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CLIMATE CHANGE AND FRESHWATER FISH BIODIVERSITY IN BHUTAN: STANDARDIZED MONITORING OF A FLAGSHIP SPECIES, GOLDEN MAHSEER (CYPRINIDAE: *TOR PUTITORA*)

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ABSTRACT: Climate change is now the most influential driver of ecosystem change, with critical impacts on freshwater systems as a substantial result. These have rapidly pushed numerous fish species towards extinction, much more so than in any other group. Conservation planning has been largely ineffective, due to limited data on global fish distributions/movements. These are slowly emerging in Bhutan, but effective data collection programs are hindered by both economy and topography. Given this, how can the conservation of Bhutanese aquatic systems be effectively promoted? Here we outline a time-tiered strategy that: (a) Uses existing albeit imperfect data to generates a predictive fish species distribution model (SDM); (b) Suggests a standardized long-term monitoring program be used to collect additional data; and (c) Anticipates future climate impacts by formulates proactive aquatic management strategies. We demonstrate this approach using Golden Mahseer (*Tor putitora*), a fish of great cultural importance in Bhutan but also one with a conservation focus as both a 'flagship' and 'umbrella' species (whose protection also benefits other species). We first identify favorable environmental parameters for Golden Mahseer by integrating historic and contemporary records with life-history characteristics. The probabilities of favorable habitats (≤1,000m elevation) were identified within Bhutan by first parsing GIS databases then superimposing those data onto a map of the seven major river drainages. In conclusion, our predictive map is but a starting point as SDMs must be validated and improved through acquisition of additional data. We thus recommend Golden Mahseer as the focal species in the development of a standardized, long-term monitoring program for Bhutan. Its status as a flagship/umbrella species would also promote opportunities to similarly quantify the distributions of other native fishes– both must immediately occur to successfully mitigate the impacts of climate change on Bhutan's aquatic ecosystems.

Keywords: GIS; Gross National Happiness; management; species delimitation; umbrella species

1. INTRODUCTION

Climate change is a natural planetary phenomenon, extending over time scales both extensive (e.g., Milankovitch cycles, tectonism) and abrupt (e.g., vulcanism, meteorite impacts) (National Research Council 2002, Douglas et al. 2009). By contrast, our anthropogenic impositions on climate have been virtually instantaneous over geologic time, overwhelming natural cycles as well as the capacity of biodiversity to adapt (Corlett 2015). Climate is now the most influential driver of ecosystem change, and consequently the greatest threat to biodiversity. Freshwater ecosystems, with their relatively low buffering capacity, have been particularly impacted and are now identified as among the most threatened of Earth's ecosystems (Millennium Ecosystem Assessment 2005, IPCC 6th Assessment Report: https://www.ipcc.ch/report/ar6/wg2/). This alarming message has sparked a global response from aquatic research societies and professional organizations, with the urgency of immediate actions being rapidly amplified to counter ongoing and future impacts (AFS 2020, Bonar et al. 2021).

Climate change has also compounded freshwater conservation and management, with species extinctions now gauged at 83%, a rate far greater than any comparable taxonomic group (Figure 6 of WWF 2020). Aquatic megafauna (defined as >30kg wt.) are especially vulnerable, particularly those with a natural history that requires migration (i.e., recurring seasonal movements between different habitats for trophic or reproductive purposes) (He et al. 2017, Carrizo et al. 2017). In managing such species. two key goals are apparent: (1) All requisite habitats must remain available, inter-connected, and accessible; and (2) Genetic diversity must be maintained (DeWoody et al. 2021), as it underlies those innate species-behaviors that initiate the timing and extent of migration. Thus, to ensure the long-term persistence of migratory freshwater species, fisheries management must concomitantly monitor both habitat connectivity and genetic variability.

Climate threats are particularly relevant for freshwater ecosystems in Asia. The 10 largest rivers in the region are regulated by precipitation and glacial melt stemming from the Qinghai-Tibetan Plateau and Himalaya Mountains (Xu et al. 2009). The livelihoods of millions of people are sustained by these rivers, yet their flows and the fishes they encompass are highly sensitive to climate change. Uncertainties focus on whether regional flow regulations and biodiversity management are sufficient to address present as well as future conservation challenges. While the future itself cannot be predicted, contemporary management decisions must be initiated to help promote the shape of those outcomes (Lahoz-Monfort et al. 2019). Reliable data are clearly essential in guiding this process.

1.1 Monitoring for fisheries management

Good science informs management and guides conservation policy, yet empirical data are required as a baseline from which changes can be gauged. In this sense, monitoring programs are an essential component of science-based fisheries management (Walters and Martell 2020), and these data provide the foundation for subsequent conservation efforts. Monitoring allows the comparison of biodiversity within and among drainages and does so by establishing baselines from which subsequent population trends can not only be assessed, but conservation efforts gauged (Lovett et al. 2007; Douglas et al. 2021).

To produce reliable data, however, sampling must be standardized, repeatable, spatially/ temporally consistent, and continuous over extended time (i.e., long-term monitoring). Such a program allows fluctuations to be quantified, then gauged against the natural variability inherent within aquatic systems. In this context, standardized monitoring can detect many prominent aquatic issues as they relate to inland fisheries (Ngor et al. 2018), undocumented harvest (Fluet-Chouinard et al. 2018), and hydropower generation (Intralawan et al. 2018; Box 1 of He et al. 2017). All are extremely relevant to Bhutan and its rivers.

Fish monitoring in Bhutan has recently been initiated by the National Research & Development Centre for Riverine and Lake Fisheries (NRDCR&LF) within the Department of Livestock (DoL), with those results subsequently published (Fishes of Western Bhutan 2017, Fishes of Eastern Bhutan 2020). Because support for this endeavor was limited to 3-year grants, the long-term effectiveness of those data in tracking fish population trends is marginalized. To document and track the impacts of climate change on aquatic biodiversity in Bhutan, standardized monitoring program for fisheries must not only be established but also sustained.

1.2 Species Distribution Models (SDM) as baseline

In addition to identifying which fish species are present in a watershed, it is also essential to quantify their locations and potential movements. Different species are generally associated with specific habitats, and researchers must first compute the relationships between species and their habitats before effective management can be devised. This is especially relevant for Himalayan rivers, where aquatic habitats are segregated by elevational gradients (Figure 1). Unfortunately, data on Bhutanese fish distributions and life histories are limited. This, in turn, constrains both short-term management and long-term conservation.

