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Review

A review on the threatened species of snow trout *Schizothorax richardsonii* Gray, 1832 (Cypriniformes: Cyprinidae): From the climate change and conservation perspectives

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Abstract

Snow trout (*Schizothorax richardsonii* Gray, 1832) occupies the Himalayan domain from the foothills to 3000 m and inhabits all types of water bodies, like rivers, rivulets, lakes, and reservoirs. It is a rheophilic fish species that can thrive in a wide range of ecological and climatic conditions. Globally snow trout is now a 'threatened' species. Invasion of its natural habitats by exotic trouts, river valley hydropower projects as well as destructive fishing in the Himalayan region have long been attributed to the vulnerability of this species. The intrinsic characteristics of snow trout also make it a weak competitor in the Himalayan rivers. Climate change coupling with above mentioned threats poses a new challenge for Himalayan fish, especially snow trout, as it is confined to the Himalaya. Given these threats, an intense drive for snow trout conservation is urgently required. This contribution is an attempt to find out solution to this fact. In line with the opinions of ecologists and conservationists, we suggest a few measures like setting up free-flowing and undammed rivers as 'fish conservation zones', environmental flow to downstream areas of existing dams, prohibition of stocking of exotic fish species in natural habitats and use of hatcheries for stocking and restocking of snow trout in the rivers for the conservation of the species.

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Introduction

Snow trout (*Schizothorax richardsonii* Gray, 1832) is a demersal and potamodromous fish of the Himalayan waters. It would be incomplete to highlight the aquatic ecology of the Himalaya without addressing the snow trout. Sharma *et al.* (2021a) mentioned it as one of the primitive natives of the Himalayan waters and compared its evolution with Himalayan orogeny. It is a 'threatened' species despite being present in all types of habitats (lower reaches and upper reaches of rivers, streams, ponds and lakes) in the Himalaya. Snow trout belongs to one of the most diverse genera of freshwater fish, *Schizothorax* (Cyprinidae). This genus is distributed in the Himalaya, China, Tibetan Plateau, and central Asia. He and Chen (2006) listed a total of 68 species and subspecies of the genus *Schizothorax,* distributed in the regions described above. Himalayan and sub-Himalayan regions are home to more than 20 species of *Schizothorax* (Bhatt *et al.*, 2012; Mir *et al.*, 2013). Out of these, a total of 10 species including *S. richardsonii* are endemic to the Himalayan waters. Among all Schizothoracine species, *S. richardsonii* is the most primitive and popular representative of Himalayan cold waters and is known to co-evolve with changing patterns of Himalayan geomorphology (Sharma *et al.*, 2019).

Many authors have long been working on various aspects of snow trout (Heckel, 1838; McClelland, 1839; Tilak and Sinha, 1975; Menon, 1971, 1974; Jhingran, 1992; Talwar and Jhingran, 1991; Jayaram, 1999). They also provided significant taxonomic accounts of *S. richardsonii*. However, there has been uncertainty in the taxonomy of this species. As a result, a total of 10 synonyms and 6 misapplied names of *S. richardsonii* have been used by different authors (https://www.fishbase.in/summary/8705).

S. richardsonii was previously identified as the most common and abundant species in the Himalayan waters, but new observations do not coincide with these facts (Mir *et al.*, 2013; Ciji *et al.*, 2021). Over the last 20-25 years, the rapid decline in the abundance and occurrence of *S. richardsoni* has placed it in the 'Vulnerable' category of the red list of IUCN (Vishwanath, 2010). The main human-induced activities that are ascribed to the declining population of fish, especially *Tor putitora* and *S. richardsonii* in the Himalayan rivers, include habitat degradation, destructive fishing, river regulation, and the introduction of alien species (Vishwanath, 2010; Bhatt *et al.*, 2012; Pandit and Grumbine, 2012; Bhatt *et al.*, 2017; Dubey *et al.*, 2019). The current research reports *S. richardsonii* as the most susceptible and vulnerable fish to the climate change in the Himalaya (Sharma *et al.*, 2021a, b). We believe that due to the ubiquity of snow trout in the Himalayan waters, the factors mentioned above have more adverse impacts on snow trout as compared to other threatened fish species. Therefore, snow trout conservation needs to be given top attention in Himalayan water resource initiatives, since it is considered a "flagship species."

