



Exploring trade-offs between SDGs for Indus River Dolphin conservation and human water security in the regulated Beas River, India

Andrea Momblanch¹  · Nachiket Kelkar² · Gill Braulik³ · Jagdish Krishnaswamy^{2,4} · Ian P. Holman¹

Received: 20 April 2021 / Accepted: 10 August 2021 / Published online: 11 October 2021
© The Author(s) 2021

Abstract

In India's Indo-Gangetic plains, river flows are strongly altered by dams, barrages and water diversions for irrigation, urban supply, hydropower production and flood control. Human demands for freshwater are likely to intensify with climatic and socio-economic changes, exacerbating trade-offs between different sustainable development goals (SDGs) dependent on freshwater (e.g. SDG2, SDG6, SDG7, SDG11 and SDG15). Freshwater ecosystems and endangered aquatic species are not explicitly addressed in the SDGs, but only nested as targets within SDG6 and SDG15. Thus, there is high risk that decisions to advance other SDGs may overlook impacts on them. In this study, we link a water resource systems model and a forecast extinction risk model to analyze how alternative conservation strategies in the regulated Beas River (India) affect the likelihood of survival of the only remaining population of endangered Indus River Dolphins (IRD) in India in the face of climate change-induced impacts on river hydrology and human water demands, explicitly accounting for potential trade-offs between related SDGs. We find that the frequency of low flow released from the main reservoir may increase under some climate change scenarios, significantly affecting the IRD population. The strongest trade-offs exist between the persistence of IRD, urban water supply and hydropower generation. The establishment of ecologically informed reservoir releases combined with IRD population supplementation enhances the probability of survival of the IRD and is compatible with improving the status of relevant SDGs. This will require water managers, conservation scientists, and other stakeholders to continue collaborating to develop holistic water management strategies.

Keywords Sustainable development goals · Dams and barrages · Punjab · Floodplain rivers · Indus Dolphin · Conservation planning

Introduction

Water is essential to the achievement of the Sustainable Development Goals (SDGs) such as Zero Hunger (SDG2), Clean Water and Sanitation (SDG6), access to Affordable and Clean Energy (SDG7), Sustainable Cities and Communities (SDG11) and Life on Land (SDG15). The SDGs are highly intertwined and understanding their inter-relationships is essential to ensure balanced progress towards their achievement (Fonseca et al. 2020; Hall et al. 2020; Banerjee et al. 2019). Water-related SDGs represent different and often competing ways of using water; for example, water use for irrigation, urban, and industrial supply and hydropower production (Momblanch et al. 2019a). Moreover, water supply to these uses generally involves dams, barrages and water

Handled by Fabrice Renaud, University of Glasgow, United Kingdom.

✉ Andrea Momblanch
andrea.momblanch-benavent@cranfield.ac.uk

- ¹ Cranfield Water Science Institute, Cranfield University, Cranfield, UK
- ² Ashoka Trust for Research in Ecology and the Environment, Bengaluru, India
- ³ Sea Mammal Research Unit, University of St. Andrews, St Andrews, Scotland
- ⁴ Indian Institute for Human Settlements, Bengaluru, India

diversions that strongly alter natural river flows that sustain freshwater ecosystems (Grill et al. 2019). These relationships, along with the way in which SDGs are defined and structured, require careful consideration of the targets and indicators to use in SDG assessments. Importantly, the IPCC Report on Climate Change and Land (Hurlbert et al. 2019) highlights the absence of an explicit goal for conserving freshwater biodiversity. Freshwater ecosystems and biodiversity are only mentioned as targets nested under SDG6 and SDG15 (Reid et al. 2017, 2019) in contrast to conservation of marine and terrestrial ecosystems that are defined as explicit goals (SDGs 14 and 15). Although conservation of fresh-water ecosystems is covered in target 6 under SDG 6, in practice, diversions of river water are often prioritised to the detriment of ecological requirements, to meet targets related to drinking water for cities and towns (George et al. 2009; Shrestha et al. 2017; Bhave et al. 2018; Long et al. 2020). This omission at the goal level might aggravate and pose significant risk for freshwater biodiversity conservation (Irvine 2018) by masking the existing trade-offs in water management between human demands, climate change mitigation and ecological conservation targets (Clark et al. 2021).

Climate change, population growth and economic development are expected to intensify pressures for further regulation and use of water resources around the world (Madhusoodanan et al. 2016; Vörösmarty et al. 2010, 2013). This can increase water scarcity and adversely impact freshwater environments, biodiversity and ecosystem services (e.g. habitat for endangered aquatic fauna, fisheries, tourism, water purification). In this context, understanding and mitigating trade-offs between water-related SDGs and their targets are crucial to develop consistent sectoral policies.

The transformation of river ecosystems for irrigation, urban supply and hydropower forms a major threat to the two species of endangered river dolphins in the Indian subcontinent (Braulik et al. 2014, 2021). In regulated rivers, trade-offs between human water needs and river ecology become particularly acute when small populations of endangered species are directly affected by water management decisions. The Beas River in Northwestern India is a typical example of conflicting human and environmental uses of water and, thereby, the related SDGs. The Beas flows from the Western Himalayas to the plains of Punjab, India, and sustains rural communities, growing cities, substantial hydropower generation and extensive irrigated lands, with water diversions from the river extending to the neighbouring states of Haryana and Rajasthan. These demands overlap an important conservation area for endangered Indus River Dolphins (*Platanista minor* (Braulik et al. 2021); hereafter IRD). River flows in the Beas River are determined by the management of existing water infrastructures in relation to dynamic hydrological processes. None of these aspects

will remain static in the future due to climatic and socio-economic changes. Therefore, tools capable of integrating hydrology, water demands and infrastructure management policies are required to understand future water availability and address potential water security problems for human and environmental uses through basin planning (Momblanch et al. 2019b).

Our paper aims to understand the relative ability of different plausible measures for the conservation of the IRD population in the Beas River to enhance its probability of survival across the full uncertainty spectrum of climate change scenarios and the associated implications for other water-related SDGs. We evaluated three conservation scenarios: (1) business as usual (based on the current Beas Conservation Reserve measures); (2) ecologically-informed reservoir management and (3) conservation translocations for IRD population supplementation, by combining a system modelling approach that integrates both the natural and socio-economic aspects of water resources management, with an extinction risk model for the IRD population incorporating environmental and demographic stochasticity. Our coupled modelling outputs identify the range of future changes in the timing and magnitude of water availability due to climate change that could influence trade-offs between SDGs. We also discuss the conditions and emerging opportunities for IRD conservation planning in the near future and how they can be aligned with socio-economic development.

Methods

Study system

The Beas River flows in the Indian states of Himachal Pradesh and Punjab and joins the Sutlej River, a tributary of the Indus (Fig. 1). The Beas flows from the Rohtang pass in the Himalayas at an altitude of 4361 m above sea level (m asl) for 320 km until it meets the Sutlej at Harike Pattan in the plains of Punjab, India. The hilly and mountainous parts of the river basin have mainly natural land cover, while the lower reaches are almost entirely irrigated cropland and urban areas. Average temperatures in the Beas basin are highly variable, ranging from 14 to 36 °C in the summer (March–May) and 0.2–15 °C in winter (December–February) (Bhattacharya et al. 2019). An annual average precipitation of 1500 mm falls mainly as rainfall during the monsoon season (July–September), although westerlies contribute a significant amount of snowfall above 2000 m asl in winter (Bookhagen and Burbank 2010) and facilitate groundwater recharge in the plains. The hydrological regime is highly seasonal, with low flows occurring from winter to summer and the highest river discharges taking place during the monsoon. The Beas has been regulated since the late nineteenth

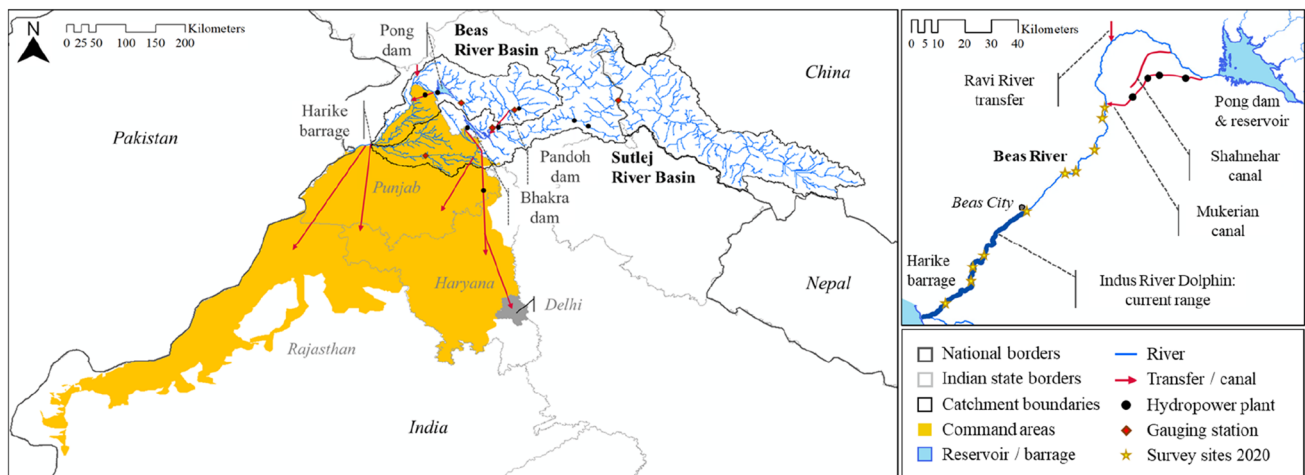


Fig. 1 Location and main features of the Beas–Sutlej water resource system and detail of the Beas River downstream Pong dam. National borders (Bjorn Sandvik; <http://thematicmapping.org>); regional borders (GADM version 1.0; <http://gadm.org>); Sutlej and Beas river

catchments, sub-catchments and river network (delineated with GIS tools), main reservoirs (official shapefiles; National Institute of Hydrology Roorkee); command areas (India Water Resources Information System; <https://indiawris.gov.in>)

century by weirs and diversion channels, principally by the Pong dam constructed in 1975. Because of a large interbasin water transfer from Pandoh reservoir on the Beas to the Sutlej, the Pong, Pandoh and Bhakra (on the Sutlej River) dams (Fig. 1) are conjunctively managed for hydropower generation, flood control and irrigation. These dams, along with the Harike barrage, commissioned in 1953 at the confluence of the Beas and Sutlej rivers, supply water for canal irrigation across the states of Punjab, Haryana and Rajasthan, with most canals diverting water from Sutlej River upstream and downstream its confluence with the Beas.

The Beas River stretches along approximately 185 km between Pong and Harike and has been declared as the Beas Conservation Reserve (WWF-India 2018). The annual average flow in the Beas River in this stretch ranges between 250 and 400 m³/s (WWF-India 2018). It receives hydrological inputs from its catchment area and additional resources from a water transfer from the Ravi River with a discharge of approx. 100 m³/s transferable to the Beas downstream of the Pong dam (Rao and Ramaseshan 1985). Additionally, downstream of the Pong dam, Beas water is diverted at Talwara headworks through the Shahnehar canal for irrigation and the Mukerian canal for hydropower generation, the latter being returned to the main river channel approximately 60 km downstream of its intake. The Beas city is located by the river around 50 km upstream of Harike barrage and abstracts river flows for urban use. At Harike, the contribution of flow from the Beas is about 60% and from the Sutlej is around 40% of annual flows (Rao and Ramaseshan 1985), which have shown recent declines (Jain et al. 2008). Releases from the Pong dam account for over 88% of the average annual flow of the Beas River. The maximum contribution

to flows from Pong dam releases can be over 95% during the postmonsoon and winter months (October–December) and the minimum contribution from Pong dam releases to river flow is during April (14–44%) which indicates the period of lowest dry-season flows in the Beas River.

