Understanding the effects of trans-boundary barrage operations on the Nepal-India border for Ganges river dolphin habitat and population dynamics

Final Report Submitted to the IWC Small Cetacean Fund

by

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Note about river names: Throughout the report, we follow a joint naming system with the Nepalese name of the river mentioned first, followed by hyphen and Indian name (e.g. Narayani-Gandak is used to refer to the Narayani or Gandak river). The joint names may be abbreviated occasionally by the two first letters of each name.

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Executive Summary

The survival of endangered Ganges river dolphins *Platanista gangetica* and the availability of suitable habitat in dam-regulated rivers has been an important conservation concern. In trans-boundary river basins of South Asian countries, availability of habitat for remnant populations of these river dolphins is directly determined by water sharing mechanisms, intensity of human demands on freshwater, and dam/barrage operations that regulate and alter seasonal flow regimes. In Nepal, Ganges river dolphins occur in small remnant populations (total < 50 dolphins) in three trans-boundary rivers: Karnali-Ghaghra, Narayani-Gandak, and Koshi-Kosi. On these rivers, three barrages have been built on the India-Nepal border to divert the river water for irrigation needs and hydropower generation. These barrages, completed by the 1970s, may have caused fragmentation of river dolphin population connectivity upstream and downstream. However, there have been no studies on how the operation of these barrages would exactly affect the upstream and downstream populations of Ganges river dolphins and river habitat availability. In this project, we addressed this knowledge gap through an investigation of 1) river dolphin population dynamics in river channels upstream and downstream of barrages, 2) past reports of river dolphin occurrence in isolated upstream reaches, 3) river flow and water level trends upstream, at-barrage, and downstream sites, 4) barrage operation schedules, design comparisons, and annual flow releases into the river and canals, 5) assessments of major flooding events, 6) analysis of reach-averaged hydraulic habitat at-barrage for river dolphins to determine optimum discharge releases, and 7) identification of time-windows of opportunity for river dolphins to pass through barrages, based on flow release operations and magnitudes.

Based on the above analyses and data, we concluded that there may be significant trade-offs involved in barrage operations to provide downstream ecological flows and maintain upstream habitat for Ganges river dolphins. In recent years, barrage operations may be increasing flows downstream, due to higher inflows in the flood and dry-season coupled with barrage inefficiencies and sedimentation-related problems in barrage infrastructure. Under climate change scenarios of increased glacial melt and extreme rain events, these changes are likely to intensify, benefitting river dolphin conservation in India but negatively affecting Nepal's river dolphins; at least in the short-term. Our analysis identifies river discharges and water impoundment area management thresholds that could help optimize maintenance of upstream and downstream habitats for river dolphins. The inferences and insights from our study can help inform future research on engineering efficiency, river sediment flux management, barrage retrofitting designs, as well as future trans-boundary water management and conservation planning for Ganges river dolphins in Nepal and India.

Introduction

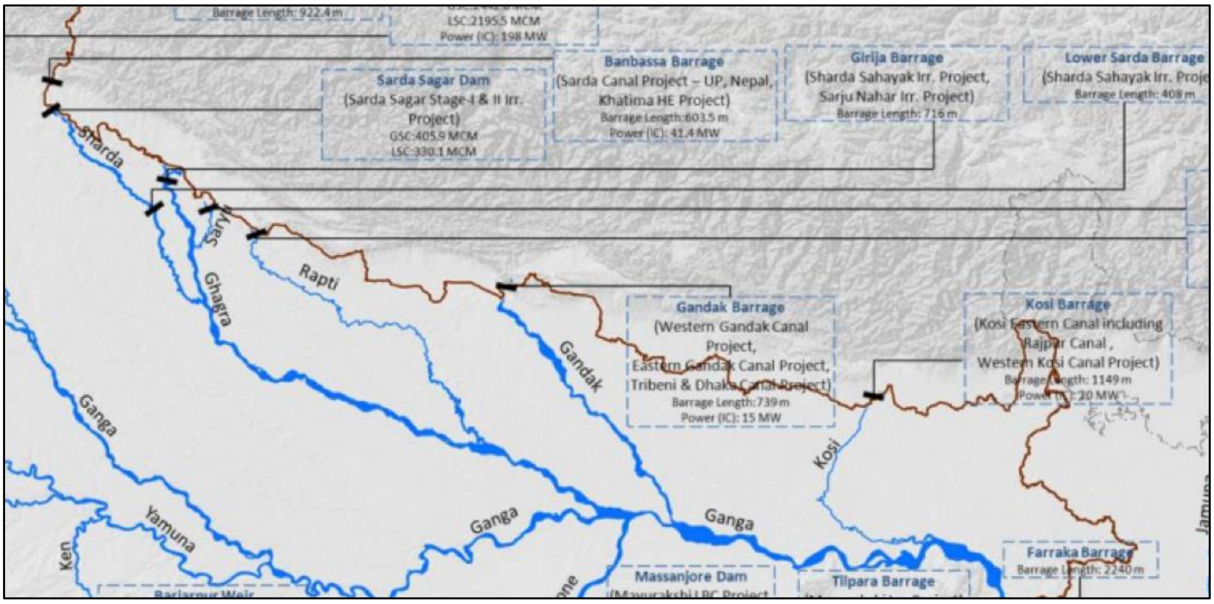
The survival of endangered riverine species in regulated international or trans-boundary rivers depends on water governance mechanisms and policies between the countries sharing their waters. Dams and barrages that are operated to provide for proportionate water allocations between countries directly determine the amount of remaining water available as river flows, both upstream and downstream (Pun 2013). Water sharing treaties often operate under inequities caused by geopolitics, upstream-downstream biophysical differences, and the economic clout and power of the participating countries (Crow & Singh 2000, Baten & Tutimir 2016, Surinaidu et al. 2020). As the longitudinal connectivity of transboundary rivers is directly affected by impoundments and diversions, population persistence of riverine species in upstream or downstream reaches can be compromised. In South Asia, water sharing between countries has been a complicated affair given the political history of the Indian subcontinent (Salman & Uprety 2021). Examples are seen in the Indus Waters Treaty (1960) between India and Pakistan, India-Nepal water sharing on multiple rivers: Mahakali, Narayani, etc. the Indo-Bangladesh Water Sharing Treaty (1996) over the Ganges waters regulated by the Farakka barrage built in 1975. Recent studies in India, on endangered species such as the endangered Indus and Ganges river dolphins surviving in transboundary river basins, have illustrated the control of historical factors of water sharing treaties on river dolphin habitat and population persistence (Momblanch et al. 2021, Samad et al. 2022). Trans-boundary barrages were constructed on rivers from the 1950s onwards along the Nepal-India border, for the purposes of water sharing for canal irrigation, flood control, and hydropower generation between the countries (Pun 2013, Maharjan 2018, Dixit 2018). The barrages constructed on three important rivers of the Gangetic plains: Karnali-Ghaghra, Narayani-Gandak, and Sapta Koshi-Kosi, led to fragmentation of riverine habitats for Ganges river dolphin populations upstream and downstream (Smith & Smith 1998, Smith et al. 2000, Paudel et al. 2021, Campbell et al. 2022, Kelkar et al. 2022).

For Nepal, the persistence of the small river dolphin populations within its borders is a really urgent and important conservation priority. The total number of dolphins in Nepal's floodplain rivers may not more be than 40-50 individuals across the three rivers round the year (WWF-Nepal 2006, Paudel et al. 2015, 2016a; Shrestha & Ranjan 2023, Labh 2023), including river dolphins that may migrate upstream during the flood-season from lower reaches in India (Shah et al. 2020). Maintaining these small populations has also been a foremost priority of Nepal's recently developed Dolphin Conservation Plan (2021). The IWC Scientific Committee's task team on South Asian River Dolphins, in its 2020 report (South Asian River Dolphin Task Team 2020), recommended that: "As a priority, studies should be conducted to fully understand movements of dolphins across barrages in all countries and quantify the extent of population connectivity and impacts on dolphin populations in fragmented riverine habitats." The need for studies on effects of river barrages and flow modification on dolphin habitats, seasonal movements, population persistence, and clustering of threats was emphasized by the latest IUCN Red List assessment for Ganges river dolphins (Kelkar et al. 2022) and the Convention on Migratory Species Report (CMS 2020). Over the years, India and Nepal have regularly acknowledged in bilateral dialogues the need to extend transboundary cooperation not only for water and power sharing, but also for biodiversity conservation. Such plans and meetings have been organized for terrestrial wildlife conservation, especially for rhinoceros and tigers in the contiguous Bardia-Katerniaghat-Dudhwa and Chitwan-Valmiki tiger conservation areas (Talukdar & Sinha 2013, Chanchani et al. 2014, Liu et al. 2020). However, for freshwater species, most plans have not yet been formulated or implemented (Khatiwada et al. 2021).

A key aspect of transboundary river wildlife conservation is related to the hydrological operations and management of barrages on the shared rivers between India and Nepal (Figure 1). The Karnali-Ghaghra stretch upstream of the barrage holds a population of 30-40 dolphins (including stretches in Nepal and India), the Narayani-Gandak may hold only 1 to 3 upstream of the Triveni (Gandak) barrage in Nepal, and the Koshi-Kosi holds 15-20 dolphins, which are restricted only to the river stretches downstream of the Birpur (Koshi) barrage (barring the river dolphins that may be occasionally seen upstream in the Kosi Tappu Wildlife Reserve in the flood-season months). These estimates have come from a substantial body of work on population status, in-stream habitat availability, and major conservation threats faced by Ganges river dolphins in Nepal (Shrestha, 1989; Smith, 1993; Smith et al. 1994; WWF-Nepal 2006; Khatri et al., 2010; Paudel *et al.*, 2015, 2020a, 2020b; Khanal *et al.*, 2016; Shah & Paudel 2016, Shah et al., 2020). The lengths of river stretches within in India and Nepal, upstream of the barrages, are also different. Interestingly, though the three rivers are roughly similar in mean annual discharge, rainfall-runoff dynamics, and geomorphology, the barrages seem to have had differential impacts on river dolphin habitats and population connectivity/persistence. The need for trans-boundary conservation planning to protect the small populations of Ganges river dolphins in Nepal has been felt from a long time (Smith et al., 1994; WWF-Nepal 2006; Khanal et al., 2016). Such planning hinges on the effective understanding of how water-sharing agreements are managed and barrages are operated on the three shared rivers between the two countries, where river dolphins still persist (Rai et al. 2023). In the last few years, studies on e-flows, and hydraulic habitat assessments on river biodiversity conservation have been conducted in Nepal (Paudel et al. 2021, Smakhtin et al. 2006). Yet, hydrological studies of barrage operation impact on upstream river dolphin populations have not been assessed in detail.

The operating schedules, water demand-supply dynamics, and engineering decision-making about barrage operations, may have enabled or constrained Ganges river dolphin habitats in the three river reaches of concern. There may be significant inter-annual variability between upstream-downstream connectivity and probability of passage due to flood strength and barrage gate opening periods[1]. Our project aimed to identify, by combining seasonal field surveys of river dolphins and habitat availability with hydrological studies on barrage operations: 1) what hydraulic and hydro-geomorphic factors and barrage operations may allow for river dolphin movement from downstream to upstream in particular, 2) what operations maintained adequate water area and depth upstream of the barrages for river dolphins, and 3) how seasonal differences in barrage operating schedules may affect inter-annual and seasonal residency patterns of river dolphins in Nepal. The study's primary contribution lies in its detailed comparative assessment of the windows of opportunity that the three barrages might offer to river dolphin movement and upstream habitat maintenance, based on their engineering similarities or differences. We have also systematically compiled river dolphin occurrence data from past information and our own river dolphin surveys for specific river reaches in Nepal. Our assessment also makes it possible to understand trade-offs between upstream and downstream habitat availability resulting from river flow regulation and diversion decisions made at the barrage level. Based on observed hydrological trends, it is possible to make future predictions about river dolphin population persistence in Nepal, which was the primary motivation of our project.

Figure 1. Barrages on rivers along the India-Nepal border. Source: National Mission for Clean Ganga, Govt. of India.



[1] Barrages are large dam-like structures on floodplain rivers with low flow gradients. They operate through a series of gates, whose closing or opening allow water releases into canals or rivers round the year. They differ from dams in that they typically do not involve much water storage in the upstream reservoir. See Samad et al. (2022) for details.

Methods

Study Area

The three major rivers flowing along the India-Nepal border and with year-round occurrence of Ganges river dolphins that we focused on were the Karnali-Ghaghra, Narayani-Gandak, and Koshi-Kosi. These three rivers are among the five largest tributaries of the Ganges by river discharge and are Himalayan/ Tibetan in their origins (Gyawali 2001, Hannah et al. 2005, India-WRIS 2014). The Karnali-Ghaghara hosts the westernmost resident population of river dolphins in Nepal and passes through Bardia National Park (NP) in Nepal and Katernighat Wildlife Sanctuary (WLS) in India (Shrestha et al. 2010). The Narayani-Gandak river flows through the Chitwan NP in Nepal and Valmiki Tiger Reserve in India, and the Koshi-Kosi river flows through the Kosi Tappu WLS in Nepal, upstream of the Koshi (Birpur) barrage. In contrast to Karnali-Ghaghra where the barrage is located completely within India (20km downstream (south) of India-Nepal border), the barrages on the Narayani-Gandak and Koshi-Kosi lie at the Indo-Nepal border. In the Koshi-Kosi, a western channel of the river (20 km river distance) falls in Nepal's boundaries, i.e., under Nepal's authority. As of 2022-23, the Narayani-Gandak has very few river dolphins (0 to 3 max.) reported in the river in Nepal upstream of the Triveni barrage, while the Koshi-Kosi upstream of the barrage recorded dolphins only occasionally in the flood-season. A channel of the Koshi-Kosi flowing through Nepal, downstream of the barrage, has a small population of 10-15 river dolphins (Paudel 2022, Labh 2023). The Karnali-Ghaghra basin to the west is the largest, followed by the Koshi-Kosi (easternmost), and the Narayani-Gandak (central), in terms of catchment area and mean annual river flow. However, in terms of annual rainfall, there is a west-east gradient of increase, with the Koshi-Kosi basin having the highest of the three (Hannah et al. 2006). There are three barrages located at or near the India-Nepal border, one on each of these rivers. Table 1 provides the basic details of these river catchments. Even though other regulated rivers such as Mohana, Bagmati, Rapti, Mahakali-Sharda, and associated streams have had rare reports of river dolphin occurrence, these have been strictly during the monsoon flood-season when the rivers are in spate (Shah et al. 2020), and cannot be included in the minimum population size for Nepal. We too excluded these rivers from our hydrological studies. Local informants reported seeing Ganges river dolphins in the monsoon months in the Rapti river (tributary of the Narayani) over 30 years ago. However, the present hydrological conditions in the river make this impossible today even in the flood-season.

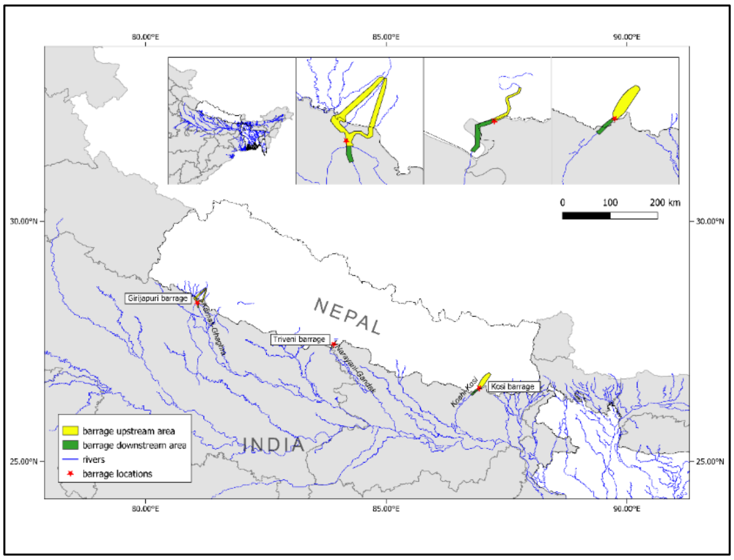
Table 1. A comparison of the three river basins studied in our project (also see Figure 2).