The aim of this contribution is to examine the knowledge that is currently available regarding the distribution, ecology, evolution, spawning, habitat sensitivity, intrinsic traits, and anthropogenic pressures that contribute to the vulnerability of *S. richardsonii*. This in-depth analysis also aims to pinpoint the crucial information that will be useful in formulating management strategies, which might ultimately play a significant role in building conservation plans.

Natural history

S. richardsonii is widely distributed in the Himalayan waters of Afghanistan, Pakistan, India, Nepal, and Bhutan (Petr, 1999; Bhatt *et al.*, 2012; Sohail *et al.*, 2014) (Fig.1). Also, it has an extended distribution in the north-east region of India such

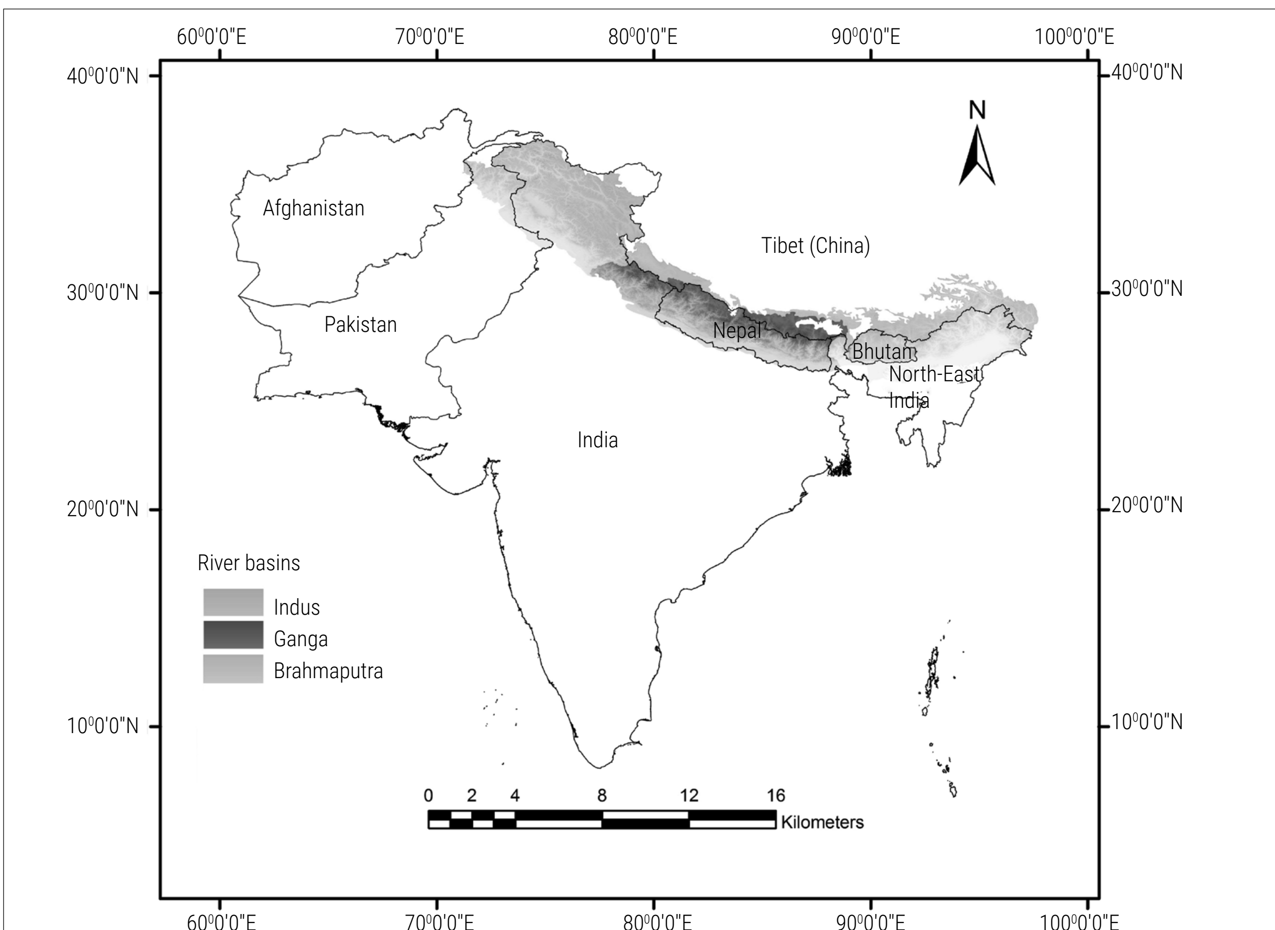

Fig. 1. Distribution of *S. richardsonii* in the different river basins of the Himalayan region. Though *S. richardsonii* is known to be native to the Himalayas, the species has been reported from the rivers of North-eastern states of India *viz*. Manipur and Nagaland.

as Assam, Manipur, Nagaland, and Meghalaya (Sharma, 1989; Selim, 1998; Singh, 1998; Vishwanath, 2002; Goswami *et al.*, 2012; Limatemjen, 2015). The species can thrive in a wide range of temperatures (8-22°C) and is distributed well in the shallow pools, deep pools, rapids, and riffles of rivers and stagnant waters of lakes and reservoirs (Singh *et al.*, 1995; Agarwal *et al.*, 2018).

S. richardsonii can grow up to 60.0 cm in length and 4.0 kg in weight in the Himalayan rivers (Talwar and Jhingran, 1991; Sharma and Mehta, 2010). The average annual increment ranges from 8.85 to 10.22 cm in size. Studies indicated that the growth rate gradually decreased at higher ages (Singh and Sharma, 1995). The species has been described as a herbivore. Food of the species comprises diatoms, green algae, blue-green algae, and detritus. Diatoms are major components of food, contributing more than 50% of the total food (Koundal *et al.*, 2016; Sharma *et al.