Indus river dolphins in the Beas: the current status and likely trajectories of decline

IRD were once found throughout the Beas and Sutlej rivers in the plains of Punjab (Anderson 1879) but were thought to have been extirpated. However, a remnant population of IRD was discovered by scientists of the Punjab Forest Department and World Wide Fund for Nature (WWF-India) in 2007 (Behera et al. 2008). It is the only IRD population in India, as the major population occurs in the main stem of the Indus in Pakistan (Braulik et al. 2014). This small population of an estimated 5–11 dolphins has since been monitored and is known to occur within a 50 km river stretch of the Beas River upstream of the Harike barrage (Khan and Pant 2014). The IRD were historically extirpated from all tributaries of the Indus in India (except the Beas), mainly due to sequential decline in river habitat following flow regulation barriers and diversions (Braulik et al. 2014), besides other factors such as pollution. The Beas–Sutlej Rivers have witnessed increasing flow regulation since 1920 (described in Table S1), which reduced the potential riverine extent available to the IRD from 380 km to about 50 km (about 87%) in the period from 1920 to date (Figure S1). The strongest declines in available extent were between 1953 and 1975, which marked the period of most intensive water regulation on both Beas and Sutlej rivers. It is likely that that the

extent of river habitat reduction during this period would be directly correlated with a corresponding decline in the local dolphin population in the Beas. The past four to seven decades of continued habitat degradation may be estimated to have caused population reduction down to 11.5% of the original abundance from simulations based on Huang et al. (2012), suggesting that the Beas–Sutlej Rivers might have had between 52 and 87 dolphins at the time of the construction of the Harike barrage in the early 1950s.

In March–April 2017, the Beas River witnessed a major water management-induced hydrological stress event that posed a serious risk to the survival of the IRD population. The water releases from the Pong dam were stopped to allow de-silting operations of the downstream Harike barrage (WWF-India 2018). The de-silting of the Harike barrage was planned to improve the efficiency of canal operations and also remove the sediment and macrophytes affecting the barrage reservoir and led to a major de-watering crisis for the Beas River. The IRD were found, during a WWF-India survey, to be restricted to and isolated in river pools. A similar incident recurred on 25th March 2018, when the flow released from the Pong dam was reduced from around 340 m³/s to around 55 m³/s (an 84% reduction; WWF-India 2018). These de-watering events of the Beas River led to major disruptions in longitudinal connectivity and reduction in channel area (over 25%) available to dolphins. This makes it apparent that a water management perspective and practices that ignore aquatic ecosystem requirements can pose “catastrophic risks” to the survival and persistence of this endangered IRD population, emphasising the need for conservation measures that adopt ecologically oriented water management. Additionally, the recent reintroduction of the endangered gharial crocodile in the Beas Conservation Reserve increases the concern and importance regarding ecological flows in the river.

Data

Physical data about the catchment, e.g. land use/land cover, soils, was obtained from global datasets (European Space Agency Climate Change Initiative land use/land cover map, Hollmann et al. 2013; Harmonised World Soil Database, Fischer et al. 2008). The data related to water resources including reservoir storage in Bhakra and Pong along with the main policies and operation strategies driving their management; technical data on hydropower plants; and the main crops in the states of Punjab, Haryana and Rajasthan and their irrigation schedules were obtained from stakeholders (i.e. Bhakra–Beas Management Board, State Water Resources and Irrigation Departments and hydropower companies). Historic meteorological data were available for the mountainous and hilly regions (Bannister et al. 2019) and the plains (ERA-Interim downscaled with RegCM4 from

CORDEX), while future projections of temperature and precipitation were sourced from the Climate Model Inter-comparison Project Phase 5 (CMIP5) through the KNMI Climate Explorer (Trouet and van Oldenborgh 2013) and downscaled using the monthly delta change method (Mombloch et al. 2020).

Time series of river flows at five river gauges (Fig. 1) and reservoir releases were available from the Bhakra–Beas Management Board. In addition, the data on inflows into the Harike barrage were obtained from a report by WWF-India (2018). We collected the data on dry-season discharge, cross-sectional area, depth, channel width and flow velocity at ten reference sites along the Beas between Pong and Harike in 2020 (Fig. 1). These were used to derive statistical relationships between dry-season river discharge and channel width so that river channel width (measured from past satellite images) could be used as a proxy (Pavelsky 2014) for Beas flows in past years (1989–2020) and related changes in Indus dolphin habitat (Braulik et al. 2012). This helped characterise ‘catastrophic’ events taking March 2017 and 2018 as the worst known conditions in the Beas River. For extinction risk models, we used an IRD population size of 10 as the initial input, based on the estimate of 5–11 reported by WWF-India (2018).

Modelling approach

A water resource systems model and an extinction risk model were combined to assess how future changes in climate and the effects of conservation measures can moderate or exacerbate future extinction risks to the IRD population in the Beas River and affect water-related SDGs (Fig. 2). The outputs of the previously calibrated water resource systems model for the historic period 1991–2008 were used as the baseline for climate change impact analysis and to identify the Pong flow release threshold that could lead to a hydrological risk or “catastrophe” used in the extinction risk model. The water resource systems model was forced with climate change data and subsequently modified to introduce ecologically oriented reservoir management. The generated dry-season river flow frequencies were fed as hydrologic risks to the extinction risk model, which also incorporated nonhydrologic background risks and conservation measures in different scenarios as appropriate. Figure 2 presents a schematic describing the model integration and important variables included. The components of the methodology are described in detail in later sections (“Indus river dolphin population model: forecasting extinction risk”, “Water resource systems model”, “Description of future scenarios” and “Analysis of trade-offs in the SDGs”).

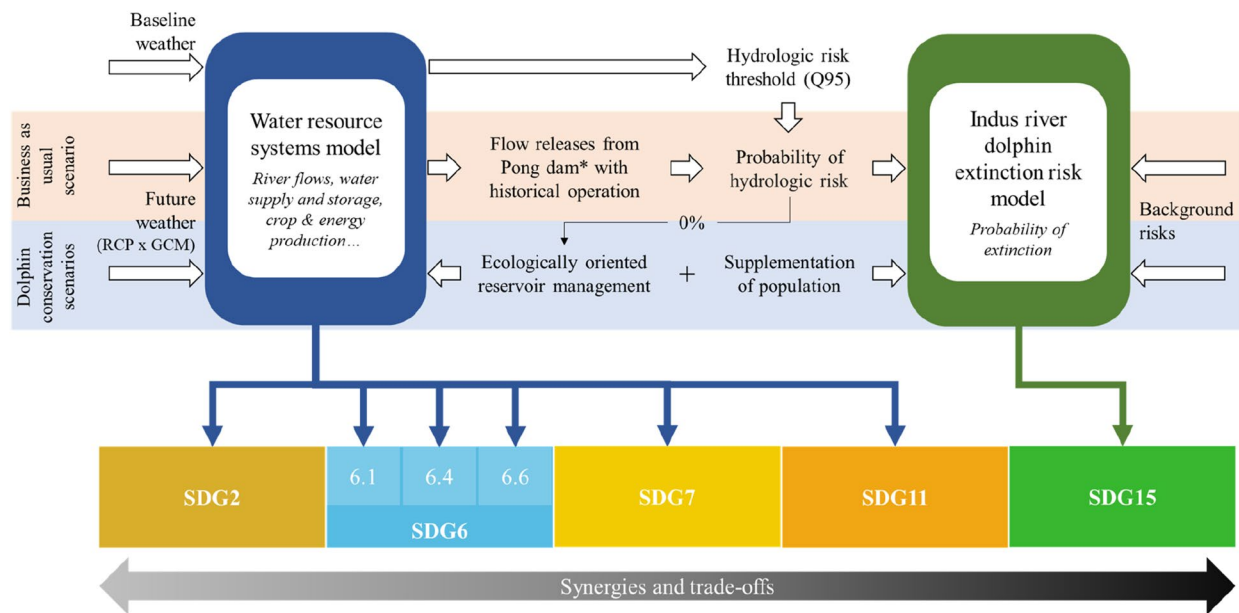


Fig. 2 Diagram of the modelling approach and scenario development. *For a subset of Global Climate Models (GCM) in each Representative Concentration Pathway (RCP) covering the range of frequency of low flow releases from Pong dam (see “Climate change scenarios”)

Indus river dolphin population model: forecasting extinction risk

We used stage-based population projection models to forecast IRD population trends and stochastically simulate future extinction risk for the IRD until mid-century, i.e. 2050, in the software Vortex 10.5.0 (Lacy and Pollack 2020). In all models, extinction risk was defined as “animals of only one sex remaining” within the small population. We evaluated intrinsic extinction risk (due to small population size and related genetic and demographic stochasticity) in our baseline extinction risk model. All models included appropriate parameterisation for population abundance, demographic and genetic variables based on Huang et al. (2012) and Braulik et al. (2015). Details of the models can be found in Table S2 of Supporting Information.

We simulated changes in future extinction risk (expressed as probability of population persistence or survival) by reducing the probability of survival of IRD by 10% in the event of each ‘catastrophic’ hydrological risk. We assumed that an event of catastrophic hydrologic risk might cause this reduction in individual survival of dolphins, due to mortality from indirect threats such as stranding in the event of de-watering or sudden reduction in dry-season flows, causing loss of along-river connectivity. The levels of ‘catastrophic’ risk were informed from estimates of lowest dry-season flows simulated by the water resource systems model (see “Water resource systems model”) under future climate change scenarios. The hydrological risk was defined as a water release from Pong

dam into the Beas of around twice the discharge observed in the critically low flow conditions in 2017 and 2018 (as described in “Indus river dolphins in the Beas: current status and likely trajectories of decline”), equivalent to the 5th percentile (Q95) of Pong dam releases in the baseline scenario (127.35 m³/s). The lack of access to the “classified” or restricted data as per Government of India policy for the Beas River water level and discharge, in the stretch where IRD are now surviving, prevented the derivation of metrics such as 7Q10. Therefore, an alternative approach was used based on setting a threshold of twice the discharge known (from previous data and knowledge) to have adversely impacted dolphins. This way, we allowed for sufficient buffering flows in the dry season, as compared to the observed catastrophic risk conditions, to ensure that the probability of hydrological risk was zero. In addition, we included a “background risk” variable (with 0%, 5% and 10% annual risk of occurrence) in the extinction risk model to include uncertainty from any undesirable events such as sudden releases of polluting effluents (as seen in 2018; WWF-India 2018), risks from illegal fishing or other risks, e.g. from diseases. Background risks events were assumed to have a 30% reduction in individual IRD survival rates and to act independently from effects of hydrological risks. The reductions in survival rates assumed in this study were based on factors known from other literature (e.g. Williams et al. 2011; Ackleh et al. 2017; Lacy et al. 2017) on direct mortality rates of cetaceans (lethal effects) and indirect effects on mortality through fecundity, prey resource scarcity or health-related risks (sublethal

effects) of human impacts. For IRD, direct threats such as entanglement in fishing nets or diseases coupled with pollution would have a higher impact than hydrological risks, which would have more indirect effects on survival. Hence, the rationale for using a reduction in survival rates by 30% was to include a higher level of impact than that of hydrologic risk (10%). The assumed rates were similar to those reported by Domiciano et al. (2016) for cetaceans with similar body size and ecology. Related biological details are presented in Table S2 and associated references of Supporting Information.