River	Karnali-Ghaghra	Narayani-Gandak	Koshi-Kosi
Origin	Mapchachungo Glacier, Tibet	Nhubine Himal Glacier, Nepal Himalaya	Sun Kosi, Arun, and Tamur river catchments along Tibetan

			plateau, Himalayas, Himalayan mid-hill belt, Siwalik hills
Length (km)	1080	814	740
Length (km, in India)	672	300	248
Catchment area (km²)	127,950	46,300	74,500
Annual rainfall (mm)	1200	1125	1456
Mean annual flow (m³/s)	~3,000	~2,025	~2,500
Dry-season flow (m³/s, Nov-May)	~500	~520	~750
Barrage name and location	Girijapuri or Kailashpuri barrage (Nanpara, India)	Triveni (Valmikinagar), India-Nepal border	Birpur (Bhimnagar), India-Nepal border

The three rivers have deep gorges and flow down along steep slopes of the Nepal Himalaya and carry huge amounts of sediment. The sediment is deposited along the Terai plains where these river valleys show a rapid reduction in gradient, losing energy and leading to large-scale silt deposition and massive flooding in the Nepal plains and the Indian states of Uttar Pradesh and Bihar (Adhakari 2013, Dhar & Nandargi 2002). The sediment concentrations further carried down the valleys of the now-floodplain rivers into India remain quite large. The three basins, based on shape and energy gradient, have been described as “riding piggyback” on the river floodplain (Densmore et al. 2016), where the river channel is the most well-defined. The barrages built along the three rivers are operated based on India-Nepal water sharing treaties mainly for irrigation, hydropower generation, and flood control. Details of the water sharing arrangements have been described in Dixit (2018) and Pun (2013). To meet these allocations, the barrages have seasonal operating schedules to divert river water and supply it through widespread canal networks. The canals were designed to irrigate kharif and rabi crops (summer monsoon: Jun-Oct and winter crops: Dec-Mar) in India, and generate hydropower. The barrages also have one or two 15-day to 1-month periods (in the post-monsoon and early summer) for release of water into the river downstream with the main purpose of sediment flushing from the barrage gates and under-sluices. At all other times, most gates of the barrages are shut for achieving the targeted storage and water diversions to the canal network.

Figure 2. The locations of the three rivers, barrages and corresponding river stretches along the India-Nepal border included in our study.



Ganges river dolphin surveys

We conducted river dolphin distribution and abundance surveys in the upstream (Nepal) and downstream (India) reaches of the three river systems: Karnali-Ghaghara, Narayani-Gandak and Koshi-Kosi in the dry-season, in the duration of the project (2021-23, barring the COVID-19 affected months in 2021-22). For surveys in the Karnali-Ghaghra stretches in Nepal and India, and the Koshi-Kosi stretch downstream of the barrage, the methodology of Smith & Reeves (2000) of a boat-based single-observer team was followed. The details of our survey method are provided in Khanal et al. (2016). In the Karnali-Ghaghra, the surveyed stretch was around 120 km upstream of the barrage. This included around 80 km within Nepal boundary (46 km in Karnali channel and 34 km in Geruwa channel) and about 40 km in India (20 km Gerua channel and 20 km in Kaudiyala channel). The Karnali channel in Nepal follows into Kaudiyala channel in Nepal whereas Geruwa channel in Nepal follows into Gerua channel in India. Both channels meet ~ 1 km upstream of the barrage and are barrage backwater-affected channels. These surveys were carried out in February 2022, October 2022, and March-April 2023 to cover the different seasons' water levels. In May 2023, the entire length of the Karnali-Ghaghra River in India downstream of the barrage (627 km) was surveyed for Ganges river dolphins using double-observer surveys (see Braulik et al. 2012a, Kelkar & Dey 2021 for methodological details). For the Narayani-Gandak and Koshi-Kosi, distances of 60 km and around 40 km respectively, were covered upstream of the barrages in Nepal and India. In these rivers, due to the very low abundance of river dolphins and the extent of the protected areas, short stretches were covered by boats to look out for dolphins. The larger area was covered through bank-based surveys and visits to spots where river dolphins had been recorded by local informers. Local informers included park wardens, foresters, rangers, tourists, and other conservationists and scientists working along the respective river stretches. The Narayani-Gandak stretch was surveyed in April 2022 and April-May 2023, and the Koshi-Kosi stretch downstream of the barrage was surveyed in March 2023.

We surveyed the Gandak river stretch in India downstream of the barrage (290 km) in November 2022 and the Kosi in India downstream of the barrage (232 km) in February 2023. Table 2 provides a summary of the timeline of our survey effort.

We also collected information on any sightings or cases of river dolphin movement through any of the three barrages during the flood-season, from fishing communities and other informers located near barrage sites, to note whether they had observed river dolphins moving through barrages during water release and sediment flushing operations through the year. We also conducted some field visits and timed observations immediately upstream and downstream of barrages for river dolphins, during the peak flood-season (Aug-Sep 2022) at the Triveni barrage to check if any movement of Ganges river dolphins was possible through the barrages.

Table 2. Timeline of surveys and other data collection on river dolphin abundance and distribution in the study river stretches.

River stretch | Months	Jan-May 2022	Jun-Sep 2022	Oct-Dec 2022	Jan-May 2023	Jun-Sep 2023	Oct-Dec 2023
Karnali-Ghaghra (Nepal, upstream of barrage)						
Karnali-Ghaghra (India, upstream of barrage)						
Ghaghra (India, downstream of barrage)						
Narayani-Gandak (Nepal, upstream of barrage)						
Narayani-Gandak (India, downstream of barrage)						
Koshi-Kosi (Nepal, upstream of barrage)						
Koshi-Kosi (Nepal, downstream of barrage)						
Koshi-Kosi (India, downstream of barrage)						

The Koshi barrage at Birpur on the India-Nepal border. A few river dolphins can be spotted immediately downstream of this barrage, around the year. Photo: Wikimedia.

Past data on river dolphin counts and occurrence records

A detailed literature review was conducted on river dolphin populations in the upstream reaches of the barrage, for the Nepal sections. The focus was on the upstream areas as river dolphins in those habitats are expected to be the most vulnerable to the impacts of barrage operations, where one-way downstream migration may happen and lead to loss of connectivity for upstream and downstream individual dolphins. Published papers, official reports, funding reports, news articles, travel websites, and social media pages were thoroughly scanned to record any river dolphin sightings and survey data from these reaches. Information was also collected from local conservationists, park officials and staff, tourist guides, tourists, scientists familiar with the area, local pilgrim boats, fishers, etc. The information obtained was tabulated with respect to year, to know the years when sightings were confirmed and in years when despite surveys, no dolphins were detected. We also recorded other information such as the exact details of the stretch surveyed, methods used, and opportunistic sighting details, to the extent possible. Upstream-barrage sighting years and seasonal information on dolphin occurrence were matched with hydrological data on river flow and water levels for the corresponding times and barrage operations, to qualitatively check if any correlations existed between them.

Hydrological time-series datasets

For the Nepal sections, we obtained monthly river discharge and stage (water-level) data from the Department of Hydrology and Meteorology, Government of Nepal, for three stations in Nepal: a) Chisapani on Karnali-Ghaghra, b) Devghat on Narayani-Gandak, and c) Chatara-Kothu on Koshi-Kosi, from 1970 to 2021. We obtained data for later years on river stage (water level) from satellite imagery-based sources such as the RADAR altimetry-based estimates (Zakharova et al. 2020) from Theia-Hydroweb (Papa et al. 2015, Crétaux et al. 2011, Frappart et al. 2006) and DAHITI (Schwatke et al. 2019).

For the barrages, we obtained river stage-discharge rating curves from available data in the public domain, from the Flood Management Information System (FMIS) of Water Resources Department, Govt. of Bihar, and the Irrigation and Water Resources Department, Govt. of Uttar Pradesh. For the Triveni and Birpur barrages (on the Narayani-Gandak and Koshi-Kosi rivers), we obtained year-round downstream river discharge and stage data and canal discharge/stage data for 2019 and 2023, and flood-season water level data from 2013 to 2023. For the Girijapuri barrage, we were able to obtain only flood-season water level data from 2018 to 2023, and some additional readings for the dry-season from 2020 and 2023 from the FMIS databases.

For sites downstream of the barrages in India, we obtained satellite altimetry-based water level data from 2003 to 2023 (from the same sources as above), and satellite microwave reflectance-based discharge estimates from 1998 to 2023 from RiverWatch 4.5 (Brakenridge et al. 2023, www.floodobservatory.colo.edu). Flood-season data from ground stations are made publicly available to users by the Central Water Commission, Government of India, and the FMIS of Uttar Pradesh and Bihar. However, dry-season flow data from ground stations are classified. We calibrated satellite-based estimates of trends in dry-season water levels and discharge from field measurements of hydrological cross-sections from selected downstream sites (see Rai et al. 2021).

For all three sections, we graphically assessed temporal and seasonal trends in water level and discharge data from the above data sources. Change-points in specific years were compared with information from our current surveys and past river dolphin occurrence reports in upstream-barrage sites, to check if larger floods or periods of extended river flow releases were correlated with years or seasons of upstream sightings. We compared trends of upstream and downstream flows and water levels, to see if inflows into barrages and outflows followed similar trends. If trends were similar, e.g. if both upstream and downstream water levels showed similar increases it could point to a greater incipient flow (perhaps due to climate-induced rainfall or snowmelt increases) to which the barrage operations are adapting. But if upstream flows were not showing an increase or decrease, yet downstream flows show increases, it could be interpreted either as inefficient barrage operations, or as improved environmental flows provided to the river stretches downstream.

Information on barrage operation schedules

We compiled information on the operating schedules of the three barrages in relation to canal diversions of water made to meet seasonal irrigation demand. The canals from all barrages irrigate summer-monsoon or *kharif* crops (e.g. rice, sugarcane) from June to October and winter or *rabi* crops (e.g. wheat) from November to March. Barrages also release water into the river downstream during the post-monsoon and dry-season for sediment flushing, usually in March-April and November. Additionally, we conducted interactions with senior hydrologists, engineers, and climate change experts on the operation of barrages in terms of adaptive management as well as in the context of India-Nepal water sharing agreements. We also obtained as many details of barrage engineering design as possible to evaluate flow passage operations from upstream to downstream.

Changes in barrage impoundment area

As a proxy for upstream water availability and deep-water habitat, we extracted barrage area from multi-temporal satellite images from the Global Surface Water Explorer tool (1984-2023) using Google Earth Engine. Temporal trends in monthly barrage-impounded area were examined to assess their effects on both upstream and downstream river dolphin habitats. For example, a decreasing trend in water impounded area was taken to indicate an increase in downstream water releases from the barrage, which could have tradeoffs for upstream habitat retention.

The Triveni barrage on the Gandak River in three seasons: February (top), June (middle), and November (bottom). All gates are closed until March 25th, although river flows are released in April and November, with most gates being opened. Photos: Nachiket Kelkar and Subhasis Dey.

Analyses of reach-averaged hydraulic habitat availability

At the three barrages, estimated reach-averaged hydraulic habitat for Ganges river dolphins based on the methods described by Gronsdahl et al. (2021) and Sonkar et al. (2020, 2022). We derived statistical relationships between depth, width, and river flow velocity to assess the level of discharge needed to be released for river dolphin habitat maintenance (based on their known in-stream habitat preferences) right below the barrages. For this we used the Geomorphic Instream Flow (A)ssessment Tool (GIFT) model (on an R Shiny app: https://sgronsdahl.shinyapps.io/GIFT/), which was parameterized with available data on average and minimum bankfull width and bankfull depth (Andreadis et al. 2013) and D84 (84th percentile of grain size distribution of river sediment, from literature, e.g. Rahaman et al. 2017, Dingle et al. 2016) for the surveyed sections. We also evaluated, based on the model cross-section output and site visits, the potential for channel geometry to be stably maintained in relation to sediment flushing management in relation to environmental/ecological flow management schedules. Sediment plugging at and damage to barrage gates is a well-known issue with barrages on Himalayan rivers, mainly due to massive sediment fluxes these barrages handle round the year (Collins & Hasnain 1995, Sinha et al. 2017, 2019).

Estimating windows of opportunity for through-barrage movements of Ganges river dolphins

From the long-term hydrological time-series data on the flood and dry-season flows and water levels, we estimated potential windows of opportunity where upstream-downstream movement may be possible for Ganges river dolphins. This was tried for all three barrages with available information on flood-season flow data, and for the Triveni and Birpur barrages with year-round flow data. A window of opportunity of passage was defined as those instances of data recorded where upstream water levels and downstream water levels differed by only less than 1 m, indicating that the river flow was levelled by the opening of the barrage gates. The corresponding discharge needed to maintain the level was also estimated from the barrage stage-discharge rating curves. The windows of opportunity were expressed as the probability (in % of time events) of an average-sized river dolphin being able to move through the barrage in one year. These assessments also helped compare the three barrages to understand the key factors and boundary conditions that could allow for higher connectivity of river dolphins upstream and downstream.

Based on the above assessments, we also discuss the fate of upstream-barrage dolphin populations in Nepal in particular, faced with scenarios of change in water availability from climate change, projected human water demand, and evolving trans-boundary water sharing and management decisions. Accordingly, the implications for current barrage management are discussed.

Downstream (top) and upstream (bottom) of Girijapuri barrage on the Karnali-Ghaghra. Photos: Local contact.

Results

Ganges river dolphin abundance estimates

The Karnali-Ghaghra river channels upstream of the barrage had a significant population of Ganges river dolphins, of which almost 88% (38 of 43) was within India as of April 2023. Within Nepal, the dolphins recorded in the Karnali and Geruwa are directly sourced from this population, and the fluctuating numbers in Nepal's Karnali and Geruwa channel appear to reflect seasonal differences in backwater area impounded by the barrage gate closure and opening schedules. In the dry-season, when the barrage gates are largely shut, the Karnali channel in Nepal recorded 5-7 dolphins, as against 3 in October when the barrage gates were open (Table 3). In contrast to the Karnali-Ghaghra system, the Narayani-Gandak and Koshi-Kosi had not more than 1 or 2 dolphins in the river stretch upstream of the barrages within Nepal's boundary (Table 3). The river dolphin populations downstream of the barrages in India ranged between 200 and 315 dolphins in these rivers, respectively. In the Koshi-Kosi, the 20 km Nepal channel downstream of the barrage had ~20 dolphins, and the much longer Indian river stretch had over 290.

Table 3. Population counts and estimates for all the study area stretches surveyed in 2022 and 2023.

River stretch	Survey month and year	Method	River length (km)	Population count or estimate (mean ± SD)
Karnali-Ghaghra (Nepal, upstream of barrage)	February 2022 October 2022 April 2023	Single-observer, downstream counts	80*	7 3 5
Karnali-Ghaghra (India, upstream of barrage)	April 2023	Single-observer, downstream count	40	38**
Ghaghra* (India, downstream of barrage)**	May 2023	Tandem double-observer surveys, two boats	627	954 ± 17
Narayani-Gandak (Nepal, upstream of barrage)	April to Dec 2022 Nov 2022, Oct 2023	Opportunistic sightings and local information	60 10	1 to 2 (from Bhalauji, Golaghat, Amaltari in Chitwan NP) 1-2 in Triveni area
Narayani-Gandak (India, downstream of barrage)	Nov-Dec 2022	Tandem double-observer surveys, two boats	290	202 ± 9
Koshi-Kosi (Nepal, upstream of barrage)	July 2022	Opportunistic sightings and local information	40	1 (in flood-season in Koshi Tappu WLS)
Koshi-Kosi (Nepal, downstream of barrage)	June-July 2023 March 2023	Single-observer downstream count	20	17-19 17-22
Koshi-Kosi (India, downstream of barrage)	Feb 2023	Tandem double-observer surveys, two boats	232	292 ± 6

*This included 46 km in Karnali river channel and 34 km in Geruwa river channel in Nepal. Gerua channel recorded zero dolphin sightings on all surveys. **This included 18 dolphins in the Giruwa (Gerua) channel in India and 20 in the Karnali (Kaudiyala) channel in India. ***The Ghaghra-Sharda link channel was not surveyed, and may have a few dolphins residing there (Prajapati et al. 2021). Das et al. (2022) estimated 600-650 dolphins in the Ghaghra River from a single-observer count survey correcting for detection probability. ****The Koshi-Kosi range is based on minimum and best counts, from the surveys by Rai, A. and Laba, K.C.

Past records of river dolphin counts upstream of barrages (until 2021)

Karnali-Ghaghra: Reports on river dolphin counts are available for the Nepal and India channels upstream of the barrage over the last 40 years. The population size in the Indian channels appears to have remained stable between 30 and 50 individuals over this time. Between 1982 and 1986, Shrestha reported counts of as many as 12 to 23 dolphins in Nepal channels, but from 1990 onwards, counts of only 2 to 12 dolphins have been reported, with the latest highest estimate being 6-7 in the Karnali channel of Nepal (also see Khatiwada et al. 2021). There is thus a likelihood of long-term as well as short-term declines in Nepal's population, in spite of the seasonal fluctuations in numbers. Until our surveys in 2022 and 2023, there seems to have been a gap in population surveys from 2016 onwards.

Table 4. Counts from surveys of Ganges river dolphins in the Karnali river in India and Nepal upstream of the Girija barrage from 1982 to 2021, from multiple information sources.