*, 2018; Naganyal and Saxena, 2019). *S. richardsonii* prefers to spawn in shallow waters with stony substrates. It selects tributaries and banks of large rivers for spawning. As regards the breeding season of *S. richardsonii*, there are different conclusions by authors from different study areas of the Himalaya, but it is widely accepted that the fish reproduces in two phases (Qadri *et al.,* 1983; Agarwal *et al.*, 2004; Mohan, 2005; Sharma and Mehta, 2010; Joshi *et al.*, 2016). Qadri *et al.* (1983) opined that the breeding of *S. richarsonii* considerably relied on environmental conditions like food availability, water temperature and duration of photoperiod. Probably, for this reason, various breeding seasons have been reported in different rivers. The fecundity in *S. richardsonii* ranged from 15,000 to 58,000 ova per kg body weight (Qadri *et al.*, 1983; Joshi *et al.*, 2016). Thapliyal *et al.* (2011) recorded an embryonic hatching period of 116-122 h in *S. richarsonii* under natural conditions. In the upper reaches of the Himalayan rivers, temperatures between 16 and 21°C are considered most favourable for spawning activities in *S. richardsonii,* whereas in lower reaches, it spawns in the range of 19-22°C (Sehgal, 1988).

Major threats

Identifying existing and imminent threats is essential for formulating a biodiversity conservation strategy for a species (Costa *et al.*, 2021). Some threats to snow trout are linked to its natural history, while many are external threats.

Intrinsic characteristics

Certain intrinsic characteristics of snow trout such as herbivorous food habit, relatively slow growth, low fecundity and late sexual maturation, make this species incapable to withstand the threats of invaders. (Wagle *et al.*, 2016). In the middle and upper reaches of the Himalaya, the potential competitors of snow trout are exotic brown trout (*Salmo trutta fario*), rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), and landlocked salmon (*Salmo salar*). These exotic trouts are carnivores and are reported to be voracious feeders of the fry and fingerlings of snow trout (Sharma and Mehta, 2010). These characteristics can be attributed to the competing inability of snow trout for food and space in the upper and middle stretches of Himalayan rivers.