Water resource systems model

The Water Evaluation and Planning (WEAP) (Yates et al. 2005) systems model was used to simulate multisectoral water allocations in the interlinked Beas–Sutlej river basins. The development, calibration and validation of the Beas–Sutlej WEAP model is fully detailed in Momblanch et al. (2019a, 2020), but is briefly described here. WEAP represents the main hydrological processes including snow and glacier accumulation and melt which are particularly relevant for Himalayan hydrology, water demands (i.e. urban, hydropower and irrigation), water infrastructures (e.g. reservoirs, canals, hydropower barrages and interbasin transfers) and management (e.g. irrigation scheduling, reservoir operation rules, demand priority and supply preferences), through a node and link structure that allows representing spatial dependencies.

The Sutlej and Beas basins were spatially distributed into 165 elements resulting from the intersection of 23 sub-basins and 600 m elevation bands based on the location of main water management infrastructures, to achieve a balanced representation of the study area that took advantage of the high-resolution meteorological data (Bannister et al. 2019) and accounted for the influence of elevation on hydro-meteorological variables (Momblanch et al. 2019a). The characterisation of glaciers within the two basins (area, ice depth and elevation) was informed by comprehensive glacier surveys and modelling (Prasad et al. 2019). WEAP parameters were manually calibrated and validated, in a sequential process from upstream to downstream using Nash–Sutcliffe, percent bias and Pearson's correlation coefficient as model performance indicators (Moriassi et al. 2007). Firstly, the soil, vegetation and cryosphere parameters controlling river flows were calibrated by comparing simulated and observed river flows at three gauging stations in the Sutlej River and two in the Beas River (Fig. 1). Secondly, the supply priorities and reservoir operation rules were calibrated to match the observed water storage in the main reservoirs (i.e. Bhakra and Pong) and the water transferred from Beas to Sutlej

through the Dehar transfer. The model performance was further evaluated against the published studies on observed monthly average inflows to the Harike wetland (Ahluwalia et al. 2013) and the relative importance of meltwater in the total runoff (Ahluwalia et al. 2013; Wulf et al. 2016). Finally, the calibrated operation rules of the Pong and Bhakra reservoirs were compared with optimised rule curves (Adeloye and Dau 2019) to ensure that the volumes in the reservoirs were reproduced in line with common reservoir operation strategies. Based on the detailed process understanding and the robust model evaluation, the model produces reliable outputs related to runoff, river flows, water storage in reservoirs, water supply to different uses and associated productivity at a monthly time step.

Description of future scenarios

Climate change scenarios

The largest water demands in the interconnected Beas–Sutlej basins are located downstream of Pong and Bhakra reservoirs, which is also the current range of IRD. In order to reduce the number of climate change scenarios to analyse, but still account for the whole spectrum of uncertainty, we selected a subset of future climate change scenarios based on the frequencies of releases from Pong reservoir below the hydrological risk threshold as simulated by the water resource systems model under all scenarios (since the strongest trade-offs between water uses mostly emerge under low flow conditions; Laaha and Blöschl 2005; Yin et al. 2011; Rolls et al. 2012; Pang et al. 2018; Crespo et al. 2019). Firstly, all scenarios resulting from the combination of Representative Concentration Pathways (RCP) and Global Climate Models (GCM) available in CMIP5, i.e. RCP×GCM, were run in the water resource systems model for the period 2033–2050. Then, for each RCP, we selected the five GCMs that resulted in the maximum; 10th, 50th and 90th percentiles; and minimum number of months in the period 2033–2050 with simulated releases from Pong dam below the hydrological risk threshold. For each of the selected scenarios, we also used model outputs to derive SDG indicators (see “Analysis of trade-offs in the SDGs”).

Indus River Dolphin conservation scenarios

To understand how the IRD population will be affected by future climate and reservoir management changes, we modelled the potential effects of three incremental conservation scenarios on future population persistence.

Business as usual (Beas Conservation Reserve) The Beas Conservation Reserve was declared in 2017 along 185 km of the Beas River with measures to regulate pollution and fishing, to strengthen the conservation of the IRD (WWF-India 2018). We assumed these will continue until 2050 with effective protection measures for the dolphin population to prevent future increases in these threats. The operation of Pong dam was not modified with respect to the baseline so that under business as usual, hydrologic risks would continue affecting the IRD population, which would add to the environmental stochasticity impacts on the population in the extinction risk model. To minimise the possible negative impacts of climate change-driven risk on the IRD population, we further assessed the effects of two potential future conservation measures.

Ecologically oriented reservoir management This scenario considered future reservoir operation rules to incorporate ecological considerations that ensure that reservoir release thresholds are always well above the critical conditions of March 2017 and 2018 (0–55 m³/s released from the Pong dam) at any time until 2050. In the water resource systems model, we considered a flow release requirement for the Pong dam at 127.35 (m³/s), which is more than twice above the worst-case scenario of the de-watering event. Therefore, we assumed that maintaining flows above this threshold would result in zero probability of hydrological risk to IRD.

Indus river dolphin population supplementation In the extinction risk model, we evaluated the impact of future “conservation translocations” to supplement the IRD population with two bouts of translocation of one male and one female dolphin separated by an interval of 10 years (i.e. in 2030 and 2040) from other source populations of the IRD in Pakistan. This measure was implemented together with ecologically oriented reservoir management. However, it did not require simulations in the water resources systems model, as it did not affect any hydrological, water demand or water management variables.

Analysis of trade-offs in the SDGs

Based on the global indicator framework for the Sustainable Development Goals and the targets of the 2030 Agenda for Sustainable Development (A/RES/71/313: United Nations General Assembly 2017), we identified a set of indicators for the SDG targets sensitive to water availability and management and directly derived from our modelling outputs. Table 1 shows the selection of SDG targets and the estimation of corresponding indicators for every simulated year. For comparison across scenarios, the annual values were averaged to obtain a single value per scenario. All indicators took values from 0 to 1 with higher values indicating better status of the SDG goal or target.

In order to identify trade-offs that can hamper the simultaneous progression of the selected SDGs, we analysed the relationships between SDG targets using Pearson’s correlation coefficient within the baseline and future periods, based on the annual values of pairs of indicators. We considered correlation values > 0.5 as synergies and < -0.5 as trade-offs (Kroll et al. 2019).

Results

Climate change scenarios and impacts on Pong dam releases

Climate change was predicted to have a major impact on annual future average temperature with increasing greenhouse gas emissions (lowest and highest emissions in RCP2.6 and RCP8.5, respectively) across the full range of climate change scenarios in CMIP5 (RCP $\times$ GCM; Fig. 3a), with median change of +1.0 °C (RCP2.6) to +1.7 °C (RCP8.5). Annual average precipitation will likely increase under all RCPs (from a median change of +4.0% (RCP4.5) to +9.7% (RCP6.0), but a small number of climate models projected a significant decrease (Fig. 3b). Due to the complex hydrology of the region, which is the result of land–atmosphere interactions, rainfall–runoff and cryospheric processes, many climate change scenarios led to an increase in water resources up to mid-century (2050), which can be partly explained by the accelerated melting of glaciers (Immerzeel et al. 2013; Su et al. 2016; Shirsat et al. 2021). This, along with the regulation provided by Pong reservoir, resulted in most scenarios projecting lower likelihood of catastrophic low releases (dam releases below the baseline 5th percentile, Q95, i.e. 127.35 m³/s) compared to the baseline. RCP6.0 had the lowest median number of months with low releases across all GCMs (median values in Fig. 3c). However, RCP6.0 also produced the scenario with the largest number of months with low dam releases across the four RCPs (i.e. 69 months) within the 17 years modelled, with the other RCPs producing maximum number of months with low flow dam releases from some GCM up to 24–51 months which were significantly higher than the baseline (Fig. 3c and Table 2) and translated into high hydrologic risk for IRDs. Table 2 summarises the changing hydrologic risk of low flow ‘catastrophes’ for each RCP for the final selection of climate change scenarios representing the median, 10th and 90th percentiles and minimum and maximum number of months with low flow dam releases.

We estimated that nearly 90% of variability in Beas flows from December to April can be attributed to discharge from the Pong dam, even though winter rains in the catchment below the dam, driven by Western disturbances

Table 1 Definition of SDGs, targets and indicators based on the modelling outputs for those indicators that are sensitive to water availability and management and can be directly derived from the modelling outputs

Goal ^b	Target ^a	Indicator ^a	Calculation
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	2.4.1 Proportion of agricultural area under productive and sustainable agriculture	Annual crop yield of irrigated land/Potential crop production
Goal 6. Ensure availability and sustainable management of water and sanitation for all	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all 6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes 7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	6.1.1 Proportion of population using safely managed drinking water services 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources 6.6.1 Change in the extent of water-related ecosystems over time 7.2.1 Renewable energy share in the total final energy consumption	Population receiving 100% of their per capita annual water requirements/Total population 1—(Annual water withdrawal/Annual runoff) Median of monthly streamflow entering to Harike barrage/(2*Median during baseline)^b Annual hydropower production/Annual energy production from any source
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	11.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	1—(Months that Pong or Bhakra reservoirs enter into the flood protection or water saving zones/(2*Total number of simulated months))
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt reverse land degradation and halt biodiversity loss	15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	15.5.1 IUCN Red List Index	<i>1—(Indus River Dolphin extinction risk due to hydrological risk only)</i>

Bold cells indicate calculations using results from the water resource systems model and italics cells from the forecasting extinction risk model

^aAs in the original source (UN 2017)

^bThe denominator of this indicator is the doubling of the baseline median to show that potentially increased future flows at Harike are beneficial to water-related ecosystems

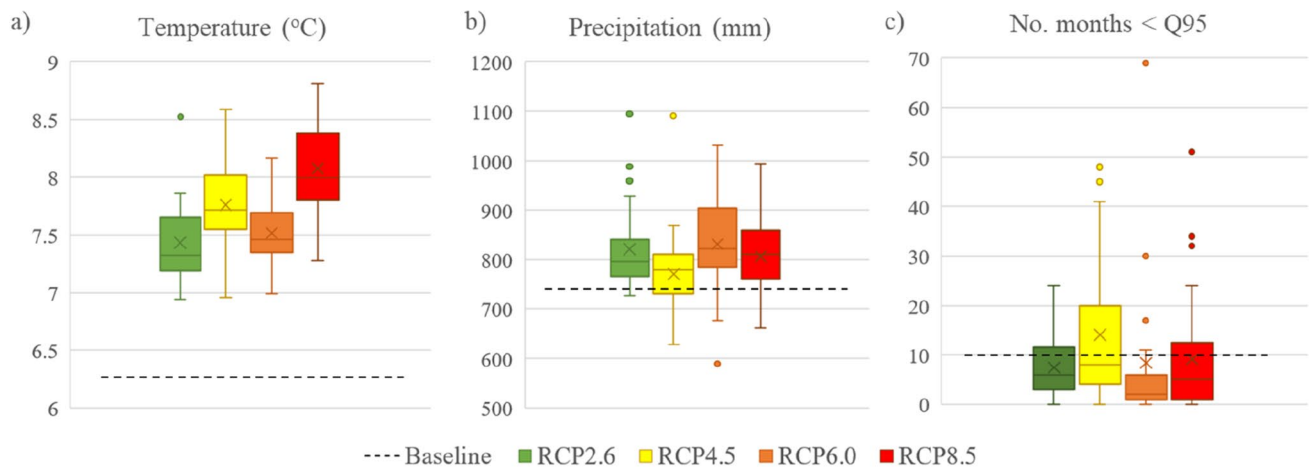


Fig. 3 Uncertainty in future (a) annual average temperature, (b) precipitation and (c) number of months with Pong flow releases below baseline Q95 across all GCMs for each RCP

