and through escapes of cultured non-native species.

The Baral is an important river for supplying water to the Chalan Beel and the disrupted water flow, due to the water regulatory structures, may have an adverse impact on this wetland. The impact of upstream water regulatory structures is the most widespread and serious threat to wetland ecosystems all over the world (Kingsford et al., 2016). Additionally, natural siltation, high evapotranspiration and fragmentation effects from road building (Hossain et al., 2009) are impacting the Chalan Beel. A reduction in overall size of this wetland (from 2635 km^2 in 1967 to a permanent area of 73 km^2 [area including water-dependent fringing vegetation] in 2012) is likely a result of these processes (Islam & Kitazawa, 2013). Similar impacts on floodplains and rivers, including those subjected to drying process, are widespread (Brunke, 2002; Perkin, Gido, Costigan, Daniels, & Johnson, 2015). Negative effects of water regulatory structures (e.g. weirs, embankments etc.) on water movement through the main channel and anabranches can bring a drastic reduction (up to 98%) in the supply of nutrients to floodplains (Thoms et al., 2005).

Such synergistic and pervasive impacts will likely have wider effects on biodiversity in the Baral and Chalan Beel than just reducing fish. The beel supports a large number of permanent resident and migratory bird species. Based on this study, several wetland bird species may have become locally extinct from the Chalan Beel area in the last 20 years and the majority of species appear to be decreasing or have become rare. The information reported here are not quantitative counts of birds over time, as such data are not available for most of Bangladesh, but they are the best that are available within the limitations of the current study. The life cycle of these wetland bird species relies completely (for permanent residents) or partially (for migrants) on the quality of the local aquatic environment. It is likely that the reduction in wetland size and reduced quality of habitat are the major causes of wetland bird population decline in the Chalan Beel. For several of the fish-eating bird species, reduced availability of prey may also be a factor, since stocks of fish in the Chalan Beel have declined strongly in recent years (Hossain et al., 2009). Illegal trapping and netting of several of the bird species (e.g. *Ardea alba*, *A. intermedia, A. purpurea* and *Mareca strepera*) are known to occur (S. Galib, personal observation) and may also be a factor in their decline, as may disturbance. No areas of the beel currently have any statutory protection for birds or wetland habitat.

Although a very small part of the beel (<0.5%) has been declared a fish sanctuary this is unlikely to be sufficient to protect fish populations or other aspects of biodiversity. But, protected areas can be extremely important for conserving biodiversity including freshwater biodiversity and can help ensure maintenance of ecosystem services (Harrison et al., 2016, Xu et al., 2017). Nevertheless, given that the beel has decreased to 3% of its former dry-season size, due to natural and anthropogenic change, including the conditions of current floodplain management, expansion of a protected area for a wider range of biota is a moot point. More sympathetic floodplain management seems crucial to reducing the extent of impacts for remaining wetland biota.

5.2 | Fish diversity, abundance and conservation

The number of fish species recorded in this study represents only about one-fifth (18.5%) of the total freshwater fish species reported in Bangladesh (Rahman, 1989). Flowra et al. (2013) reported 60 fish species from the Bagatipara area of the Baral (approximately 30 km downstream of present study location) but they did not describe the sampling methods. Compared to the Padma River (71 species; Joadder, Galib, Haque, & Chaki, 2015) from where the Baral originates, fish species richness in this study was 32% lower. The greatest number of species (47) and total effort-standardised abundance (1789 fish) recorded in this study (47) were obtained at S-1, very close to the origin, at the Padma River. The number of fish species declined across sampling sites further downstream and was the lowest at S-4. However, it should be noted that this pattern is largely a result of the effect of the 3-month partial sluice closure, when species richness and CPUE decreased highly significantly at the downstream sites (S-3 and S-4). Nevertheless, this pattern agrees with the findings of Tsai & Ali (1986) who found that fish abundance, especially of larvae, decreased significantly on their way down towards the floodplain. However, in heavily managed floodplain river systems fish encounter numerous water management structures such as sluices as they attempt to migrate (De Graaf, Born, Uddin, & Marttin, 2001). This is the case in the study area where fishes from the Padma River, entering the Baral, may find it difficult to orientate and access the floodplain, including the Chalan Beel. Moreover, fish catches can be up to 51% lower in the modified waterbody where timing, extent and duration of flood pulse have been modified by hydraulic structures which restrict migration of fishes (Halls et al., 1999).

This study revealed that the difference in fish abundance and richness occurs principally during the high flood period when the sluices were in operation. It is likely that sluice management during the rainy season played the key role in the distribution of fishes among sampling locations in the study area. Significant interaction effects of sluice operation versus upstream-downstream location were evident for water temperature, oxygen and pH indicating a water environment response to the sluice operation. Similar effects of flow variation on several physico-chemical parameters have been reported elsewhere (e.g. water temperature, Poff & Hart, 2002; oxygen or nutrient concentrations, Friedl & Wüest, 2002). However, flow regulation can also have impacts on ecosystem processes such as sediment transport (Vericat & Batalla, 2005) and organic matter retention (Dewson, James, & Death, 2007). All these, in turn, affect recruitment and growth of aquatic plants which subsequently may affect many other aquatic organisms, including fish (Arthington, Olden, Balcombe, & Thoms, 2010; Bunn & Arthington, 2002). This reflects the realisation that the ecological health of floodplain and wetland habitats is affected primarily by river regulation (Ren & Kingsford, 2011). However, influences of sluice operation on water quality parameter are complex and show different trends of increase or decrease depending on mode of operation (Zuo, Chen, Dou, Zhang, & Li, 2015).

Partial opening of sluice gates results in rapid acceleration of flow and high turbulence immediately downstream, with substantial effects on fishes. Small fishes do not have the swimming performance to pass upstream (Halls et al., 1998) although arguably most fish movement during the flood period is downstream and onto the floodplain. Fish tagging or tracking studies were not carried out in this study, but in similar conditions, such studies have shown restricted passage at water control structures (Halls et al., 1998). Fishes may exhibit behavioural avoidance of zones with sudden acceleration of flow (Haro, Odeh, Noreika, & Castro-Santos, 1998; Kemp, Gessel, & Williams, 2008), suggesting that for juveniles and adults at least (which have the capacity not to be entrained in substantial flows), a strong degree of behavioural avoidance might occur at the flow transition area around the sluices, generating the temporal and spatial patterns of CPUE observed in this study. Juveniles may also be primarily exploiting marginal habitats, and so be more subject to diversion into lateral channels, such as the Baral River, and onto inundated floodplains upstream of the sluices when those are in operation. Fish larvae can be subjected to high mortality

(>40%) when passing through the sluice gates operated in an undershot condition (De Graaf et al., 2001; Marttin & De Graaf, 2002). Floodplain breeders such as the silurid catfish *Wallago attu* are potentially vulnerable to sluice gate impacts because this species, a major contributor of openwater fisheries in Bangladesh, migrates from large rivers to nearby floodplain and builds nests there prior to reproduction.

Fish recruitment might be affected in the study area due to insensitive operation of sluices during the high flood because the majority of the freshwater fishes in Bangladesh breed in the rainy season (Rahman, 1989, 2005). During the rainy season when floodplains are expected to receive flood water from major river systems, closure of sluice gates has potentially very damaging impacts on floodplain ecosystems because the flood is considered the principal driver responsible for the existence, productivity, and interactions of the major biota in river-floodplain systems (De Graaf et al., 2001; Junk et al., 1989). Small rivers allow fishes and invertebrates from the main river channel of large rivers to migrate or drift to inundated floodplains to exploit the ephemeral surge in primary and secondary production (Louca et al., 2009; Marttin & De Graaf, 2002; Welcomme, 1979). The sluice gates present an obstacle to regular fish migrations (e.g. breeding, feeding) to the largest floodplain and beel area, which would be expected to lead to a reduction in recruitment, population decline, and a loss of biodiversity (Craig et al., 2004; Welcomme, 1979). For the adults and larger juvenile fishes these migrations are likely to be active movements, but passive for drifting eggs and partly passive for larvae and young fry (Lucas & Baras, 2001). Sluices can be responsible for degradation of downstream habitats by changing bed and sediment characteristics (Khaleel & Othman, 1997), and affect migration of fishes (Gardner, Rees-Jones, Morris, Bryant, & Lucas, 2016; Harris et al., 2017). Flow regulation can also affect types of natural food production including plankton abundance and composition, and this is the main food for newly hatched and juvenile floodplain fish (Havel, Eisenbacher, & Black, 2000; Gozdziejewska et al., 2016; Pithart et al., 2007).