In the lower stretches, it shares its habitat with indigenous *Schizothorax curvifrons*, *S. progastus*, Golden mahseer (*Tor putitora*) and the deep bodied mahseer (*Tor tor*). Asynchronisation of gonadal maturation in males and females and low density of sperm in the milt ($3.77\pm0.78\times10^8$ sperms ml^{-1}) as compared to other associates (*S. curvifrons*-$6.89\pm1.09\times10^8$ sperms ml^{-1}, *S. progastus*-$8.67\pm0.50\times10^8$ sperms ml^{-1}, *T. putitora*-17±0.29×108 sperms ml^{-1}) make it more vulnerable in the lower parts of the Himalaya (Agarwal and Raghuvanshi, 2009; Agarwal and Singh, 2009). These characteristics of the snow trout contribute to the increase in its vulnerability.

River valley projects

The high potential of water resources in the Himalaya attracted developers and governmental agencies to construct maximum hydropower projects in recent decades. Consequently, all major Himalayan rivers have been subjected to the cascade development of hydropower projects. Pandit and Grumbine (2012) reported more than 300 dams/barrages/weirs in the Indian Himalayan region, which are in different stages of development. The situation is not different in other parts of the Himalaya (*e.g.* Nepal and Bhutan). The series of dams led to habitat fragmentation, siltation of river beds, and interruption in the longitudinal and lateral connectivity in the Himalayan rivers (Bhatt *et al.*, 2017). The modification in the flow of rivers leads to various consequences on the snow trout (Elbein, 2020). The dams were not only reported to hamper the upstream and downstream movements of snow trout (Gubhaju, 2002), but also the dammed rivers affected the growth adversely and delayed the maturation in snow trout in the Himalaya (Johal *et al.*, 2021). The physiographic changes due to river regulation, *i.e.* diversion of water from main channel and creation of reservoirs in the rivers, affect the native snow trout adversely by altering its preferred lotic habitats (Agarwal *et al.*, 2018). For instance, an inconsistent longitudinal distribution and drastic decline in the population of snow trout were reported from the regulated rivers (Kali, Gandaki, Trishuli, Kulekhani, Khimti) of Nepal (ADB, 2018).

The flow modification and interruptions in the longitudinal and lateral connectivity destroy the spawning and feeding grounds of snow trout as well as trigger changes in the water quality parameters, especially in the thermal regime (Horne *et al.*, 2004). Such modifications eventually result in a non-conducive environment for snow trout (Agarwal and Singh 2009, Agarwal *et al.*, 2018). Reports indicate that the low flow promoted wanton fishing in the downstream areas of dams. Bhatt *et al.* (2017) found that wanton fishing affected adults, fry, and fingerlings, as well as the recruitment process adversely in a Himalayan rivers. The regular fluctuation in the flow by dam operation leads to instability in the habitat properties, which in turn affect the fish fauna adversely (Bhatt *et al.*, 2017). River regulation also causes indirect and secondary effects on the aquatic environment in addition to the direct effects, which together have a cumulative effect on the fish population (McAllister *et al.*, 2001).

Habitat invasion

Many exotic fish species (trouts and carps) were introduced into Himalayan waters between 1905 and 1969 to promote the recreational, sport and commercial fisheries (Sehgal, 1999). Over time, brown trout and rainbow trout have developed their own self-sustaining populations in many Himalayan rivers, and they now have strong competition with indigenous trout. The exotic trouts have an advantage over the snow trout due to their fast reproductive habits, better body conditions, fighting qualities, short life cycles, flexible adaptive strategies, and early maturation (Dubey *et al.*, 2019). The exotic trouts, especially brown trout is one of the powerful invader, which share a substantial part of their habitat with snow trout in the Himalaya (Johal *et al.*, 2021). The exotic trouts have been reported to diminish the population as well as the habitat of snow trout in the Himalayan rivers (Johal *et al.*, 2021; Sharma *et al.*, 2021a).