Year	Month	Country	River channels	River dolphin count	Source
1982		Nepal	Gerua	12	Shreshta et al., 1989
1983		Nepal	Gerua	20	Shreshta et al., 1989
1986		Nepal	Gerua	23	Shreshta 1995
1990	Jan-Apr	Nepal	Gerua	7	Smith 1993
1993	Feb	Nepal	Gerua	2	Smith et al., 1994
1993	Feb	India	Gerua	19-28	Smith et al., 1994
1994		Nepal	Gerua	6	Shreshta 1995
1995		Nepal	Gerua	8	Shreshta 1995
1998		Nepal	Gerua	6	Smith 2000
1999		Nepal	Gerua	4	Timilsina 1999
2001	Feb	India	Both	30	Behera et al. 2013, 2014
2003		Nepal	Gerua	4	Joshi 2004
2005		Nepal	Gerua	4	WWF-Nepal 2006
2006	Dec	India	Both	44	Behera et al. 2013, 2014
2009	Dec	India	Both	49	Behera et al. 2013, 2014
2009	Nov	Nepal	Gerua	8	Khanal et al., 2016
2012	Oct	India	Both	39	Singh & Behera 2018, Behera et al. 2014; Basu 2012
2012	Nov	India	Both	39	WWF-India (in Kelkar et al. 2022)
2012	Nov	Nepal	Both	11	Khanal et al., 2016
2013	Feb-Mar	India	Both	35	Behera et al. 2013, 2014; Denlay 2013
2013	Jan	India	Karnali	12	Khanal et al., 2016
2013	Jan	Nepal	Gerua	0	Khanal et al., 2016
2013	Jan	Nepal	Karnali	6	Khanal et al., 2016
2013	Apr	Nepal	Karnali	8	Paudel et al., 2015

2013	Nov	Nepal	Karnali	9	Khanal et al., 2016
2014	Dec	Nepal	Karnali	5	Paudel et al., 2015
2014	Nov	Nepal	Karnali	8	Khanal et al., 2016
2015	Mar	India	Giruwa	34	WWF-India (in Kelkar et al., 2022)
2015	Mar	India	Karnali	11	WWF-India (in Kelkar et al., 2022)
2015	Nov	Nepal	Karnali	6	Khanal et al., 2016
2016	Oct	India	Giruwa	21	Chauhan 2016
2016	Oct	India	Karnali	12	Chauhan 2016
2016	Oct	Nepal	Gerua	0	Khanal et al., unpublished
2016	Oct	Nepal	Karnali	6	Khanal et al., unpublished
2016	Jul	Nepal	Both	0	Shah et al., 2020

Narayani-Gandak: Table 5 summarizes the available sighting records of the species from the Narayani in Nepal from 1963 onwards. The oldest reports come from a Japanese doctor in 1963-64, before the barrage was constructed, from Pitonj Ghat on the Narayani, over 70 km upstream of the barrage. Kasuya & Haque (1972) also reported infrequent to regular sightings upstream in the years after 1968 when the barrage was completed. At least until 1986, reports of 5-7 dolphins can be confirmed, after which, from the 1990s, there may have been a gradual decline. From 1990 onwards, the remnant or seasonally migratory population may not have had more than 1 to 2 dolphins in the whole stretch. Since 2014-15, a peculiar pattern was seen in sightings of Ganges river dolphins, recurring after every three years. One or two dolphins appear to have been sighted in 2014-15, 2018-19, and 2022-2023 – whether this three-year recurrence is due to inconsistent coverage/detection or actual occurrence patterns is not possible to say at present. The most recent records from April 2022 and later were from Triveni (upstream of the barrage), Golaghat, Sisuar, Sylabas, Baghmara, Bhalauji, and Meghauli on the Narayani-Gandak river in Nepal. Local residents found an adult river dolphin in the eastern main canal of the Gandak around the 15th of October 2023, which they claimed was the first time ever that they had seen a dolphin in the canal. The canal gates were kept open and the dolphin also moved back upstream of the barrage. Around October end, boatmen at Triveni temple confirmed having seen 1 or 2 individuals in the area around 20th of October. The dolphin is likely to have entered the eastern canal from the gates of the Gandak barrage, from the upstream side, as entry from the downstream part would be near impossible.

Table 5. Sightings and occurrence records of Ganges river dolphins in Nepal's Narayani river upstream of the Triveni barrage from 1963 to 2022, from multiple information sources.

Year(s)	Locations	Details of sightings	Reference
1963-64*	Pitonj Ghat	One dolphin regularly sighted in December-January	Kasuya & Haque 1972
1969	Dio Ghat	Regular sightings reported by locals round the year	Kasuya & Haque 1972
1970-72	Dio Ghat, Narayani	Infrequent sightings in the dry and wet	Kasuya & Haque 1972

	Bazaar, Golaghat to Tribeni	seasons. Golaghat was estimated to be the upper limit of the distribution range.	
1980	Tribeni to Golaghat	Seven dolphins in three locations	Maskey, T. (CNP 2015)
1986	-	Five dolphins in Narayani river in Nepal	T.K. Shreshtha (1995)
1993	Tribeni to Dio Ghat	2 dolphins	Smith (1993)
1994	-	1 dolphin	Smith et al. (1994)
2000	-	0	Jnawali & Bhuju (2000)
2014	Bhalauji	One or two dolphins on 02 April 2014	Paudel et al. (2015)
2015	Bhalauji	One dolphin near Bhalauji area in May	Paudel et al. (2015); also reported by tourists in CNP
2018	near Tribeni	Calf of dolphin (1) on 28 June 2018	Bed Bahadur Khadka, Wildlife Warden of CNP
2019	-	Subadult dolphin (1) in April-May	Pujan Adhikari (Rufford Small Grant report)
2022	Bhalauji	8-10 Jan 2022, then in February 2022	Tek Mahato, other staff and wardens of CNP (Facebook, Nepali Times)
2022	Golaghat area	21-22 April 2022	Karun Dewan, Rajeev Kumal (Twitter)
2022	Amaltari	Nov-Dec 2022	Tek Mahato
2022	Triveni	Dec 2022	Sighting of 1 dolphin by boat people at Triveni temple upstream of barrage

*Only known record before the construction of Tribeni barrage on the Narayani-Gandak in 1967-68.

Koshi-Kosi: Surveys since 1989 have reported fluctuating numbers of Ganges river dolphins upstream of the Koshi (Birpur) barrage. These have varied from 5-8 in 1989 and 2008-09, to 2-3 in 1993 and 2016, and an estimate of 2 to 6 from 2009-10. Post 2016, however, only occasional reports of 1 dolphin during the flood season are available. This may indicate a reduction in the overall population upstream. The downstream population in the Nepal channel appears to have been stable between 15 and 25 as this channel is connected with the main stem of the Kosi in India. Table 6 provides a summary of sightings from 1989 to 2022-23. Our team did not record a single sighting upstream of the barrage in 2023.

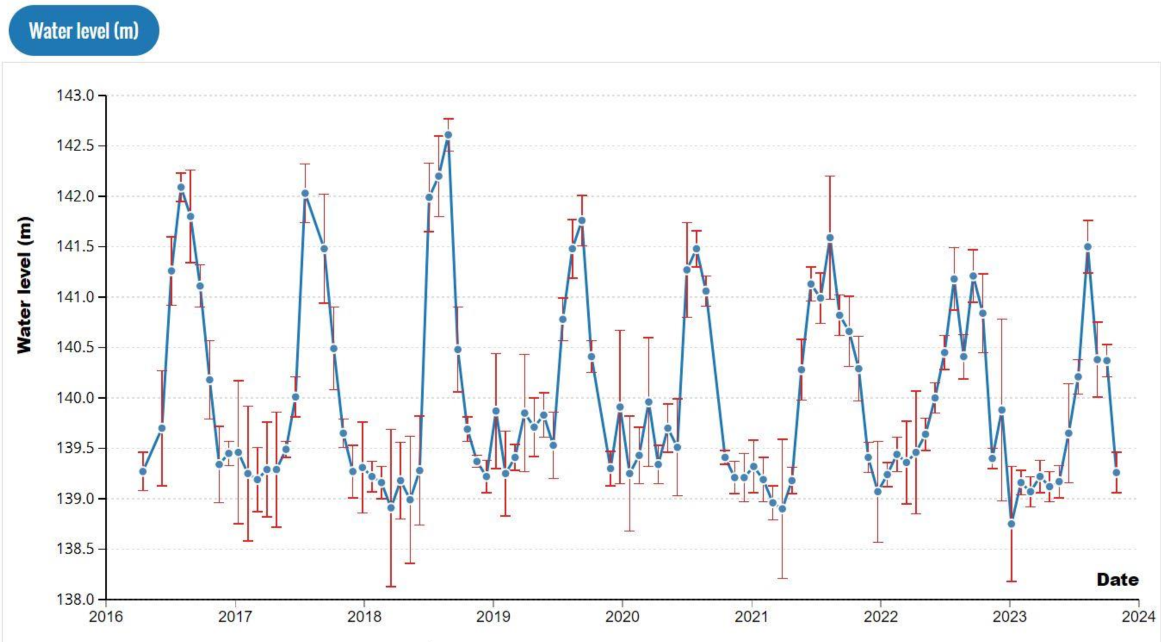
Table 6. Sightings and occurrence records of Ganges river dolphins in Nepal's Koshi river upstream of the Birpur barrage from 1989 to 2022-23, from multiple information sources.

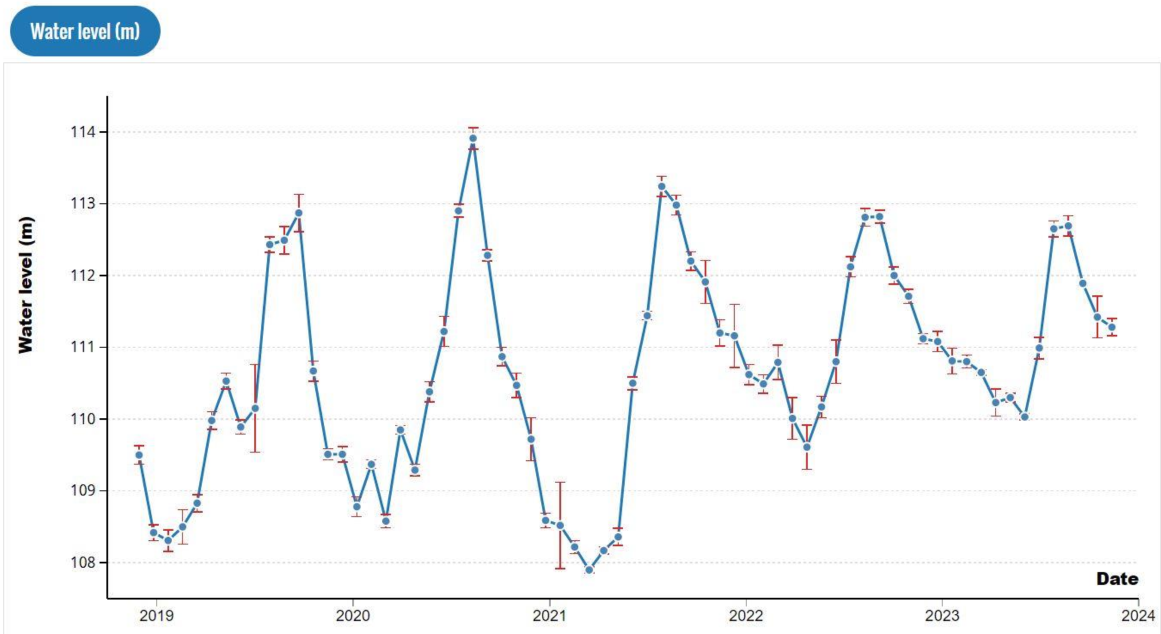
Year(s)	Details of sightings	Reference
1989	8	Shreshta 1989
1990-93	2-3	Smith et al. 1994
2007	0	Chaudhary 2007
2008-09	5-8	Khatri et al. 2010, Aryal et al. 2010, Limbu & Subba 2012, Baral 2013
2009-10	2-6	Aryal et al. 2010, Khatri et al. 2010
2013-14	0	Paudel et al. 2015
Aug 2016	3-4?	Shah et al. 2020
Dec 2018	1?	Yetaa Utaa (Koshi Tappu WLS): https://yetaautaa.blogspot.com/2018/
2021-22	1	Pers. comm. Mr. Swapnil Chaudhary (in monsoon months)
2022-23	0	Our study

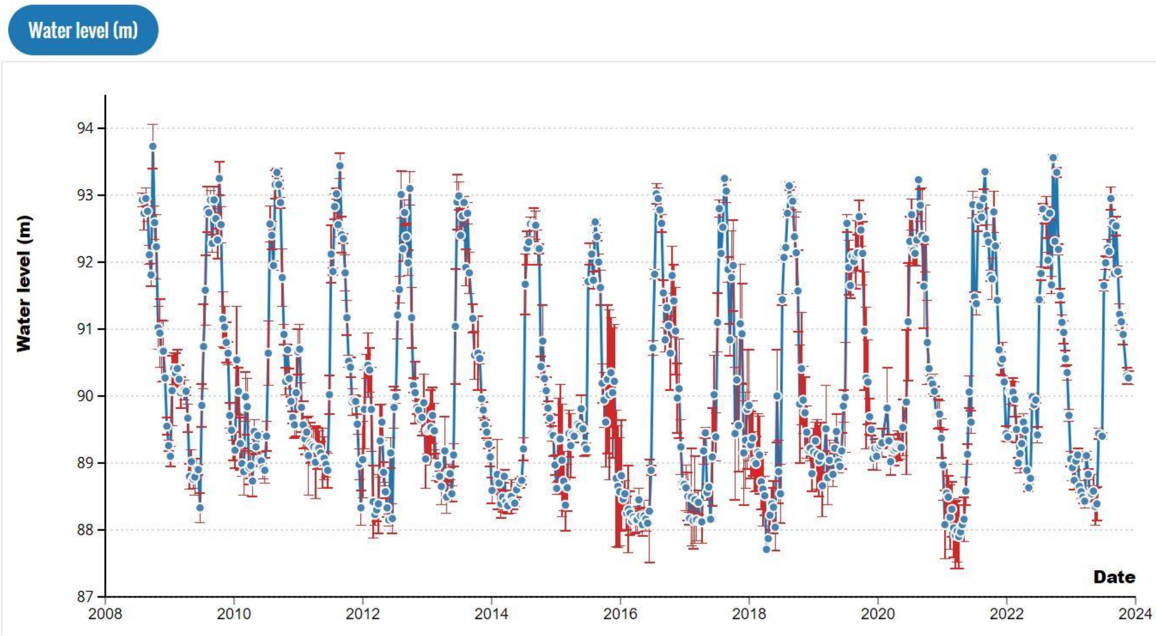
Hydrological time-series analyses of India-Nepal gauging stations and barrages

Karnali-Ghaghra: Stable water levels were recorded in the altimetry station upstream of the Ghaghra barrage (2016-2023), but an increase in river water levels was recorded in the downstream station from 2019 to 2023 (Figure 3). This indicated greater barrage flow releases downstream into the river even at similar levels of inflow. At the altimetry station further downstream on the Ghaghra at Ayodhya in India, water levels from 2008 to 2023 were recorded to be largely stable, probably due to the effects of tributary contributions and local groundwater-surface water interactions.

Figure 3. Water levels (m) estimated from satellite altimetry (Theia-Hydroweb) for stations upstream of the Girijapuri barrage (top), downstream (middle), and downstream at Ayodhya (bottom) on the Karnali-Ghaghra.