Table 2 Summary of the months with values less than Q95 of Pong dam flow releases ($127.35 \text{ m}^3/\text{s}$), for the different RCPs and GCM models used

RCP	No. months < Q95 (statistic)	GCM	No. months	Hydrologic risk	Predicted mean probability of persistence
2.6	Maximum	MIROC-ESM	24	0.11	0.26
	90th percentile	GFDL-CM3	18	0.08	0.28
	Median	BNU-ESM	6	0.03	0.35
	10th percentile	IPSL-CM5A-MR	1	0	0.40
	Minimum	BCC-CSM1-1	0	0	0.40
4.5	Maximum	HadGEM2-AO	48	0.22	0.19
	90th percentile	GISS-E2-Hp1	41	0.19	0.20
	Median	NorESM1-M	12	0.06	0.36
	10th percentile	CSIRO-Mk3-6-0	3	0.014	0.35
	Minimum	CESM1-CAM5	1	0	0.40
6.0	Maximum	GFDL-ESM2G	69	0.32	0.14
	90th percentile	FIO-ESM	17	0.08	0.28
	Median	HadGEM2-AO	2	0.009	0.40
	10th percentile	GISS-E2-Hp1	0	0	0.40
	Minimum	BCC-CSM1-1	0	0	0.40
8.5	Maximum	GFDL-ESM2G	51	0.24	0.11
	90th percentile	FGOALS-g2	32	0.15	0.15
	Median	GFDL-ESM2M	5	0.02	0.35
	10th percentile	BCC-CSM1-1	0	0	0.40
	Minimum	IPSL-CM5B-LR	0	0	0.40

Predicted mean probabilities of population persistence from models, including only hydrologic risk corresponding to all GCM models are also shown

(i.e. cyclonic circulation originated in the Mediterranean region which produces extreme precipitation events during winter in the north of the Indian subcontinent; Hunt et al. 2018) could make a significant contribution in some years. The effective contribution of winter rains to Beas flows in this period could be affected by groundwater pumping, which could have otherwise maintained higher base flow.

Effects of Indus River Dolphin conservation measures and implications for SDGs

Business as usual

The probability of population survival based on intrinsic risks, i.e. the effects of stochastic demographic and genetic

processes affecting the dynamics of small populations was estimated at 0.40 (range 0.38–0.43), assuming no changes in the hydrologic conditions of the Beas between 2020 and 2050. In comparison, our climate change scenarios that included purely hydrologic risks (with zero background risk), predicted lower persistence probabilities. Considering the range of frequencies of RCP-predicted hydrologic risks as “catastrophes”, median persistence probabilities were similar across the RCPs. However, for the maximum risks, RCP2.6 yielded the highest persistence probability (i.e. 0.26) with the RCPs 4.5, 6.0 and 8.5 predicting the lowest probabilities (range 0.11–0.19; Table 2 and Fig. 4).

Upon adding different levels of background risks to the above results, extinction risks increased (probability of persistence reduced) across climate change scenario uncertainty. Adding 5% and 10% background risk to the RCP-predicted hydrologic risks, survival probabilities ranged between 0.16 and 0.03, indicating almost certain extinction.

The outputs from the water resource systems and extinction risk models were used to produce indicators for water-related SDG targets for the baseline period and for the subset of future climate change scenarios which represent the uncertainty across RCPs and GCMs in relation to dam catastrophic low flow releases. SDG15, which refers to the probability of survival of the river dolphin population only accounting for intrinsic and hydrological risks (business as usual), takes a value of 1 during the baseline since we know the IRD population has persisted over the baseline period. Climate change led to reduced SDG15 (and increasing uncertainty) due to the effect of intrinsic extinction risk of the small IRD population linked to the increased likelihood of low release shocks in some climate change scenario (Fig. 5). This was despite the status of most of the other SDGs improving given the increased water resources availability which seems to offset the climate-induced changes in water demand for irrigation due to the changing balance between precipitation and evapotranspiration. However, there was significant uncertainty in the direction of magnitude of change across the subset of climate change scenarios (variability between models providing the maximum, 90th–50th–10th percentiles and minimum of catastrophic low discharges from Pong dam).

The correlation analysis for the scenario representing the median number of months with catastrophic low dam releases within each RCP indicated that the selected SDG targets are highly inter-dependent. Significant synergies (green ribbons in Fig. 6) and trade-offs (red ribbons in Fig. 6) emerged for all indicators. Notably, SDG15 only presented negative correlations with other SDG targets, particularly with SDG6.1 (urban water supply) and SDG7 (hydropower production). The SDG15–SDG7 trade-offs derive from the fact that water that is diverted through

Pandoh dam for hydropower production in the Dehar plant (one of the most productive plants in the system), does not reach Pong and cannot contribute to water releases to the Beas. Strangely, SDG2 was not negatively correlated with SDG15, owing to the fact that there are not large irrigation demands directly dependent on Pong dam. SDG6.4 and SDG11 were always positively related, which was reasonable as less water stress could translate into increased water reserves. Trade-offs between the multiple SDG6 targets were most pronounced under RCP6.0, which poses a challenge to the achievement of the overarching SDG6.

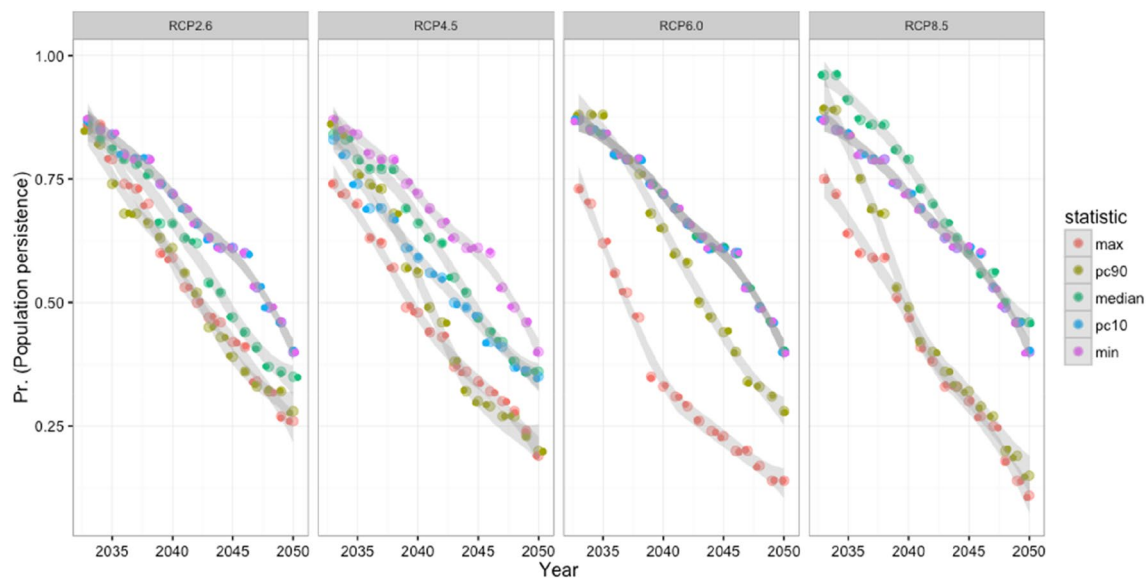
Ecologically oriented reservoir management

The implementation of ecologically oriented reservoir management had obvious positive effects on the probability of survival of the river dolphin population as it removed hydrologic risks, increasing the likelihood of population persistence up to 40%. This increased probability was 15% above the business as usual scenario that included 0% background risk and RCP-predicted hydrologic risks and predicted values of 25% (range 11–36%) across climate change scenarios, by the mid-century (2050).

This measure had variable impacts on other SDG targets as compared to the indicator values under the Business as usual scenario (Table 3). SDG7 were the most negatively affected relative to those climate change scenarios which originally provided the highest frequency of catastrophic low flow releases from Pong. SDG2, SDG6.1, SDG6.4 and SDG11 were also impacted but the magnitude of the impact was lower than 1% with respect to the Business as usual scenario. The trade-off analysis revealed that the reduction of diversions through the Dehar transfer negatively impacted energy production (SDG7) while coverage of supply to urban water uses was slightly reduced upstream of Pong and in the Sutlej basin causing a decrease in the corresponding SDG6.1. Efficiency issues linked to these trade-offs need to be understood in future studies incorporating cost–benefit analyses as well. The increase in requirements of low flow releases in the driest years reduced storage in reservoirs (SDG11) which further impacted the coverage of irrigation demands (SDG2). However, under most future scenarios, SDG indicators remained unchanged with ecologically oriented reservoir management. In addition to SDG15 that is the “target” of the measure, SDG6.6 experienced the largest improvement as the increase of releases from Pong also increased inflows to Harike barrage. SDG6.4 was also enhanced owing to the slight reduction of water supply in some scenarios.

Table 3 Changes in SDG indicators under future climate change scenarios with the application of ecologically oriented reservoir management relative to future scenarios with business-as-usual management. Positive changes indicate an improvement

	GCM uncertainty	SDG2	SDG6.1	SDG6.4	SDG6.6	SDG7	SDG11	SDG15
RCP2.6	Minimum	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 0.3%
	10th percentile	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 0.3%
	Median	0.0%	0.0%	0.0%	▲ 0.2%	0.0%	0.0%	▲ 17.3%
	90th percentile	0.0%	0.0%	0.0%	▲ 0.4%	▼ -0.1%	▼ -0.6%	▲ 30.5%
	Maximum	0.0%	0.0%	▲ 0.1%	▲ 0.9%	▼ -0.2%	▼ -0.6%	▲ 33.6%
RCP4.5	Minimum	0.0%	0.0%	0.0%	▲ 0.1%	0.0%	0.0%	▲ 0.3%
	10th percentile	0.0%	0.0%	0.0%	▲ 0.1%	0.0%	0.0%	▲ 16.9%
	Median	0.0%	▼ -0.1%	0.0%	▲ 0.4%	▼ -0.1%	▼ -0.6%	▲ 26.5%
	90th percentile	▼ -0.2%	▼ -0.2%	0.0%	▲ 1.0%	▼ -1.0%	▼ -1.6%	▲ 45.0%
	Maximum	▼ -0.2%	▼ -0.5%	▲ 0.3%	▲ 1.6%	▼ -1.1%	▼ -3.5%	▲ 56.8%
RCP6.0	Minimum	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 0.3%
	10th percentile	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 0.3%
	Median	0.0%	0.0%	0.0%	▲ 0.2%	0.0%	0.0%	▲ 15.7%
	90th percentile	0.0%	0.0%	0.0%	▲ 0.7%	▼ -0.1%	▼ -1.8%	▲ 21.1%
	Maximum	▼ -0.4%	▼ -0.5%	▲ 0.3%	▲ 2.7%	▼ -1.4%	▼ -3.5%	▲ 104.7%
RCP8.5	Minimum	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 0.3%
	10th percentile	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 0.3%
	Median	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	▲ 16.9%
	90th percentile	▼ -0.1%	▼ -0.1%	0.0%	▲ 0.8%	▼ -0.6%	▼ -2.0%	▲ 50.4%
	Maximum	▼ -0.3%	▼ -0.4%	▲ 0.5%	▲ 2.0%	▼ -1.4%	▼ -3.7%	▲ 72.0%

