

Impact of Climate Change on Fish Breeding in the Himalayas: A Review

Neha Bains¹ & H.S. Banyal^{2*}

¹Research Scholar, Department of Bio-Sciences, Himachal Pradesh University, Shimla, 171005, India

^{2*} Associate Professor, Department of Bio-Sciences, Himachal Pradesh University, Shimla, 171005,

India

ABSTRACT

Climate change is increasingly affecting the environmental conditions that regulate reproduction of freshwater fishes in the Himalayan region. Himalayan rivers and streams support cold-water and migratory fishes such as golden mahseer (*Tor putitora*), snow trout (*Schizothorax richardsonii*) and other schizothoracines, many of which depend on seasonal combinations of water temperature, discharge, precipitation, dissolved oxygen, substrate and habitat connectivity for successful spawning. Climate warming can modify these cues directly through higher water temperature and indirectly through earlier snowmelt, altered glacier and precipitation regimes, floods, droughts and changes in river flow. Fish reproduction may consequently be affected through altered gonadal maturation, fecundity, gamete quality, spawning migration, breeding season and egg and larval survival. Evidence from the lesser Himalaya indicates historical changes in golden mahseer breeding phenology, while modelling and reviews indicate increasing climate-related habitat pressure on snow trout. These effects are compounded by hydropower development, habitat fragmentation, sedimentation, pollution, destructive fishing and loss of riparian vegetation. This review synthesizes current evidence on the mechanisms through which climate change may affect fish breeding in the Himalayas and discusses research priorities and climate-resilient conservation measures.

Keywords: Climate change; fish breeding; spawning phenology; Himalaya; golden mahseer; snow trout; reproductive biology; river temperature; hydrology; conservation.

1. Introduction

The Himalayan region contains an extensive network of rivers and streams that supports distinctive freshwater fish communities and provides important ecological and socioeconomic benefits. Cold-water fishes are strongly influenced by seasonal changes in temperature and river discharge, and many species use particular tributaries, riffles and gravel beds as spawning habitats. Reproduction in such fishes is therefore synchronized with environmental conditions that provide suitable cues for migration, maturation, spawning and early development (Myers et al., 2017). Climate change has become an additional major pressure on Himalayan freshwater ecosystems. The Intergovernmental Panel on Climate Change (IPCC) has reported widespread climate-related changes in the distribution, phenology and physiology of freshwater species, including changes associated with warming and increasing climatic extremes (Parmesan et al., 2022). In the Hindu Kush–Himalaya, changing temperature and precipitation regimes are also affecting glacier and snow hydrology and consequently river discharge (Miller et al., 2012). Because fish breeding is closely coupled with temperature and flow, alterations in these variables can influence both the timing and success of reproduction. The problem is particularly important for cold-water Himalayan fishes because many species occupy relatively narrow thermal and elevational ranges. Golden mahseer (*Tor putitora*) is a migratory cyprinid of Himalayan rivers whose reproduction is associated with suitable tributary temperature, hydrology and spawning substrate (Joshi et al., 2018; Rana & Tarafdar, 2022). Snow trout (*Schizothorax richardsonii*), another characteristic Himalayan rheophilic fish, is also vulnerable to climate change because warming interacts with hydropower development, habitat alteration, invasive species and fishing pressure (Bhatt & Manish, 2023). Understanding these interactions is essential for developing effective conservation strategies.

2. Environmental Factors Regulating Fish Breeding

Fish breeding in Himalayan rivers is regulated by several interacting environmental cues. Water temperature is a fundamental regulator of endocrine activity, gametogenesis, gonadal maturation, ovulation and spawning. A comprehensive review of teleost reproduction showed that temperatures above species-specific optima can alter the brain–pituitary–gonad axis, change gamete quality and advance, delay or inhibit spawning (Alix et al., 2020). The response is species-specific and depends on the magnitude, timing and duration of thermal exposure. River discharge is another important reproductive cue. Seasonal increases in discharge can facilitate upstream movement, connect main channels with tributaries and provide hydraulic conditions suitable for spawning. Conversely, exceptionally high flows may disturb spawning substrates and wash away eggs, whereas prolonged low flows may reduce access to spawning grounds and increase thermal stress. Changes in Himalayan snow and glacier melt can alter the seasonal pattern of runoff, potentially affecting these cues (Miller et al., 2012). Photoperiod is relatively stable from year to year and can provide a seasonal biological signal, whereas temperature and discharge are more directly influenced by climate variability. When these cues become decoupled, reproductive timing may become mismatched with habitat and food availability. Such phenological mismatches can reduce recruitment even when adult fish remain physiologically capable of spawning (Alix et al., 2020; Parmesan et al., 2022).