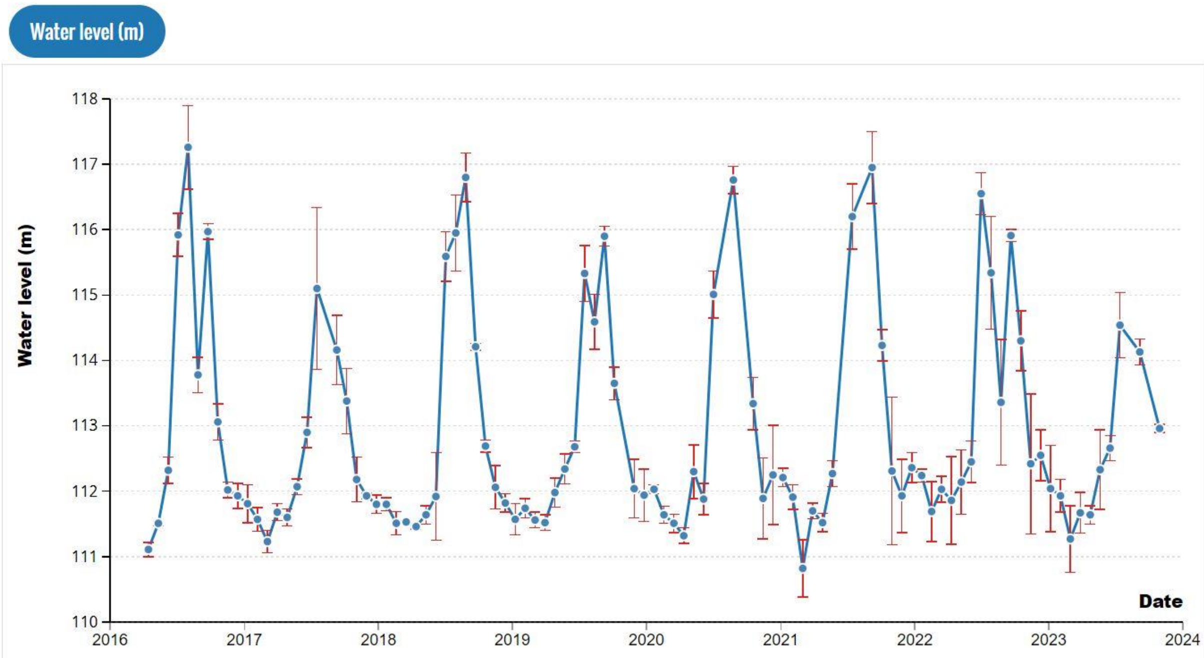


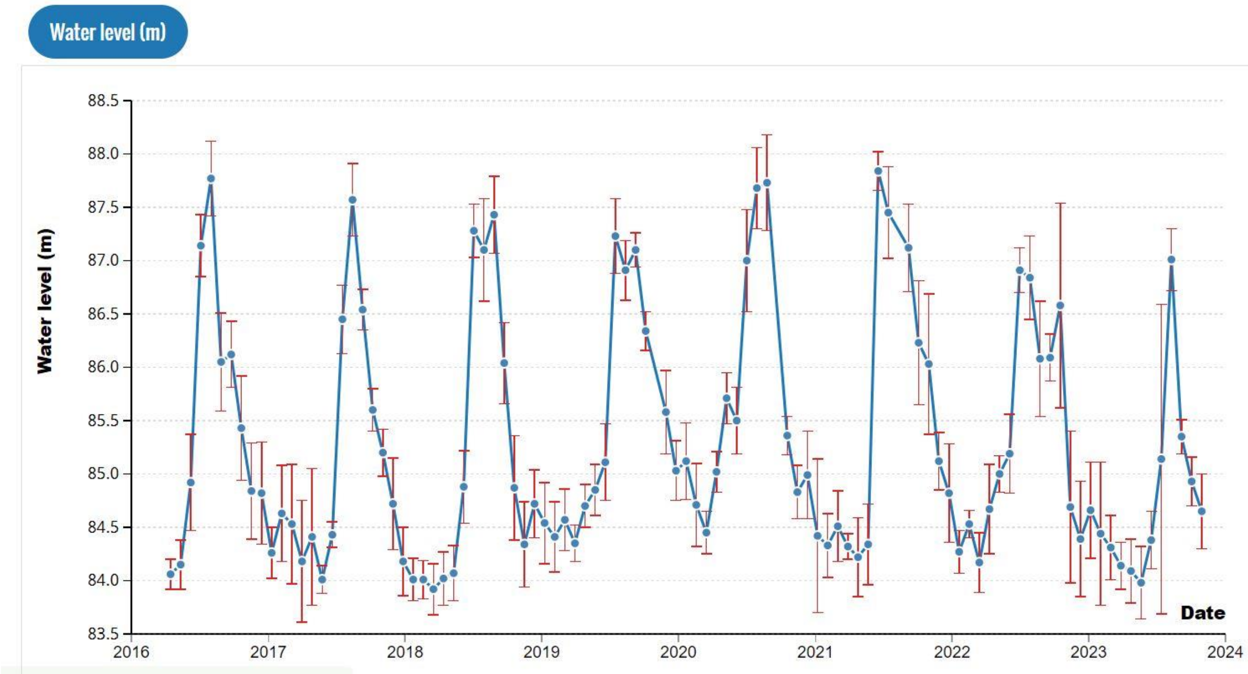




Narayani-Gandak: Between 2016 and 2023, inflow water levels and outflow water levels from the Triveni barrage were both stable. The downstream water levels did show a hint of increase between 2016 and 2020, but in the following years, water levels were lower and more stable. A reduction in 2023 dry-season water levels was also noted, unlike previous years (Figure 4).

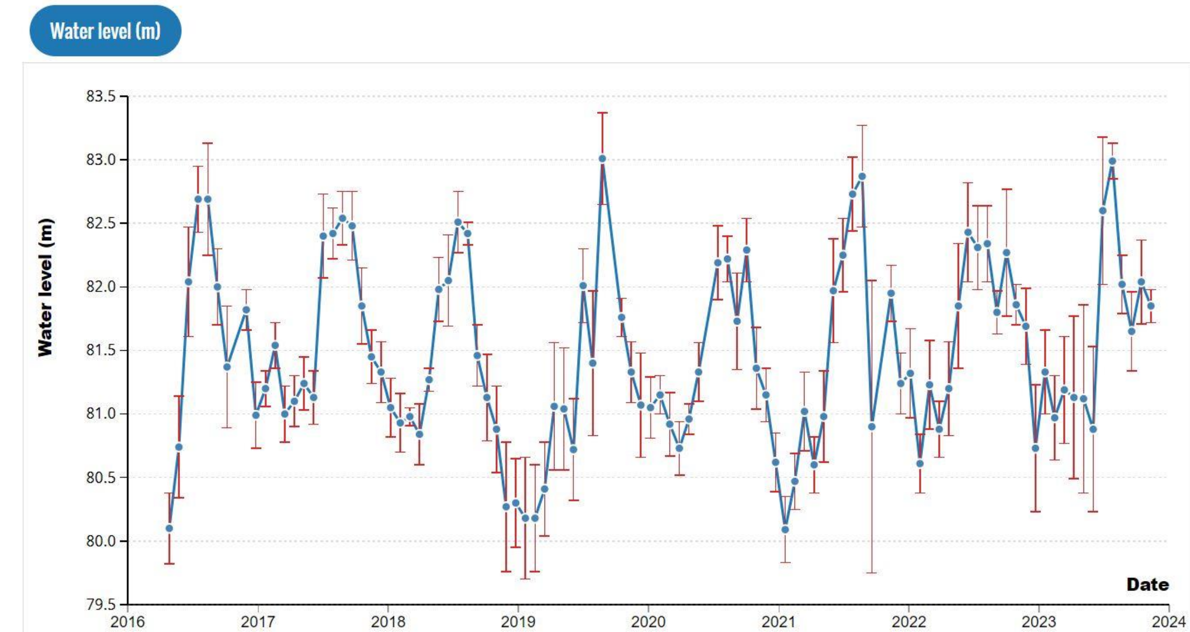
Figure 4. Water levels (m) estimated from satellite altimetry (Theia-Hydroweb) for stations upstream of the Triveni barrage (top) and downstream (bottom) on the Narayani-Gandak river.

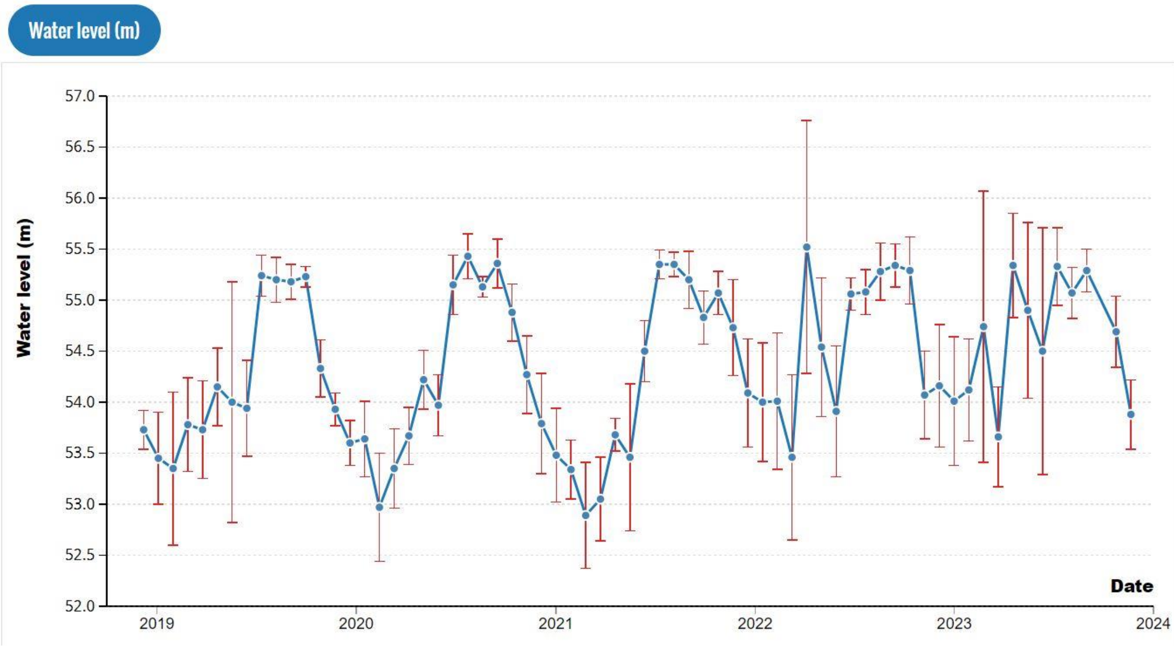




Koshi-Kosi: Upstream water levels as well as downstream water levels did show increases from 2019 to 2023 (Figure 5). The increase was more pronounced for the downstream altimetry station. This indicated a combination of barrage-driven flow releases and greater inflow availability, suggesting interaction of increasing flows potentially driven by rainfall irregularities or climate change and barrage operational inefficiencies.

Figure 5. Water levels (m) estimated from satellite altimetry (Theia-Hydroweb) for stations upstream of the Birpur barrage (top) and downstream (bottom) on the Koshi-Kosi river.





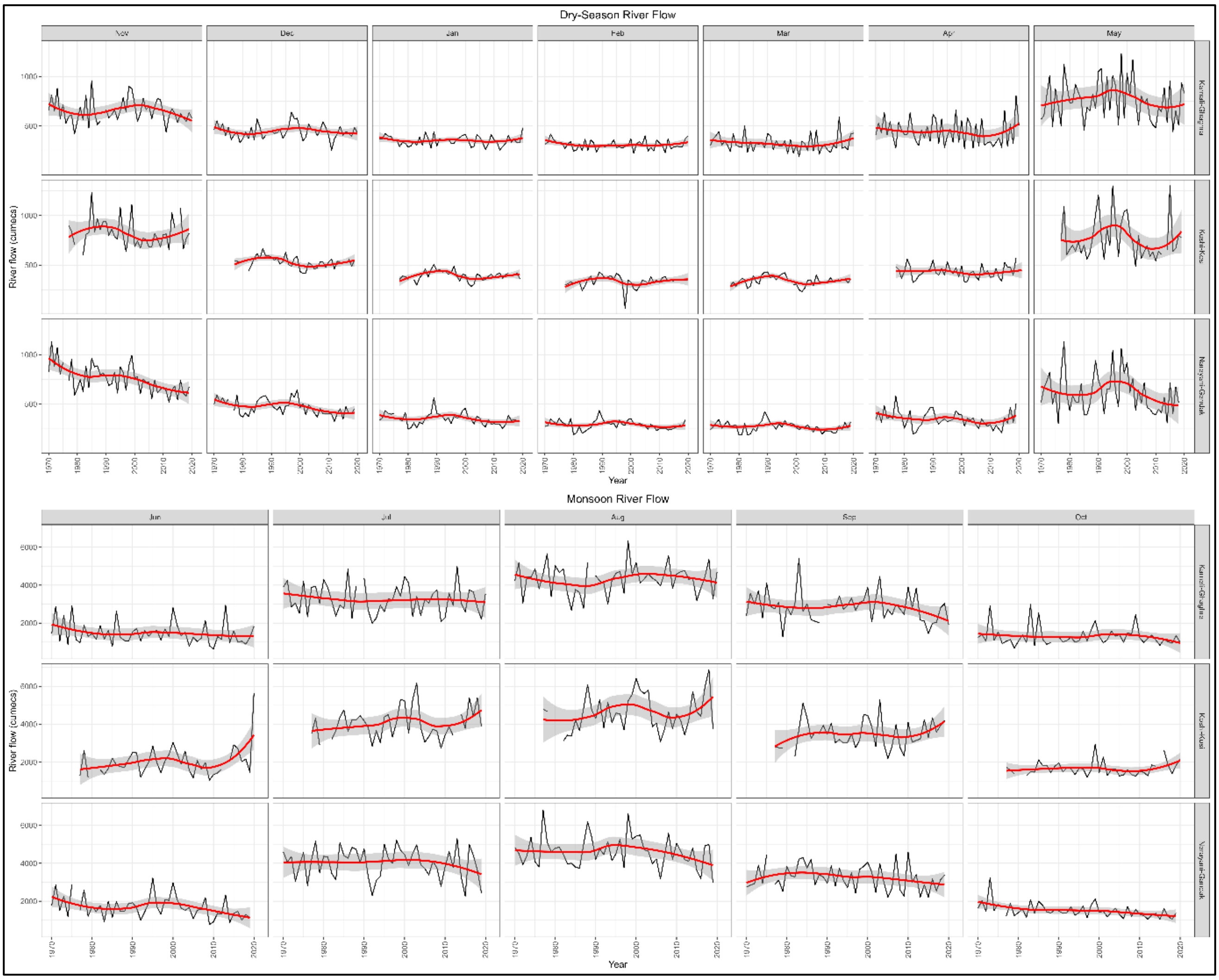
River inflow: Discharge trends at gauging stations in Nepal upstream of barrages.

Long-term trends (1970-2020) in river discharge or inflow into the barrage were overall quite stable across months for the Karnali river, barring minor recent increases in March and April, and recent declines in September and October. For the Narayani-Gandak, a declining trend in inflow was noted for the post-monsoon (Sep-Dec) and pre-monsoon seasons (May-June). For the Koshi-Kosi, flood-season inflows showed consistent increases from June to October but stable flows were seen through the dry-season. Figure 6 summarizes these trends month-wise for the three rivers. The early 1990s, interestingly, witnessed reduced peak flooding (Jul-Sep) in all three rivers.

Correspondence of upstream-barrage sighting records with major floods or barrage-related events

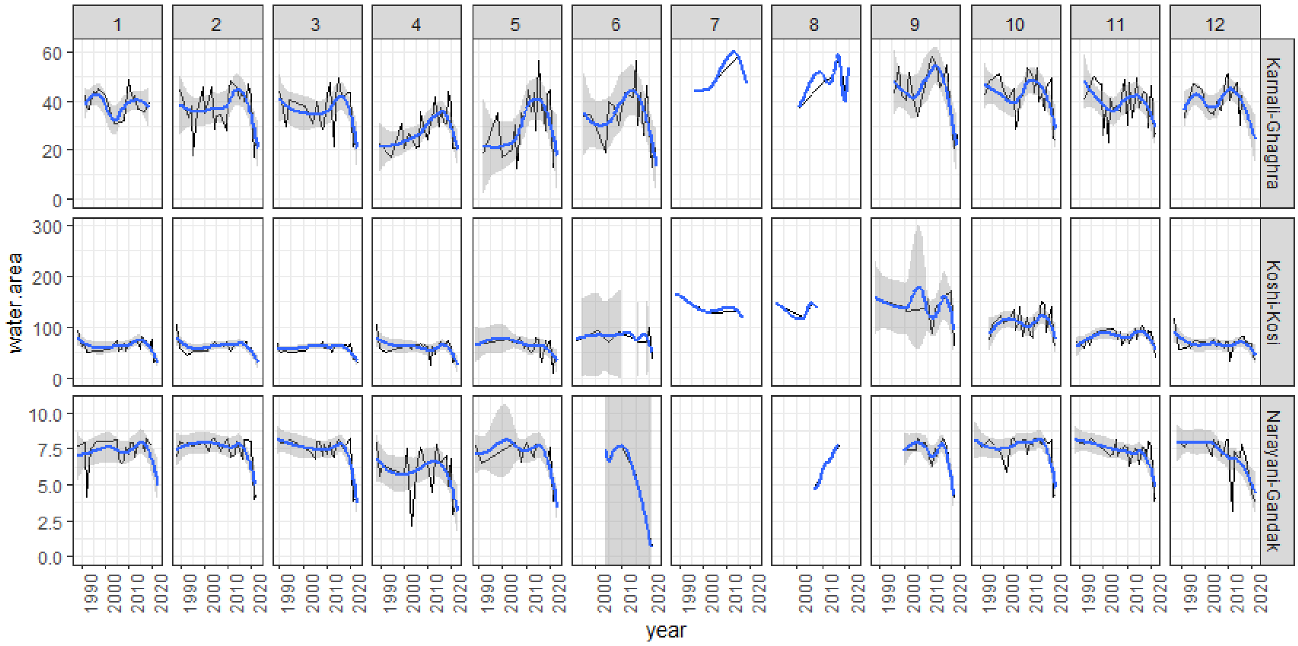
It may be hypothesized that in Karnali-Ghaghra and Narayani-Gandak, where river dolphin count data are available in the 10-20 years post barrage commissioning, it is clear that local abundances were higher than at present, only to have declined over time. Such data are not available for the Koshi-Kosi, as the barrage was the earliest one to be built (1963). For the former two rivers, it is likely that the higher abundances could be due to dolphins persisting in upstream reaches post barrage construction, for approximately one generation length. After these remnant individuals died out, colonization from downstream populations may have become increasingly rare as irrigation networks intensified in later years and the river channel downstream received lower flows and higher sediment loads. In the Koshi-Kosi, the massive flood of 2008, which was due to an embankment breach in Nepal causing the river to abandon its current course and partly flow through one of its paleo-channels, could have possibly been a reason for the sudden reduction in river dolphin abundances (Baral 2013). But other than such events, we did not find a clear correspondence between upstream-barrage changes in dolphin numbers and major flooding events.