**Fig. 4** Probability of Indus dolphin population persistence only under hydrologic risks predicted by different RCP–GCM scenarios from 2033 to 2050. Grey lines denote loess-fitted trends for the different statistics under each of the scenarios

Indus River Dolphin population supplementation

Under the conservation scenario based on IRD population supplementation, the average probability of

survival until 2050 was 0.60 (range 0.22–0.85) across all climate change scenarios (all hydrologic risks) and all background risks. In contrast, average probability of population persistence was 0.21 (range 0.01–0.46) under

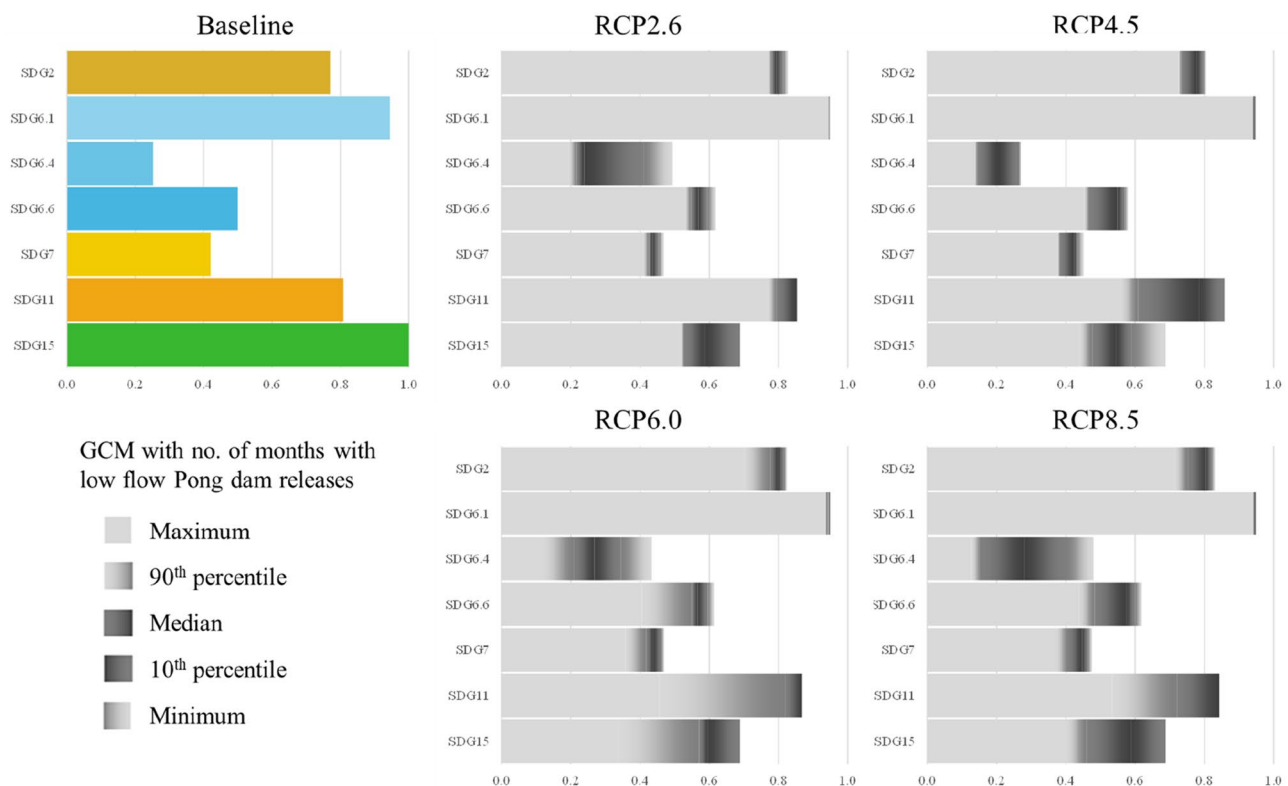


Fig. 5 SDG indicators for the baseline and future climate change scenarios considering GCM uncertainty under each RCP

business as usual with background risks added. This indicated that conservation translocations might reduce IRD extinction risk by three times, irrespective of hydrological risks or other background risk factors (Fig. 7). Under combined scenarios of ecologically oriented reservoir management and supplementation, probabilities of population persistence were maximised across all scenarios by 1.5–4 times (Fig. 8). All SDGs except SDG15 remained identical to the scenario with ecologically oriented reservoir management.

Discussion

Biodiversity is threatened in many regions by multiple direct (e.g. land and water use, hunting, climate change) and indirect drivers of change (e.g. production and consumption patterns, human population dynamics, trade) (IPBES 2019), resulting in ecologically unintended consequences of socio-economic development. The 2030 Agenda for Sustainable Development recognises that while socio-economic development is essential to end poverty, hunger and other deprivations related to health, education, or inequality, its management must go hand-in-hand with tackling climate change and preservation of natural ecosystems and resources. This

is only possible through a deep understanding of the synergies and trade-offs between natural capital and existing development strategies (Papadimitriou et al. 2019), which become most critical in case of increasingly stressed freshwater resources and endangered aquatic biodiversity.

Our results indicate complex and interesting trade-offs between water related SDGs under future climate change scenarios, particularly in relation to water human demands and ecological needs in the Beas River. Despite future scenarios forecasting an increase in water availability by the middle of the century, a substantial number of simulated scenarios (in the maximum and 90th percentile of the distribution of number of months with very low flow releases from Pong) projected drier conditions than the baseline. The general prediction of our models is that the persistence of IRD hinges critically on (1) allowing adequate dry-season releases from the Pong dam into the Beas and (2) optimal management of the operating space for allocations to hydropower, urban and irrigation demands. Other aspects not considered in this study may exacerbate the identified tensions. By the end of the century, many studies predict a reduction in dry-season flows in the region, partly related to substantial reductions in glacial extent, which could initially cause an increase in future summer stream flow followed by a reduction, with significant uncertainty (Wijngaard et al. 2017;

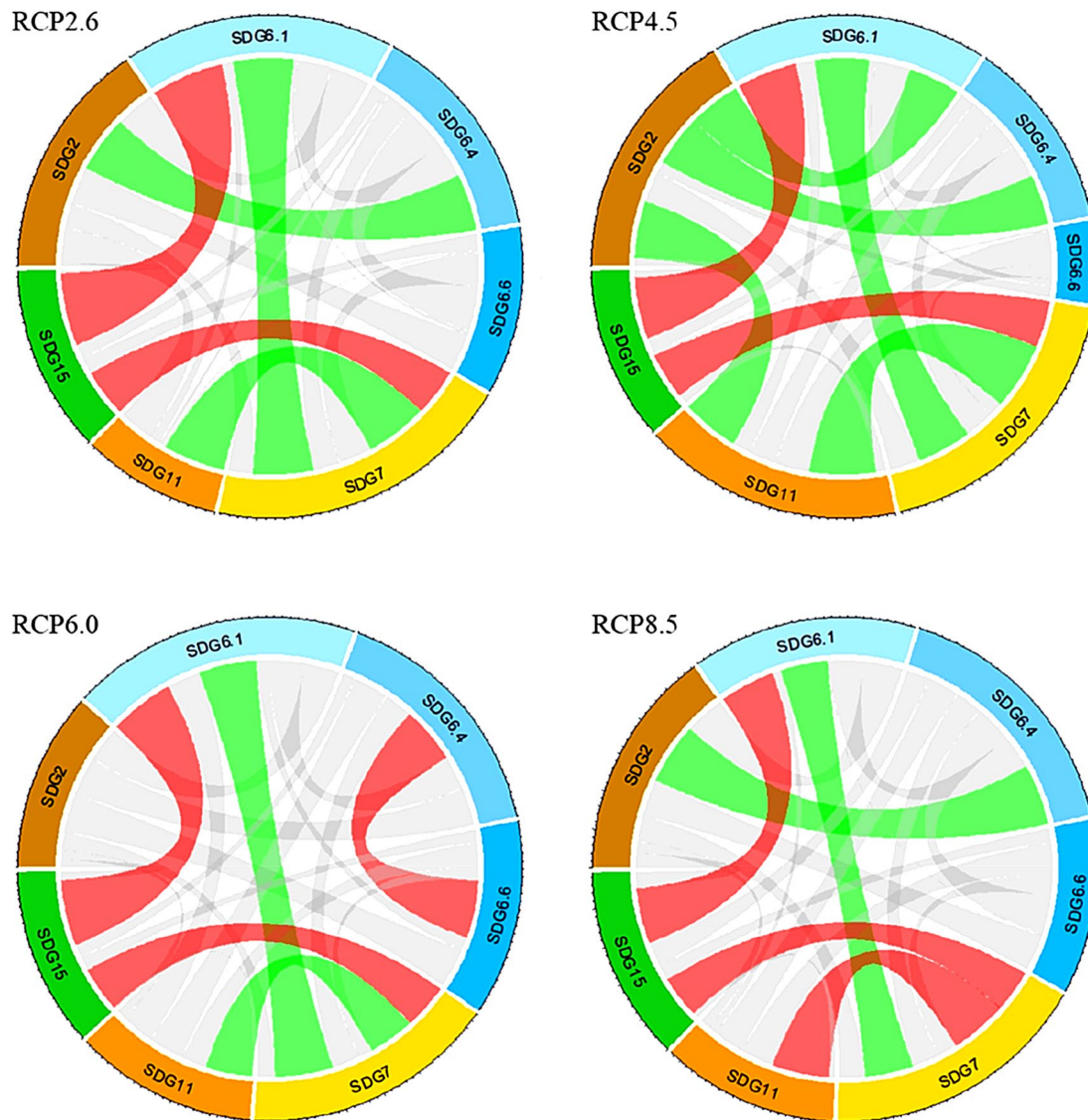


Fig. 6 Chord diagrams representing synergies (green ribbons) and trade-offs (red ribbons) between annual time series of SDG indicators for the median scenario of each RCP. Grey ribbons indicate cor-

relations between -0.5 and 0.5 . The width of the ribbon indicates the absolute value of the Pearson's correlation coefficient between the linked SDGs

Krakauer et al. 2019; Li et al. 2019; Momblanch et al. 2020). Moreover, the contribution of winter rains to ecologically compatible flows in the Beas, especially in the dry season, will depend on the strength of tele-connections with Western Disturbances under future climate change (Pal et al. 2015; Kumar et al. 2015; Dimri et al. 2015; Yin et al. 2016). This will come in addition to expected socioeconomic changes linked to population growth and increase in water demands for drinking, irrigation and energy production. For example, the increased abstractions from Beas City located just upstream of the reaches inhabited by the endangered IRD could have significant effects on IRD habitat.