As far as commercial fisheries are concerned, the rearing and farming of exotic fish species are preferred over snow trout in the Himalayan region, which can be attributed to the want for high yield. For instance, a report of the ICAR-Directorate of Coldwater Fisheries Research (ICAR-DCFR), Nainital, India stated that a total of 62 fish farms, 29 hatcheries, and more than 700 cultivation units have been developed in Indian Himalayan states for alien species like trouts (http://geographyandyou.com/wp-content/uploads/2016/06/Coldwater-Fisheries-in-Indian-Himalaya-Debajit-Sarma.pdf). Similarly, in Nepal, commercial fisheries prefer exotic fish (Karki, 2016). The ova and fry of exotic species are purposely or accidentally introduced into the natural water bodies, which has a negative impact on snow trout populations (Singh and Lakra, 2011). Snow trout culture in the Himalayan region is still in the experimental stage when compared to alien fish species.

Wanton fishing

In the Himalayan region, many conventional fishing techniques are used in subsistence fisheries; some of them are unscientific and malicious leading to the mass destruction of brooders, fry, and fingerlings. Explosives, electric shocks, ichthyotoxic plants, and chemicals (bleaching powder) are often used in the streams, especially brooks and rivulets (Srivastava *et al.*, 2002; Agarwal and Singh, 2009; Procter *et al.*, 2012). Particularly in the western Himalayan rivers, snow trout makes a substantial contribution to capture fisheries. It contributed up to 80% of the capture fisheries in a few rivers, thus affected largely by wanton fishing practices (Agarwal and Singh, 2009). Generally, the wanton practices, *viz*. use of electric shocks, ichthyotoxic plants, and chemicals are effective in small streams (tributaries) (Agarwal and Singh, 2014), which are habitats of fry, fingerlings and juveniles of snow trout. In addition, activities like sand mining and collection of boulders for building construction, and siltation of river beds due to river regulation were reported to lead to adverse impacts on the snow trout populations, especially in the lower reaches (Agarwal and Singh, 2009).

Impact of climate change

The Himalayan mountains are one of the global geographic regions experiencing unprecedented impacts of climate change (Shrestha, 2012). This fact is evidenced by the increase in temperature of 0.2^0C to 0.47^0C in the last few decades in the waters of Ganga basin (Das *et al.*, 2016). The climate change impacts in the Himalaya have their implications on the various aspects of the sustainability including water resources and biodiversity (Negi *et al.*, 2017). Large glacier-fed rivers, *viz*. the Indus, Ganga and Brahmaputra, originate from the Himalayan mountains and are significant 'hotspots' of biodiversity including ichthyofauna. The rivers originating from the Himalaya are also largely affected by climate change. Climate change was also reported to have an impact on the ichthyofaunal richness of Himalayan rivers by causing lower flow, inconsistent seasonal flow, and severe monsoon in addition to an increase in the average temperature (Gautam *et al.*, 2014). According to Gillette *et al.* (2022), the fish fauna of the Kaligandaki-Narayani river system in Nepal has been severely impacted by climate change. The adverse impacts are projected to intensify from river regulation coupled with climate change (Gillette *et al.*, 2022).

A temperature range between 12 and 18^0C is considered most conducive for the metabolic activities of *S. richardsonii*, but the activities, *viz*. maturation, breeding, essential for the life cycle strategies require specific temperatures and other climatic conditions (Ayyappan and Mahanta, 2009). Thus, a change by 1^0C may have unpredictable effects on the populations of snow trout (Gopal, 2009). Not only does the rising river water temperature increase the vulnerability of *S. richardsonii,* but the existence of Himalayan glaciers is directly linked to the survival of this species. Based on the current rate of retreat (15 m per year), major Himalayan glaciers are predicted to recede significantly by 2035 (Dwivedi, 2009).

S. richardsonii is a widely distributed species among the cold water fishes occupying the entire temperate zone of the Himalaya. The adverse effects of climate change are being seen as a new threat to *S. richardsonii*, especially in the middle and upper reaches. Based on the model developed by Sharma *et al.* (2021b), it was estimated that *S. richardsonii* would lose a significant part of its habitat, ranging from 7.41 to 16.29% and from 9.46 to 26.56% by 2050 and 2070, respectively, due to the consequences of climate change. The major habitat loss was predicted below 1000 m, where under extreme scenarios the species would lose 20 and 28% of the habitat by the years 2050 and 2070, respectively. They also predicted that *S. richardsonii* would adapt to climate change by shifting its distribution range upward. This result was also supported by Retnaningtyas (2021), who also identified high elevation tributaries as potential refugia for *S. richardsonii*. Notably, as models predict, the expansion of the distribution will depend on the geophysical appropriateness in the high elevation regions of the Himalaya. The slopes, river gradients, topography, current velocity, and channel morphology are a few geophysical characteristics of the high altitudes of the Himalaya, which play an important role in facilitating the environmental corridors for a species (Robillard *et al.*, 2015).