Figure 1: Left. Tsheringom Ri, tributary of Dangme Chhu, ~6km S Trashigang [Phomshing,Trashigang District]. [Picture courtesy of M.E. Douglas, University of Arkansas]. Right. Dringru Chhu [tributary of Dangme Chhu] at reduced flow, in vicinity of Zarkabla village within Zhemgang District. Braided channel depicts width of stream during the monsoon season [Picture courtesy of J.E. Claussen, Fisheries Conservation Foundation].

One approach to cope with limited distributional data is first to characterize potential habitat for a species based on what is known of its ecology and habitat requirements, identify where such habitats exist, then employ these data to predict the probability of occurrence for that species (i.e., Species Distribution Model (SDM); Fois et al. 2018). This process may, in turn, provide a useful tool that not only identifies environmentally sensitive areas, but also sustains the presence of a particular species by protecting its critical habitat. We demonstrate this approach herein using as a focal species the Golden Mahseer (*Tor putitora*; Figure 2). We combine its SDM with publicly available, georeferenced environmental data to identify areas with suitable habitat, and to predict the potential for occurrence of Golden Mahseer across seven river basins in Bhutan.

1.3 Golden Mahseer as a 'flagship species'

We selected Golden Mahseer for several reasons. It represents a large-river, charismatic megafauna with elevated cultural importance in Bhutan. It is also recognized as a 'flagship species' in aquatic conservation (i.e., its extensive and established public appeal serves to promote conservation on a broad scale; Table 2 of He et al. 2017; Mussmann et al. 2020).

Surveys indicate that 93% of freshwater biodiversity co-occur with megafauna, again a result of the broad habitat affinity most often displayed by megafauna in the completion of their life histories (Supplemental Table S5.1, Carrizo et al. 2017). Golden Mahseer can also be viewed ecologically as an 'umbrella species,' in that species which share the same habitat requirements would also be similarly protected by any conservation measures developed to protect Golden Mahseer (Table 2 of He et al. 2017). Such designations help blunt ongoing but largely unnoticed declines in global freshwater biodiversity that often occur in areas difficult or even impossible to sample, such as the steep-gradient, fast-water habitats characteristic of Himalayan rivers (Gupta et al. 2014; Everhard et al. 2021). In addition, having Golden Mahseer as a focal point for standardized monitoring can be viewed as a positive response by administrative agencies to the socio-religious context within which Golden Mahseer exists (i.e., with an elevated status widely recognized and acknowledged by the Bhutanese populace).

The study is an initial attempt to broadly parameterize the distribution of Golden Mahseer and its habitat in Bhutan by first employing an SDM to identify available habitat, then applying those results to project the occurrence of Golden Mahseer within the riverine systems of Bhutan. The SDM was based on broad-scale parameter re-classifications of occurrence data, and the interpolation of important environmental layers (elevation, temperature) that yielded a probability map of Golden Mahseer habitat. Predicting the potential occurrence of Golden Mahseer based on habitat availability is not only fundamental to developing an effective management strategy for the species, but also as an initial step in developing an over-arching, proactive aquatic conservation plan for Bhutan.

2. MATERIALS AND METHODS

2.1 Study area

Bhutan is a mountainous country with peaks >7,300 msl. It extends geographically within the Eastern Himalaya from 27.5 to 29.5° E and 88 to 92.5° N, and encompasses seven substantial river basins (five major, two minor) that eventually join with the Brahmaputra River in India. These rivers comprise an extensive dendritic network of ~7200 km, with discrete aquatic habitats most often defined by elevation. Himalayan riverine systems will be severely stressed by climate change, which is manifested in the near-term by large fluctuations in the timing of riverine flows (Immerzeel 2021, Figure 1). These will impact resident aquatic communities and thus, the monitoring of freshwater biodiversity becomes a management imperative as well as a baseline for the development of proactive conservation strategies.

2.2 Study species

Golden Mahseer (Figure 2) ranges throughout the southern Himalaya (Indus, Ganges, and Brahmaputra drainages) from Pakistan in the west, through India, Nepal, Bhutan, to northeastern India, Myanmar, and Bangladesh in the east (Pinder et al. 2019) (Figure 3). It is also recognized as a constituent of the global 'aquatic megafauna' (Supplemental Table S1 in Carrizo et al. 2017).

Figure 2: Adult Golden Mahseer [*Tor putitora*, TL=94cm] captured by hook and line, 31 March 2015, Manas River, Bhutan by Karma Wangchuk [Ministry of Agriculture and Forestry, National Research & Development Centre for Riverine & Lake Fisheries, Haa, Bhutan. Photograph: Karl Anderson, provided by Fisheries Conservation Foundation].

Golden Mahseer has been extensively investigated in India, and those studies provide much of what we know about its natural history (defined as "*where organisms are and what they do in their environment, including interactions with other organisms … and encompasses changes in internal states insofar as these pertain to what organisms do*;" Greene and Losos 1988). The distribution of Mahseer in general was interpreted quite early within India: "*In practically every river of fair size in India, one will find mahseer always, provided that the river has its origin and that its course runs for a certain number of miles at an elevation of at least 1,000 ft above sea level*" (Dhu 1923).

Much of the current information on life history and ecology of Golden Mahseer is based on investigations by Indian fisheries biologists (Nautiyal 2014; Bhatt and Pandit 2016; Joshi et al. 2018). It is essentially a rheophilic (current-loving) species found in hill streams where large water volumes discharge over riverbeds of sand, silt, and small boulders. It periodically migrates upstream from larger rivers into smaller foothill streams during the pre-monsoon/monsoonal seasons, presumably for spawning (Figure 1). Well-oxygenated, gently advancing floodwaters seemingly provide the necessary breeding stimulus, with July to September as the extent of the breeding phenology i.e., the timing of seasonal life history events in relation to climate (Woods et al. 2021).

hydroelectric dams, illegal sand/ boulder mining), all of which are well-documented in India (Bhatt and Pandit 2016).