Figure 6. Trends (1970-2020) in monthly discharge for gauging stations in Nepal, upstream of the three river barrages for the dry-season and monsoon season. Data source: Department of Water Resources and Hydrology, Govt. of Nepal.



Trends in barrage impoundment area: The Koshi-Kosi and Narayani-Gandak impounded water areas showed relative stability from 1984 to 2017-18, after which a decline is evident in the water area (Figure 7). In contrast, the Karnali-Ghaghra showed a more fluctuating long-term trend in impounded water area, especially in the pre-monsoon (April-June) and post-monsoon months (October to December). After an initial decadal trend of decline in water area (1990-2000), a phase of increase is seen until 2015, after which another trend of decline is seen continuing until 2023. This may explain the lower abundances seen in the Karnali-Ghaghra channels of Nepal lately.

Figure 7. Changes in barrage impoundment area from 1984 to 2023. The panels 1-12 indicate months from Jan-Dec. The Y-axis shows impounded water area (km^2).



Barrage operations and design details: a comparison

Table 7 summarizes a comparison of the similarities and differences in the design of the three barrages. There are some clear similarities in the design discharge, operating schedules for irrigation water supply, and general design plans of spillways and under-sluices (e.g. presence of silt excluders, relative differences between upstream and downstream crest and head levels, gate dimensions, canal and channel dimensions, and difference in pond level and minimum water level). Yet there are some key differences. For instance, the Triveni barrage on the Narayani-Gandak is unique in terms of having river-sluices included, along with under-sluices and spillways. Yet, the problem of sediment plugging and siltation is quite severe at the downstream side of the barrage, and has locally altered the river's flow as well. The sluices towards the Nepal side appear more efficient in sediment flushing. The scour depth at the Kosi barrage may be greater than the other two barrages, due to which it seems to be the only barrage where river dolphins can be spotted right at the downstream end. We also noted that the Kosi barrage has a "leaky" perennial base-flow through its under-sluices even in the driest months. However, connectivity through the barrage when gates are open may be determined by many other factors. In the Triveni barrage, even with open gates, the sediment blockages due to the high silt factor may not allow for adequate depth in the dry-season for at least river dolphins to pass. The limiting depth may hinder passage for dolphins, though we have observed juvenile gharial and mugger crocodiles to actively use the opportunity to move through the gates.

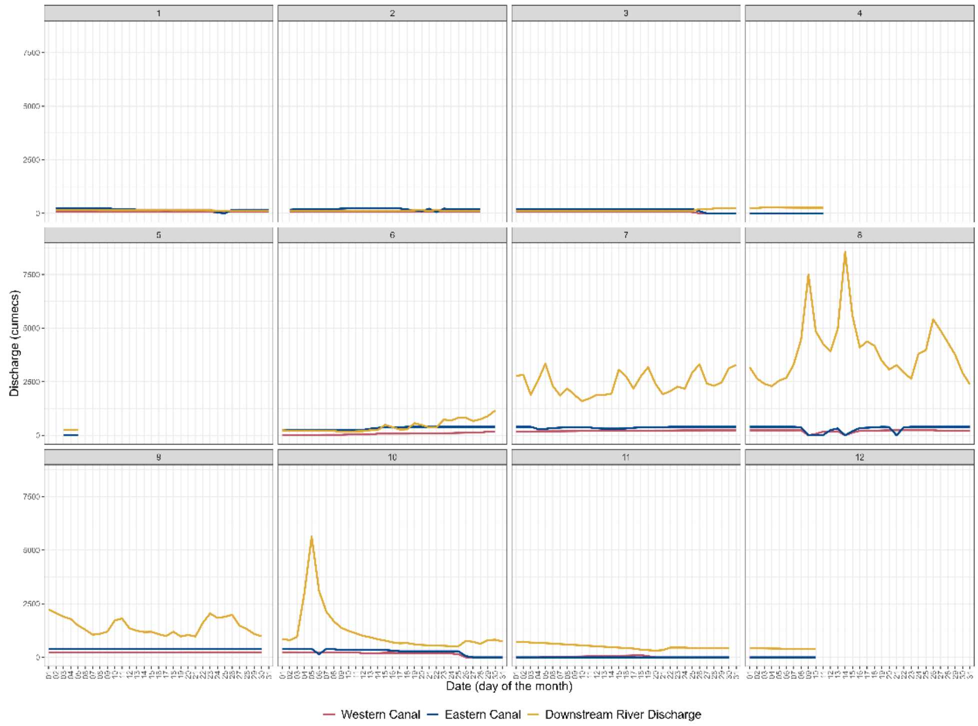
Table 7. A design comparison of the three barrages we studied in our project.

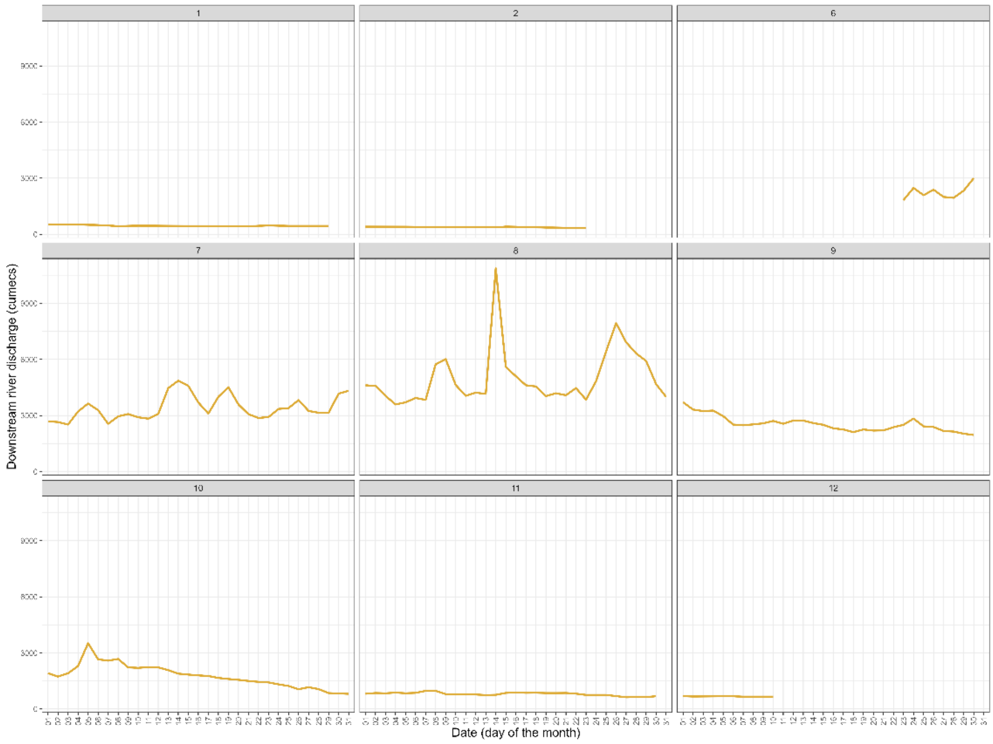
River	Karnali-Ghaghra	Narayani-Gandak	Koshi-Kosi
Barrage name	Girijapuri	Triveni	Birpur (Bhimnagar)
Commissioning/Completion Years	1970-1976	1963-68	1958-1962
Design discharge (m^3/s)	22,200	24,100	26,900
Design flood frequency	~ 1 in 200	1 in 220	1 in 600
Length of barrage (m)	716	742	1149
Looseness factor	1.011	1.005	1.45
Silt factor	~1.00	3.0	1.3
Number of gates	35	36	56
Under-sluices (R + L)	9 (6+3)	12 (6+6 river-sluices)	10 (4+6)
Spillways	26	18	46
Left head regulator	7	8	3
Right head regulator	7	8	7
Pond Level (m)	138.00	110.37	74.69
Crest Level (m)			
Spillway	130.50	105.79	70.12
Under-sluices	129.50	103.63-104.24	71.64
Size of gates (m x m)			
Spillway	18.00 x 7.80	18.30 x 6.40	18.29 x 7.92
Under-sluices	18.00 x 8.80	18.30 x 4.88	18.29 x 6.40
Canal design discharge (total, m^3/s)	675.00	980.00	665.52
Slope (km/km)	0.00075^ (from DEM)	0.00057	0.00050
Min. Water Level (m)	132.00	104.19	72.00
Schedule of operations	25 Apr to 15 Oct (Kharif) 12 Nov to 31 Mar (Rabi) 15 Oct to 11 Nov (river)	25 Apr to 25 Oct (Kharif) 10 Dec to 25 Mar (Rabi) 26 March to 25 April (river) 26 Oct to 09 Dec (river)	25 Apr to 25 Oct (Kharif) 10 Dec to 25 Mar (Rabi) 26 Mar to 25 Apr (river) 26 Oct to 09 Dec (river)
Danger Level (m)	136.78	109.67	74.70
High-Flood Level (m)	137.44	113.05	76.02

Data sources: India-WRIS 2014, Water Resources Department website, Govt. of Bihar, Irrigation and Water Resources Department website, Govt. of Uttar Pradesh, Central Water Commission-Govt. of India, ISI 1985, 1989; Vora et al. 1990, IISc-IITs 2010, Dingle et al. 2016, Singh et al. 2020, Devkota et al. 2018, Kumar 2021.

The following figures (8-9) show year-round barrage operations for the Narayani-Gandak and Koshi-Kosi rivers for 2023. The downstream discharge release regimes are quite different in both rivers (Figure 8), with the March-April and November-December flushing releases shown in the former.

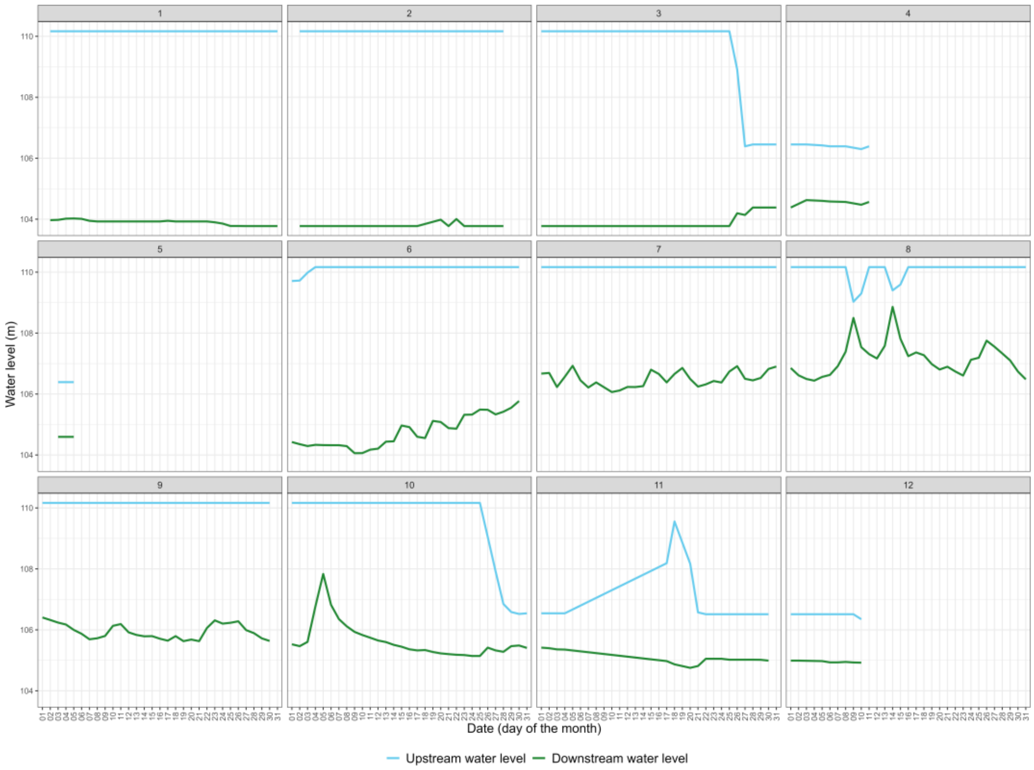
Figure 8. Barrage operations for an entire year (2023) showing discharge released downstream into the river and into canals for the Narayani-Gandak river (top) and downstream release into the river for the Koshi-Kosi river (bottom). The rivers show different periods of flow release in the same year.

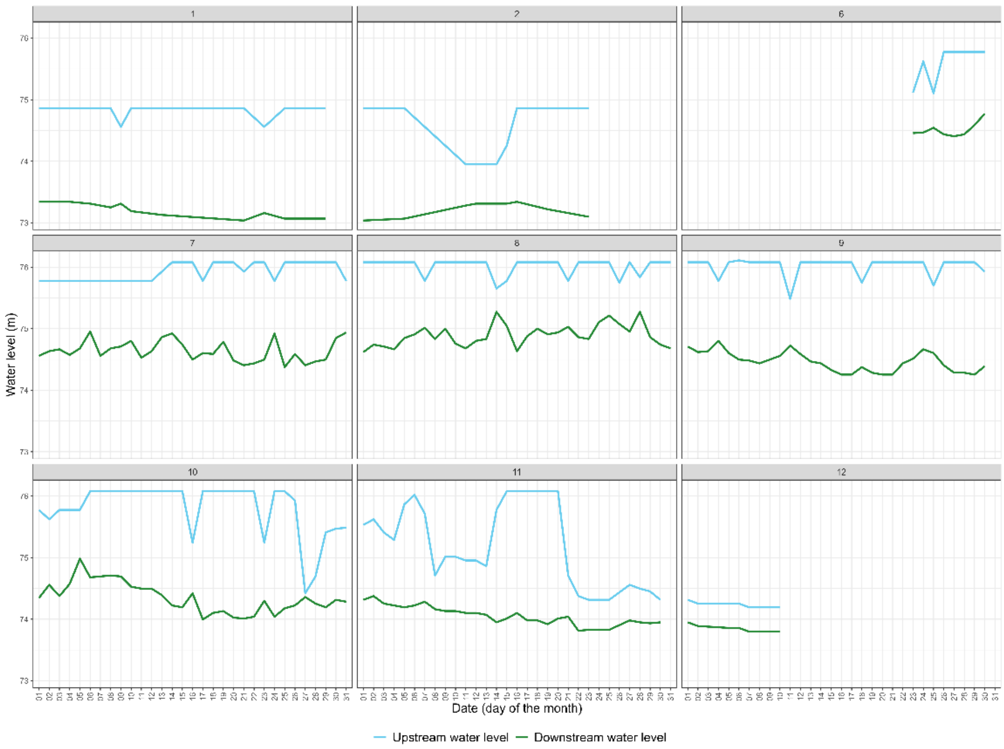




Converging of upstream and downstream water levels for the barrages (Figure 9) indicate levelling of water, which could be potential windows of opportunity for river dolphins to pass through the barrages.

Figure 9. Daily and monthly changes in upstream and downstream water levels of the Gandak and Kosi barrages (top and bottom) for the year 2023. Windows of opportunity could arise where the upstream and downstream levels come closer to each other, e.g. on 27 October in the Kosi.





