ECOLOGY AND MIGRATORY PATTERNS OF GOLDEN MAHSEER, *TOR PUTITORA* (Hamilton, 1822), IN WESTERN HIMALAYA USING RADIO TELEMETRY TECHNIQUES

Thesis submitted for the award of the degree of

Doctor of Philosophy

in

WILDLIFE SCIENCE

by

BHAWNA DHAWAN

to

Saurashtra University
Rajkot- 360005 (Gujarat)

Under the supervision of

Dr. J.A. Johnson, Supervisor

Dr. K. Sivakumar, Co-Supervisor

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

December 2023

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DECLARATION

I, hereby, declare that the work conducted under this thesis titled "**Ecology and migratory patterns of golden mahseer, *Tor putitora* (Hamilton, 1822), in western Himalaya using radio telemetry techniques**" is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Doctor of Philosophy in Wildlife Science** to the **Saurashtra University**, **Rajkot (Gujarat)**. This research work has been carried out under the guidance and supervision of Dr. J. A. Johnson Scientist-F of Wildlife Institute of India, Dehradun. The work has not formed the basis for the award of any other degree, diploma or any other qualification. I also declare that the thesis embodies my own work, analysis, observation, understanding and the particulars given in it are true to the best of my knowledge.

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CERTIFICATE

This is to certify that the thesis by **Miss Bhawna Dhawan** titled, **"Ecology and migratory patterns of golden mahseer, *Tor putitora* (Hamilton, 1822), in Western Himalaya using radio telemetry techniques,"** submitted for the degree of **Doctor of Philosophy in Wildlife Science at Saurashtra University, Rajkot, Gujarat**, embodies original research work carried under our guidance and supervision.

Miss Bhawna Dhawan has researched on this thesis for more than six terms under our supervision and guidance. The work presented in this thesis has not been submitted for any other degree. It meets all of the specifications stated forth in the ordinances of Saurashtra University in Rajkot, Gujarat, and the Wildlife Institute of India.

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CERTIFICATE FOR PRE-Ph.D. PRESENTATION

This is to certify that Miss Bhawna Dhawan has made Pre-Ph.D. presentation as per UGC guideline "University Grant Commission (Minimum Standard and Procedure for award of Ph.D. Degree) Regulation-2016" and Saurashtra University Ordinance for Ph.D. programme (O.Ph.D. 8.3), on her research work titled "**Ecology and migratory patterns of golden mahseer, *Tor putitora* (Hamilton, 1822), in western Himalaya using radio telemetry techniques" at Wildlife Institute of India, Dehradun, Research Centre of Saurashtra University, Rajkot on 14th July 2023** before all faculty members and students of the Department for getting feedback and comments.

I certify that the research work was appreciated by all who were present, and the comments made by the faculty and researchers have been appropriately included in the thesis.

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CERTIFICATE OF PLAGIARISM CHECK

It is certified that the PhD thesis titled "**Ecology and migratory patterns of golden mahseer, *Tor putitora* (Hamilton, 1822), in western Himalaya using radio telemetry techniques**" submitted by Miss Bhawna Dhawan has been examined by us for plagiarism check as per UGC (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations. The following inferences are drawn from this check:

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COURSE WORK COMPLETION CERTIFICATE

This is to certify that Ms. Bhawana Dhawan has successfully completed course work on research methodology, quantitative methods, computer application, research ethics and review of published research work in the field of Wildlife Science for a period of one semester of 10 credits with 100% attendance. Considering the presentation by the scholar and combined assessment by the Research Advisory Committee and the Department she obtains Grade "A" i.e., 75%. It is hereby declared that she is eligible to continue in programme of Ph.D. in Wildlife Science.

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CONTENTS

Dedicated to the two most beautiful families and to the love of my life-

Gourav

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Finally, I am thankful to the Almighty GOD because of the blessings; I have been able to submit my work successfully. Thank you for always giving me the best and thoughtful life.

Bhawna Dhawan

List of publications:

1. Dhawan, B., Sivakumar, K. & Johnson, J. A. (2023) Habitat suitability of golden mahseer young ones (*Tor putitora*, Hamilton 1822) in Himalayan waters, India. ***River Research and Applications***, http://doi.org/10.1002/rra.4192.
2. Dhawan, B., Sivakumar, K., Areendran, G. & Johnson, J. A. (2023) Preliminary study on the movement behavior and home range of golden mahseer (*Tor putitora*, Hamilton 1822) inhabiting Himalayan waters, India. ***Current Science***, (Accepted-in production).