Conservation

Given that *S. richarsonii* has historically been abundant in the Himalayan rivers and has a wide distribution, environmentalists and ecologists seem to overlook the need to conserve the species. As a result, the policymakers could not take this situation into account. To promote fisheries, on the one hand, exotic fish were introduced into the natural habitats of *S. richardsonii*, and on the other hand, Himalayan rivers were subjected to the cascading development of hydroelectric projects. Reduced habitat, loss of breeding and feeding grounds, disruption of longitudinal and lateral connectivity as well as damaging fishing, are some of the primary and secondary effects of such activities (Agarwal and Singh, 2009; Bhatt *et al.*, 2017).

The conservation policies in the Himalayan states do not seem to favour the native fish fauna as compared to the mammals and birds. The Government of India has a legal framework to protect the plant and animal species under the Wildlife (Protection) Act (1972). However, none of the freshwater fish species is scheduled under this act. Freshwater fish may not be included by this law because they are regarded a primary source of food in India and traditional fishing techniques lack the mechanism for selective fishing. In the Himalaya, no river has been designated as a protected area with the goal of protecting fish species. However, the conservation of fish fauna of rivers flowing through protected areas for other species is coincidental (Sarkar *et al.,* 2012). Keeping in view all these circumstances, factors, and constraints, the conservation measures for *S. richardsonii*, which may be applied in the Himalayan region are outlined below.

Setting up of a ‘fish conservation zone’ (FCZ)

Setting up of ‘fish conservation zone’ (FCZ) is the most important measure for the protection of snow trout in the Himalaya (Sarka *et al.*, 2012; Gupta *et al.*, 2014). Rivers, rivulets, or a part of the river that is free-flowing and has not been regulated so far, can be declared as FCZ. Gupta *et al.* (2014) gave a detailed account of such types of safe zones. They emphasised the need for a representative safe zone in each river system, an integrated management plan, and protection of the socio-economic interests of stakeholders. It is important to note that riverine systems have a variety of stakeholders, and that human livelihood and socio-economic interests are closely tied to riverine ecosystems (Gupta *et al.*, 2014). Following a sustainable approach, these FCZs must be designed in such a manner that all types of fishing must be banned in one part (the no-go area), and a few activities, like game fishing and sustenance fishing, should be allowed in other parts of FCZ so that the economic interests of the stakeholders are not affected.

Ecologically fragile zones (EFZs)

There have been reports on the negative effects on the health of rivers and riverine biodiversity as a result of the introduction of exotic species into the various river systems in India (Singh and Lakra, 2011; Sandilyan *et al.*, 2018). There are still many such rivers in the Himalayan region where alien fish have not yet been introduced. These rivers can be declared as "ecologically fragile zones" (EFZs). A strict ban on the introduction of alien fish species is suggested in EFZs (ADB, 2018). In order to prevent the unintentional introduction of alien fish into the natural water bodies, regular monitoring of hatcheries and fish farms rearing alien species are essential. In India, ‘The National Committee on the Introduction of Exotic Aquatic Species’ is a nodal agency for screening the introduction of exotic species. Also, the Ministry of Agriculture, Government of India has detailed guidelines on the quarantine process and post-quarantine follow-up (Tripathi, 2015; Sandilyan *et al.*, 2018). These agencies need to be strengthened and activated. There is a need to run a comprehensive awareness program and strict enforcement of the guidelines of these agencies. In order to assess the possibilities of biological invasion in the Himalayan aquatic ecosystems and to develop the framework to control and eradicate the exotic species in particular ecosystems, there is a need to run pilot research projects and regular monitoring in the rivers.