With regard to global and local conservation issues, the majority of the fish species sampled belonged to the Least Concern category of conservation and their distribution varied significantly between upstream and downstream sites. However, one locally Critically Endangered, six locally Vulnerable, seven globally Near Threatened, and five locally Near Threatened fish species varied in CPUE significantly between the two sides of the sluices which indicates that recognized threatened species are at strong risk of impact in movement, and potentially recruitment, due to the water management infrastructure. This is a significant concern as past studies in Bangladesh have not raised the cumulative potential impacts of national flood control schemes on threatened fish species, having concentrated on the effects to overall fishery production. Yet, identifying potential mechanisms of impact and taking action to reverse these is key for species conservation (O'Grady, Reed, Brook, & Frankham, 2004; Richter et al., 1997). A revised management of sluices or modification of existing structures may be considered in regard of reducing impacts on fish passage and survival. Identification of the most responsive species, including those of threatened categories, to sluice gate operation would be worth testing to determine the likely success of mitigation options.

Because a large variety of fish species of multiple ecotypes and several life stages are affected by the Baral sluice operation any fish passage structure installed needs to facilitate passage of a very broad range of species and sizes. This is a similar problem to that identified for Australian fish assemblages (Harris et al., 2017) but unlike in that situation, where the predominant efforts have been to address upstream passage, on the Baral River the most important fish movement is from the Padma downstream, and laterally onto the floodplain. It is therefore likely that a full-depth, slow-speed lateral bypass around the sluices would be needed in order to facilitate safe passage and drift by such a wide range of species and sizes. Whether this could be engineered and maintained alongside the competing (and currently prioritized) demands of sluice management requires consideration. Instead, it may be that more sympathetic sluice management could be beneficial more generally to maintaining the wetlands downstream, and enhance fish passage. To do this requires an optimization approach concerning the differing needs, as well as multiple stakeholder engagement and local training. In a study of Australian tidal creeks for which connectivity at sluices was improved by flap gate openings or intermittent manual opening, Boys et al. (2012) found that fish and crustacean communities upstream became much more diverse and similar to those in reference creeks without sluices. Although large differences in fish abundance and diversity were apparent on the Baral despite the sluice remaining partly open, Boys' study shows what can be achieved with the right management intervention for the system.

5.3 | Non-native species

Two alien species, bighead carp *Aristichthys nobilis* and silver carp *Hypophthalmichthys molitrix,* occurred on both sides of the sluices during the sampling period. Away from the sampling locations, and principally during the dry season, hatchery-reared fish are released into river fragments and harvested, together with wild fishes just before the monsoon. Thus the recorded non-natives were likely to be ranched fish that dispersed, and represent a non-native species threat. Biological invasion is a risk to native biodiversity which is not yet a priority conservation issue in Bangladesh because this issue has not been given the attention it requires. Many non-native fishes have been introduced in Bangladesh since the 1950s, mainly for the purpose of aquaculture and the aquarium trade (Galib & Mohsin, 2010), and many of these species have escaped into the wild across the country (Chaki, Jahan, Fahad, Galib, & Mohsin, 2014; Galib et al., 2009; Galib, Naser, Mohsin, Chaki, & Fahad, 2013). Introduction for aquaculture and the aquarium trade is a common route of introduction of alien aquatic animal species worldwide (Bubb, Thom, & Lucas, 2004; Ellender & Weyl, 2014; Esmaeili, Teimori, Owfi, Abbasi, & Coad, 2014; Jang, Lucas, & Joo, 2003; Patoka, Bláha, Kalous, & Kouba, 2016; Tricarico, Junqueira, & Dudgeon, 2016). It can be assumed that bighead carp and silver carp captured in this study originated from previously stocked fishes in the Baral River or entered from nearby water bodies (the Padma and Chalan Beel) where the presence of non-native species has been reported previously (Galib et al., 2009; Joadder et al., 2015; Mohsin et al., 2013). Negative impacts on aquatic ecosystems by introduced fish species are well known (Ross, 1991) and both of the species recorded are capable of modifying freshwater ecosystems (Conover, Simmonds, & Whalen, 2007; Kolar et al., 2005).

The non-native specimens recorded in this study were juveniles and it is unclear whether either of these species has become established in the wild in Bangladesh so far. But it is a matter of concern that non-native fishes are being stocked in major wild habitats of Bangladesh during the dry season, including in the Padma River (S. Galib, personal observation) under the supervision of government officials in order to enhance the production of food fishes (both native and non-native carps). This activity is intended to gain economic benefit by selling fishes which in turn pose direct threats to natural ecosystems. This means of gaining economic profit in a developing country like Bangladesh reflects the findings of Clausen & York (2008) who showed that economic growth in countries is negatively related to aquatic biodiversity. It can be assumed that more people, especially those that are landless, might feel encouraged and follow this practice in new areas in the near future which will not only modify natural habitats but also facilitate the expansion of alien species distribution in nature. This policy must be changed before it is too late and thus, study on the impacts of alien species in water bodies in Bangladesh needs to be encouraged.

6 | CONCLUSIONS

As in 2015, the highest water level at the Baral sluices in 2013 and 2014 never exceeded the danger limit (>8 m). This indicates there may be opportunities for achieving more ecologically sensitive flow management by altered sluice management. The water level rose exponentially over the period of sluice gate operation during the high flood period in these three years; this might have not been the case if the gate was fully open. Water quality parameters also varied in relation to sluice operation which may have adverse effects on ecological health of associated water bodies. More intensive research efforts are needed to determine the impacts on other water quality parameters to understand the current level of ecological impacts.

Operation of sluice gates over the wet season on the Baral River depressed fish abundance and diversity temporarily downstream, and apparently reduced the period and extent for free migration and dispersal downstream towards the Chalan Beel wetland. Insensitive sluice management, combined with intensive and unsustainable fishery practices, uncontrolled ranching of cultured non-native fishes in natural waters, increased roadbuilding and water loss for irrigation, and a lack of any significant habitat protection all put Bangladesh's largest wetland at risk of irreversible decline in the very near future. Wetland birds there already appear strongly in decline and better recording of biota abundance and diversity needs to be instituted urgently.

A revision of the management of the sluice gates on the Baral (and other similar sites in Bangladesh), in concert with more sensitive floodplain habitat protection measures is needed, to better meet biodiversity and fisheries needs, as well as for flood control and crop production. A modification of the existing Baral sluices to install a fish pass may be considered and the success rate of this structure should be tested with fish species that are most responsive to sluice operation (e.g. *C. nama, M. tengara, P. sophore, P. ranga* and *X. cancila*). Alternatively, at least one of the three gates may be opened fully all the time except if the water height exceeds the flood danger limit to improve the longitudinal movement of fish. Increased manual opening of sluice gates had proved successful for improving connectivity for biota in Australian tidal creeks (Boys et al., 2012). Another option of operating the sluices may be to adjust the operational height of the gates to pass enough water downstream to support ecological processes on the floodplain more generally. This would be similar to the environmental flows (E-flows) approach which would also be helpful for the movement and recruitment of fish and other aquatic fauna. However, further research is needed on this issue. Periodic complete opening of the gates, especially during the peak breeding period of fishes may also be considered. Equally, maintenance of a free connection with the Padma, and a cessation of destructive fishing and seasonal fish ranching practices are needed.

The results of this study may be expected to be applicable to many other floodplain sites in south east Asia with similar sluice gates and operation schedules. Therefore the concerns raised here may be much more widely applicable in those tropical and subtropical floodplain environments where there is a very strong water management regime.

ACKNOWLEDGEMENTS

This research was financially supported by a Research Support Grant of the University of Rajshahi, Bangladesh (Grant No. A-621(5)/5/52/RU/Krishi-5/2013). Thanks are also given to Taskin Parvez for his support during fieldwork.

REFERENCES

Ahmed, M. S. (2008). Assessment of fishing practices on the exploitation of the Titas Floodplain in Brahmanbaria, Bangladesh. *Turkish Journal of Fisheries and Aquatic Sciences, 8,* 329–334.

Ahmed, Z. U., Begum, Z. N. T., Hassan, M. A., Khondker, M., Kabir, S. M. H., Ahmad, M., ... Haque, E. U. (2008). *Encyclopedia of Flora and Fauna of Bangladesh*, *Volume 26: Birds*. Dhaka, Bangladesh: Asiatic Society of Bangladesh.

Ali, M. L., & Alam, S. S. (2005). *Management of sluice gate/regulators for fish stock enhancement in modified floodplain without harm to rice.* Dhaka, Bangladesh: Bangladesh Centre for Advanced Studies.

Arthington, A. H. (2009). Australian lungfish, *Neoceratodus forsteri*, threatened by a new dam. *Environmental Biology of Fishes*, 84, 211–221.

Arthington, A. H., Dulvy, N. K., Gladstone, W., & Winfield, I. J. (2016). Fish conservation in freshwater and marine realms: status, threats and management. *Aquatic Conservation: Marine and Freshwater Ecosystems, 26,* 838–857.

Arthington, A. H., Olden, J. D., Balcombe, S. R., & Thoms, M. C. (2010). Multi-scale environmental factors explain fish losses and refuge quality in drying waterholes of Cooper Creek, an Australian arid-zone river. *Marine and Freshwater Research*, 61, 842–856.

Baras, E., & Lucas, M. C. (2001). Impacts of man's modifications of river hydrology on the migration of freshwater fishes: A mechanistic perspective. *Ecohydrology and Hydrobiology, 1*, 291–304.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67, 1–51.