2.3 Data evaluation and mapping

We first characterized Golden Mahseer habitat by identifying key environmental habitat parameters based on previous studies, and publicly available sources such as online data bases, project reports, and publications. From these efforts, two key environmental parameters were identified: Elevation and temperature. Next, GIS data bases were accessed to download, analyze, and superimpose layers for these two parameters using ARCMAP 10.7.1.

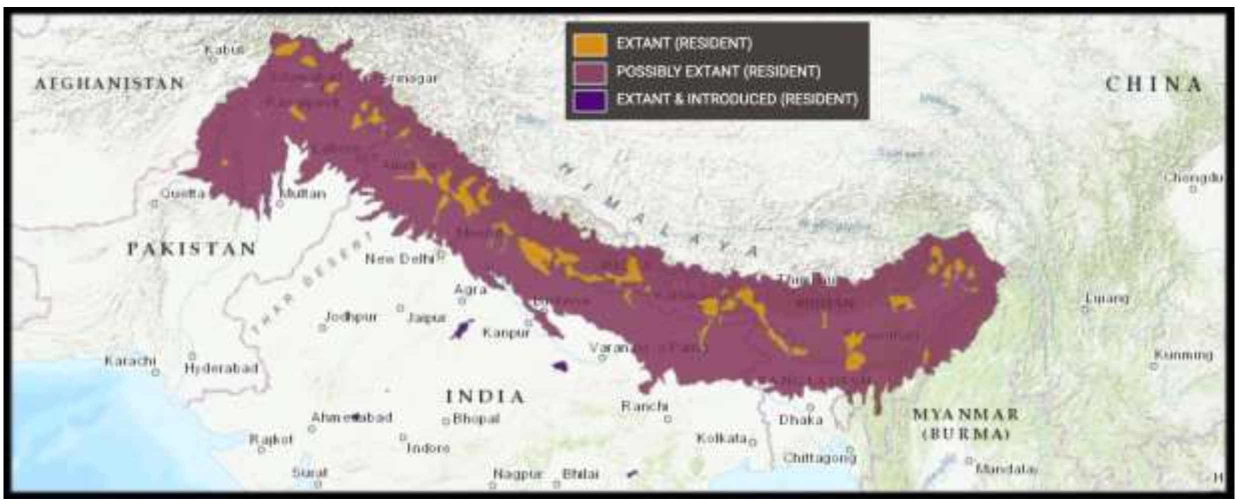

Figure 3: range of Golden Mahseer [*Tor putitora*]. Figure courtesy of: IUCN Red List - International Union for Conservation of Nature/05 August 2018; Bournemouth University 2018. *Tor putitora*. The IUCN Red List of Threatened Species. Version 2021-3].
[https://www.iucnredlist.org/species/126319882/126322226#geographic-range].

The annual, iterative long-distance Geographic movements of Golden Mahseer require the availability of, and connectivity between, spawning, over-wintering, and nursery habitat as a baseline for completing its life cycle (Figure 1). In addition, the longevity of Golden Mahseer, its larger body size, late maturity, and limited fecundity, are life-history parameters that establish it as a species highly susceptible to over-exploitation and ecosystem degradation (Nautiyal 2014; Bhatt and Pandit 2016). Golden Mahseer has already been listed globally as endangered (Jha et al. 2018), due largely to illegal fishing and over-exploitation of habitat (e.g., construction of

For elevation, we downloaded the digital elevation model (DEM) of Southeast Asia from United States Geological Service (USGS) Earth Explorer database (https://earthexplorer.usgs.gov/). An outline of Bhutan was used as a template to trim the elevational model. For temperature, we downloaded the GioRiv shapefile from World Climate database, which contains average global minimum winter temperature data (1970-2000). Raw data for Bhutan were extracted, with the shapefile subsequently converted into a raster layer. To maintain a consistent coordinate system, both elevation and temperature layers were projected to WGS84 datum.

Georeferenced occurrence data for Golden Mahseer in Bhutan were compiled from biodiversity surveys and collections (NCRDR&LF), as supplemented by location data from an ongoing radio-tracking project (https://www.fishconserve.org/wordpress/wp-content/uploads/2015/08/Mahaseer-Post-Trip-Report-Final-MAY2015.compressed.pdf). These records allowed us to constrain the environmental layers for the map with empirical data.

The layers for each site record were divided into two groups: Elevation (WWF-Bhutan 2019) and Temperature (Bhatt and Pandit 2016), which were then classified using binary criteria. If requirements within each group were met, the assignment was designated as '1,' and '0' if not. This produced the following assignments: Elevation <1,000 meters (=1); Elevation >1,000 meters (=0); Temperature >13 C (=1); Temperature <13 C (=0). After reclassification, we generated an SDM for Golden Mahseer by combining the two raster layers using Boolean intersection, with model predictions then projected onto a map (Figure 4). It is important to note that our map is based on broad-scale parameter re-classifications, as derived from the limited data available for Golden Mahseer in Bhutanese rivers. The map thus represents a predictive model of potential habitat, and these greatly exceed the actual recorded occurrences of the species, again due to limited sampling and diagnosis.

3. RESULTS AND DISCUSSION

Bhutanese citizens are duty-bound to preserve, protect and respect the environment, culture, and heritage of their nation.

> "***Every Bhutanese is a trustee of the Kingdom's natural resources for the benefit of present and future generations, and it is the fundamental duty of every citizen to contribute to the protection of the natural***