Hatcheries and fish farms

One method of fish conservation is to raise fish in hatcheries and fish farms and then restock them in the wild (Brown and Day, 2002). Alien fish have long been reared in hatcheries and fish farms in India, but their main objective has been to promote fish farming and game fishing in India. On the other hand, hatcheries and fish farms for indigenous fish have been largely ignored in the Himalayan region, as was highlighted in this contribution. Stock enhancement of native fish like *S. richardsonii* in the wild through hatcheries and fish farms is an essential prerequisite for the protection of native fish due to the negative effects of exotic fish species on indigenous fish (Rowland, 2013).

Environmental flow

Flow modifications in the downstream and upstream stretches of regulated rivers largely affect the native fish fauna (Jiang *et al.*, 2010). *S. richardsonii* has been facing similar challenges in the Himalayan rivers. If appropriate environmental flows are released to maintain the integrity of the ecosystem in the downstream region, this issue can be resolved to a great extent (Jiang *et al.*, 2010). In recent years, the importance of environmental flows in India has been increasingly recognised and its role in river valley projects has been prioritised (O'Keeffe *et al.*, 2012; Jain and Kumar, 2014). Also, there is a growing awareness of environmental flows among people. Now the environmental flow is an important part of management plans of the river valley projects (Bhatt *et al.*, 2017), however, how much should it be, how should it be determined, and how should it be monitored? There is still debate on these questions among the different stakeholders (Governmental agencies like Central Water Commission, Ministry of Environment, Forests and Climate Change, State Governments, Ecologists and Hydrologists). Initially nodal agencies were reluctant to estimate environmental flow, and there was no provision for environmental flow in dams that were constructed or commissioned before 2000. Later, the environmental flow was designed and recommended for different river basins and for a few commissioned projects (Jain and Kumar, 2014), however, there is still no consensus on this. It is important to mention that environmental flow is criticised for its inaccurate design methodology and weak implementation. We suggest that environmental flows should be mandatory for all types of projects. Also, it should be redesigned for dams/barrages that have been commissioned before 2000 in the Himalaya. *S. richardsonii* and *T. putitora* are key target species regarding the determination of environmental flow in the Himalayan rivers. Of these, *S. richardsonii* is found from the foothills to headwater zones (Tare *et al.*, 2017). Tare *et al.* (2017) computed a minimum depth of 50 cm in lean season and 80 cm in monsoon season in Himalayan rivers for these species and therefore, environmental flows would correspond to these depths.

Gene/embryonic bank and crypreservation

The measures like establishment of gene and embryonic bank as well as crypreservation of snow trout milt are suggested in order to reduce the problem of asynchronisation in snow trout (Agarwal and Singh, 2009). The decline of snow trout germ plasm resources can be prevented by various *in situ* and *ex situ* conservation measures.

Identification of refugia

A new approach to the conservation of cold-water fishes, including *S. richardsonii*, is urgently needed in the light of climate change. Sharma *et al.* (2021 a,b) have already assessed the impacts of climate change on this species. The important measures suggested by them are prioritisation of habitats towards mid-elevation zones, identification of rivers/streams in the upper reaches of the Himalaya that can act as refugia of snow trout, to enhance the energy efficiency using green technologies, and to discourage the river regulation.

Community participation

Local people are one of the stakeholders in the riverine ecosystem. Therefore, community participation is warranted for the successful implementation of conservation plans, especially in the case of setting up of fish conservation zones (Gupta *et al.*, 2014; Bhatt and Pandit, 2019).

Conclusion

Once widely distributed and abundant in the Himalayan rivers, *S. richardsonii* is experiencing a rapid population decline in recent years. Rampant anthropogenic activities in the Himalayan rivers including incessant hydropower development, infrastructure development, overfishing, exotic species introduction and habitat degradation are among the primary factors responsible for the decline in numbers of the snow trout. We propose that for the effective conservation of *S. richardsonii*, there is an urgent need to frame conservation policies that involve multiple stakeholders *viz.* government, research agencies, local people and non-governmental organisations. Together, the policy should focus on creation of snow trout conservation zones, establishment of hatcheries and fish farms, maintenance of minimum environmental flow in the rivers, dissuasion of the practice of introducing exotic species in rivers and the establishment of natural refugia for *in situ* conservation at mid-elevations in the Himalaya.

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