Estimation of optimum discharge to maintain reach-averaged hydraulic habitat downstream of barrages

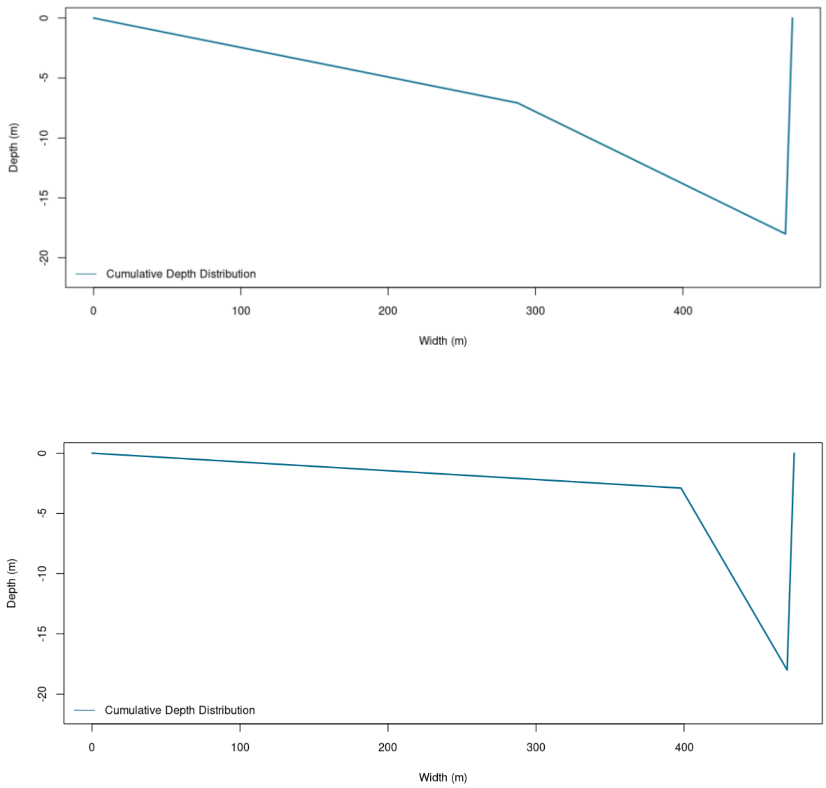
Using the GIFT tool and from empirically estimated stage-discharge rating curves for barrage flow releases to the river, we calculated the optimum ranges of discharge needed to maintain adequate habitat just downstream. On average, across the three systems, at least 350 m^3/s was estimated to be required as dry-season rate of flow release (see Table 8), to maintain adequate and suitable habitat conditions, defined as: channel depth > 3.5 m, flow velocity < 1.0 m/s, channel width > 150 m (Kelkar et al. 2010, Braulik et al. 2012b, Choudhary et al. 2012, Khanal et al. 2016, Paudel et al. 2020b, 2021; Sharma et al. 2022, Sonkar et al. 2022). Due to the equations used, the channel shapes that were estimated by the models were always asymmetrical, with the degree of irregularity increasing with reduced discharge at source. Figure 10 shows a comparison of two cross-sections of minimum and average river depth. For dolphins, maintaining low flow velocity along with greater depth is of importance, and the depth and velocity hydraulic rating curves overlapped only in a small window, which was used to estimate the range of optimum discharge release required. Wetted river channel width, however, remained limited below at the barrage, due to the high asymmetry of the cross-sections and the channel stability and constraint imposed by the afflux embankments along the flanks of the barrage gate portions facing downstream. The barrage looseness factor may be an important design consideration in this regard.

Table 8. Reach-averaged channel hydraulics and discharge required to sustain river dolphin habitat and passage from downstream of barrages. The equations in blue refer to empirically derived relationships, the ones in black indicate hydraulic model-based rating curves.

Relationship	**Karnali-Ghaghra**	**Narayani-Gandak**	**Koshi-Kosi***
Stage-discharge (dry-season)	$Q=28.36*S+108.64$; $R^2=0.97$	$Q = 1e\text{-}42*e^{0.9782*S}$; $R^2=0.99$	$Q=429.52*S-31015$; $R^2=0.85$
Stage-discharge (flood-season)	$Q=1e\text{-}42.exp(0.775*S)$; $R^2=0.99$	$Q=144.06*S^2-29058*S + (1e+06)$; $R^2=0.71$	$Q=1e\text{-}41.exp(1.37*S)$; $R^2=0.69$
Depth-discharge	$\mathbf{D=0.32*Q^{0.35}}$	$\mathbf{D=0.34*Q^{0.35}}$	$\ln(D)=0.35*\ln(Q) - 1.41$; $R^2=0.71$
Width-discharge	$\mathbf{W=10.09*Q^{0.39}}$	$\mathbf{W=11.37*Q^{0.38}}$ $Q = 0.0295*W^{\wedge 1.545}$ ($R^2=0.79$)	$W=0.276*Q+65.87$; $R^2=0.91$
Flow velocity-discharge	$\mathbf{V=0.31*Q^{0.27}}$	$\mathbf{V=0.25*Q^{0.27}}$	$V=0.17*\ln(Q) + 0.145$; $R^2=0.55$
Optimal discharge range to maintain adequate habitat conditions for river dolphins	500-600 m^3/s	~300-350 m^3/s	350-400 m^3/s

*Some of the empirical calculations for the Koshi-Kosi benefitted from the work of Gaurav et al. (2014).

Figure 10. Change in channel shape with reduction in discharge maintaining bankfull depth: (top) greater and relatively regular asymmetric cross-section maintained at average bankfull depth; and (bottom) irregular and asymmetric cross-section possible at minimum depth. This example is from the Karnali-Ghaghra GIFT model.



River dolphin movements through India-Nepal border barrages: windows of opportunity

Based on our criteria for passage, we estimated the probabilities of time-events in which river dolphins could pass through the barrages as follows. For the Karnali-Ghaghra, the flood-season appears to be the only time that dolphins may be able to successfully move to and fro downstream upstream. With the limited data availability for the Karnali-Ghaghra barrage compared to the other two barrages, we inferred that there may be a 13.2% window for potential passage. From 2020 water level data from 18 Aug to 18 Oct, passage may be possible in 7 out of 53 days. For the Narayani-Gandak, we estimated that passage may be possible in April and November too, during the sediment-flushing periods, but at much lower probabilities than during the flood season (especially August-September). We found that the water level difference criteria were met only one day during the dry-season in one year, for a discharge of above 260 m3/s, with a probability of 0.274%. Even in the flood-season, we calculated the probability of potential passage at only 1.13% (45 of 4018 days) from 2013 to 2023, at discharges above 7300 m3/s. For the Koshi-Kosi, we calculated the annual probability of passage at 9.90% (398 of 4018 days) from 2013 to 2023 at flood-season discharges above 3000 m3/s, and in the dry-season in February (only for 2023) at 1.37% (5 days of the year), with a corresponding river flow of 382 m3/s.

सुबह 6.32
शाम 5.36

18.0°
7.0°

29.02.2020

बहराइच/श्रावस्ती

बैराज में मृत मिली डॉल्फिन

वन विभाग के कर्मियों ने पोस्टमार्टम को भेजा

संवाद न्यूज एजेंसी

बिछिया (बहराइच)। कतर्नियाघाट रेंज के सदर बीट में गिरिजापुरी बैराज के गेट में एक मृत डॉल्फिन मिली है। जेई की सूचना पर वन विभाग के कर्मचारियों ने डॉल्फिन को पोस्टमार्टम के लिए भेज दिया है।

कतर्नियाघाट वन्यजीव प्रभाग अंतर्गत चौधरी चरण सिंह गिरिजापुरी बैराज के गेट में शुक्रवार की सुबह एक डॉल्फिन फंसी हुई थी। इस दौरान बैराज पर घूमने आए कुछ पर्यटकों ने गेट संख्या तीन में डॉल्फिन को फंसा देखा। जिस पर बैराज पर मौजूद कर्मचारियों को इसकी सूचना दी गई। अवर अभियंता संतराम वर्मा ने घटना की सूचना वन विभाग को दी। वन क्षेत्राधिकारी पीयूष मोहन श्रीवास्तव के निर्देश पर वन दरोगा मयंक पांडेय और लवलेश और वन रक्षक अब्दुल सलाम, वाचर लक्ष्मण मौके पर पहुंचे। इसके बाद करीब एक घंटे की कड़ी मशक्कत के बाद डॉल्फिन को बाहर निकाला गया। उसकी मौत हो चुकी थी। वन क्षेत्राधिकारी ने बताया कि रेंज कार्यालय में डॉल्फिन के शव को रखा गया है। पशु चिकित्सकों की टीम शव का पोस्टमार्टम करेगी।

कतर्नियाघाट के सदर बीट की घटना

मृत डॉल्फिन को ले जाते वनकर्मी।

News clip about a Ganges river dolphin stuck and killed in Gate no. 12 of the Girijapuri barrage on the Karnali-Ghaghra River on 29.02.2020. Source: *Amar Ujala* newspaper (Hindi), Bahraich/Shravasti.

Ecological trade-offs between downstream flow releases by barrages and upstream river dolphin habitat maintenance

Our findings collectively suggest the existence of trade-offs in managing downstream flow provisions for ecological flow requirements from these barrages on the one hand, and maintenance of available upstream river dolphin habitat on the other. As we have shown, an increase in barrage releases in recent years into the river channel downstream led to reductions in upstream water impoundment area. This could compromise the availability of flow depth in the upstream sections of Nepal. This would suggest that while the larger river dolphin populations in India may be receiving better flows and helping maintain downstream habitat at least in the short term, this may correspond with Nepal dolphin declines in all three rivers. The higher barrage flow releases in India may not even be intended to provide environmental or ecological flows. Rather, they are operations carried out due to various situations, e.g. increased inflow, extreme rain events in upper catchments requiring barrages to release water and make space, greater snowmelt leading to increased summer inflows, or the potentially most immediate issue: canal diversions of water becoming increasingly irregular due to frequent need for repairs due to sedimentation.

Discussion

Findings of the study: implications for river dolphin population persistence in Nepal

Our study could be of importance in terms of its findings and applications for the conservation of small populations of Ganges river dolphins in Nepal. We show that habitat availability for river dolphins upstream of the three barrages depends crucially on upstream/downstream trade-offs between trans-boundary water sharing, irrigation demand and barrage maintenance/repair works on the Indian side, and flow dynamics that are and will be affected by climate change and Nepal's future decision-making on hydropower development. These trade-offs will most likely imperil the remnant river dolphin populations within Nepal’s rivers. With the observed hydro-climatic trends likely to continue in the near future, it is possible that the Karnali-Ghaghra dolphins in Nepal will remain in those stretches only during the monsoon, similar to the Mohana, a tributary of the Karnali river (Khatiwada et al. 2019, Shah et al. 2020). Recent studies on canal entrapment of Ganges river dolphins in the Ghaghra-Sharda canal networks (Prajapati 2021, Singh et al. 2023) also indicate the possibility of gradual loss (@ around 4% per year) of upstream populations into marginal habitats such as canals, acting as ecological traps (also see Khanal et al. 2016, Samad et al. 2022). Rescued dolphins are usually released in downstream river channels than in upstream-barrage habitats (Singh et al. 2023). Prajapati (2021) predicted somewhat conservatively that for downstream to upstream movement of river dolphins through the Girijapuri barrage, a 40-year flood may be required. Our study suggests that even if we can be a little more optimistic, the recovery rate of upstream populations through this pathway would not match the rate of loss into the canal networks.

The dolphins occasionally seen in the Narayani-Gandak and Koshi-Kosi channels in Nepal will also likely get extirpated. The only population within Nepal’s boundaries that is likely to continue to persist would be the one downstream of the Birpur barrage on the Koshi river. There are indications that the Kosi channel is bifurcating downstream of the barrage and a westward shift into Nepal is anticipated (Baniya et al. 2023), which may promote dolphin persistence. A similar shift is seen for the Karnali channel (Rakhal et al. 2021) but that is delinked from river dolphin persistence. These results predict a different possible status from what has been expected: that the Karnali river would remain the ultimate stronghold of the species in Nepal (see Smith et al. 1996, Khatiwada et al. 2021). It is likely to be the Koshi downstream channel instead. However, fishing threats seem to be quite serious in the Koshi in Nepal (Paudel et al. 2016a, b), as compared to the Karnali, and need priority attention and can be included as such in Nepal’s Dolphin Conservation Action Plan.

Need for better monitoring upstream of barrages in Nepal protected areas

Upstream of the Narayani-Gandak and Koshi-Kosi barrages in particular, we see a need for improving existing monitoring mechanisms to track river dolphin occurrences. However, there has been no systematic effort, barring a survey by Paudel et al. (2015) to monitor the occurrence, seasonal residence, and area use of the few dolphins that may be remaining in these rivers. At present most reports of occurrence are opportunistic, and a better monitoring system is required. The seasonal or annual intervals between sightings may hold interesting insights and information about the control of barrage operations on river dolphin movement, occurrence, and habitat availability upstream. Systematic surveys, with the help of boat-based and bank-based surveys, and passive acoustic monitoring can help confirm if the 1-2 dolphins recorded from the Narayani or Koshi are resident round the year or transients moving up and downstream of the respective barrages. Rangers and field staff of the Chitwan NP and Koshi Tappu WLS could be connected in independent network or app-based messaging platforms where any opportunistic sightings from their respective ranges and field patrols are possible to share in a rapid way. There may also be scope to consider a land-based monitoring system at particular ghat sites to track the occurrence of Ganges river dolphins. Opportunistic sightings documented from memory recall, especially from 2000 to 2014, may be collected from experienced park rangers. Another monitoring approach needs to be centred on the areas immediately upstream of Triveni and Koshi barrages, during specific periods of the pre-monsoon, monsoon, and post-monsoon seasons, when most barrage gates remain open and the likelihood of Ganges river dolphins being able to move upstream through the barrage increases. Here it may be advisable to combine visual observations with passive acoustic monitoring using CPODs (www.chelonia.ac.uk) placed upstream, to monitor transient dolphin activity round the year.

Future uncertainties in trans-boundary and national water management

It is likely that India-Nepal water sharing agreements and trans-boundary barrage operations on the Karnali-Ghaghra, Narayani-Gandak, and Sapta Koshi-Kosi river systems shared between the countries will be revised in the near future in light of climate-change based adaptation needs (Sharma & Awal, 2013; Gautam & Regmi 2013). Water sharing concerns have lately been a contentious issue between Nepal and India, however bilateral negotiations for waterways development and joint barrage management are being discussed (Dixit 2018). Impacts of trans-boundary barrages are likely to be significant in light of hydropower development in both countries – especially in Nepal, coupled with climate change-induced uncertainties in water management (Shrestha & Aryal, 2011; Sharma & Awal 2013). These rivers originate in the Himalayas and Tibetan Plateau and future flow availability is likely to be highly sensitive to glacial melt rates and extreme rain events in the Himalayan catchments (Trenberth 2005, Bookhagen & Burbank 2010, Immerzeel et al. 2010, 2013; Wasko et al. 2021). Our results indicate that this may already be happening, as seen in the changing trends of climate-affected inflows and barrage operations in turn.

The floodplain areas in Nepal are in need of irrigation for sustaining agriculture, which has largely remained rainfall-dependent and subsistence-based till now. The uncertain pattern of rainfall in the face of climate change means that policy makers are interested in developing irrigation projects, which will divert substantial amounts of flow from naturally following rivers. Such projects include the four major mega-hydropower project upstream of Chisapani (Upper Karnali, Phuket Karnali, Mugu Karnali, and Betan Karnali) on the Karnali-Ghaghra river and the Sapta Koshi High Dam project upstream of Barahakshetra-Chatara Kothu on the Koshi river in Nepal (Bhusal 2014, Gyanwali et al. 2023). Recently, the Supreme Court of Nepal issued an order on the Karnali projects emphasizing considerations on the conservation of riverine ecology and aquatic biodiversity in Nepal. The Sapta Koshi High Dam project has also been a subject of debate due to factors related to hydro-safety and vulnerability due to seismic activity and construction impacts (Butler & Rest 2017). But if these projects are implemented, then the relative effects of trans-boundary water sharing might pale as compared to the impacts of hydropower-related decision-making within Nepal.

Our study makes a small but important contribution in this regard, by empirically tracing the effects of recent and unfolding hydro-climatic changes on water availability and river dolphin habitats within Nepal. Some of the decision processes involved in barrage operations, arguably, are inevitable, given that the changing hydro-climate is a reality and upstream-downstream trade-offs will emerge. In this phase, how could trans-boundary water management operations allow for both human development and conservation, is a question that needs constant scientific feedback and adaptive management. By studying the specific details of what operations can sustain Ganges river dolphin populations upstream and downstream of barrages, and allow movement of river dolphins during the flood-season or at other times of the year, the inferences that we have made may be useful in future management planning of this nature. Nepalese scientists have been producing robust evidence-based science on climate change impacts on the nation's water resources (Baidya et al. 2008, Shrestha & Aryal 2011, Shrestha et al. 2019). Their findings could be integrated with future engineering plans to manage Nepal's water resources between sustaining diverse human uses (e.g., hydropower, irrigation) and also maintaining ecologically adequate flows for the conservation of species like Ganges river dolphins. Conservation Action Plans for river dolphins in both countries need to include concrete plans for trans-boundary cooperation for aligning their conservation objectives by overcoming trade-offs to the extent possible, to protect the small populations of Ganges river dolphins in Nepal's and India's river channels isolated upstream of these barrages. Similar studies are needed also for trans-boundary conservation planning for other endangered freshwater biodiversity, e.g. gharial crocodiles.