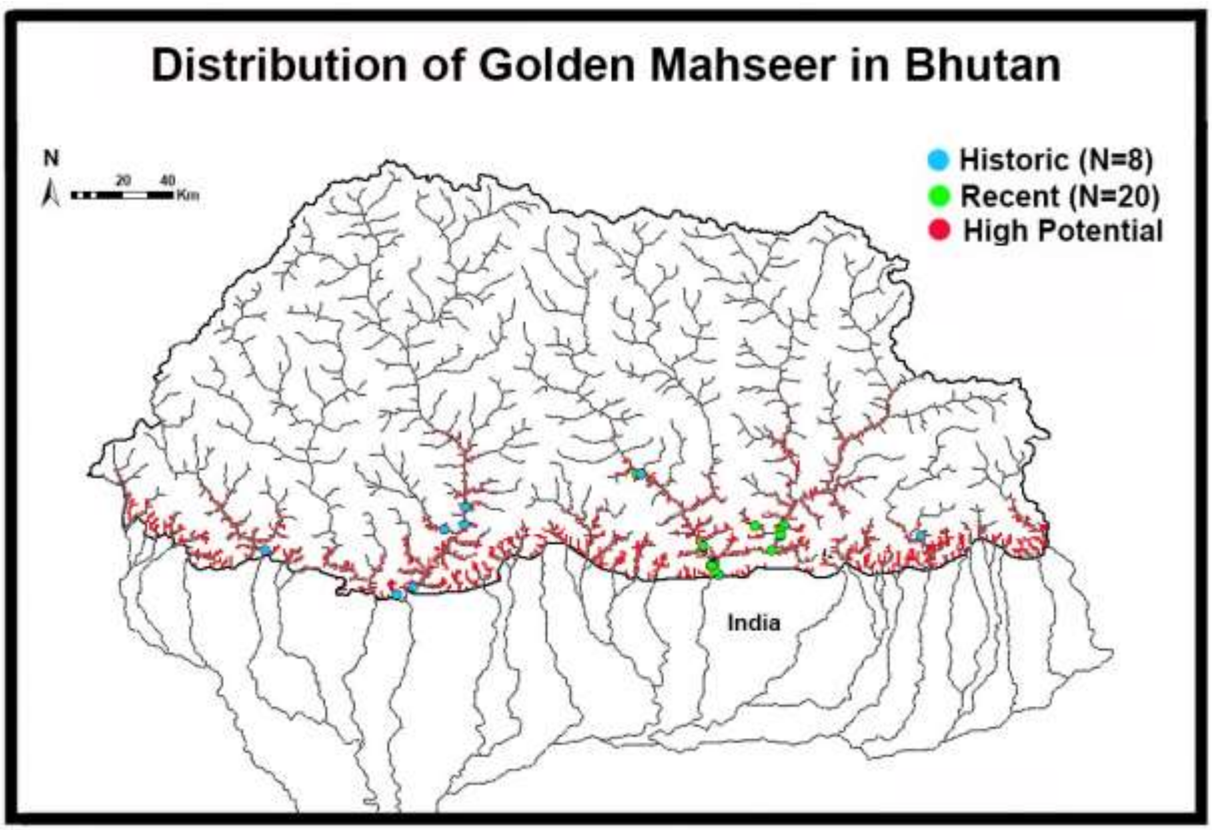

Figure 4: Distributional map for Golden Mahseer [*Tor putitora*] in Bhutan. Streams highlighted in red indicate those with high potential for harboring the species. Sites representing historic records for the species are identified with blue dots. Sites represented by green dots are where the species has been previously collected.

environment, conservation, and rich biodiversity of Bhutan, and to prevent all forms of ecological degradation including noise, visual, and physical pollution through the adoption and support of environment friendly practices." (Government of Bhutan 2008).

This constitutional commitment to conservation is one of the Bhutan's 'Four Pillars for Gross National Happiness,' and it is manifested in terrestrial ecosystems by the mandated preservation of >60% of Bhutan's forest cover. By comparison, the vast biodiversity within Bhutan's rivers has yet to receive similar protective measures.

Specific conservation goals are needed to develop management strategies and to guide policy and legislative decision-making process in Bhutan, especially when conflicting interests must be adjudicated. Here we discuss a time-tiered approach to freshwater biodiversity conservation, using Golden Mahseer as an example. We do so now with respect to the urgency of freshwater issues, the need for immediate action (AFS 2020, Bonar et al. 2021), and the challenges of insufficient data and limited funding. We pose the following questions: (1) What can be 'done now,' based on currently available data? (2) What must be initiated to overcome our current limitations? and (3) What should be 'anticipated,' so that appropriate policies and plans can be formulated.

3.1 Distribution of Golden Mahseer

Limited data on occurrences and distributions of freshwater species are problematic because interpolations performed in their absence often lead to arbitrary and/or inaccurate interpretations. We illustrate this dilemma herein by providing two interpretations of Golden Mahseer distribution in Bhutan (Figures 3 and 4). Neither are complementary nor do they coherently define the distribution of potential Golden Mahseer habitat within Bhutanese rivers.

The geographic range of Golden Mahseer across the Himalaya (Figure 3) highlights the contrast between a more broadly predicted range (i.e., potentially resident) *versus* areas where occurrence has indeed been verified. Focusing on Bhutan, the latter seemingly recognizes only the Amo Chhu (western Bhutan) and the Manas River drainages (central Bhutan) as being Golden Mahseer habitat, yet it is known to exist within other drainages as well.

In contrast, our SDM map (Figure 4) is based on historic and contemporary data for Golden Mahseer in Bhutan and depicts specific areas where environmental factors are highly conducive for its occurrence. These differ somewhat from what has been previously presented (Figure 3). Importantly, however, our map represents the output of a model, and the seemingly extensive distribution is a prediction of potential habitat not yet confirmed, whereas historic/ contemporary records are substantiated yet far more limited (Figure 4). Model predictions are only as good as data employed to produce them, and even the best models cannot overcome major deficiencies in data. This discrepancy underscores the necessity of gathering empirical data (i.e., results from a consistent, standardized, long-term monitoring program).

3.2 Golden Mahseer as a 'flagship' species

Incomplete knowledge about the distribution and movements of Golden Mahseer is but a subset of the data deficiencies that impede proactive conservation and management of Bhutanese aquatic biodiversity. In any case, modeling favorable habitat for Golden Mahseer using SDM (Figure 4) employs the scant available data to help guide management of Golden Mahseer from larger lowland rivers into smaller headwater streams. Because Golden Mahseer is an "umbrella species," conservation strategies designed to protect it will also serve to benefit other species associated with it in the same habitat (He et al. 2017). In this way, its dual status as a "flagship" and "umbrella" species not only elevates awareness about Bhutan's conservation commitment, but also supports aquatic habitat protection in general.