Baumgartner, L., Zampatti, B., Jones, M., Stuart, I., & Mallen-Cooper, M. (2014). Fish passage in the Murray-Darling Basin, Australia: not just an upstream battle. *Ecological Management & Restoration*, 15, 28–39.

Beger, M., Grantham, H. S., Pressey, R. L., Wilson, K. A., Peterson, E. L., Dorfman, D., ... & Possingham, H. P. (2010). Conservation planning for connectivity across marine, freshwater, and terrestrial realms. *Biological Conservation*, 143, 565–575.

Benstead, J. P., March, J. G., Pringle, C. M., & Scatena, F. N. (1999). Effects of a low-head dam and water abstraction on migratory tropical stream biota. *Ecological Applications, 9*, 656–668.

Boys, C. A., Kroon, F. J., Glasby, T. M. & Wilkinson, K. (2012) Improved fish and crustacean passage in tidal creeks following floodgate remediation. *Journal of Applied Ecology*, 49, 223-233.

Brunke, M. (2002). Floodplains of a regulated southern alpine river (Brenno, Switzerland): ecological assessment and conservation options. *Aquatic Conservation: Marine and Freshwater Ecosystems, 12*, 583–599.

Bubb, D. H., Thom, T. J., & Lucas, M. C. (2004). Movement and dispersal of the invasive signal crayfish *Pacifastacus leniusculus* in upland rivers. *Freshwater Biology, 49*, 357–368.

Bunn, S.E., & Arthington, A.H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, 30, 492–507.

Castaldelli, G., Pluchinotta, A., Milardi, M., Lanzoni, M., Giari, L., Rossi, R., & Fano, E. A. (2013). Introduction of exotic fish species and decline of native species in the lower Po basin, north-eastern Italy. *Aquatic Conservation: Marine and Freshwater Ecosystems, 23*, 405–417.

Chaki, N., Jahan, S., Fahad, M. F. H., Galib, S. M., & Mohsin, A. B. M. (2014). Environment and fish fauna of the Atrai River: Global and local conservation perspective. *Journal of Fisheries, 2*, 163–172.

Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology, 18*, 117–143.

Clausen, R., & York, R. (2008). Global biodiversity decline of marine and freshwater fish: a cross-national analysis of economic, demographic, and ecological influences. *Social Science Research, 37*, 1310–1320.

Conover, G., Simmonds, R., & Whalen, M. (ed.). (2007). *Management and control plan for bighead, black, grass, and silver carps in the United States*. Washington DC: Asian Carp Working Group, Aquatic Nuisance Species Task Force.

Craig, J. F., Halls, A. S., Barr, J. J. F., & Bean, C. W. (2004). The Bangladesh floodplain fisheries. *Fisheries Research, 66*, 271–286.

De Graaf, G. (2003). Dynamics of floodplain fisheries in Bangladesh, results of 8 years fisheries monitoring in the Compartmentalization Pilot Project. *Fisheries Management and Ecology, 10*, 191–199.

De Graaf, G. J., Born, B., Uddin, K., & Marttin, F. (2001). *Floods, fish and fishermen.* Dhaka, Bangladesh: University Press Limited.

Dewson, Z.S., James, A.B.W., Death, R.G., 2007. Stream ecosystem functioning under reduced flow conditions. *Ecological Applications*, 17, 1797–1808.

DoF. (2015). *Fish Sanctuaries of Bangladesh*. Dhaka Bangladesh: Department of Fisheries.

Downes, B. J., Barmuta, L. A., Fairweather, P. G., Faith, D. P., Keough, M. J., Lake, P. S., ... Quinn, G. P. (2002). *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters*. Cambridge: Cambridge University Press.

Drinkwater, K. F., & Frank, K. T. (1994). Effects of river regulation and diversion on marine fish and invertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 4, 135–151.

Duncan, J. R., & Lockwood, J. L. (2001). Extinction in a field of bullets: A search for causes in the decline of the world's freshwater fishes. *Biological Conservation, 102,* 97–105.

Ellender, B. R., & Weyl, O. L. F. (2014). A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions, 9*, 117–132.

Esmaeili, H. R., Teimori, A., Owfi, F., Abbasi, K., & Coad, B. W. (2014). Alien and invasive freshwater fish species in Iran: diversity, environmental impacts and management. *Iranian Journal of Ichthyology, 1*, 61–72.

Flowra, F. A., Islam, M. A., Jahan, S. N., Hussain, M. A., Alam, M. M., Bashir, F. A., ... Simon, K. D. (2013). Status and decline causes of fish diversity of Baral River, Natore, Bangladesh. *AACL Bioflux, 6*, 352–357.

Flowra, F. A., Islam, M. A., Jahan, S.N., Samad, M. A., & Alam, M. M. (2011). Status and decline causes of fishing activities of the Baral River, Natore, Bangladesh. *Journal of Science Foundation*, 9, 115–124.

Friedl, G., & Wüest, A., (2002). Disrupting biogeochemical cycles– consequences of damming. *Aquatic Sciences*, 64, 55–65.

Froese, R., & Pauly, D. (Ed.). (2015). List of Freshwater Fishes reported from Bangladesh. FishBase, World Wide Web electronic publication. www.fishbase.org, version (10/2015) [7 December 2016]

FRSS. (2015). *Fisheries statistical report of Bangladesh 2013–14*. Dhaka, Bangladesh: Fisheries Resources Survey System, Department of Fisheries.

Fuller, M. R., Doyle, M. W., & Strayer, D. L. (2015). Causes and consequences of habitat fragmentation in river networks. *Annals of the New York Academy of Sciences*, 13551, 31–51.

Galib, S. M. (2015). Fish fauna of the Brahmaputra River, Bangladesh: richness, threats and conservation needs. *Journal of Fisheries*, *3,* 285–292.

Galib, S. M., & Mohsin, A. B. M. (2010). Exotic ornamental fishes of Bangladesh. *Bangladesh Journal of Progressive Science and Technology, 8*, 255–258.

Galib, S. M., Naser, S. M. A., Mohsin, A. B. M., Chaki, N., & Fahad, M. F. H. (2013). Fish diversity of the River Choto Jamuna, Bangladesh: Present status and conservation needs. *International Journal of Biodiversity and Conservation, 5*, 389–395.

Galib, S. M., Rashid, M. A., Chaki, N., Mohsin, A. B. M., & Joadder, M. A. R. (2016). Seasonal variation and community structure of fishes in the Mahananda River with special reference to conservation issues. *Journal of Fisheries*, 4, 325–334.

Galib, S. M., Samad, M. A., Mohsin, A. B. M., Flowra, F. A., & Alam, M. T. (2009). Present status of fishes in the Chalan Beel- the largest beel (wetland) of Bangladesh. *International Journal of Animal and Fisheries Science, 2*, 214–218.

Gardner, C.J., Rees-Jones, J., Morris, G., Bryant, P.G., & Lucas, M.C. (2016). The influence of sluice gate operation on the migratory behaviour of Atlantic salmon *Salmo salar* (L.) smolts. *Journal of Ecohydraulics*, 1, 90–101.

Gozdziejewska, A., Glinska-Lewczuk, K., Obolewski, K., Grzybowski, M., Kujawa, R., Lew, S., & Grabowska, M. (2016). Effects of lateral connectivity on zooplankton community structure in floodplain lakes. *Hydrobiologia*, 774, 7–21.

Halls, A. S., Hoggarth, D. D., & Debnath, K. (1998). Impact of flood control schemes on river fish migrations and species assemblages in Bangladesh. *Journal of Fish Biology, 53*, 358–380.

Halls, A. S., Hoggarth, D. D., & Debnath, K. (1999). Impacts of hydraulic engineering on the dynamics and production potential of floodplain fish populations in Bangladesh. *Fisheries Management and Ecology, 6*, 261–285.

Haro, A., Odeh, M., Noreika, J., & Castro-Santos T. (1998). Effect of water acceleration on downstream migratory behavior and passage of Atlantic salmon smolts and juvenile American shad at surface bypasses. *Transactions of the American Fisheries Society 127,* 118–127.

Harris, J. H., Kingsford, R. T., Peirson, W., & Baumgartner, L. J. (2017). Mitigating the effects of barriers to freshwater fish migrations: the Australian experience. *Marine and Freshwater Research, 68*, 614–628.

Harrison, I. J., Green, P. A., Farrell, T. A., Juffe-Bignoli, D., Sáenz, L., & Vörösmarty, C. J. (2016). Protected areas and freshwater provisioning: a global assessment of freshwater provision, threats and management strategies to support human water security. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26, 103–120.

Havel, J. E., Eisenbacher, M., & Black, A. A. (2000). Diversity of crustacean zooplankton in riparian wetlands: colonization and egg banks. *Aquatic Ecology*, 34, 63–76.

Hoggarth, D. D., Dam, R. K, & Debnath, K. (1999). Recruitment sources for fish stocks inside a floodplain river impoundment in Bangladesh. *Fisheries Management and Ecology, 6*, 287–310.