In case of future extremes of dry-season climate, especially drought-like conditions, reservoir storages can buffer the impacts of water stress by allowing for urban water supply and irrigation. However, these storages can affect river flows for IRD, creating potential trade-offs. How these trade-offs can be reconciled is a significant challenge for water management and conservation policy, by state water management institutions such as the Bhakra–Beas Management Board. Our models reveal that a simple ecologically oriented reservoir management rule consisting in a guaranteed release from Pong dam can considerably improve the probability of survival of the IRD population. The threshold of release may

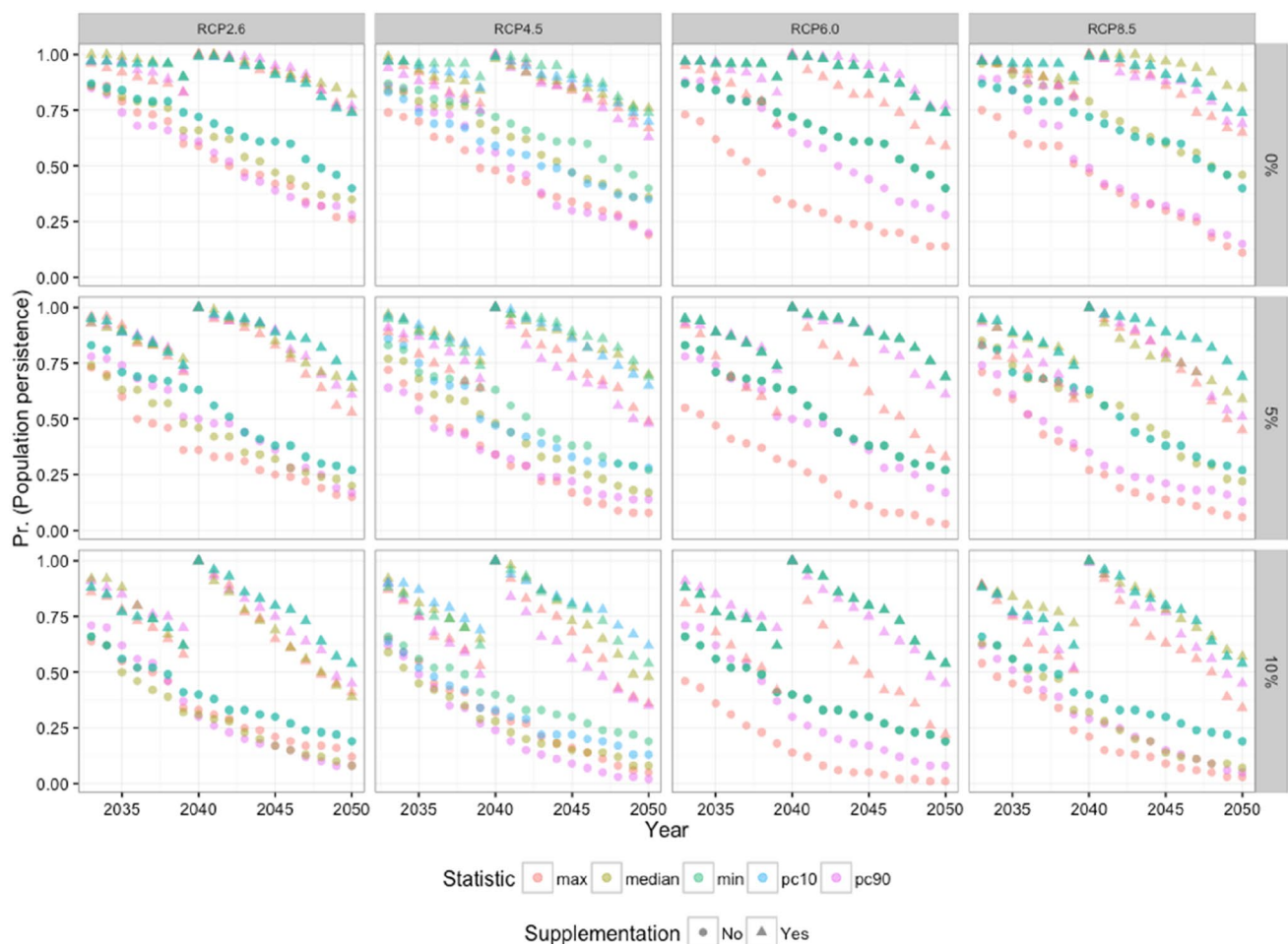


Fig. 7 Probabilities of IRD population persistence from 2033 to 2050 across the median hydrologic risk predicted by all simulated RCP×GCM scenarios and at varying levels of background risks (0%,

5% and 10%, right panels) and with and without population supplementation of IRD in the future

have to be set adaptively, in response to future changes. We emphasise here that specifying “minimum flows” for management is a limited approach. Instead, we need to consider the entire ecological flow regime, which includes the whole range of flow conditions and dynamics (e.g. peak flows, seasonal flow duration and rates of flow change) not only to ensure suitable habitat conditions but to provide multiple other ecosystem services (Acreman 2016; Grill et al. 2019). Further work to reliably define ecological flows in the Beas River should, therefore, be undertaken building upon the initial insights gained from this study. These studies should also include ecological flow and sediment requirements of other species like the gharial in the Beas River. Studies to assess potential for restoration of river dolphin and gharial habitat in the Sutlej River upstream of Harike under improved water quality and flow conditions also need to be prioritised (Najar et al. 2017; Kaur et al. 2017).

Transforming trade-offs into synergies is crucial to enable SDG progress (Kroll et al. 2019). In the Beas River, this

means maintaining river ecosystem health by ensuring water availability, so that several ecosystem services can be sustained together, by reducing potential trade-offs. This should be done by adopting measures that take advantage of modified system functioning, based on the understanding of system inefficiencies and context-specific interactions (Pham-Truffert et al. 2020) which are partly uncovered in this study. Loss of energy production in Dehar power plant could be compensated with an increase in the production capacity in Pong dam and Mukerian canal. Saturation of irrigation infrastructure in the Punjab plains, both in terms of limited surface irrigation efficiency and severe groundwater depletion can compel farmers to shift towards alternative crops with lower irrigation demands (Jalota et al. 2007; Kaur et al. 2010; Sidhu et al. 2011; Srivastava et al. 2017). Such shifts can result in greater water use efficiency than rice and wheat, which are now approaching asymptotes in terms of yield and productivity gains. This can potentially improve water use efficiency and help in restoring river flows, provided surface

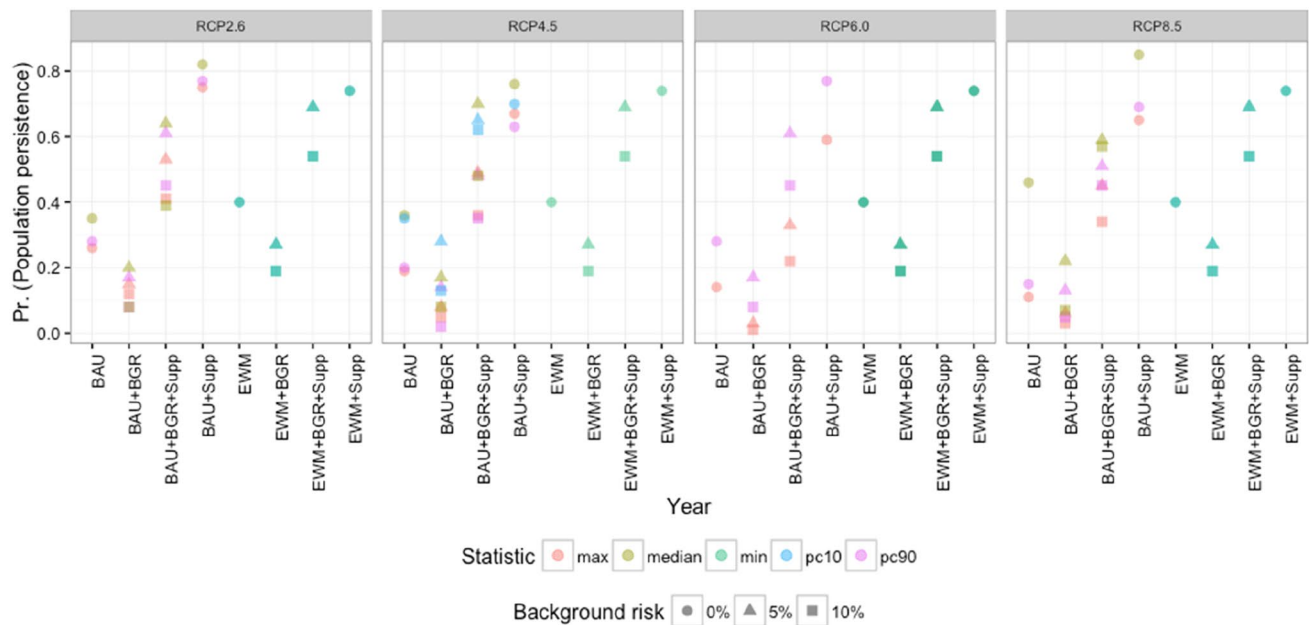


Fig. 8 Mean probabilities of Indus dolphin population persistence under different conservation scenarios: (1) BAU=Business As Usual (hydrologic risk but no background risks because of conser-

vation reserve), (2) BGR=Background Risk added (5–10%), (3) EWM=Ecologically oriented reservoir management (to ensure 0% hydrologic risk), (4) Supp.=Population Supplementation (future)

water irrigation demands from canals and reservoirs are actively reduced and the saved water allocated for ecological and conservation needs along the Beas River. The effectiveness of these alternative management scenarios, which could be assessed with the modelling framework proposed in the current study, should be accompanied with cost–benefit analyses to inform low regret actions.

Combining the ecologically oriented reservoir management with supplementation of the IRD population in the Beas River emerged as a critical measure for further reducing extinction risk through the increase in IRD population size. Reduction in pollution (SDG6) and maintenance of ecological flows in the Sutlej could also create additional habitat for IRD. Supplementation would require “conservation translocations” of near-mature individuals of IRD from the nearest source population in the Indus River in Pakistan, possibly in exchange for Gharials (extinct in Pakistan). Such an unprecedented conservation agreement between India and Pakistan would need the creation of institutional coordination between the environmental ministries of both countries. Given the historic conflict between the two nations, there is a need to make progress on the SDGs 16 and 17 for peace and partnerships for conservation. This is only possible when the countries take active steps towards peaceful negotiations for cooperative and integrated management of shared transboundary water resources and biodiversity (SDG 6.5). For this, one needs to first examine the relevance of the specific contingencies of the Indus Waters Treaty of 1960 between the two nations. Tributary flows in the Indus basin, which

includes the Beas River, are exclusively used by India as per the treaty. In this context, the barrages on the Beas may have even played a part in sustaining the small IRD population in the Beas. In the future, ecological flow considerations need to be aligned with any possible revisions of the Treaty. Further, the practicalities of conservation translocations of endangered aquatic mammal species across international borders are challenging. To actually consider this in reality (beyond the theoretical implementation discussed here) there would be the need for a rigorous assessment of risks, consideration of tools to monitor success and the necessity of more localised trials within one jurisdiction (IUCN/SSC 2013). Other actions that favour conservation-related SDGs are linked to the positive interventions made by the Punjab Forests and Wildlife Department and WWF-India, through the designation of the Beas River as a conservation reserve in 2017, followed by an effectively enforced and managed ban on fishing with nets in the area and sustained community-based monitoring initiatives over the last several years (actions enabling SDGs 11.4 and 15.1). These actions contribute to indicators for SDG 11.4.1 related to positive total expenditure towards the preservation, protection and conservation of all cultural and natural heritage, including public as well as private funding and with governmental commitment to the cause of conservation.