Prospects for analytical and engineering design studies

Our largely statistical and graphical analyses can be expanded further with the use of analytical tools used by engineers, hydrologists, and climate-change experts in river flow and flood modelling and forecasting (e.g. river routing, flood depth models, barrage gate physical models, etc.) to fine-tune options for adaptive management. With such analytical models, it may be possible to build realistic scenarios and test their impacts on optimization of future water availability for river dolphins in upstream habitats (Derepasko et al. 2022, Sharma et al. 2022). From such studies, engineering solutions and retrofitting possibilities (e.g. Valbuena-Castro et al. 2020) may also emerge to allow better prospects of downstream-upstream connectivity and passage for river dolphins through the existing barrages. At present, connectivity may be hypothetically available for 10% of times in a year, but the actual passage of river dolphins may be constrained by on-ground issues like sedimentation and siltation. Sediment flux studies at barrage sites will also be important, therefore, to identify ways and means to facilitate better longitudinal connectivity, and also find ways to resolve barrage and canal maintenance issues.

We note here that barrages are typically not thought of as barriers to "free-flowing rivers" (see Grill et al. 2015, 2019; which only include dams and not barrages). However, this is fallacious because as we show quite clearly, even barrages present many impediments to river flow and connectivity. For all the above to be realized, however, the most important need is to increase the ecological awareness and technical capacity of barrage operators and authorities to enable them for ecologically oriented management of trans-boundary barrages. Similar studies can also be taken to the barrage design level in other transboundary water sharing contexts. Samad et al. (2022) showed that the India-Bangladesh water sharing treaty under which the Farakka barrage releases water may provide habitat for Ganges river dolphins downstream of the barrage, but their persistence is negatively affected by the high-intensity and unregulated fishing in that stretch. A similar possibility might exist in the Koshi channel in Nepal downstream of the Birpur barrage. Momblanch et al. (2022) assessed the impacts of climate-change driven vulnerability and future flow unavailability on endangered Indus River Dolphins in the Beas River of India. In the India-Nepal context, the challenge for river dolphin conservation lies in the intersection of political boundaries in which river dolphins need to be maintained vis-à-vis the hydrological and geographic asymmetries inherent in the system.

Conclusions

The key conclusions of our study is that there are clear trade-offs involved in barrage operations to provide downstream ecological flows and maintain upstream habitat for the same species. Barrage operations may be increasing flows downstream, due to higher inflows in the flood and dry-season coupled with barrage inefficiencies and sedimentation-related problems in canals and barrage infrastructure. Under climate change scenarios of increased glacial melt and extreme rain events, these changes are likely to intensify, benefitting river dolphins in India but negatively affecting Nepal's river dolphins; at least in the short-term. Our analysis also identifies river discharges and water impoundment area management thresholds that could help optimize the maintenance of upstream and downstream habitats for river dolphins. Imminent revisions to existing trans-boundary water sharing agreements and Nepal's hydropower development push is likely to, however, directly affect such regimes for optimization. Our study integrates hydrologic and water management trends, barrage design and operation similarities and differences, boundary conditions and infrastructure constraints, with long-term river dolphin population persistence, occurrence in marginal habitats, habitat availability, and longitudinal connectivity. The baseline integration of such information can help in future studies on engineering efficiency, river sediment flux management, barrage retrofitting designs, as well as climate change uncertainty and impacts on future water management. The inferences and insights of the study could inform Conservation Action Plans for endangered Ganges river dolphins that are being actively implemented in both Nepal and India.

References

1. Adhakari, B. R. (2013). Flooding and Inundation in Nepal Terai: Issues and Concerns. *Hydro Nepal: Journal of Water, Energy and Environment*, *12*, 59–65. https://doi.org/10.3126/hn.v12i0.9034
2. Andreadis, K. M., Schumann, G. J. P., & Pavelsky, T. (2013). A simple global river bankfull width and depth database. *Water Resources Research*, *49*(10), 7164-7168.
3. Aryal, M., Shrestha, T. K., & Sapkota, R. P. (2013). Status, distribution and local initiatives taken to conserve river dolphin, *Platanista gangetica* at Prakashpur-Koshi Barrage section of Koshi River. *Nepal Journal of Environmental Science*, *1*(May), 8–16. https://doi.org/10.3126/njes.v1i1.36542
4. Baidya, S. K., Shrestha, M. L., & Sheikh, M. M. (2008). Trends in daily climatic extremes of temperature and precipitation in Nepal. *Journal of Hydrology and Meteorology*, *5*(1), 38-51.
5. Baniya, S., Deshar, R., Chauhan, R., & Thakuri, S. (2023). Assessment of channel migration of Koshi River in Nepal using remote sensing and GIS. *Environmental Challenges*, *11*, 100692.
6. Baral, H. S. (2013). An assessment of the impact of Koshi floods to birds and mammals. *Nepalese Journal of Biosciences*, *2*, 1–4. https://doi.org/10.3126/njbs.v2i0.7482

7. Basu, D. (2012). The abundance and distribution of the Ganges River Dolphin, susu, in the Geruwa and Ghagra rivers of Uttar Pradesh, India. WWF-India & The Uttar Pradesh Forest Department, India.
8. Behera, S.K., Singh, H. & Sagar, V. (2013). Status of Ganges River Dolphin (*Platanista gangetica gangetica*) in the Ganga River Basin, India: a review. Aquatic Ecosystem Health and Management 2: 425-432.
9. Behera, S.K., Singh, H., Sagar, V. & De, R. (2014). Current status of Ganges river dolphin *Platanista gangetica gangetica* in the rivers of Uttar Pradesh, India. Rivers for Life. Proceedings of the International Symposium on river biodiversity: Ganges-Brahmaputra-Meghna river systems, Patna, India.
10. Bhusal, J. K. (2014). Climate change implication for hydropower development in Nepal Himalayan region. *Direct Research Journal*, *2*, 27-35.
11. Bookhagen, B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface*, *115*(3), 1–25. https://doi.org/10.1029/2009JF001426
12. Brakenridge, G.R., Kettner, A.J., Paris, S., Cohen, S., & Nghiem, S.V. (2023). River and Reservoir Watch Version 4.5, Satellite-based river discharge and reservoir area measurements, DFO Flood Observatory, University of Colorado, USA. https://floodobservatory.colorado.edu/SiteDisplays/20.htm. (Accessed 20 February 2023).
13. Braulik, G.T., Bhatti, Z.I., Ehsan, T., Hussain, B., Khan, A.R., Khan, A., Khan, U., Kundi, K., Rajput, R., Reichert, A.P., Northridge, S.P., Bhaagat H.B., and Garstang R. (2012a). Robust abundance estimate for endangered river dolphin subspecies in South Asia. *Endangered Species Research* 17: 201-215.
14. Braulik, G. T., Reichert, A. P., Ehsan, T., Khan, S., Northridge, S. P., Alexander, J. S., & Garstang, R. (2012b). Habitat use by a freshwater dolphin in the low-water season. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *22*(4), 533-546.
15. Butler, C., Rest, M. (2017). Calculating risk, denying uncertainty: seismicity and hydropower development in Nepal. Himalaya: The Journal of the Association for Nepal and Himalayan Studies, 37: 2-6.
16. Campbell, E., Alfaro-Shigueto, J., Aliaga-Rossel, E., Beasley, I., Briceño, Y., Caballero, S., da Silva, V. M. F., Gilleman, C., Gravena, W., Hines, E., Khan, M. S., Khan, U., Kreb, D., Mangel, J. C., Marmontel, M., Mei, Z., Mintzer, V. J., Mosquera-Guerra, F., Oliveira-da-Costa, M., … Godley, B. J. (2022). Challenges and priorities for river cetacean conservation. *Endangered Species Research*, *49*(September), 13–42. https://doi.org/10.3354/esr01201
17. Chanchani, P., Lamichhane, B. R., Malla, S., Maurya, K., Bista, A., Warrier, R., ... & Borah, J. (2014). Tigers of the Transboundary Terai Arc Landscape: Status, distribution and movement in the Terai of India and Nepal. *National Tiger Conservation Authority, Government of India, and Department of National Park and Wildlife Conservation, Government of Nepal NTNC/DNPWC*, *3*.
18. Chaudhary, S. (2007). Status of, and threats to, the Ganges River Dolphin (*Platanista gangetica gangetica*) in the Koshi River, Nepal. M.Sc. Thesis (*Management of Protected Areas*), Dept. of Economics, University of Klagenfurt, Austria, 38 pp.

19. Chauhan, R. (2016). A preliminary report on status and distribution of Ganges river dolphin in Geruwa and Kaudiyala River, Katarniyaghat Wildlife Sanctuary, India. Submitted to the PCCF-Wildlife, Uttar Pradesh Forest Department. Society for Conservation of Nature, Etawah, India.
20. Choudhary, S., Dey, S., Sagar, V., Nair T., and Kelkar, N. (2012). River dolphin distribution in regulated river systems: implications for dry-season flow regimes in the Gangetic basin. Aquatic Conservation: Marine and Freshwater Ecosystems 22: 11-25.
21. CNP. (2015). Chitwan National Park and its buffer zone management plan, 2013- 2017. Government of Nepal Ministry of Forests and Soil Conservation, Department of National Parks and Wildlife Conservation, Chitwan National Park Office, Kasara, Chitwan.
22. Collins, D. N., & Hasnain, S. I. (1995). Runoff and sediment transport from glacierized basins at the Himalayan scale. Effects of Scale on Interpretation and Management of Sediment and Water Quality (Proceedings of aBoulder Symposium, July 1995), IAHS Publ. No. 226, 17–25.
23. Convention on Migratory Species (CMS). (2020). Proposal for a Concerted Action for the Ganges River Dolphin (*Platanista gangetica gangetica*) already listed on Appendix I and II of the Convention. Prepared by the Government of India. Agenda Item 28.2 UNEP/CMS/COP13/Doc.28.2.6/Rev.2. *presented at the 13th Meeting of the Conference of the Parties, Gandhinagar, India, 17-22 February 2020*.
24. Crétaux, J. F., Arsen, A., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., ... & Maisongrande, P. (2011). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in space research*, *47*(9), 1497-1507.
25. Crow, B., & Singh, N. (2000). Impediments and innovation in international rivers: The waters of South Asia. *World Development*, *28*(11), 1907–1925.
26. Das, G. C., Sharma, S. P., Ali, S. Z., Gawan, S., Usmani, A. A., Sarkar, A., Katdare, S., Rawat, A., Gangaimaran, P., Panda, A. K., Agnihotri, U., Ramachandran, A., Guha, S., Barthwal, S., Johnson, J. A., Badola, R., & Hussain, S. A. (2022). Prioritising river stretches using multi-modelling habitat suitability of Gangetic dolphin (*Platanista gangetica*) as a flagship species for aquatic biodiversity conservation in the Ganga River Basin, India. *Ecological Indicators*, *145*(October), 109680. https://doi.org/10.1016/j.ecolind.2022.109680
27. Densmore, A. L., Sinha, R., Sinha, S., Tandon, S. K., & Jain, V. (2016). Sediment storage and release from Himalayan piggyback basins and implications for downstream river morphology and evolution. *Basin Research*, *28*(4), 446-461.
28. Devkota, L., Giri, S., Crosato, A., & Baral, B. (2018). Impact of the Koshi barrage and embankments on river morphology and dynamics. *Seventh International Conference and Exhibition on Water Resource and Renewable Energy Development in Asia*, *March*, 13–15. https://www.researchgate.net/publication/323166806
29. Dhar, O. N., & Nandargi, S. (2002). Flood study of the Himalayan tributaries of the Ganga river. *Meteorological Applications: A journal of forecasting, practical applications, training techniques and modelling*, *9*(1), 63-68.
30. Dingle, L, Sinclair, H, Attal, M, Milodowski, D & Singh, V. (2016). Subsidence control on river morphology and grain size in the Ganga Plain. American Journal of Science. https://doi.org/10.2475/08.2016.03
31. Dixit, A. (2018). Trans-Boundary Water Governance in South Asia: the beginning of a new journey. *South Asian Rivers: A Framework for Cooperation*, 81-101.

32. Denlay, K. (2013). EC Flag 118 Summary of an expedition which carried Explorers Club Flag # 118 to the Karnali River (west Nepal) and the Girijapuri Barrage (Utter Pradesh, northern India), investigating the habitat of the endangered Gangetic River Dolphin (*Platanista gangetica*). Survey Report. March 2013.
33. Derepasko, D., Peñas, F. J., Barquín, J., & Volk, M. (2021). Applying optimization to support adaptive water management of rivers. Water, 13(9), 1281.
34. Frappart, F., Calmant, S., Cauhopé, M., Seyler, F., & Cazenave, A. (2006). Preliminary results of ENVISAT RA-2-derived water levels validation over the Amazon basin. *Remote sensing of Environment*, *100*(2), 252-264.
35. Gaurav, K., Métivier, F., Devauchelle, O., Sinha, R., Chauvet, H., Houssais, M., & Bouquerel, H. (2015). Morphology of the Kosi megafan channels. *Earth Surface Dynamics*, *3*(3), 321-331.
36. Gautam, D. K., & Regmi, S. K. (2013). Recent trends in the onset and withdrawal of summer monsoon over Nepal. *Ecopersia*, *1*(4), 353–367. http://ecopersia.modares.ac.ir/article-24-11752-en.html
37. Grill, G., Lehner, B., Lumsdon, A. E., Macdonald, G. K., Zarfl, C., & Reidy Liermann, C. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, *10*(1). https://doi.org/10.1088/1748-9326/10/1/015001
38. Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., ... & Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature*, *569*(7755), 215-221.
39. Gronsdahl, S., McParland, D., Eaton, B., Moore, R. D., & Rosenfeld, J. (2021). Evaluation of a geomorphic instream flow tool for conducting hydraulic-habitat modelling. *River Research and Applications*, *37*(10), 1520–1537. https://doi.org/10.1002/rra.3847
40. Gyawali, D. (2001). *Water in Nepal* (Vol. 280). Kathmandu: Himal books.
41. Gyanwali, K., Adhikari, P., Khanal, S., Bhattarai, N., Bajracharya, T. R., Komiyama, R., & Fujii, Y. (2023). Integrating glacio-hydrological and power grid models to assess the climate-resiliency of high mountain hydropower in Nepal. *Renewable and Sustainable Energy Reviews*, *183*, 113433.
42. Hannah, D. M., Kansakar, S. R., Gerrard, A. J., & Rees, G. (2005). Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. *Journal of Hydrology*, *308*(1–4), 18–32. https://doi.org/http://dx.doi.org/10.1016/j.jhydrol.2004.10.018
43. Immerzeel, W. W., Pellicciotti, F., & Bierkens, M. F. P. (2013). Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, *6*(9), 742–745. https://doi.org/10.1038/ngeo1896
44. Immerzeel, W. W., Van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the asian water towers. *Science*, *328*(5984), 1382–1385. https://doi.org/10.1126/science.1183188
45. Indian Insitute of Science (IISc), Indian Institutes of Technology (IITs) (2010). Module 4 Hydraulic structures for flow diversion and storage Lesson 2 Design of the Main Diversion Structure of a Barrage. *Water Resources Engineering and Management*, 34 p.
46. India-WRIS. (2014). Ganga Basin. Version 2.0. CWC and NRSC, ISRO, India.
47. Irrigation and Water Resources Department, Govt. of Uttar Pradesh. Flood Management Information System. URL: . Accessed 15th October 2023.
48. ISI (1989). IS-6966-1. Hydraulic design of barrages and weirs - Guidelines, Part 1: Alluvial Reaches [WRD 22: River Training and Diversion Works]