3. Impact of Rising Water Temperature on Reproductive Physiology

As ectothermic animals, fishes are particularly sensitive to changes in ambient water temperature. Temperature influences metabolic rate, endocrine signalling and the rate of gonadal development. Under temperatures above the optimum, abnormal gametogenesis, reduced sperm and oocyte quality, altered fecundity and changes in ovulation or spawning can occur (Alix et al., 2020). Therefore, climate warming may affect reproduction before obvious population-level declines become visible. For Himalayan cold-water fishes, increasing temperature can also reduce the amount of suitable habitat. Sharma et al. (2021) used ensemble modelling to examine climate-related distributional changes in snow trout and reported a high-altitude squeeze, with substantial loss of suitable habitat at the warmer lower-elevation margin and comparatively limited opportunities for compensatory expansion at higher elevations. Bhatt and Manish (2023) similarly emphasized climate change as an increasing threat to snow trout in combination with other anthropogenic pressures. The reproductive consequences of warming are not necessarily linear. Moderate warming within the physiological tolerance of a species may accelerate maturation and advance spawning, whereas temperatures above the optimum may reduce reproductive performance. Consequently, breeding responses must be evaluated against species-specific thermal thresholds rather than simply using annual mean temperature (Alix et al., 2020).

4. Changes in Breeding Phenology

Breeding phenology describes the seasonal timing and duration of reproductive events. Climate-driven changes in temperature, precipitation and snowmelt can shift the timing of gonadal maturation, migration and spawning. The IPCC has identified substantial evidence that climate change has altered the phenology and physiology of freshwater organisms (Parmesan et al., 2022). One of the clearest Himalayan examples is golden mahseer. Joshi et al. (2018) studied *T. putitora* in the Kosi River of Uttarakhand and compared contemporary reproductive observations with historical records. The observed breeding season extended from July to September, while gonadosomatic indices increased from late June or early July and peaked in August. Their historical analysis suggested changes in breeding phenology over the historical period, indicating that the species may be responding or adapting to changing climatic conditions (Joshi et al., 2018). Changes in breeding timing can have important consequences for recruitment. If spawning occurs before suitable nursery conditions develop, newly hatched larvae may encounter inadequate food or unsuitable flow. Conversely, delayed spawning may expose eggs and juveniles to unfavourable temperatures or late-season flow conditions. Thus, even a relatively small shift in spawning date can influence year-class strength (Alix et al., 2020; Parmesan et al., 2022).

5. Altered Snowmelt, Glacier Dynamics and River Flow

Himalayan rivers receive water from rainfall, snowmelt and, in many basins, glacier melt. Climate change is modifying these components and their seasonal contribution. Miller et al. (2012) reviewed evidence that rising temperature and changing precipitation influence glacier hydrology and river discharge across the Indus, Ganges and Brahmaputra basins. Such hydrological changes have direct ecological relevance because river discharge determines connectivity, habitat availability, water depth, velocity and sediment transport. For breeding fishes, the timing of flow can be as important as the total annual discharge. Migratory adults require access to tributaries and suitable spawning reaches, while eggs and larvae require stable hydraulic conditions. Changes in the timing of high-flow events can therefore create a mismatch between adult migration and the availability of appropriate spawning habitat. Extreme floods are another concern. High-energy flows can scour gravel beds, mobilize sediment and physically disturb eggs and larvae. At the opposite extreme, drought and low-flow conditions can isolate habitats, decrease wetted area and increase water temperature. Climate variability may therefore affect

reproduction through both increased flood disturbance and increased low-flow stress (Miller et al., 2012; Parmesan et al., 2022).

6. Effects on Spawning Habitat, Eggs and Larvae

Successful reproduction depends not only on mature adults but also on the availability and quality of spawning and nursery habitats. Himalayan rheophilic fishes commonly use shallow, flowing habitats with coarse substrate. Eggs deposited among gravel and cobble require adequate water exchange and oxygen supply. Increased sedimentation can fill interstitial spaces and reduce oxygen exchange, thereby lowering egg survival. Climate change can intensify sediment disturbance through changes in intense rainfall and catchment erosion. Extreme flow events can remove eggs or alter the structure of spawning beds, while low flows can reduce the connectivity of tributaries and nursery areas. In addition, warmer water can reduce dissolved oxygen availability while increasing metabolic demand, potentially increasing stress during embryonic and larval development (Alix et al., 2020; Parmesan et al., 2022). Food availability may also be affected. Changes in temperature and hydrology can alter planktonic and benthic communities, which may shift the availability of food for larvae. If spawning advances more rapidly than the seasonal development of prey communities, a trophic mismatch can occur. Consequently, climate impacts on breeding should be evaluated across the entire reproductive cycle rather than only through adult gonadal measurements (Alix et al., 2020).

7. Species-Specific Vulnerability of Himalayan Fishes

Golden mahseer and snow trout illustrate different but overlapping pathways of climate vulnerability. Golden mahseer undertakes movements between river channels and suitable tributaries and requires appropriate temperature, flow and substrate for spawning (Joshi et al., 2018; Rana & Tarafdar, 2022). Rana and Tarafdar (2022) emphasized that climate and land-use changes influence temperature, precipitation, snow cover and hydrology in Himalayan rivers and can consequently affect the reproductive ecology of golden mahseer. Snow trout is closely associated with cold, flowing Himalayan waters. Bhatt and Manish (2023) described climate change as an emerging threat that acts together with river-valley hydropower projects, habitat invasion by exotic trout and destructive fishing. Distribution modelling by Sharma et al. (2021) further indicated that climatic and hydrogeomorphic variables strongly influence snow-trout habitat suitability and that warming may produce a high-altitude squeeze. These examples demonstrate that there is no single climate response for all Himalayan fishes. Species differ in thermal tolerance, reproductive strategy, migration, elevation and habitat requirements. Even populations of the same species may respond differently depending on local hydrology and habitat condition. Climate-resilience assessments should therefore be species- and basin-specific (Myers et al., 2017).