We have uncovered the existence of trade-offs between targets nested under SDG6 which, while not generating unapproachable issues in the analysed context, may well create them in the long term, given the likely impacts of flow

reductions and socioeconomic development by the end of the century. The structure of SDGs and their targets, which includes water-related ecosystems and endangered freshwater species within the more general SDG6 and SDG15, may also disguise existing trade-offs. With 17 SDGs comprising 169 targets, there is a high chance that assessments to monitor the progression of the 2030 Agenda for Sustainable Development would focus on a subset of targets across all SDGs (Forestier and Kim 2020). Some studies overlook target 6.6 on the protection and restoration of water-related ecosystems when looking at trade-offs between zero hunger and clean water (Banerjee et al. 2019; Yang et al. 2020). Similarly, endangered freshwater species tend to be excluded from evaluations of target 15.5.1 under ‘Life on Land’ (Reid et al. 2017, 2019). Therefore, a new explicit SDG for freshwater ecosystems and their biodiversity would be highly desirable. If progress on achieving the SDGs is to be made with the assumption that all goals and targets are equally important, efforts should be done to promote more systematic assessments that adequately cover all relevant SDG targets in the given context. This, at the very least, requires that assessments of SDGs account for all nested targets rather than just summarising the overall status of the general goals.

Conclusions

The isolated effects of climate change by the middle of the century (without consideration of socioeconomic changes) may not affect the capacity of the Beas–Sutlej water resource system to sustain water (SDG6) and food security (SDG2), hydropower production (SDG7) and water-risk reduction (SDG11) under the majority of scenarios across the full range of equally plausible RCP–GCM combinations. However, the survival of the small population of endangered Indus dolphins (SDG15) could still be threatened by increasing hydrologic risks predicted in some scenarios. The avoidance of catastrophic low flow events linked to the management of Pong dam will remove hydrologic risks without generating significant trade-offs on other SDGs. Along with reduction of other background risks with the maintenance of the Beas Conservation Reserve, conservation translocations of Indus dolphins could be promising conservation measures in addition to water management. Our study shows that modifying the management of water supply infrastructure to support the protection of rare and endangered aquatic species need not be at the expense of human sustainable development and the status of other relevant SDGs.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11625-021-01026-6>.

Acknowledgements This work was supported by the Global Challenges Research Fund through quality-related funding (QR GCRF) and the UK Natural Environment Research Council (Grant number NE/N015541/1). J. Krishnaswamy acknowledges support from the Climate Change and Disaster Risk Mitigation component of the National Mission on Biodiversity and Human Well-being supported by the Office of the Principal Scientific Adviser to the Government of India and Google Research (Google Grant for AI on Social Good). The funding agencies have no involvement in the design of the study or interpretation of the results. The authors are extremely grateful to Suresh Babu and Gitanjali Kanwar from WWF-India for their valuable contributions to understanding the river flow management issues in the Beas River for the conservation of the Indus dolphin population and to all field staff of WWF-India’s Beas project. We also thank the Ashoka Trust for Research in Ecology and the Environment (ATREE), Bengaluru, for institutional and field support. We thank the World Climate Research Programme’s Working Group on Regional Climate and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. Data underlying this study which is not in the public domain or subject to sharing restrictions can be accessed through NERC’s Environmental Information Data Centre at <https://doi.org/10.5285/f899fbc5-7034-45c0-a15c-9ee1d92a693f>.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ackleh AS, Chiquet RA, Ma B, Tang T, Caswell H, Veprauskas A, Sidorovskaia N (2017) Analysis of lethal and sublethal impacts of environmental disasters on sperm whales using stochastic modeling. *Ecotoxicology* 26(6):820–830
- Acreman M (2016) Environmental flows-basics for novices. *Wiley Interdiscip Rev Water* 3(5):622–628. <https://doi.org/10.1002/wat2.1160>
- Adeloye AJ, Dav QV (2019) Hedging as an adaptive measure for climate change induced water shortage at the Pong reservoir in the Indus Basin Beas River, India. *Sci Total Environ* 687:554–566. <https://doi.org/10.1016/j.scitotenv.2019.06.021>
- Ahluwalia RS, Rai SP, Jain SK, Kumar B, Dobhal DP (2013) Assessment of snowmelt runoff modelling and isotope analysis: a case study from the western Himalaya, India. *Ann Glaciol* 54:299–304. <https://doi.org/10.3189/2013AoG62A133>
- Anderson J (1879) Anatomical and zoological researches: comprising an account of zoological results of the two expeditions to Western Yunnan in 1868 and 1875; and a monograph of the two Cetacean Genera, *Platanista* and *Orcella* [sic], vol 2. Bernard Quaritch, London
- Banerjee O, Cicowiez M, Horridge M, Vargas R (2019) Evaluating synergies and trade-offs in achieving the SDGs of zero hunger and clean water and sanitation: an application of the IEEM Platform to Guatemala. *Ecol Econ* 161:280–291. <https://doi.org/10.1016/j.ecolecon.2019.04.003>

- Bannister D, Orr A, Jain SK, Holman IP, Momblanch A, Phillips T, Adeyoye AJ, Snapir B, Waine TW (2019) Bias correction of high-resolution regional climate model precipitation output gives the best estimates of precipitation in Himalayan catchments. *J Geophys Res* 124:14220–14239. <https://doi.org/10.1029/2019JD030804>
- Behera SK, Nawab A, Rajkumar B (2008) Preliminary investigations confirming the occurrence of Indus River dolphin *Platanista gangetica minor* in River Beas, Punjab, India. *J Bombay Nat Hist Soc* 105(1):90–126
- Bhattacharya T, Khare D, Arora M (2019) A case study for the assessment of the suitability of gridded reanalysis weather data for hydrological simulation in Beas river basin of North Western Himalaya. *Appl Water Sci* 9:1–15
- Bhave AG, Conway D, Dessai S, Stainforth DA (2018) Water resource planning under future climate and socioeconomic uncertainty in the Cauvery River Basin in Karnataka, India. *Water Resources Res* 54(2):708–728
- Bookhagen B, Burbank DW (2010) Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *J Geophys Res Earth Surf* 115:F03019. <https://doi.org/10.1029/2009JF001426>
- Braulik GT, Reichert AP, Ehsan T, Khan S, Northridge SP, Alexander JS, Garstang R (2012) Habitat use by a freshwater dolphin in the low-water season. *Aquat Conserv Mar Freshw Ecosyst* 22:533–546
- Braulik GT, Arshad M, Noureen U, Northridge SP (2014) Habitat fragmentation and species extirpation in freshwater ecosystems: causes of range decline of the Indus River Dolphin (*Platanista gangetica minor*). *PLoS ONE* 9:101657
- Braulik GT, Barnett R, Odon V, Islas-Villanueva V, Helzel AR, Graves JA (2015) One species or two? Vicariance, lineage divergence and low mtDNA diversity in geographically isolated populations of South Asian River dolphin. *J Mamm Evolut* 22:111–120. <https://doi.org/10.1007/s10914-014-9265-6>
- Braulik GT, Archer FI, Khan U, Imran M, Sinha RK, Jefferson TA, Donovan C, Graves JA (2021) Taxonomic revision of the South Asian River dolphins (*Platanista*): Indus and Ganges River dolphins are separate species. *Mamm Mar Sci* 37(3):1022–1059. <https://doi.org/10.1111/mms.12801>
- Clark B, DeFries R, Krishnaswamy J (2021) India's commitments to increase tree and forest cover: consequences for water supply and agriculture production within the central Indian Highlands. *Water* 13(7):959
- Crespo D, Albiac J, Kahil T, Esteban E, Baccour S (2019) Tradeoffs between water uses and environmental flows: a hydroeconomic analysis in the Ebro Basin. *Water Resour Manage* 33:2301–2317. <https://doi.org/10.1007/s11269-019-02254-3>
- Dimri AP, Niyogi D, Barros AP, Ridley J, Mohanty UC, Yasunari T, Sikka DR (2015) Western disturbances: a review. *Rev Geophys* 53(2):225–246
- Domiciano IG, Domit C, Broadhurst MK, Koch MS, Bracarense AP (2016) Assessing disease and mortality among small cetaceans stranded at a world heritage site in southern Brazil. *PLoS ONE* 11(2):e0149295
- Fischer G, Nachtergaele F, Prieler S, van Velthuizen HT, Verelst L, Wiberg D (2008) Global agro-ecological zones assessment for agriculture. IIASA, Laxenburg, Austria and FAO, Rome, Italy
- Fonseca LM, Domingues JP, Dima AM (2020) Mapping the sustainable development goals relationships. *Sustainability* 12(8):3359
- Forestier O, Kim RE (2020) Cherry-picking the sustainable development goals: goal prioritization by national governments and implications for global governance. *Sustain Develop* 28:1269–1278. <https://doi.org/10.1002/sd.2082>
- George BA, Malano HM, Khan AR, Gaur A, Davidson B (2009) Urban water supply strategies for Hyderabad, India—future scenarios. *Environ Model Assess* 14(6):691–704
- Grill G, Lehner B, Thieme M, Geenen B, Tickner D, Antonelli F, Babu S, Borrelli P, Cheng L, Crochetiere H, Ehalt Macedo H, Filgueiras R, Goichot M, Higgings J, Hogan Z, Lip B, McClain ME, Meng J, Mulligan M, Nilsson C, Olden JD, Opperman JJ, Petry P, Reidy Liermann C, Saenz L, Salinas-Rodriguez S, Schelle P, Schmitt RJP, Snider J, Tan F, Tockner K, Valdujo PH, van Soesbergen A, Zarfl C (2019) Mapping the world's free-flowing rivers. *Nature* 569(7755):215–221
- Hall NL, Creamer S, Anders W, Slatyer A, Hill PS (2020) Water and health interlinkages of the sustainable development goals in remote Indigenous Australia. *NPJ Clean Water* 3:10. <https://doi.org/10.1038/s41545-020-0060-z>
- Hollmann R, Merchant CJ, Saunders R, Downy C, Buchwitz M, Cazenave A, Chuvieco E, Defourny P, de Leeuw G, Forsberg R, Holzer-Popp T, Paul F, Sandven S, Sathyendranath S, van Roozendaal M, Wagner W (2013) The ESA climate change initiative: satellite data records for essential climate variables. *Bull Am Meteor Soc* 94:1541–1552. <https://doi.org/10.1175/BAMS-D-11-00254.1>
- Huang SL, Hao Y, Mei Z, Turvey ST, Wang D (2012) Common pattern of population decline for freshwater cetacean species in deteriorating habitats. *Freshw Biol* 57:1266–1276. <https://doi.org/10.1111/j.1365-2427.2012.02772.x>
- Hunt KMR, Turner AG, Shaffrey LC (2018) The evolution, seasonality and impacts of western disturbances. *Q J R Meteorol Soc* 144:278–290. <https://doi.org/10.1002/QJ.3200>
- Hurlbert M, Krishnaswamy J, Davin E, Johnson FX, Mena C, Morton J, Myeong S, Viner D, Warner K, Wreford A, Zakieldeen S, Zommers Z (2019) Risk management and decision-making in relation to sustainable development. In: Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change, p 673–800
- Immerzeel WW, Pellicciotti F, Bierkens MFP (2013) Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nat Geosci* 6:742–745. <https://doi.org/10.1038/ngeo1896>
- IPBES-Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Díaz S, Settele J, Brondízio ES, Ngo HT, Guèze M, Agard J, Arneth A, Balvanera P, Brauman KA, Butchart SHM, Chan KMA, Garibaldi LA, Ichii K, Liu J, Subramanian SM, Midgley GF, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razaque J, Reyers B, Roy Chowdhury R, Shin YJ, Visseren-Hamakers IJ, Willis KJ, Zayas CN (eds) IPBES secretariat, Bonn, Germany
- Irvine K (2018) Editorial: aquatic conservation in the age of the sustainable development goals. *Aquat Conserv Mar Freshwat Ecosyst* 28:1264–1270
- IUCN/SSC (2013) Guidelines for reintroductions and other conservation translocations. Version 1.0. IUCN Species Survival Commission, Gland, pp viiii + 57
- Jain SK, Sarkar A, Garg V (2008) Impact of declining trend of flow on Harike Wetland, India. *Water Resources Manag* 22(4):409–421
- Jalota SK, Sood A, Vitale JD, Srinivasan R (2007) Simulated crop yields response to irrigation water and economic analysis:

- increasing irrigated water use efficiency in the Indian Punjab. *Agron J* 99(4):1073–1084
- Kaur B, Sidhu RS, Vatta K (2010) Optimal crop plans for sustainable water use in Punjab. *Agric Econ Res Rev* 23(347–2016–16934):273–284
- Kaur J, Walia H, Mabwoga SO, Arora S (2017) Water quality monitoring of an international wetland at Harike, Punjab and its impact on biological systems. *Appl Water Sci* 7(3):1107–1115
- Khan MS, Pant A (2014) Conservation status and distribution pattern of the Indus River Dolphin in River Beas, India. *Biodiversitas* 15:75–79
- Krakauer NY, Lakhankar T, Dars GH (2019) Precipitation trends over the Indus Basin. *Climate* 7:116
- Kroll C, Warchold A, Pradhan P (2019) Sustainable Development Goals (SDGs): are we successful in turning trade-offs into synergies? *Palgrave Commun.* <https://doi.org/10.1057/s41599-019-0335-5>
- Kumar N, Yadav BP, Gahlot S, Singh M (2015) Winter frequency of western disturbances and precipitation indices over Himachal Pradesh, India: 1977–2007. *Atmósfera* 28(1):63–70
- Laaha G, Blöschl G (2005) Low flow estimates from short stream flow records—a comparison of methods. *J Hydrol* 306:264–286. <https://doi.org/10.1016/j.jhydrol.2004.09.012>
- Lacy RC, Pollack JP (2020) Vortex: a stochastic simulation of the extinction process. Version 10.3.8. Chicago Zoological Society, Brookfield
- Lacy RC, Williams R, Ashe E, Balcomb KC III, Brent LJN, Clark CW, Croft DP, Giles DA, MacDuffee M, Paquet PC (2017) Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans. *Sci Rep* 7:14119. <https://doi.org/10.1038/s41598-017-14471-0>
- Li L, Shen M, Hou Y, Xu C, Lutz AF, Chen J, Jain SK, Li J, Chen H (2019) Twenty-first-century glacio-hydrological changes in the Himalayan headwater Beas River basin. *Hydrol Earth Syst Sci* 23:1483–1503
- Long D, Yang W, Scanlon BR, Zhao J, Liu D, Burek P, Pan Y, You L, Wada Y (2020) South-to-North Water Diversion stabilizing Beijing's groundwater levels. *Nat Commun* 11(1):1–10
- Madhusoodhanan CG, Sreeja KG, Eldho TI (2016) Climate change impact assessments on the water resources of India under extensive human interventions. *Ambio* 45(6):725–741. <https://doi.org/10.1007/s13280-016-0784-7>
- Momblanch A, Papadimitriou L, Jain SK, Kulkarni A, Ojha CSP, Adeleye AJ, Holman IP (2019a) Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *Sci Total Environ* 655:35–47. <https://doi.org/10.1016/j.scitotenv.2018.11.045>
- Momblanch A, Holman I, Jain S (2019b) Current practice and recommendations for modelling global change impacts on water resource in the Himalayas. *Water* 11(6):1303. <https://doi.org/10.3390/w11061303>
- Momblanch A, Beevers L, Srinivasalu P, Kulkarni A, Holman IP (2020) Enhancing production and flow of freshwater ecosystem services in a managed Himalayan river system under uncertain future climate. *Clim Change* 162(2):343–361. <https://doi.org/10.1007/s10584-020-02795-2>
- Moriassi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans Am Soc Agric Biol Eng* 50(3):885–890
- Najar GN, Bhardwaj A, Pandey P (2017) A spatio-temporal water quality assessment of the Beas and Sutlej Rivers at the Harike Wetland: a Ramsar site in Punjab, India. *Lakes Reserv Res Manag* 22(4):364–376
- Pal I, Robertson AW, Lall U, Cane MA (2015) Modeling winter rainfall in Northwest India using a hidden Markov model: understanding occurrence of different states and their dynamical connections. *Clim Dyn* 44(3–4):1003–1015
- Pang A, Li C, Sun T, Yang W, Yang Z (2018) Trade-off analysis to determine environmental flows in a highly regulated watershed. *Sci Rep* 8:1–11. <https://doi.org/10.1038/s41598-018-32126-6>
- Papadimitriou L, Holman IP, Dunford R, Harrison PA (2019) Trade-offs are unavoidable in multi-objective adaptation even in a post-Paris Agreement world. *Sci Total Environ* 696:134027. <https://doi.org/10.1016/j.scitotenv.2019.134027>
- Pavelsky TM (2014) Using width-based rating curves from spatially discontinuous satellite imagery to monitor river discharge. *Hydrol Proc* 28(6):3035–3040
- Pham-Truffert M, Merz F, Fischer M, Rueff H, Messerli P (2020) Interactions among Sustainable Development Goals: knowledge for identifying multipliers and virtuous cycles. *Sustain Dev* 28:1236–1250. <https://doi.org/10.1002/sd.2073>
- Prasad V, Kulkarni A, Pradeep S, Pratibha S, Tawde SA, Shirsat T, Arya AR, Orr A, Bannister D (2019) Large losses in glacier area and water availability by the end of twenty-first century under high emission scenario, Satluj basin, Himalaya. *Curr Sci* 116:1721–1730. <https://doi.org/10.18520/cs/v116/i10/1721-1730>
- Rao PS, Ramaseshan S (1985) Integrated operation of the Beas-Sutlej system. *Sadhana* 8:207–221
- Reid AJ, Brooks JL, Dolgova L, Laurich B, Sullivan BG, Szekeres P, Wood SLR, Bennett JR, Cooke SJ (2017) Post-2015 Sustainable Development Goals still neglecting their environmental roots in the Anthropocene. *Environ Sci Policy* 77:179–184
- Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol Rev* 94:849–873. <https://doi.org/10.1111/brev.12480>
- Rolls RJ, Leigh C, Sheldon F (2012) Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshw Sci* 31:1163–1186. <https://doi.org/10.1899/12-002.1>
- Shirsat TS, Kulkarni AV, Momblanch A, Randhawa SS, Holman IP (2021) Towards climate-adaptive development of small hydropower projects in Himalaya: a multi-model assessment in upper Beas basin. *J Hydrol Regional Stud* 34:100797. <https://doi.org/10.1016/j.ejrh.2021.100797>
- Shrestha S, Shrestha M, Babel MS (2017) Assessment of climate change impact on water diversion strategies of Melamchi Water Supply Project in Nepal. *Theor Appl Climatol* 128(1–2):311–323
- Sidhu RS, Vatta K, Lall U (2011) Climate change impact and management strategies for sustainable water-energy-agriculture outcomes in Punjab. *Indian J Agric Econ* 66:902–2016–67320
- Srivastava SK, Chand R, Singh J, Kaur AP, Jain R, Kingsly I, Raju SS (2017) Revisiting groundwater depletion and its implications on farm economics in Punjab, India. *Curr Sci* 113(3):422–429
- Su F, Zhang L, Ou T, Chen D, Yao T, Tong K, Qi Y (2016) Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau. *Glob Planet Change* 136:82–95. <https://doi.org/10.1016/j.gloplacha.2015.10.012>
- Trouet V, van Oldenborgh GJ (2013) KNMI climate explorer: a web-based research tool for high-resolution paleoclimatology. *Tree-Ring Res* 69:3–13. <https://doi.org/10.3959/1536-1098-69.1.3>
- United Nations General Assembly (2017). Resolution A/RES/71/313. <https://undocs.org/A/RES/71/313> (Accessed 01 Jan 2020)
- Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Reidy Liermann

- C, Davies PM (2010) Global threats to human water security and river biodiversity. *Nature* 467(7315):555–561
- Vörösmarty CJ, Pahl-Wostl C, Bunn SE, Lawford R (2013) Global water, the anthropocene and the transformation of a science. *Curr Opin Environ Sustain* 5(6):539–550
- Wijngaard RR, Lutz AF, Nepal S, Khanal S, Pradhananga S, Shrestha AB, Immerzeel WW (2017) Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. *PLoS ONE* 12(12):e0190224
- Williams R, Gero S, Bejder L, Calambokidis J, Kraus SD, Lusseau D, Read AJ, Robbins J (2011) Underestimating the damage: interpreting cetacean carcass recoveries in the context of the Deepwater Horizon/BP incident. *Conserv Lett* 4(3):228–233
- Wulf H, Bookhagen B, Scherler D (2016) Differentiating between rain, snow, and glacier contributions to river discharge in the western Himalaya using remote-sensing data and distributed hydrological modeling. *Adv Water Resour* 88:152–169. <https://doi.org/10.1016/j.advwatres.2015.12.004>
- WWF-India (2018) Status of the Indus River dolphin in India. Technical report submitted to the Department of Forests and Wildlife Preservation, Punjab. WWF-India, Lodhi Estate, Delhi, p 62
- Yang S, Zhao W, Liu Y, Cherubini F, Fu B, Pereira P (2020) Prioritizing sustainable development goals and linking them to ecosystem services: a global expert's knowledge evaluation. *Geogr Sustain* 1(4):321–330. <https://doi.org/10.1016/j.geosus.2020.09.004>
- Yates D, Purkey D, Sieber J, Huber-Lee A, Galbraith H (2005) WEAP21—a demand-, priority-, and preference-driven water planning model. *Water Int* 30:501–512. <https://doi.org/10.1080/02508060508691894>
- Yin XA, Yang ZF, Petts GE (2011) Reservoir operating rules to sustain environmental flows in regulated rivers. *Water Resour Res* 47:W08059. <https://doi.org/10.1029/2010WR009991>
- Yin Y, Xu C, Chen H, Li L, Xu H, Li H, Jain SK (2016) Trend and concentration characteristics of precipitation and related climatic teleconnections from 1982 to 2010 in the Beas River basin, India. *Glob Planet Change* 145:116–129

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



DSPACE

<https://dspace.org/>

Exploring trade-offs between SDGs for Indus River Dolphin conservation and human water security in the regulated Beas River, India

Momblanch, Andrea; Kelkar, Nachiket; Braulik, Gill; Krishnaswamy, Jagdish; Holman, Ian P.

2021-10-11

Springer

<https://doi.org/10.1007/s11625-021-01026-6>

Momblanch A, Kelkar N, Braulik G, et al., (2021) Exploring trade-offs between SDGs for Indus River Dolphin conservation and human water security in the regulated Beas River, India. Sustainability Science, Volume 17, Issue 4, July 2022, pp. 1619–1637