List of short articles:

1. Dhawan, B. Endangered Water Tigers of the Himalayas; story of Golden Mahseer, *Science Reporter*, October 2023.

List of conferences:

International conferences

1. B. Dhawan, J. A. Johnson and K. Sivakumar **(2018),** Distribution status of golden mahseer *Tor putitora* (Hamilton, 1822) in Uttarakhand, India and way forward. **Abstract: International Mahseer Conference, Paro, Bhutan,** 2-8 December,2018.
2. B. Dhawan, J. A. Johnson and K. Sivakumar **(2019)** topic 'flow for development or conservation…? Indeed, time to concern about 'tiger' of freshwater ecosystems' **Abstract: International Conservation Conference** held at Aligarh, U.P., India during 21st to 23rd October 2019.

3. B. Dhawan, J. A. Johnson and K. Sivakumar **(2019**), Status of golden mahseer (*Tor putitora*) in river Kosi Uttarakhand in **International Conference in Ecology and Environment held in Pune from** 18-20 February, 2019.
4. B. Dhawan, J. A. Johnson and K. Sivakumar **(2020)**, Habitat use of young golden mahseer in rivers of Uttarakhand, India **Abstract: Second International Mahseer Conference, Chiang Mai, Thailand**, 11-15th February, 2020.

Institutional conferences

1. B. Dhawan, J. A. Johnson and K. Sivakumar **(2018),** Status of golden mahseer (*Tor putitora*) in river Kosi Uttarakhand. **Abstract: Annual Research Seminar, Wildlife Institute of India, 10-20 September**, 2018.
2. B. Dhawan J. A. Johnson and K. Sivakumar **(2019)**, Habitat use of young golden mahseer in rivers of Uttarakhand, India **abstract: Annual Research Seminar, Wildlife Institute of India**, **18-27, August**, 2019.

THESIS STRUCTURE

This doctoral thesis is the work done on one of the most important and iconic freshwater fish species, golden mahseer *Tor putitora* (Hamilton, 1822), that provides crucial insights into the assemblage structure, food and space resource of the species, habitat ecology, life-history characteristics and movement ecology of the species. This study is the first detailed study of any freshwater fish species in which movement patterns in the streams have been studied using radio telemetry techniques in the Himalayan streams.

In the Introduction, I have detailed the general Introduction of the work undertaken here, the study species, the research hypothesis, and the objectives of the thesis. I have also provided details on record from previous studies on the species based on which the present work was planned.

Study area: give the details of the research area regarding geographic structure, climatic conditions, and river systems of Himalayan rivers.

Chapter I gives an overview of the fish assemblage structure in the studied river sites. The seasonal pattern of the fish assemblage structure has been discussed. The study results about the water quality parameters and their relation with the fish species. A detailed description of the golden mahseer distribution and assemblage patterns has been provided in the chapter.

Chapter II of the present work provides information on the food and space partitioning of the studied species and other co-existing species in their fundamental niche. Gut analysis was performed to understand the food-feeding habits of the fish species. Also, the study provided details on the habitat suitability for these fish species.

Chapter III details the understanding of the spatial ecology of golden mahseer. The thesis uses manual tracking as radio telemetry to describe the movement, habitat preference, and home range of the fish species. Habitat preference was analyzed using kernel density Home Range (KDHR). Variation concerning water quality and habitat preference by the golden mahseer has been detailed in the present chapter.

Chapter IV of the thesis explains the suitability of breeding and nursery grounds for the golden mahseers' young ones (fingerlings and juveniles). The study provides insight into the habitat suitability of young golden mahseers concerning different seasons and body sizes. Habitat suitability was evaluated by generating Habitat Suitability Curves (HSCs). Poisson generalized linear modeling (GLM) was used to analyze the subset of environmental characteristics.

In conclusion, the main findings of the thesis that add to the understanding of the habitat ecology of the golden mahseer in the three significant tributaries of the Ramganga basin that flow through the Western Himalayas are discussed. Also, the study contributes to the conservation and management measures of this endangered fish species in the Himalayan rivers. Also, it provides the baseline for future long-term studies in India's distributional range.

So far, this thesis has resulted in two peer-reviewed research publications and six conference presentations (two international, two national, and two institutional seminars).