Hossain, M. A. R. (2014). Habitat and fish diversity: Bangladesh perspective. In: Wahab, M. A., Shah, M. S., Hossain, M. A. R., Barman, B. K., & Hoq, M.E. (eds.). *Advances in Fisheries Research in Bangladesh* (pp. 1-26). Dhaka, Bangladesh: Bangladesh Agricultural Research Council and Bangladesh Fisheries Research Forum.

Hossain, M. A. R., Nahiduzzman, M., Sayeed, M. A., Azim, M. E, Wahab, M. A., & Olin, P.G. (2009). The Chalan beel in Bangladesh: Habitat and biodiversity degradation, and implications for future management. *Lakes and Reservoirs: Research and Management, 14*, 3–19.

Imteazzaman, A. M., & Galib, S. M. (2013). Fish fauna of Halti Beel, Bangladesh. *International Journal of Current Research, 5,* 187–190.

Islam, M. N., & Kitazawa, D. (2013). Modeling of freshwater wetland management strategies for building the public awareness at local level in Bangladesh. *Mitigation and Adaptation Strategies for Global Change, 18*, 869–888.

IUCN Bangladesh. (2000). *Red book of threatened fishes of Bangladesh*. IUCN- The world conservation Union. Dhaka, Bangladesh: IUCN, International Union for Conservation of Nature, Bangladesh Country Office.

IUCN Bangladesh. (2015). *Red list of Bangladesh a brief assessment of result 2015*. Dhaka, Bangladesh: IUCN, International Union for Conservation of Nature, Bangladesh Country Office.

IUCN. (2016). The IUCN Red List of Threatened Species. Version 2016-3. http://www.iucnredlist.org [20 November, 2016]

Jang, M., Lucas, M.C., & Joo, G. (2003). The fish fauna of mountain streams in South Korean national parks and its significance to conservation of regional freshwater fish biodiversity. *Biological Conservation, 114,* 115–126.

Joadder, M. A. R., Galib, S. M, Haque, S. M. M, & Chaki, N. (2015). Fishes of the river Padma, Bangladesh: current trend and conservation status. *Journal of Fisheries, 3,* 259–266.

Junk, W. B., Bayley, P. B., & Sparks, R. E. (1989). The flood pulse in river floodplain systems. In: Dodge, D.P. (ed.). Proceedings of the International Large River Symposium. *Canadian Special Publication Fisheries Aquatic Sciences, 106,* 110–127.

Jutagate, T., Krudpan, C., Ngamsnae, P., Lamkom, T., & Payooha, K. (2005). Changes in the fish catches during a trial opening of sluice gates on a run-of-the river reservoir in Thailand. *Fisheries Management and Ecology, 12*, 57–62

Kemp, P. S., Gessel, M. H., & Williams J. G. (2008). Response of downstream migrant juvenile Pacific salmonids to accelerating flow and overhead cover. *Hydrobiologia, 609*, 205–217.

Khaleel, M. S., & Othman, K. I. (1997). Degradation downstream from a sluice gate; variation of bed and sediment characteristics with time and discharge. *Journal of Hydrology, 191,* 349–363.

Kingsford, R. T., Basset, A., & Jackson, L. (2016). Wetlands: conservation's poor cousins. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26: 892–916.

Kolar, C. S., Chapman, D. C., Courtenay Jr, W. R., Housel, C. M., Williams, J.D., & Jennings, D. P. (2005). *Asian carps of the genus Hypophthalmichthys (Pisces, Cyprinidae) — a biological synopsis and environmental risk assessment.* USA: Report to U.S. Fish and Wildlife Service.

Kruskal, J. B., & Wish, M. (1978). Multidimensional Scaling. London: Sage Publications.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2016). lmerTest: Tests in Linear Mixed Effects Models. R package version 2.0-33. https://CRAN.R-project.org/package=lmerTest

Leigh, C., & Sheldon, F. (2008). Hydrological changes and ecological impacts associated with water resource development in large floodplain rivers in the Australian tropics. *River Research and Applications*, 24, 1251–1270.

Louca, V., Lindsay, S.W., & Lucas, M.C. (2009). Factors triggering floodplain fish emigration: importance of fish density and food availability. *Ecology of Freshwater Fish,* 18, 60–64.

Lowe-McConnell, R.H. (1987). *Ecological Studies in Tropical Fish Communities*. London: Longman Press.

Lucas, M. C., & Baras, E. (2001) *Migration of Freshwater Fishes*. Oxford: Blackwell Science Ltd.

Lucas, M. C, Bubb, D. H., Jang, M., Ha, K., & Masters, J. E. G. (2009). Availability of and access to critical habitats in regulated rivers: effects of low-head barriers on threatened lampreys. *Freshwater Biology, 54,* 621–634.

Marttin, F., & De Graaf, G. J. (2002). The effect of a sluice gate and its mode of operation on mortality of drifting fish larvae in Bangladesh. *Fisheries Management and Ecology, 9,* 123–125.

McDonald, J. H. (2014). *Handbook of Biological Statistics* (3rd ed.). Maryland: Sparky House Publishing.

Mohsin, A. B. M., Haque, S. M. M., Galib, S. M., Fahad, M. F. H., Chaki, N., Islam, M.N., & Rahman, M.M. (2013). Seasonal abundance of fin fishes in the Padma River at Rajshahi District, Bangladesh. *World Journal of Fish and Marine Sciences, 5,* 680–685.

Naeem, S., Duffy, J. E., Zavaleta, E. (2012). The functions of biological diversity in an age of extinction. *Science, 336,* 1401–1406.

Nelson, J. S. (2006). *Fishes of the World* (4th ed.). Hoboken: John Wiley & Sons, Inc.

Nilsson, C., Reidy, C. A., Dynesius, M., & Revenga, C. (2005). Fragmentation and flow refulation of the world's large river systems. *Science, 308,* 405–408.

Northcote, T. G. (1998). Migratory behaviour of fish and its significance to movement through riverine fish passage facilities. *Migration and Fish Bypasses* (eds. Jungwirth, M., Schmutz, S. & Weiss, S.), pp. 3–18. Oxford: Fishing News Books.

O'Grady, J. J., Reed, D. H., Brook, B. W., & Frankham, R. (2004). What are the best correlates of predicted extinction risk? *Biological Conservation, 118*, 513–520.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E., & Wagner, H. (2017). vegan: community ecology package. R package version 2.4-3. https://CRAN.R-project.org/package=vegan

Patoka, J., Bláha, M., Kalous, L., & Kouba, A. (2016). Irresponsible vendors: non-native, invasive and threatened animals offered for garden pond stocking. *Aquatic Conservation: Marine and Freshwater Ecosystems*; doi: 10.1002/aqc.2719

Pe'er, G., Henle, K., Dislich, C., Frank, K. (2011). Breaking functional connectivity into components: a novel approach using an individual-based model, and first outcomes. *PLoS One*, 6, e22355.

Perkin, J. S., Gido, K. B., Costigan, K. H., Daniels, M. D., & Johnson, E. R. (2015). Fragmentation and drying ratchet down Great Plains stream fish diversity. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *25*, 639–655.

Phomikong, P., Fukushima, M., Sricharoendham, B. Nohara, S., & Jutagate, T. (2015). Diversity and community structure of fishes in the regulated versus unregulated tributaries of the Mekong River. *River Research and Applications, 31*, 1262-1275.

Pithart, D., Pilchova, R., Bıly, J., Hrabacek, J., Novotna, K., & Pechar, L. (2007). Spatial and temporal diversity of small shallow waters in river Luznice floodplain. *Hydrobiologia*, 548, 265–275.

Poff, N. L., & Hart, D. D., (2002). How dams vary and why it matters for the emerging science of dam removal. *Biogeosciences*, 52, 659–738.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., & Stromberg, J.C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *BioScience*, 47, 769.

R Core Team. (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rahman, A. K. A. (1989). *Freshwater fishes of Bangladesh* (1st ed.). Dhaka, Bangladesh: Zoological Society of Bangladesh.

Rahman, A. K. A. (2005). *Freshwater fishes of Bangladesh* (2nd ed.). Dhaka, Bangladesh: Zoological Society of Bangladesh.

Ren, S., & Kingsford, R. T. (2011). Statistically integrated flow and flood modelling compared to hydrologically integrated quantity and quality model for annual flows in the regulated Macquarie River in arid Australia. *Environmental Management*, 48,177–188.

Richter, B. D., Braun, D. P., Mendelson, M. A., & Master, L. L. (1997). Threats to imperiled freshwater fauna. *Conservation Biology, 11,* 1081–1093.

Ross, S. T. (1991). Mechanisms structuring stream fish assemblages: are there lessons from introduced species. *Environmental Biology of Fish, 30,* 359–368.

Samad, M. A., Galib, S. M., & Flowra, F. A. (2009). Fish drying in Chalan Beel areas. *Bangladesh Journal of Scientific and Industrial Research, 44,* 461–466.