3.3 Long-term fish monitoring

Fish monitoring programs are one mechanism to quantify the occurrences of, and variances in, fish biodiversity, and to track those physical disturbances that stem from anthropogenic habitat alterations and environmental degradation (via regional water withdrawals and urban/ agricultural/ industrial engineering) (McClellan et al. 2012). Although ecosystems normally change but slowly, climate change has substantially accelerated this process. To effectively quantify these changes, monitoring programs must now be both consistent as well as long-term. For developing countries, the implementation of long-term, standardized monitoring is a major challenge, often due to financial constraints and/or technical limitations. These must be recognized when a monitoring program is initiated, so that limited resources can be more effectively allocated. Additional challenges, such as difficult topography, geographic isolation, conflicts with local governance, and communication difficulties also contribute to lowering the effectiveness of monitoring programs. The six most important issues to be addressed in Bhutan for the initiation of a long-term fish monitoring program are as follows:

(a) Aquatic monitoring is logistically difficult. Some aquatic systems, such as large rivers, are not easily accessed or sampled and, as a result, data on resident fishes are not only difficult to collect but also attempted on a limited scope. This is amplified in river systems where the seasonal hydrograph fluctuates by orders of magnitude, often with severe damage to infrastructure, further complicating access. All the above most certainly apply to Bhutan. While these natural challenges cannot be altered, they can be anticipated and subsequently strategized within a monitoring program.

(b**) Monitoring is technically and analytically difficult.** Monitoring data, once collected, are also demanding to analyze. Ecological data are not only inherently variable, but statistical expertise is also required for their successful processing and accurate interpretations. As a result, biologists must be trained in both data management and analytics. They must also be cross trained in multiple disciplines that include (but are not restricted to): Ichthyology, fisheries management, natural resource conservation, GIS, as well as laboratory techniques.

(c) Monitoring requires dedicated budgets. Professional capacity must be developed, and staff adequately trained (as above). Biologists must possess appropriate field and analytical skills, and necessary field equipment must be purchased and maintained. Both require consistent, predictable funding. Establishment of a skilled fisheries management workforce should be an integral part of Bhutan's developing capacity in resource conservation.

(d) *Funding must also be consistent and long-term*. Data collection must be continuous and consistent over extended time periods. One-off assessments, or those completed but sporadically every few years, yield limited data that cannot be used by stakeholders to identify long-term trends, or to build effective strategies for aquatic biodiversity management, both of which will shift as climate change intensifies. Thus, commitment to a dedicated budget line is essential, and should be viewed as a long-term resource investment.

(e) Results must drive management decisions. Local and regional managers must be invested in monitoring programs from the onset, gain sufficient understanding of key results, and remain continually informed of subsequent results. This level of involvement ensures that management goals are guided by sound science, have appropriate objectives, remain on target, and are clearly understood by all stakeholders. These communications must occur at all levels prior to the formulation of management decisions.

(f) Results must be disseminated. More specifically, monitoring results must be divulged and explained to all stakeholders, as well as local communities where livelihoods are often tied to riverine resources. It is best promoted through extensive dialogue and outreach programs that are an integral part of the monitoring program, with all stakeholders being incorporated. These results can be delivered through exhibits, presentations, online resources, and educational materials for schools, to name several. This dialogue should also include community-based fisheries (those associations that fish sustainably for designated species, and which actively work to protect freshwater species and their habitats).

3.4 Current threats to Golden Mahseer

Freshwater fish species are threatened globally, and this provides a necessary incentive for Bhutan to initiate a national freshwater fish monitoring plan, with Golden Mahseer distribution and habitat use being an initial focus. Many freshwater megafaunal species such as Golden Mahseer are found in relatively remote areas, and their declines or losses are often unnoticed and/or unreported due to limited or non-existent monitoring (He et al. 2017). In addition, the longer lifespans displayed by these fishes, their larger body sizes, slower maturity, and limited fecundities, establish them as extremely susceptible to ecosystem degradation. These life history characteristics are viewed from a management and conservation perspective as potential red flags in need of quantification (Nautiyal 2014; Bhatt and Pandit 2016). The vast hydro-electric potential of Himalayan rivers is now seen as a mechanism by which the rising energy demands of the region can be addressed (Grumbine and Pandit 2013). Unfortunately, the negative by-products of these endeavors are wide-ranging alterations in quantity and quality of waters downstream from dams, as well as the upstream flooding of large riverscapes and other terrestrial areas. These also impact the migratory Golden Mahseer, as well as a variety of native fish species (Gupta et al. 2014).

3.5 Climate threats and the future of Bhutanese aquatic conservation

Climate change is now a compounding factor that severely impacts freshwater habitats and, by association, the fish assemblages therein. These impacts will complicate management decisions and will be particularly pronounced in high-elevation regions such as Bhutan and the Himalaya. Many of these are already observable (with others being predicted; Table 1), and given this, they must be duly considered when long-term conservation goals and management strategies are defined.

Bhutanese freshwater biodiversity will shift considerably as climate change progresses, particularly as those indicators trend negatively. For example, water temperatures in tributaries are predicted to increase while dissolved oxygen diminishes, thus enhancing the probable occurrence of invasive fishes that subsist under such induced conditions. As a result, cool-adapted native fishes that persist within the mid-elevational range are predicted to decrease in overall growth, body-size, and reproductive fitness, with numerous local populations going extinct (Table 1). This, in turn, will deplete population numbers and diminish their genetic variability accordingly. Species-richness will also decrease as isotherms (i.e., latitudinal lines on a weather map that link points of equal temperature) shift upward in elevation. This, again, provides potential opportunity for the development of novel, warm-water invasive-fish communities, again to the detriment of native fish communities.

3.6 Climate threats and Golden Mahseer

Climate change may have already impacted Golden Mahseer by reducing the extent of its breeding phenology. For example, Indian scientists indicate that from 1911–1981, the onset of Golden Mahseer reproduction began in May (Figure 4 of Joshi et al. 2018), whereas contemporary post-2000 studies (N=4) now point to July as the onset. This two-month reduction in reproductive span suggests the potential influence of climate change on timing of reproduction in Golden Mahseer (although recruitment and overfishing may be implicated as well; Joshi et al. 2018). Furthermore, climate change will also drive seasonal shifts in precipitation (Table 1), and this will alter the onset and duration of the monsoon, with stream discharge expanding or diminishing by location. Again, this will alter aquatic and riverscape habitats (i.e., those parts of the landscape which have (or had) served as the focus of a watercourse). As a result, the fundamental niches of rheophilic fishes will potentially shrink, whereas those cues required by other native fishes will be simultaneously confounded. This would be particularly damaging for species such as Golden Mahseer that have a life history that incorporates a strong migratory component, as initiated by physicochemical cues.