49. ISI. (1985). IS 11130 (1984): Criteria for Structural Design of Barrages and Weirs [WRD 22: River Training and Diversion Works].
50. Jnawali, S. R., & Bhuju, U. R. (2000). The Ganges river dolphin: Current status and conservation threats. Paper presented in WWF Regional Workshop on South Asian River Dolphins (pp. 4-7).
51. Joshi, D. 2004. Status, Distribution and Management of River dolphin (Platanista gangetica) in Lowland Karnali. M.Sc. Thesis, Pokhara University, Nepal.
52. Kasuya, T., & Haque, A.K.M.A. (1972). Some informations on distribution and seasonal movement of the Ganges dolphin. *Scientific Reports of the Whales Institute,* 24, 109–115.
53. Kelkar, N., Krishnaswamy, J., Choudhary S., and Sutaria D. 2010. Coexistence of fisheries with river dolphin conservation. *Conservation Biology* 24(4): 1130-1140.
54. Kelkar, N. & Dey, S. (2021). Ganges river dolphins and other biodiversity in the Mahananda River in Bihar and West Bengal: A report on the first complete survey, November 2021. Report for the Department of Environment, Forests, and Climate Change, Government of Bihar. Wildlife Conservation Trust, Mumbai, India.
55. Kelkar, N., Smith, B.D., Alom, M.Z., Dey, S., Paudel, S. & Braulik, G.T. 2022. *Platanista gangetica*. *The IUCN Red List of Threatened Species* 2022: e.T41756A50383346. https://dx.doi.org/10.2305/IUCN.UK.2022-1.RLTS.T41756A50383346.en.
56. Khan, M. R., Michael, H. A., Bresnyan, E. W., & Yu, W. (2022). Impacts of basin-wide irrigation pumping on dry-period stream baseflow in an alluvial aquifer in the Kosi Fan region of India and Nepal. *Hydrogeology Journal*, *30*(6), 1899–1910.
57. Khanal, G., Suryawanshi, K. R., Awasthi, K. D., Dhakal, M., Subedi, N., Nath, D., Kandel, R. C., & Kelkar, N. (2016). Irrigation demands aggravate fishing threats to river dolphins in Nepal. *Biological Conservation*, *204*, 386–393. https://doi.org/10.1016/j.biocon.2016.10.026
58. Khatiwada, J. R., Adhikari, J. N., Rijal, D., & Sharma, L. N. (2021). Freshwater biodiversity in western Nepal: A review. *Nepalese Journal of Zoology*, *5*(1), 34–46. https://doi.org/10.3126/njz.v5i1.38290
59. Khatiwada, K. R., Panthi, J., Shrestha, M. L., & Nepal, S. (2016). Hydro-climatic variability in the Karnali River Basin of Nepal Himalaya. *Climate*, *4*(2). https://doi.org/10.3390/cli4020017
60. Khatiwada, S., Chalise, M. K., & Sharma, S. (2019). Distribution and habitat status of Ganges River Dolphin (*Platanista gangetica*) in Mohana River Segment of Western Nepal. *Journal of Institute of Science and Technology*, *24*(2), 58–67. https://doi.org/10.3126/jist.v24i2.27258
61. Khatri, T. B., Shah, D. N., & Mishra, N. (2010). Post-flood status of the Endangered Ganges River Dolphin *Platanista gangetica gangetica* (Cetartiodactyla: Platanistidae) in the Koshi River, Nepal. *Journal of Threatened Taxa*, *2*(13), 1365–1371. https://doi.org/10.11609/jott.o2496.1365-71
62. Kumar, R. (2021). Assessment of Environmental Flows in Ghaghra River Systems. *International Journal of Recent Development in Engineering and Technology Website: Www.Ijrdet.Com*, *10*(1). www.ijrdet.com
63. Labh, S. N. (2023). Behaviour, distribution and conservation threats of Dolphin Platanista gangetica (Roxburgh, 1801) in rivers of Nepal. *Aquatic Ecosystem Health and Management*, *26*(1), 32–39. https://doi.org/10.14321/aehm.026.01.32
64. Limbu, K. P., & Subba, B. R. (2013). Status of key faunal species in Koshi Tappu Wildlife Reserve after Koshi flood disaster 2008. *Nepalese Journal of Biosciences*, *1*(August 2008), 41–54. https://doi.org/10.3126/njbs.v1i0.7469

65. Liu, J., Yong, D. L., Choi, C. Y., & Gibson, L. (2020). Transboundary frontiers: an emerging priority for biodiversity conservation. *Trends in Ecology & Evolution*, *35*(8), 679-690.
66. Maharjan, K. (2018). *Political Ecology of Water Governance in South Asia: A Case Study of the Koshi River Communities* (Doctoral dissertation). *June*. https://ses.library.usyd.edu.au/handle/2123/19749
67. Momblanch, A., Kelkar, N., Braulik, G., Krishnaswamy, J., & Holman, I. (2022). Exploring trade-offs between SDGs for Indus River Dolphin conservation and human water security in the regulated Beas River, India. *Sustainability Science*.
68. Papa, F., Frappart, F., Malbeteau, Y., Shamsudduha, M., Vuruputur, V., Sekhar, M., ... & Calmant, S. (2015). Satellite-derived surface and sub-surface water storage in the Ganges–Brahmaputra River Basin. *Journal of Hydrology: Regional Studies*, *4*, 15-35.
69. Paudel, S. (2022). *Management of Nepalese Rivers to Conserve Ganges River Dolphin (Doctoral dissertation, The University of Arizona).*
70. Paudel, S., Koprowski, J. L., & Cove, M. V. (2020a). Seasonal flow dynamics exacerbate overlap between artisanal fisheries and imperiled Ganges River dolphins. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-75997-4
71. Paudel, S., Koprowski, J. L., Thakuri, U., Sigdel, R., & Gautam, R. C. (2020b). Ecological responses to flow variation inform river dolphin conservation. *Scientific Reports*, *10*(1), 1–13. https://doi.org/10.1038/s41598-020-79532-3
72. Paudel, S., Koprowski, J. L., Thakuri, U., & Karki, A. (2021). In-stream habitat availability for river dolphins in response to flow: Use of ecological integrity to manage river flows. *PLoS ONE*, *16*(July). https://doi.org/10.1371/journal.pone.0241099
73. Paudel, S., Levesque, J.C., Saavedra, C., Pita, C. and Pal, P. (2016a). Characterization of the artisanal fishing communities in Nepal and potential implications for the conservation and management of Ganges River Dolphin (*Platanista gangetica gangetica*). *PeerJ*: 4:e1563 https://doi.org/10.7717/peerj.1563
74. Paudel, S., Pal, P., Cove, M. V., Jnawali, S. R., Abel, G., Koprowski, J. L., & Ranabhat, R. (2016b). The endangered Ganges River dolphin *Platanista gangetica gangetica* in Nepal: Abundance, habitat and conservation threats. *Endangered Species Research*, *29*(1), 59–68. https://doi.org/10.3354/esr00702
75. Paudel, S., Timilsina, Y. P., Lewis, J., Ingersoll, T., & Jnawali, S. R. (2015). Population status and habitat occupancy of endangered river dolphins in the Karnali River system of Nepal during low water season. *Marine Mammal Science*, *31*(2), 707–719. https://doi.org/10.1111/mms.12192
76. Prajapati, S. (2021). Stranding cases of endangered Ganges river dolphins in the Ghaghara-Sharada irrigation canals, Ganges river basin, India: Conservation implications. *Mammalia*, *85*(1), 39–46. https://doi.org/10.1515/mammalia-2019-0110
77. Pun, S. B. (2013). World Bank's 2012 Ganges Strategic Basin Assessment: A View from Nepal. *Hydro Nepal: Journal of Water, Energy and Environment*, *12*, 6–12. https://doi.org/10.3126/hn.v12i0.9025
78. Rahaman, W., Wittmann, H., & von Blanckenburg, F. (2017). Denudation rates and the degree of chemical weathering in the Ganga River basin from ratios of meteoric cosmogenic 10Be to stable 9Be. *Earth and Planetary Science Letters*, *469*, 156–169. https://doi.org/10.1016/j.epsl.2017.04.001

79. Rai, A. K., Beg, Z., Singh, A., & Gaurav, K. (2021). Estimating discharge of the Ganga River from satellite altimeter data. *Journal of Hydrology*, *603*, 126860.
80. Rai, A., Bashir, T., Lagunes–Díaz, E. G., & Shrestha, B. (2023). The effect of physiographic and hydrologic complexities and their alterations on the distribution of obligate freshwater dolphins. *Ecology and Evolution*, *13*(5), 1–13. https://doi.org/10.1002/ece3.10106
81. Rakhal, B., Adhikari, T. R., Sharma, S., & Ghimire, G. R. (2021). Assessment of channel shifting of Karnali Megafan in Nepal using remote sensing and GIS. *Annals of GIS*, *27*(2), 177–188. https://doi.org/10.1080/19475683.2021.1871950
82. Salman, S. M. A., & Uprety, K. (2021). Conflict and Cooperation on South Asia's International Rivers. World Bank Publications, number 15171. https://doi.org/10.1163/9789004480216
83. Samad, I., Kelkar, N., & Krishnaswamy, J. (2022). Life at the borderline: Responses of Ganges river dolphins to dry-season flow regulation of river and canal habitats by the Farakka barrage. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *32*(2), 294–308. https://doi.org/10.1002/aqc.3763
84. Schwatke C., Scherer D., Dettmering D. (2019). Automated Extraction of Consistent Time-Variable Water Surfaces of Lakes and Reservoirs based on Landsat and Sentinel-2. Remote Sensing, 11(9), 1010, doi:10.3390/rs11091010
85. Shah, D. N., Poudyal, A., Sharma, G., Levine, S., Subedi, N., & Dhakal, M. (2020). Status, distribution, threats, and conservation of the Ganges River Dolphin *Platanista gangetica* (Mammalia: Artiodactyla: Cetacea) in Nepal. *Journal of Threatened Taxa*, *12*(1), 15106–15113. https://doi.org/10.11609/jott.4397.12.1.15106-15113
86. Shah, K.B., and Paudel, S. 2016. Ecology of crocodile and dolphin in the Koshi Basin. Chapter 11. In: Doody, T.M., Cuddy, S.M., Bhatta, L.D. (ed.), *Connecting flows and ecology in Nepal: current state of knowledge of the Koshi Basin. Sustainable Development Investment Portfolio (SDIP) project*, pp. 123 -128. CSIRO, Australia.
87. Sharma, A., Baruah, A., Mangukiya, N., Hinge, G., & Bharali, B. (2022). Evaluation of Gangetic dolphin habitat suitability under hydroclimatic changes using a coupled hydrological-hydrodynamic approach. *Ecological Informatics*, *69*(April), 101639. https://doi.org/10.1016/j.ecoinf.2022.101639
88. Sharma, R. H., & Awal, R. (2013). Hydropower development in Nepal. *Renewable and Sustainable Energy Reviews*, *21*, 684-693.
89. Shrestha, M. K., & Ranjan, R. (2023). Territory and status of dolphins in Nepalese rivers: A review. *Aquatic Ecosystem Health and Management*, *26*(1), 40–48. https://doi.org/10.14321/aehm.026.01.40
90. Shrestha, A. B., & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers. *Regional environmental change*, *11*, 65-77.
91. Shrestha, T.K. 1989. Biology, status and conservation of the Ganges River dolphin, *Platanista gangetica*, in Nepal. In: W.F. Perrin, R.L. Brownell Jr., K. Zhou and J. Liu (eds. *Biology and Conservation of River Dolphins*, pp. 70-76. IUCN Species Survival Commission Occasional Paper 3, Gland, Switzerland and Cambridge, UK.
92. Shrestha, T.K. (1995). The Ganges River Dolphin, Variety Printers, Kathmandu.
93. Shrestha, U. B., Shrestha, S., Chaudhary, P., & Chaudhary, R. P. (2010). How representative is the Protected Areas System of Nepal? *Mountain Research and Development*, *30*(3), 282–294. https://doi.org/10.1659/MRD-JOURNAL-D-10-00019.1

94. Shrestha, U. B., Shrestha, A. M., Aryal, S., Shrestha, S., Gautam, M. S., & Ojha, H. (2019). Climate change in Nepal: a comprehensive analysis of instrumental data and people's perceptions. *Climatic Change*, *154*, 315-334.
95. Singh, H. & Behera, S.K. (2018) Status of the Important Bioresources of Girwa River with Special Reference to Ganges River Dolphin (*Platanista gangetica gangetica*) in Katerniaghat Wildlife Sanctuary, Uttar Pradesh, India. Intech Open: Biological Resources of Water, pp. 285-296, http://dx.doi.org/10.5772/intechopen.72661.
96. Singh, A. P., Arya, A. K., & Singh, D. S. (2020). Morphometric analysis of Ghaghara River Basin, India, using SRTM data and GIS. *Journal of the Geological Society of India*, *95*, 169-178.
97. Singh, S., Singh, A., Dutta, S., & Srivastava, S. (2023). Rescuing Ganges river dolphins (*Platanista gangetica*) from irrigation canals in Uttar Pradesh, North India, 2013-2020. J. Cetacean Res. Manage., 24(1), 175-188.
98. Sinha, R., Mohanta, H., Jain, V., & Tandon, S. K. (2017). Geomorphic diversity as a river management tool and its application to the Ganga River, India. *River Research and Applications*, *33*(7), 1156–1176. https://doi.org/10.1002/rra.3154
99. Sinha, R., Gupta, A., Mishra, K., Tripathi, S., Nepal, S., Wahid, S. M., & Swarnkar, S. (2019). Basin-scale hydrology and sediment dynamics of the Kosi river in the Himalayan foreland. *Journal of Hydrology*, *570*, 156-166.
100. Smakhtin, V. U., Shilpakar, R. L., & Hughes, D. A. (2006). Hydrology-based assessment of environmental flows: An example from Nepal. *Hydrological Sciences Journal*, *51*(2), 207–222. https://doi.org/10.1623/hysj.51.2.207
101. Smith, A. M., & Smith, B. D. (1998). Review of status and threats to river cetaceans and recommendations for their conservation. *Environmental Reviews*, *6*(3–4), 189–206. https://doi.org/10.1139/a99-002
102. Smith, B. D. (1993). 1990 Status and conservation of the Ganges River dolphin *Platanista gangetica* in the Karnali River, Nepal. *Biological Conservation*, *66*(3), 159-169.
103. Smith, B. D., Sinha, R. K., & Regmi, U. (1994). Status of Ganges river dolphins (Platanista gangetica) in the Karnali, Mahakali, Narayani and Sapta Kosi rivers of Nepal and India in 1993. Marine Mammal Science, 10(3), 368-375.
104. Smith, B.D., Bhandari, B., Sapkota, K. (1996) Aquatic biodiversity in the Karnali and Narayani river basins, Nepal. IUCN Nepal, Kathmandu, xii + 59 p.
105. Smith, B. D., Sinha, R. K., Kaiya, Z., Chaudhry, A. A., Renjun, L., Ding, W., ... & Sapkota, K. (2000). Register of water development projects affecting river cetaceans in Asia. *Biology and conservation of freshwater cetaceans in Asia*, *22*, 22-39.
106. Smith, B.D. & Reeves, R.R. (2000). Survey methods for population assessment of Asian River dolphins. In: Reeves, R.R., Smith, B.D. and Kasuya, T. (eds), *Biology and Conservation of Freshwater Cetaceans in Asia*, pp. 152. IUCN Species Survival Commission Occasional Paper No. 23. IUCN, Gland, Switzerland and Cambridge, UK.
107. Sonkar, G. K., & Gaurav, K. (2020). Assessing the impact of large barrages on habitat of the Ganga River dolphin. *River Research and Applications*, *36*(9), 1916–1931. https://doi.org/10.1002/rra.3715
108. Sonkar, G. K., Gaurav, K., Rai, A. K., Taigor, S., & Beg, Z. (2023). Integrating satellite altimeter data and geomorphic in-stream flow tool to assess reach average hydraulic habitat of the Ganga River dolphin. *Ecohydrology*, *16*(2). https://doi.org/10.1002/eco.2497

109. South Asian River Dolphin Task Team. (2020). 19-21 July 2019 Workshop Report, Kuala Lumpur, Malaysia. International Whaling Commission Scientific Committee Meeting SC/68B/REP04/REV1.
110. Surinaidu, L., Amarasinghe, U., Maheswaran, R., & Nandan, M. J. (2020). Assessment of long-term hydrogeological changes and plausible solutions to manage hydrological extremes in the transnational Ganga river basin. *H2Open Journal*, *3*(1), 457–480. https://doi.org/10.2166/h2oj.2020.049
111. Talukdar, B., & Sinha, S. (2013). Challenges and opportunities of transboundary rhino conservation in India and Nepal. *Pachyderm*, *54*, 45-51.
112. Timilsina, N. 1999. Present status and conservation of Gangetic dolphin in the Karnali River, Western Lowland of Nepal. M.Sc. Thesis. Tribhuwan University. Katmandu. 45pp
113. Trenberth, K. E. (2005). The impact of climate change and variability on heavy precipitation, floods, and droughts. *Encyclopedia of hydrological sciences*, *17*, 1-11.
114. Valbuena-Castro, J., Fuentes-Pérez, J. F., García-Vega, A., Bravo-Córdoba, F. J., Ruiz-Legazpi, J., de Azagra Paredes, A. M., & Sanz-Ronda, F. J. (2020). Coarse fishway assessment to prioritize retrofitting efforts: A case study in the Duero River basin. *Ecological Engineering*, *155*, 105946.
115. Vora, K. H., & Divakar Naidu, P. (1990). The use of marine geophysical methods in geo-engineering investigations of dams/barrages - a case study of Kosi Barrage. *Irrigation & Power J.*, *47*(4 Oct.), 85–96.
116. Wasko, C., Nathan, R., Stein, L., & O'Shea, D. (2021). Evidence of shorter more extreme rainfalls and increased flood variability under climate change. *Journal of Hydrology*, *603*, 126994.
117. Water Resources Department, Govt. of Bihar. Flood Management Information System. URL: https://wrd.fmiscwrdbihar.gov.in/. Accessed 31st October 2023.
118. World Wildlife Fund (WWF-Nepal). (2006). Status, distribution and conservation threats of Ganges River Dolphin in Karnali River, Nepal. WWF-Nepal.
119. Zakharova, E., Nielsen, K., Kamenev, G., & Kouraev, A. (2020). River discharge estimation from radar altimetry: Assessment of satellite performance, river scales and methods. *Journal of Hydrology*, *583*(June 2019), 124561. https://doi.org/10.1016/j.jhydrol.2020.124561

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