Sayeed, M. A., Hossain, M. A. R., Wahab, M. A., Hasan, M. T., Simon, K. D., & Mazumder, S. K. (2015). Water and sediment quality parameters in the Chalan Beel, the largest wetland of Bangladesh. *Chinese Journal of Oceanology and Limnology, 33,* 895–904.

Schmidt, J. C., Webb, R. H., Valdez, R. A., Marzolf, G. R., & Stevens, L. E. (1998). Science and values in river restoration in the Grand Canyon. *BioScience*, 48, 735–747.

Shafland, P. L., & Lewis, W. M. (1984). Terminology associated with introduced organisms. *Fisheries, 9,* 17–18.

Shankar, B., Halls, A., & Barr, J. (2004). Rice versus fish revisited: On the integrated management of floodplain resources in Bangladesh. *Natural Resources Forum, 28,* 91–101.

Stewart-Oaten, A., Murdoch, W. W., & Parker, K. R. (1986). Environmental impact assessment: pseudoreplication in time? *Ecology*, 67, 929–940.

Sultana, N., & Islam, M. N. (2016). Fishing methods in the Chalan Beel, Bangladesh. *Journal of Fisheries, 4,* 377–384.

Talwar, P. K., & Jhingran, A. G. (1991). *Inland Fishes of India and Adjacent Countries Vol. 1 and 2*. New Delhi-Calcutta, India: Oxford and IBH Publishing Co. Pvt. Ltd.

Thoms, M.C., Southwell, M., & McGinness, H.M. (2005). Floodplain–river ecosystems: fragmentation and water resources development. *Geomorphology*, 71, 126–138.

Tricarico, E., Junqueira, A. O. R., & Dudgeon, D. (2016). Alien species in aquatic environments: a selective comparison of coastal and inland waters in tropical and temperate latitudes. *Aquatic Conservation: Marine and Freshwater Ecosystems, 26*: 872–891.

Tsai, C. F., & Ali, L. (1986). Carp spawn fishery in the Padma (Ganges)-Brahmaputra river system, Bangladesh. *Indian Journal of Fisheries, 33,* 386–401.

Vericat, D., & Batalla, R.J., (2005). Sediment transport in a highly regulated fluvial system during two consecutive floods (lower Ebro River, NE Iberian Peninsula). *Earth Surface Processes and Landforms*, 30, 385–402.

Walker, K., & Thoms, M. (1993). Environmental effects of flow regulation on the lower River Murray, Australia. *River Research and Applications*, 8, 103–119.

Warren, M. L., & Pardew, M. G. (1998). Road crossings as barriers to small-stream fish movements. *Transactions of the American Fisheries Society*, 127, 637–644.

Welcomme, R. L. (1979). *The Fisheries Ecology of Floodplain Rivers*. London: Longman.

Williams, J. E., Johnson, J. E., Hendrickson, D. A., Contreras-Balderas, S., Williams, J. D., Navarro-Mendoza, M., ... Deacon, J. E. (1989). Fishes of North America endangered, threatened, or of special concern: 1989. *Fisheries, 14,* 2–20.

Xu, W., Xiao, Y., Zhang, J., Yang, W., Zhang, L., Hull,V., ... & Ouyang, Z. (2017). Strengthening protected areas for biodiversity and ecosystem services in China. *Proceedings of the National Academy of Sciences of the United States of America*, 114, 1601–1606.

Zuo, Q., Chen, H., Dou, M., Zhang, Y., & Li, D., (2015). Experimental analysis of the impact of sluice regulation on water quality in the highly polluted Huai River Basin, China. *Environmental Monitoring and Assessment*, 187, 1–15.

TABLE 1 Linear Mixed Model (LMM) results showing spatial and temporal variation of fish abundance and water quality parameters in the Baral River following a before-after-control-impact (BACI) approach. Location refers to upstream (Control condition) or downstream (Impact condition)

Factors	***Temp.***		***Trans.***		***pH***		***DO***		***Fish***	
	F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Sluices status (BA)	4.72	0.051	0.32	0.583	0.04	0.845	2.95	0.112	7.06	0.020
Location (CI)	32.62	0.028	1.77	0.190	0.94	0.337	0.56	0.529	45.69	0.021
Interaction (BA×CI)	15.28	<0.001	0.80	0.378	6.60	0.014	0.01	0.927	158.43	<0.001

BA, Before-After; CI, Control-Impact; DO, Dissolved oxygen; Fish, Fish abundance; Temp., Water temperature; Trans., Water transparency.

TABLE 2 Fish species sampled in the Baral River with their conservation and population trend status Numbers of individuals refers to total catch, with effort standardised across sites and so reflects Catch Per Unit Effort.

Family and fish species	*No. of individuals at sampling sites*				*Life stage (%)*			*Max length in BD[1] (cm)*	*Conservation status*		*Global pop.[2]*
	S-1	*S-2*	*S-3*	*S-4*	*Fry*	*Juvenile*	*Adult*		*Global[2]*	*BD[3]*	
Belonidae											
Xenentodon cancila	52	45	12	7	56.0	27.6	16.4	26	LC	LC	UN
Clupeidae											
Gudusia chapra	72	63	55	53	67.5	22.6	9.9	20	LC	VU	DE
Tenualosa ilisha	1	0	0	0	100	0.0	0.0	53	LC	LC	DE
Engraulidae											
Setipinna phasa	7	8	1	0	87.5	12.5	0.0	29	LC	LC	DE
Cyprinidae											
Amblypharyngodon mola	122	102	97	86	72.5	9.3	18.2	9	LC	LC	ST
Aristichthys nobilis	1	1	1	0	0.0	100	0.0	112	DD	NN	DE
Aspidoparia morar	18	15	5	1	61.6	25.6	12.8	13	LC	VU	UN
Cirrhinus reba	32	31	21	14	87.8	10.2	2.0	33	LC	NT	ST
Catla catla	2	1	1	0	100	0.0	0.0	97	LC	LC	UN
Esomus danricus	65	45	32	33	37.1	32.0	30.9	6	LC	LC	ST
Hypophthalmichthys molitrix	2	2	1	0	0.0	100	0.0	105	NT	NN	DE
Labeo bata	21	11	1	1	94.1	5.9	0.0	29	LC	LC	UN
Labeo calbasu	6	3	0	0	100	0.0	0.0	71	LC	LC	UN
Labeo rohita	2	1	0	0	100	0.0	0.0	94	LC	LC	UN
Puntius sarana	5	1	0	0	0.0	0.0	100	42	LC	NT	UN
Puntius sophore	178	189	153	143	60.6	16.9	22.5	12	LC	LC	UN
Puntius ticto	13	14	3	1	38.7	25.8	35.5	7	LC	VU	UN
Salmophasia bacaila	86	81	66	57	54.8	16.6	28.6	14	LC	LC	ST
Salmophasia phulo	103	96	76	71	64.7	16.8	18.5	10	LC	NT	UN
Cobitidae											
Botia dario	2	2	0	0	100	0.0	0.0	15.1	LC	EN	UN
Botia lohachata	7	5	1	2	93.3	6.7	0.0	6.6	AB	EN	AB
Lepidocephalus guntea	22	15	14	14	52.3	7.7	40.0	9.6	LC	LC	ST
Ambassidae											
Chanda nama	233	221	165	149	55.0	5.7	39.3	10	LC	LC	DE
Parambassis lala	13	2	0	0	93.3	6.7	0.0	3	NT	LC	DE
Parambassis ranga	177	141	108	76	64.9	11.8	23.3	8	LC	LC	ST
Gobiidae											
Glossogobius giuris	67	53	13	11	95.8	4.2	0.0	29.2	LC	LC	UN
Osphronemidae											
Trichogaster fasciata	20	25	19	16	50.0	0.0	50. 0	10	LC	LC	UN
Trichogaster lalius	16	13	6	7	34.2	0.0	65.8	8.8	LC	LC	UN
Channidae											
Channa orientalis	0	1	0	3	53.9	19.2	26.9	14	LC	LC	UN
Channa punctata	32	35	21	16	50.0	28.1	21.9	24	LC	LC	UN
Mastacembelidae											
Macrognathus aculeatus	14	14	1	1	52.3	40.7	7.0	24	AB	NT	AB
Mastacembelus armatus	4	1	0	0	100	0.0	0.0	90	LC	EN	UN
Mastacembelus pancalus	6	5	1	0	70.0	30.0	0.0	14	LC	LC	UN
Bagridae											
Sperata aor	1	1	0	0	100	0.0	0.0	94	LC	VU	ST
Sperata seenghala	6	6	0	0	77.3	13.6	9.1	112	LC	VU	UN