3.7 Golden Mahseer compliance and policy decisions

To complete its life cycle, the Golden Mahseer requires seasonal movements among diverse habitats (i.e., the annual migration between low elevation overwintering habitats and higher elevation (<1000m) tributary spawning habitats). These obligatory movements impose a reliance upon habitat connectivity, which in turn makes the Golden Mahseer more vulnerable to habitat fragmentation or loss. Unfortunately, these life history requirements are often in conflict with the economic endeavors of stakeholders and corporations (e.g., water acquisitions/ depletions/ impoundments, as well as substrate disturbances and/or removals). It falls upon governments to properly manage these competing interests by formulating operational plans for river basins, and by legislating appropriate compliance with numerous international agreements (CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora, https://cites.org/eng; CMS: Convention on the Conservation of Migratory Species of Wild Animals, http://www.cms.int/; FAO CCRF: U.N. Food & Agricultural Organization Code of Conduct for Responsible Fisheries, https://www.fao.org/fishery/en/code/en). The development of sound and efficient conservation strategies that align with management plans and regulations require reliable data on the status and trend of fish populations, as well as a mechanism for the timely dissemination of those results to relevant stakeholders (defined as any organization, governmental entity, or individual that may be impacted by a given approach to environmental regulation, pollution prevention, energy conservation, and other such issues).

3.8 Ancillary approaches to the protection of Golden Mahseer

Although legal mandates are obviously important for the protection of aquatic biodiversity (with several discussed above), there are also supplemental mechanisms that can be employed to elicit protection. Several of these, such as eco-tourism, have an economic footprint that easily (and importantly) translates to local communities. It also aligns the livelihood of local communities together with damages that occur to native fishes in the Himalaya (Gupta et al. 2021). This obviously promotes the conservation of species and habitats at the local level. Religious and cultural beliefs are also factors that can promote biodiversity conservation (Olden et al. 2020). The Golden Mahseer is identified in Buddhist culture as one of eight auspicious signs, representing good luck (https://www.nationalgeographic.com/animals/article/golden-mahseer-conservation-bhutan).

In addition, rural communities within India interpret fish as symbols of divine power, with protection provided in pools associated with temples (Gupta et al. 2016). Mahseer are particularly valued in this regard for their capacity to placate the souls of deceased ancestors (Nautiyal 2014). In this sense, conservation, as perceived through a religious lens, can indeed be beneficial in that it promotes an ethos that is not only respected at the local level but also relatively consistent across localities as well. Some religious practices, however, can negatively impact freshwater fish conservation, such as a desire to gain religious favor by releasing captive fishes and other aquatic vertebrates (Lowe et al. 2019). This ritual is implemented to counter the mortality caused by fishing, yet because captive-bred non-native fishes are most often involved, it also promotes the spread of invasive species (Severinghaus and Chi 1999; Shiu and Stokes 2008).

3.9 Golden Mahseer as a focus for Bhutan's biodiversity commitment

Will today's important questions regarding the conservation of Bhutanese Golden Mahseer remain unanswered decades into the future? Although we acknowledge the difficulty in determining which threats may increase/ diminish over time, we suggest Bhutan (as well as other Himalayan countries) adopt an important first step, which is: To develop a scientifically sound, standardized monitoring program for aquatic biodiversity, with focus on Golden Mahseer as a flagship species. This would reinforce Bhutan's commitment to conservation, human well-being, and national happiness. We should note as well that new opportunities may also arise, particularly if managers and policymakers take the initiative to first document on a regular basis the breadth and depth of existing freshwater fish biodiversity (as above), then subsequently adapt policies to meet emerging conditions brought about by unrelenting climate change (Table 1).

Table 1: Key changes and impacts of climate change on inland fisheries of Bhutan, with potential approaches and opportunities for adaptation indicated [modified from FAO, 2018].

Impact	Negative	Positive	Adaptation
	Increase in air and water temperatures		
Increased temperature and reduced dissolved oxygen (DO)	Shift in conditions for cold and cool-adapted fishes	Extended fishing season	Establish long-term monitoring
	Reduction in average size (if not limited by temps)	Reduction in cold-weather injuries	Use adaptive management for flexible approaches
	Local extinctions when thermal regime exceeded	Increased fish growth in temperature-limited areas	Develop new ecological knowledge by collaborating with community fishers
	Loss of traditional knowledge	Increased potential for warm-water/ low-DO fishes	
Increase in warm weather frequency and intensity	Elevated thermal stress	None	None
Shift in altitudinal isotherms post-warming	Potential decrease in fish species richness	Possible new fishing opportunities	Train community fishers for new climate reality
	Formation of novel fish communities		Establish long-term monitoring
	Changes in precipitation		
Seasonal shifts in precipitation patterns	Loss of environmental cues for native fishes	Potential shifting of target species due to change	Develop new ecological knowledge by collaborating with community fishers
	Loss of traditional knowledge		Train community fishers for new climate reality
Increased discharge and flooding	Increased scouring, flooding and loss of habitat	Potential shifting of target species due to change	Promotes migratory fishes
	Elevated riverscape input	Elevated productivity	
Reduced discharge and flooding	Essential habitats reduced	Less urban damage	
	Loss of migratory and rheophilic fishes	Altered fish communities	
	Biological Impacts		
Species introductions	Competition for native fishes		Additional long-term monitoring
	New parasites and diseases		New fishing regulations
	Habitat degradation		

4. CONCLUSIONS & RECOMMENDATION

Although climate change will undoubtedly alter Bhutan's aquatic ecosystems and profoundly impact freshwater fishes, its conservation mandates offer the opportunity to initiate proactive management strategies that can mitigate those impacts. Even though reliable scientific data are needed to direct policy decisions on occurrences and distribution of fishes in Bhutan, they are often limited or unavailable. Thus, we recommend the following 3-tired approach that spans what can be accomplished now with limited data, what must be initiated immediately to eliminate data deficiencies, and what must be anticipated regarding future climate impacts. We first discuss how Species Distribution Models (SDM) can be utilized as a short-term blueprint, despite the issues with incomplete historic and contemporary records. It is important to understand, however, these models represent only probabilities. A failure to acknowledge sets the stage for gross over-interpretations. We employ the Golden Mahseer as a real-time demonstration.