8. Interaction with Hydropower, Habitat Fragmentation and Other Stressors

Climate change rarely acts independently. Himalayan fish populations are simultaneously exposed to hydropower development, river regulation, habitat fragmentation, pollution, catchment disturbance, sedimentation and fishing pressure (Bhatt & Manish, 2023; Rana & Tarafdar, 2022). These pressures can reduce the capacity of populations to cope with climatic variability. River fragmentation is particularly important for migratory fishes. If warming causes fish to move toward cooler upstream habitats, dams and other barriers may prevent access to thermal refugia and spawning tributaries. Similarly, alteration of natural flow regimes can weaken or remove seasonal spawning cues. The reproductive habitat requirements of golden mahseer make the conservation of suitable tributaries especially important (Joshi et al., 2018; Rana & Tarafdar, 2022). The interaction between warming and habitat degradation can also increase local thermal stress. Loss of riparian vegetation reduces shade and can raise water temperature, while catchment degradation can increase sediment input. Therefore, reducing non-climatic stressors is one of the most practical ways of increasing the resilience of Himalayan fish populations to climate change (Bhatt & Manish, 2023; Parmesan et al., 2022).

9. Climate-Resilient Conservation and Management

Conservation of Himalayan fish breeding habitats should begin with identification and protection of critical spawning tributaries and nursery areas. Environmental-flow management should preserve ecologically important seasonal discharge and maintain connectivity between main channels and tributaries. Such measures are particularly relevant where hydropower development has modified natural flow regimes (Bhatt & Manish, 2023; Rana & Tarafdar, 2022).

Riparian restoration can provide shade, stabilize banks and reduce sediment delivery. Regulation of sand and gravel extraction is also important because spawning fishes depend on appropriate coarse substrates. Where barriers interrupt migration, scientifically designed fish-passage measures and, where feasible, restoration of longitudinal connectivity should be considered. Long-term monitoring should integrate environmental and biological variables. Temperature, discharge, dissolved oxygen, turbidity and substrate should be recorded together with gonadosomatic index, maturity stages, fecundity, spawning date, migration timing, egg survival and juvenile recruitment. These data can distinguish climate-related

reproductive responses from the effects of local habitat degradation. Captive breeding may provide a supplementary conservation tool for severely depleted populations, but it should not replace protection of natural spawning habitats. Maintaining wild populations preserves local adaptations and ecological processes that are difficult to reproduce in hatchery conditions (Myers et al., 2017).

10. Research Gaps and Future Directions

Although climate change is increasingly recognized as a threat to Himalayan freshwater fishes, direct long-term datasets linking climate variables with reproductive success remain limited. Myers et al. (2017) highlighted broad geographic and taxonomic gaps in the global evidence base for climate impacts on inland fishes. These gaps are especially relevant in the Himalayas, where many fish populations are poorly monitored over long periods. Future research should establish long-term records of temperature and discharge at known spawning sites and relate these data to gonadal development, migration, spawning dates, egg survival and juvenile recruitment. Telemetry, environmental DNA and habitat modelling could improve identification of spawning migrations and climate refugia. Experimental studies are needed to establish species-specific thermal thresholds for gametogenesis, fertilization and embryonic development. Research should also consider compound events, such as warming combined with low flow, extreme rainfall following prolonged heat, or altered snowmelt combined with hydropower regulation. Because Himalayan fishes experience multiple simultaneous stressors, climate-impact assessments based on a single environmental variable are likely to underestimate reproductive risk (Myers et al., 2017; Parmesan et al., 2022).

11. Conclusion

Climate change is emerging as an important threat to fish breeding in the Himalayas because reproduction depends on the synchronization of temperature, river discharge, habitat structure and connectivity. Warming can directly alter gonadal development, gamete quality and spawning, while changes in snowmelt, glacier hydrology and rainfall can modify migration cues and spawning habitats (Alix et al., 2020; Miller et al., 2012; Parmesan et al., 2022). Extreme floods, drought, sedimentation and habitat fragmentation can further reduce egg and larval survival. Evidence from golden mahseer demonstrates historical changes in breeding phenology, while studies of snow trout indicate increasing climate-related pressure on suitable habitat (Bhatt & Manish, 2023; Joshi et al., 2018; Sharma et al., 2021). However, responses are species- and location-specific, and some populations may possess adaptive capacity. Climate-resilient management should therefore combine protection of spawning tributaries, maintenance of environmental flows, restoration of riparian habitats, improved river connectivity and long-term reproductive monitoring. Integrating fish reproductive biology with climate and hydrological science will be essential for conserving Himalayan freshwater biodiversity and sustaining fisheries in a changing climate.

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