Mystus cavasius	62	76	43	22	55.9	27.9	16.2	23	LC	NT	DE
Mystus tengara	188	241	165	145	66.0	15.4	18.6	6	LC	LC	UN
Rita rita	6	5	0	0	95.9	4.1	0.0	60	LC	EN	DE
Schilbeidae											
Ailia coila	25	19	12	1	64.5	29.0	6.5	15	NT	LC	DE
Eutropiichthys vacha	2	0	0	0	66.7	33.3	0.0	30	LC	LC	DE
Clupisoma garua	21	24	13	10	64.3	27.8	7.9	26	LC	EN	DE
Pseudeutropius artherinoides	44	23	16	15	69.4	28.6	2.0	8	AB	LC	AB
Silonia silondia	1	0	0	0	100	0.0	0.0	79	LC	LC	UN
Siluridae											
Ompok bimaculatus	15	13	7	3	62.9	29.0	8.1	25	NT	EN	UN
Ompok pabda	6	4	1	0	66.7	33.3	0.0	16	NT	EN	DE
Ompok pabo	1	0	0	0	87.9	12.1	0.0	24	NT	CR	DE
Wallago attu	7	2	0	0	96.7	0.0	3.3	180	NT	VU	DE
Pangasiidae											
Pangasius pangasius	3	1	1	0	100	00	00	120	LC	EN	DE

BD, Bangladesh; [1], Rahman (2005); [2], IUCN (2016); [3], IUCN Bangladesh (2015); AB, Absent; DD, Data Deficient; DE, Decreasing; EN, Endangered; NN, Non-native; LC, Least Concern; NT, Near Threatened; ST, Stable; UN, Unknown; VU, Vulnerable.

TABLE 3 Comparison between standardised total effort-standardised catches of groups of species of conservation importance at upstream (sites 1 and 2 combined) and downstream sites (sites 3 and 4 combined), categorised on the basis of their IUCN conservation status globally and in Bangladesh.

Considerations	**Categories**	***n species***	***Fish abundance (Mean ± SD)***		***Comparison***	
			Upstream	***Downstream***	***F***	***P-value***
Global conservation	LC	37	230.4±45.9	144.9±68.6	15.44	<0.01
	NT	07	7.6±3.2	1.7±2.6	38.84	< 0.001
Local or national (Bangladesh) conservation	LC	26	190.6±39.2	120.2±56.4	14.33	< 0.001
	NT	05	31.0±8.6	17.8±13.5	17.95	< 0.001
	VU	06	15.6±5.6	8.4±6.8	37.25	< 0.001
	EN	08	8.5±2.8	2.7±3.2	32.40	< 0.001

EN, Endangered; LC, Least Concern; NT, Near Threatened; VU, Vulnerable.

TABLE 4 List of wetland birds occurring in the Chalan Beel and changes in their abundance in the last 20 years, based upon focus groups and interviews.

Taxa	Vernacular name	Scientific name	Residence type	Local breeding	Population trend	Conservation	
						Global[1]	BD[2]
Accipitriformes							
Accipitridae	Black kite	*Milvus migrans* (Boddaert, 1783)	Permanent	Yes	?	LC	LC
Pandionidae	Osprey	*Pandion haliaetus* (Linnaeus, 1758)	Migratory	No	?	LC	LC
Anseriformes							
Anatidae	Lesser whistling-duck	*Dendrocygna javanica* (Horsfield, 1821)	Unknown	UN	↓	LC	LC
Anatidae	Gadwall	*Mareca strepera* (Linnaeus, 1758)	Migratory	No	↓↓	LC	LC
Anatidae	Common shelduck	*Tadorna tadorna* (Linnaeus, 1758)	Migratory	No	↓	LC	LC
Charadriiformes							
Jacanidae	Pheasant-tailed jacana	*Hydrophasianus chirurgus* (Scopoli, 1786)	Permanent	Yes	↓	LC	LC
Scolopacidae	Dunlin	*Calidris alpina* (Linnaeus, 1758)	Permanent	Yes	↓↓	LC	LC
Scolopacidae	Little stint	*Calidris minuta* (Leisler, 1812)	Migratory	No	↓↓	LC	LC
Scolopacidae	Temminck's stint	*Calidris temminckii* (Leisler, 1812)	Migratory	No	↓↓	LC	LC
Scolopacidae	Common greenshank	*Tringa nebularia* (Gunnerus, 1767)	Permanent	Yes	↓	LC	LC
Coraciiformes							
Alcedinidae	Common kingfisher	*Alcedo atthis* (Linnaeus, 1758)	Permanent	Yes	↓	LC	LC
Alcedinidae	White-breasted kingfisher	*Halcyon smyrnensis* (Linnaeus, 1758)	Permanent	Yes	↓	LC	LC
Alcedinidae	Stork-billed kingfisher	*Pelargopsis capensis* (Linnaeus, 1766)	Permanent	Yes	↓	LC	LC
Ciconiidae	Asian open-bill stork	*Anastomus oscitans* (Boddaert, 1783)	Permanent	Yes	↓	LC	LC
Ciconiidae	Black-necked stork	*Ephippiorhynchus asiaticus* (Latham, 1790)	Permanent	Yes	↓	NT	EN
Pelecaniformes							
Ardeidae	Great white egret	*Ardea alba* (Linnaeus, 1758)	Permanent	Yes	↓	LC	LC
Ardeidae	Intermediate egret	*Ardea intermedia* Wagler, 1829	Permanent	Yes	↔	LC	LC
Ardeidae	Purple heron	*Ardea purpurea* Linnaeus, 1758	Permanent	Yes	↓	LC	LC
Ardeidae	Indian pond-heron	*Ardeola grayii* (Sykes, 1832)	Permanent	Yes	↓	LC	LC
Ardeidae	Cattle egret	*Bubulcus ibis* (Linnaeus, 1758)	Permanent	Yes	↓	LC	LC
Ardeidae	Green backed heron	*Butorides striata* (Linnaeus, 1758)	Permanent	Yes	↓	LC	LC
Ardeidae	Little egret	*Egretta garzetta* (Linnaeus, 1766)	Permanent	Yes	↓	LC	LC
Podicipediformes							
Podicipedidae	Little grebe	*Tachybaptus ruficollis* (Pallas, 1764)	Permanent	Yes	↓↓	LC	LC
Suliformes							
Phalacroco-racidae	Little cormorant	*Microcarbo niger* (Vieillot, 1817)	Permanent	Yes	↓	LC	LC
Phalacroco-racidae	Indian cormorant	*Phalacrocorax fuscicollis* Stephens, 1826	Permanent	Yes	↔	LC	LC

↑, Increase; ↔, stable; ↓, Decrease; ↓↓, Decrease and rare; ?, Unknown; 1, IUCN (2016); 2, IUCN Bangladesh (2015); AB, Absent; EN, Endangered; LC, Least Concern; NT, Near Threatened; VU, Vulnerable

TABLE S1 Results of the SIMPER analysis showing response of native taxa to the sluice gate operational status and their contribution to the overall variation (for 'sluices closed' condition only) based on Bray-Curtis dissimilarity index.

Species	***Fish CPUE when sluices not in operation (Open)***			***Fish CPUE when sluices in operation (Closed)***			
	Up	***Down***	***P-value***	***Up***	***Down***	***P-value***	***Contribution (%)***
Chanda nama	11.7	12.2	0.937	22.3	9.9	0.001***	12.9
Mystus tengara	16.8	16.4	0.626	13.4	4.0	0.001***	10.2
Puntius sophore	13.1	14.1	0.987	13.1	5.9	0.002**	7.9
Parambassis ranga	12.1	8.9	0.109	10.3	3.5	0.001***	7.1
Xenentodon cancila	1.6	1.1	0.170	5.9	0.2	0.001***	6.1
Glossogobius giuris	3.1	1.3	0.030*	5.9	0.3	0.001***	5.9
Salmophasia bacaila	5.6	6.2	0.748	6.5	2.0	0.004**	4.8
Salmophasia phulo	7.4	7.4	0.985	6.7	2.4	0.004**	4.6
Channa punctata	0.9	1.9	0.088	4.4	0.6	0.001***	4.3
Mystus cavasius	5.2	3.6	0.098	4.6	0.7	0.001***	4.2
Amblypharyngodon mola	8.4	8.4	0.818	7.4	4.0	0.001***	3.8
Pseudeutropius artherinoides	2.3	1.8	0.647	2.6	0.2	0.001***	2.5
Esomus danricus	4.1	2.8	0.167	3.7	1.7	0.004**	2.3
Gudusia chapra	5.3	4.1	0.140	4.2	3.6	1.000	2.2
Ailia coila	1.4	0.8	0.034*	1.8	0.1	0.001***	1.9
Clupisoma garua	1.3	1.3	0.968	2.0	0.3	0.001***	1.9
Trichogaster fasciata	1.3	1.9	0.035*	2.0	0.4	0.001***	1.7
Cirrhinus reba	2.7	1.9	0.311	1.7	0.3	0.001***	1.5
Trichogaster lalius	0.8	0.8	0.857	1.3	0	0.001***	1.4
Macrognathus aculeatus	0.8	0.1	0.005**	1.3	0	0.001***	1.4
Aspidoparia morar	1.1	0.4	0.009**	1.3	0	0.001***	1.3
Puntius ticto	0.8	0.3	0.123	1.2	0	0.001***	1.2
Setipinna phasa	0.2	0.1	0.225	1.0	0	0.001***	1.1
Ompok bimaculatus	1.0	0.6	0.188	1.0	0	0.001***	1.1
Mastacembelus pancalus	0.1	0.1	0.964	0.8	0	0.001***	0.9
Parambassis lala	0.3	0.0	0.062	0.8	0	0.001***	0.9
Labeo bata	1.4	0.1	0.001***	0.8	0	0.001***	0.8
Sperata seenghala	0.3	0	0.048*	0.7	0	0.001***	0.7
Ompok pabda	0.2	0.1	0.164	0.6	0	0.001***	0.7
Rita rita	0.3	0	0.011*	0.6	0	0.001***	0.6
Puntius sarana	0	0	1	0.5	0	0.001***	0.6
Wallago attu	0.3	0	0.060	0.4	0	0.001***	0.4
Sperata aor	0	0	1	0.2	0	0.001***	0.2
Catla catla	0.1	0.1	0.964	0.2	0	0.001***	0.2
Labeo rohita	0.1	0	0.071	0.2	0	0.001***	0.2
Lepidocephalus guntea	2.3	1.7	0.528	0.1	0.1	1	0.2
Labeo calbasu	0.4	1.0	0.002**	0.2	0	0.001***	0.1
Tenualosa ilisha	0	0	1	0.1	0	0.001***	0.1
Mastacembelus armatus	0.3	0	0.008**	0.1	0	0.001***	0.1