We then address how to immediately improve the predictions of the model through standardized, long-term monitoring programs. Again, Golden Mahseer is a focus, given its recognized status as both flagship and umbrella species. A monitoring program built around Golden Mahseer has a secondary benefit by promoting supplementary data collection for those aquatic species less well known.

And lastly, we underscore those contemporary management decisions that address future climate outcomes, as provoked by climate-induced fluctuations in precipitation and riverine discharge. Mitigation strategies are best developed by envisioning potential outcomes (i.e., future-casting), as interpreted from reliable scientific data. Here, a standardized-long-term monitoring program provides the data source, using as a baseline the life history of Golden Mahseer. This, in turn, will help promote conservation mandates and sustain resource development – both of which are key factors for Bhutan's Gross National Happiness.

Competing interests

Co-authors acknowledge they have no competing interests regarding manuscript content.

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REFERENCES

AFS. (2020). Statement of world aquatic scientific societies on the need to take urgent action against human-caused climate change, based on scientific evidence. Cybium, 44(4):375–388. https://doi.org/10.26028/cybium/2020-444-007.

Bonar SA. (2021). More than 100 aquatic-science societies sound climate alarm. Nature, 589: 352. https://www.nature.com/articles/d41586-021-00107-x.

Bhatt JP and Pandit MK. (2016). Endangered golden mahseer Tor putitora Hamilton: A review of natural history. Review of Fish Biology and Fishe ries, 26: 25–38. https://doi.org/10.1007/s11160-015-9409-7.

Carrizo SF, Jähnig SC, Bremerich V, Freyhof J, Harrison I, He F, Langhans SD, Tockner K, Zarfl C and Darwall W. (2017). Freshwater megafauna: Flagships for freshwater biodiversity under threat. BioScience, 67: 919–927. https://doi.org/10.1093/biosci/bix099.

Corlett RT. (2015). The Anthropocene concept in ecology and conservation. Trends in Ecology and Evolution, 30: 36–41. https://doi.org/10.1016/j.tree.2014.10.007

DeWoody JA, Harder AM, Mathur S and Willoughby JR. (2021). The long-standing significance of genetic diversity in conservation. Molecular Ecology, 30: 4147–4154. https://doi.org/10.1111/mec.16051

Dhu S. (1923). The Angler in India or the Mighty Mahseer. Allahabad (Reprinted 1993 Natraj Publishers, Dehradun).

Douglas ME, Douglas MR, Schuett GW and Porras LW. (2009). Climate change and evolution of the New World pitviper genus Agkistrodon (Viperidae). Journal of Biogeography, 36: 1164–

1180. https://doi.org/10.1111/j.13652699.2008.02075.x

Douglas MR, Mussmann SM, Chafin TK, Anthonysamy WJBA, Davis MA, Mulligan MP, Schooley RL, Louis W and Douglas ME. (2021). Metapopulation connectivity in Vole (Microtus spp.) as a gauge for tall grass prairie restoration in Midwestern North America.

PLoS-ONE Restoration, 16: e0260344. https://doi.org/10.1371/journal.pone.0260344

Everhard M, Pinder AC, Claussen JC and Orr S. (2021). Assessing the societal benefits of mahseer (Tor spp.) fishes to strengthen the basis for their conservation. Aquatic Conservation: Marine and Freshwater Ecosystems, 31: 2979–2986. https://doi.org/10.1002/aqc.3683

FAO (Food and Agriculture Organization of the United Nations). (2018). Impacts of climate change on fisheries and aquaculture. FAO Fisheries and Aquaculture Technical Paper 627, Table, 628pp. http://www.fao.org/3/i9705en/i9705en.pdf.

Fishes of Western Bhutan. Assessment of Species Composition and Distribution of Fish in Bhutan's Three Major River Basins (Amochhu, Punatsangchhu, and Wangchhu) (2017). National Research Centre for Riverine and Lake Fisheries, Department of Livestock, Ministry of Agriculture and Forests, Royal Government of Bhutan. Kuensel Corp. Ltd. Publisher, Thimphu.

Fishes of Eastern Bhutan. Species Composition and Distribution of Fishes in the Aiechhu, Manas, and Nyera-Amachhu River Systems (2020). National Research Centre for Riverine and Lake Fisheries, Department of Livestock, Ministry of Agriculture and Forests, Royal Government of Bhutan. Kuensel Corp. Ltd. Publisher, Thimphu.

Fluet-Chouinard E, Fungen-Smith S and McIntyre PB. (2018). Global hidden harvest of freshwater fish revealed by household surveys. Proceedings of the National Academy of Sciences USA, 115: 7 623–7628. https://doi.org/10.1073/pnas.1721097115.

Fois M, Cuena-Lombraña A, Fenu G and Bacchetta G. (2018). Using species distribution models at local scale to guide the search of poorly known species: Review, methodological issues, and future directions. Ecological Modelling, 385; 124 –132. https://doi.org/10.1016/j.ecolmodel.2018.07.018.

Government of Bhutan. (2008). Constitution of Bhutan Article 5(1). Thimphu, Bhutan.

Greene HW and Losos JB. (1988). Systematics, natural history, and conservation: Field biologists must fight a public image problem. Bioscience, 38 : 458–462. https://doi.org/10.2307/1310949

Grumbine RE and Pandit MK. (2013). Threats from India's Himalaya dams. Science, 339: 36–37. https://doi.org/10.1126/science.1227211.

Gupta N, Sivakumar K, Mathur VB and Chadwick MA. (2014). The 'Tiger of Indian rivers:' Stakeholders' perspectives on the golden mahseer as a flagship fish species. Area, 46: 389–397. https://doi.org/10.1111/area.12124.

Gupta N, Kanagavel A, Dandekar P, Dahanukar N, Sivakumar K, Mathur VB and Raghavan R. (2016). God's fishes: Religion, culture, and freshwater fish conservation in India. Oryx, 50, 244–249. https://doi.org/10.1017/S0030605315000691

Gupta N, Everard M and Namchu CV. (2021). Declining native fish, diminishing livelihood security: The predicament of Indian Himalayan communities. International Journal of River Basin Management, 19: 255–259. https://doi.org/10.1080/15715124.2020.1790578.