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

TABLE S2 List of wetland birds, formerly present but now possibly extinct from the Chalan Beel region

Order	Family	Vernacular and scientific name	Residence type	Conservation Global[1]	Conservation BD[2]
Accipitriformes	Accipitridae	Grey-headed fish eagle; *Ichthyophaga ichthyaetus* (Horsfield, 1821)	Permanent	AB	NT
Anseriformes	Anatidae	Pintail; *Anas acuta* Linnaeus, 1758	Migratory	LC	LC
Anseriformes	Anatidae	Greylag goose; *Anser anser* (Linnaeus, 1758)	Migratory	LC	LC
Anseriformes	Anatidae	Ferruginous duck; *Aythya nyroca* (Güldenstädt, 1770)	Migratory	NT	NT
Anseriformes	Anatidae	Indian spot-billed duck; *Anas poecilorhyncha* Forster, 1781	Permanent	LC	LC
Coraciiformes	Alcedinidae	Blue-eared kingfisher; *Alcedo meninting* Horsfield, 1821	Permanent	LC	LC
Charadriiformes	Burhinidae	Great thick-knee; *Esacus recurvirostris* (Cuvier, 1829)	Permanent	NT	NT
Ciconiiformes	Ciconiidae	Painted stork; *Mycteria leucocephala* (Pennant, 1769)	Migratory	NT	CR
Pelecaniformes	Ardeidae	Grey heron; *Ardea cinerea* Linnaeus, 1758	Permanent	LC	LC
Pelecaniformes	Ardeidae	White-bellied heron; *Ardea insignis* Hume, 1878	Unknown	CR	RE
Suliformes	Phalacroc-oracidae	Great cormorant; *Phalacrocorax carbo* (Linnaeus, 1758)	Unknown	LC	LC

1, IUCN (2016); 2, IUCN Bangladesh (2015); AB, Absent; CR, Critically Endangered; EN, Endangered; LC, Least Concern; NT, Near Threatened; RE, Regionally Extinct; VU, Vulnerable

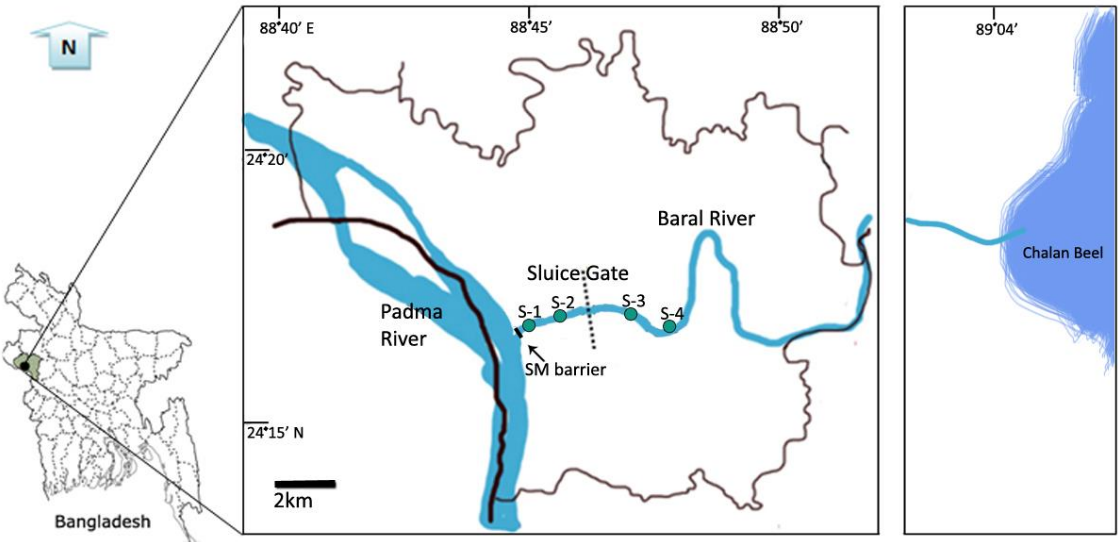

FIGURE 1 Map of the Baral River showing sampling sites (S-1 to S-4) on both sides of the sluices. This river originates from the Padma River (upstream of sluices) and runs through the Chalan Beel, the largest wetland of Bangladesh (indicated in the right-hand panel, downstream). SM barrier refers to location of a bank sand and mud built at the mouth of the Baral to facilitate sand extraction from the Padma – this was entirely submerged throughout the sampling period mid-May to December, but is a physical barrier through the dry season, January to April.

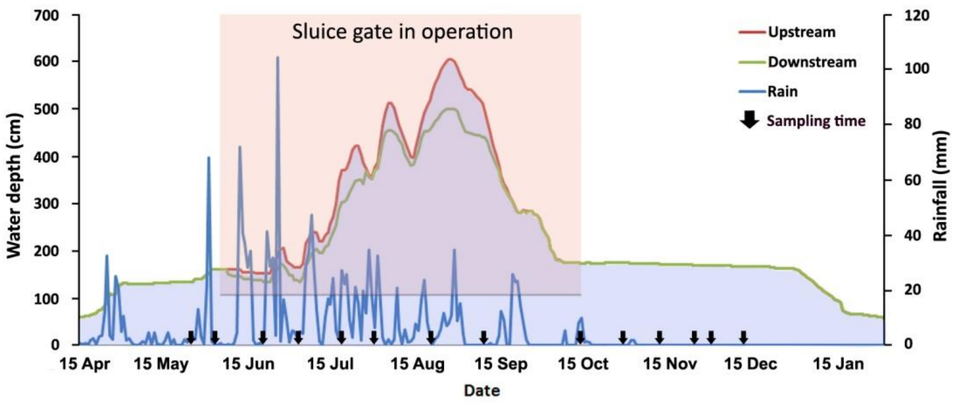

FIGURE 2 Mean water depth immediately upstream and downstream of the sluices in the Baral River over the study period. Daily rainfall is also shown. During the period of sluice operation (shaded box) the sluice gates were 1 m above the sill, whereas before and after the gates were raised above water level, as in Figure S2. Fish sampling dates are shown by arrows.

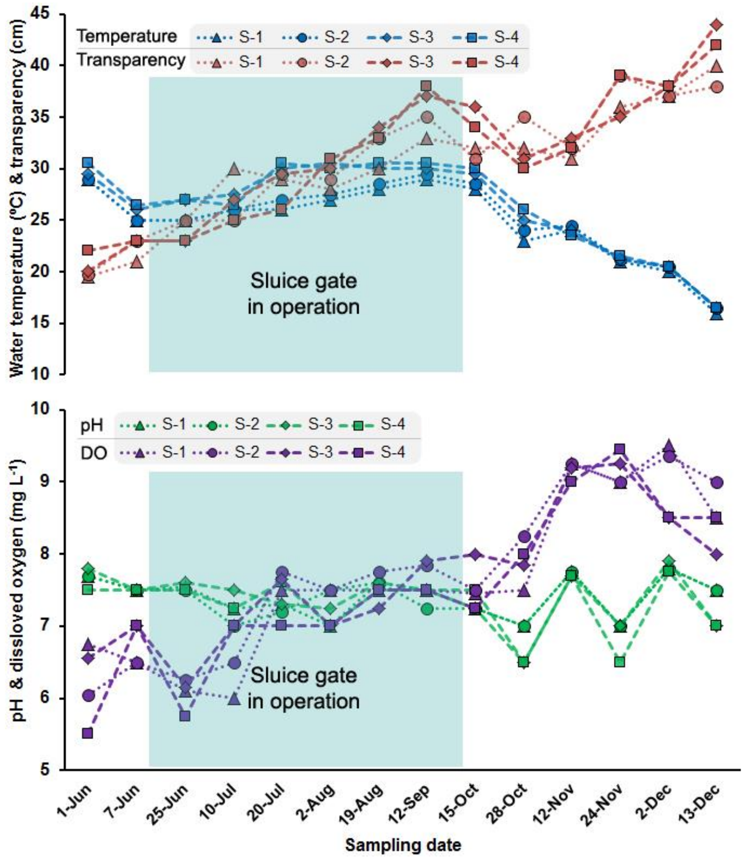

FIGURE 3 Physical (above) and chemical (below) parameters of water at four study sites (S-1 to S-4) in the Baral River from June to December 2015.

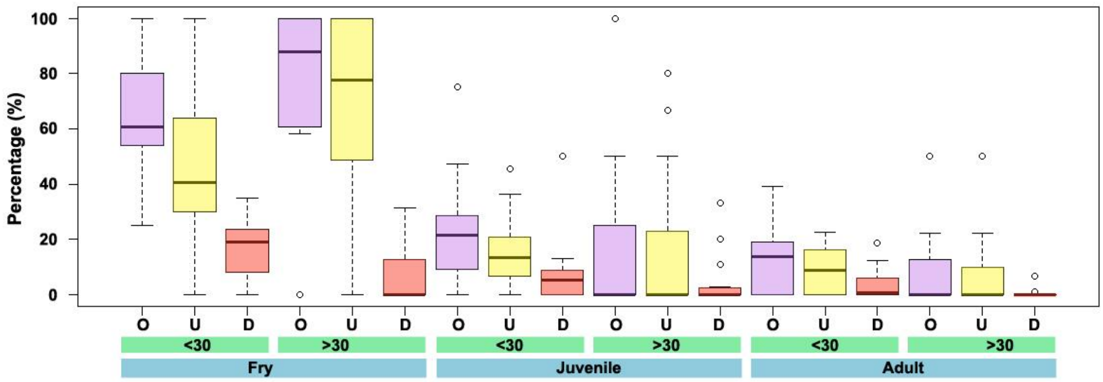

FIGURE 4 Characteristics of total survey catch, based on the maximum length and life stages of fish species in the Baral River. <30 indicates the small-sized fish species that do not grow beyond 30 cm; whereas, >30 represent those species that grow to more than 30 cm in Bangladesh. O, U and D refer to overall, upstream and downstream respectively. Midline within the box is the median; upper and lower limits of the box represent the third and first quartile (75th and 25th percentile) respectively.

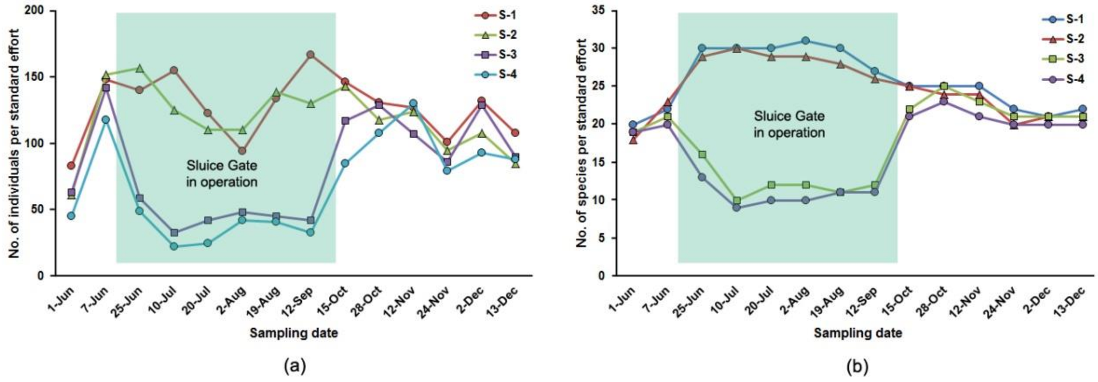

FIGURE 5 Variation in fish abundance (as Catch Per Unit Effort) (a) and species richness (b) between different sampling sites before, during and after the flooding period (June-December) in the River Baral. The period over which the sluices were partially closed is shown by the shaded area. Sites 1 and 2 are upstream of the sluices, sites 3 and 4 are downstream of the sluices.

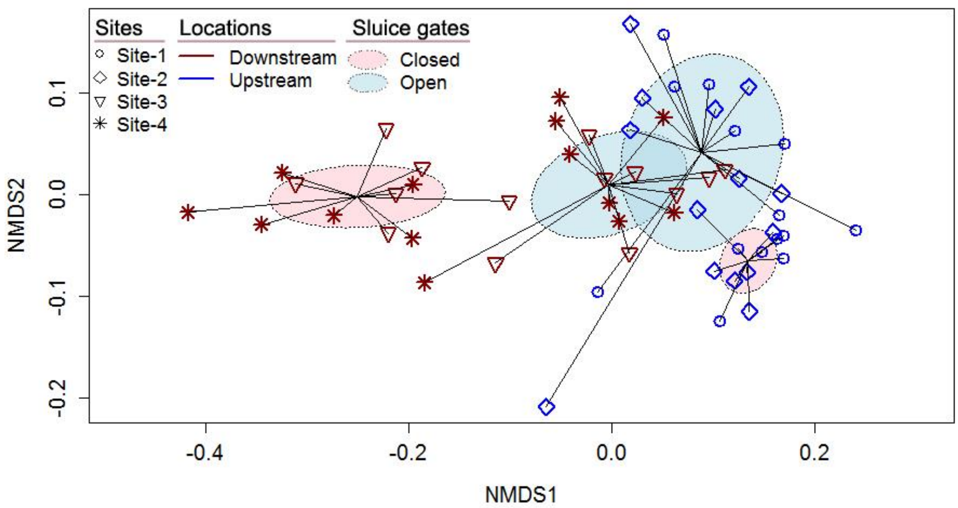

FIGURE 6 Non-metric multidimensional scaling (NMDS) ordination plot showing spatial variation of fish abundance in relation to sluice gate operational status in the Baral River.

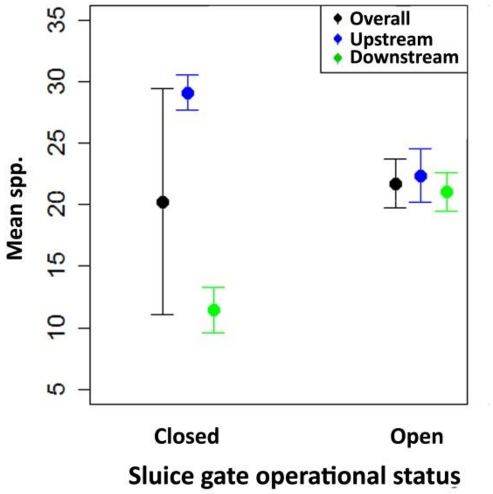

FIGURE 7 Number of fish species (Mean ± SD) occurrence on each side of the sluices in relation to gate operational status.

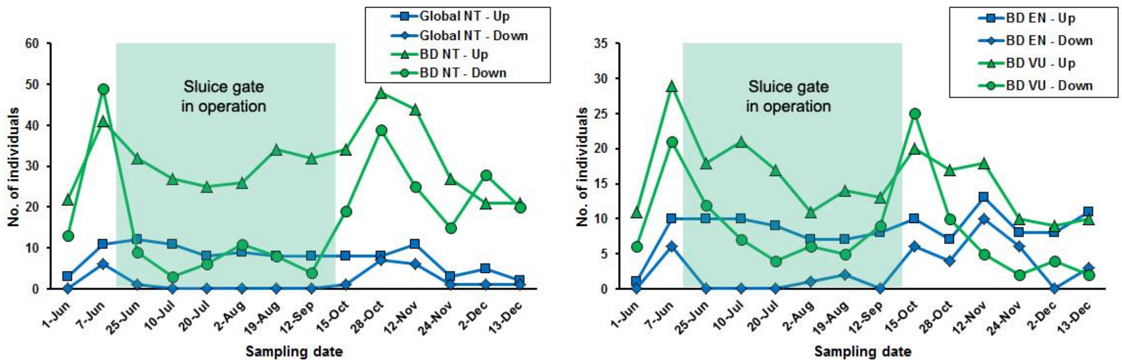

FIGURE 8 Spatial and temporal variation in CPUE (catches combined over full study period) of fishes belonging to selected global and national (BD) conservation categories upstream and downstream of the sluices on the Baral River (Down, Downstream; EN, Endangered; NT, Near Threatened; Up, Upstream; VU, Vulnerable).

FIGURE S1 The sluice gates at the Baral River, ~2 km downstream from its origin at the Padma River. Photograph was taken in January, at the start of the dry season.

FIGURE S2 The sand-mud barrier built across the Baral River (right of image) to facilitate sand mining from the Padma River (top left of image)