He F, Zarfl C, Bremerich V, Henshaw A, Darwall W, Tockner K and Jähnig SC. (2017). Disappearing giants: A review of threats to freshwater megafauna. WIREs Water, 4: e1208. https://doi.org/10.1002/wat2.1208.

Immerzeel W. (2021). Mountain water supply to two billion people could change. Scientific American, 324: 54–61. https://www.scientificamerican.com/article/mountain-water-supply-to-two-billion-people-could-change/.

Intralawan A, Wood D, Frankel R, Constanza R and Kubiszewski I. (2018). Tradeoff analysis between electricity generation and ecosystem services in the Lower Mekong Basin. Ecosystem Services, 30 : 27–35. https://doi.org/10.1016/j.ecoser.2018.01.007.

Jha BR, Rayamajhi A, Dahanukar N, Harrison A and Pinder A. (2018). Tor putitora. The IUCN red list of threatened species 2018: https://doi.org/10.2305/IUCN.UK.20182.RLTS.T126319882A126322226.en. Accessed 13 Mar 2022.

Joshi KD, Das SCS, Pathak RK, Khan A, Sarkar UK and Roy K. (2018). Pattern of reproductive biology of the endangered golden mahseer Tor putitora (Hamilton 1822) with special reference to regional climate change implications on breeding phenology from lesser Himalayan region, India. Journal of Applied Animal Research, 46: 1289–1295. https://doi.org/10.1080/09712119.2018.1497493

Lahoz-Monfort JJ, Chadès I, Davies A, Fegraus E, Game E, Guillera-Arroita G, Harcourt R, Indraswari K, McGowan J, Oliver JL, Refisch J, Rhodes J, Roe P, Rogers A, Ward A, Watson DM, Watson JEM, Wintle BA and Joppa L. (2019). A call for international leadership and coordination to realize the potential of conservation technology. BioScience, 69: 823–832. https://doi.org/10.1093/biosci/biz090

Lovett GM, Burns DA, Driscoll CT, Jenkins JC, Mitchell MJ, Rustad L, Shanley JB, Likens GE and Haeuber R. (2007). Who needs environmental monitoring? Frontiers in Ecology and the Environment, 5: 253-260. https://doi.org/10.1890/1540295(2007)5(253:WNEM)2.0.CO;2.

Lowe BS, Jacobso SK, Anold H, Mbonde AS and Lorenzen K. (2019). The neglected role of religion in fisheries management. Fish and Fisheries, 20: 1024–1033. https://doi.org/10.1111/faf.12388.

McClelland MA, Sass G., Cook TR., Irons KS, Michaels NN, Irons KS and O'Hara TM. (2012). The long-term Illinois River fish population monitoring program. Fisheries, 37: 340–350. https://doi.org/10.1080/03632415.2012.704815.

Millennium Ecosystem Assessment. (2005). Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf.

Mussmann SM, Anthonysamy WJBA, Douglas MR, Davis MA, Simpson SA, Louis W and Douglas ME. (2020). Genetic rescue, the Greater Prairie Chicken, and conservation reliance in the Anthropocene. Royal Society Open Science, 4: 16 0736. https://doi.org/10.1098/rsos.160736

National Research Council. (2002). Abrupt Climate Change: Inevitable Surprises. Washington, DC: The National Academies Press. https://doi.org/10. 17226/10136.

Nautiyal P. (2014). Review of the art and science of Indian mahseer (game fish) from nineteenth to twentieth century: Road to extinction or conservation? Proceedings of the National Academy of Sciences, India (Section B Biological Sciences), 84: 215–236. https://doi.org/10.1007/s40011-013-0233-3.

Ngor PB, McCann KS, Grenouillet G, So N, McMeans BC, Fraser E and Lek S. (2018). Evidence of indiscriminate fishing effects in one of the world's largest inland fisheries. Scientific Reports, 8, 8947. https://doi.org/10.1038/s41598-018-27340-1.

Olden JD, Vitule JRS, Cucherousset J, Kennard MJ. (2020). There's more to fish than just food: Exploring the diverse ways that fish contribute to human society. Fisheries, 45: 453–464. https://doi.org/10.1002/fsh.10443.

Pinder AC, Britton RJ, Harrison AJ, Nautiyal P, Bower SD, Cooke SJ, Lockett S, Everard M, Katwate U, Ranjeet K, Walton S, Danylchuk AJ, Dahanukar N and Raghavan R. (2019). Mahseer (Tor spp.) fishes of the world: Status, challenges, and opportunities for conservation. Reviews in Fish Biology and Fisheries, 29: 417–452. https://doi.org/10.1007/s11160-019-09566-y.

Severinghaus LL and Chi L. (1999). Prayer animal release in Taiwan. Biological Conservation, 89: 301–304. https://doi.org/10.1016/S0006-3207(98)00155-4.

Shiu H and Stokes L. (2008). Buddhist animal release practices: Historic, environmental, public health and economic concerns. Contemporary Buddhism, 9: 181–196. https://buddhiststudies.utoronto.ca/wpcontent/uploads/2021/10/Shiu_Stokes_2008_Animal-Release.pdf

Walters CJ and Martell SJD. (2020). Fisheries Ecology and Management. Princeton University Press, Princeton, NJ.

Woods T, Kaz A and Giam X. (2021). Phenology in freshwaters: A review and recommendations for future research. Ecography, 44: 1–14, 2021. https://doi.org/10.1111/ecog.05564

WWF-Bhutan. (2019). Proceedings, 1st International Mahseer Conference, Paro, Bhutan, 02-09 December 2018. Sponsored by: World Wildlife Fund-Bhutan, Ministry of Agriculture and Forests Royal Government of Bhutan, and Fisheries Conservation Foundation. http://mahseerconference.org/wp-content/uploads/2019/07/Internl-Mahseer-Conference-Proceedings.pdf.

WWF. (2020). Living Planet Report 2020. Bending the curve of biodiversity loss: a deep dive into freshwater. Almond REA, Grooten M and Petersen T (Eds). World Wildlife Fund, Gland, Switzerland. https://wwf.ro/app/uploads/2020/09/LPR-2020-Deep-dive-into-freshwater-pages_EMBARGO-10.09.20.pdf.

Xu J, Grumbine RE, Shrestha A, Eriksson M, Yang X, Wang Y and Wilkes A. (2009). The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. Conservation Biology, 23: 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x