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Golden mahseer, *Tor putitora* (Hamilton, 1822)

Introduction

General Introduction

The word '**Mahseer**' is often used for the large-scaled carp belonging to the genera *Tor, Neolissochilus*, and *Naziritor* (Pinder et al., 2019). *'Tor'* mahseer is widely distributed in India, Bhutan, Nepal, Pakistan, Bangladesh, and Sri Lanka (Bhatt and Pandit, 2016), and so far, 16 valid species have occurred in these regions (Eschmeyer et al., 2004; Pinder et al., 2019). Since the eighteen century, Indian mahseers have been a popular sport fish attracting anglers and naturalists worldwide (Langer et al., 2013). Mahseers are not only popular as a sport and food fish; they are also part of our national heritage (Oliver et al., 2007). In comparison to other mahseer species in the genus, the Golden Mahseer (*Tor putitora*) (Hamilton, 1822) is the most well-recorded and popular species among naturalists and conservationists (Nautiyal, 1984; Nautiyal and Singh, 1989; Nautiyal and Lal, 1984a; Pinder et al., 2019; Pinder and Raghavan, 2013). It is one of the splendid large-sized freshwater fishes of India. This stream-lined, golden-finned fish with large scales all over its body is known to reach an impressive length of 2.71 meters and weight of 54 kg (Hora, 1939; Talwar and Jhingran, 1991) and known for its migratory behavior for breeding and spawning (Bhatt et al., 2004; Joshi et al., 2018). Undoubtedly, the golden mahseer is one of India's fiercest fighting freshwater game fishes, with unparalleled power and endurance (Dhillon, 2004). In the Himalayan water, golden mahseer is considered an "umbrella species," living close to or at the top of the aquatic food chain (Bhatt et al., 2004). In 1833, the Oriental Sporting Magazine was the first to mention “Mahseer” as an angling fish. The Indian Government's book, 'With Gun and Rod in India' (1958), described mahseer as an everfascinating lure to the hunter. 'Circumventing the Mahseer and Other Sporting Fish in India and Burma' (Mac Donald, 1948) is one of the finest books on Indian Mahseer, which investigated the indigenous knowledge of this fish.

Although they are valued commercial and local fish, people in hilly areas rely on mahseers for their livelihoods. Because of their precarious nature, they have become a significant species in terms of the health of the aquatic systems and ecosystem, making them important for conservation. Further, earlier reports mention that golden mahseer migrates upstream to spawn and breed in the upper reaches of the Himalayan Rivers (Nautiyal and Singh, 1989). Also, it has been observed that monsoonal rains are the ideal time when it migrates to find a suitable spawning ground (Bhatt et al., 2004; Johnsingh, 2006). Studies have been conducted to answer fundamental ecological questions about the Himalayan mahseer's movement in the river Ganga (Nautiyal et al., 2001; Nautiyal, 2002).

However, climate change, overfishing, pollution, habitat modification, sand and boulder mining, and the construction of hydroelectric power plants have all been linked to a decline in the population of the golden Mahseer in Himalayan rivers (Atkore et al., 2011; Everard et al., 2019; Gupta et al., 2014; Nautiyal, 2014; Sharma et al., 2016). Due to the rapid construction of hydropower dams and barrages and other anthropogenic activities, the fish species face a serious threat of extinction (Pinder et al., 2019; Nautiyal, 2014). Due to modification and altered flow in the Himalayan Rivers, this species is threatened to be extinct locally in many regions, and there is a higher chance of losing this charismatic species if the threats continue (Bhatt and

Pandit, 2016). Because of its considerable depletion, Golden Mahseer's population trend and status are considered 'declining' trends. Hence, this species is reported in the Endangered category on the IUCN Red List (Jha et al., 2018).

Population distribution of Golden Mahseer

Being the most fascinating freshwater fish species of the Indian sub-continent, the golden mahseer is endemic to the Himalayan rivers (Fig. i) (Everard and Kataria, 2011; Gupta et al., 2014; Gupta et al., 2015). It has been recorded globally in Afghanistan, Bangladesh, Bhutan, Nepal and Pakistan. Overall, its longitudinal distribution extends from the Hindu Kush–Kabul–Kohistan (Indus) in the North-West Himalaya to Sadiya (Brahmaputra) in the North-East Himalaya, covering Indus, Ganges, and Brahmaputra River systems (Talwar and Jhingran, 1991; Mirza, 2004; Pervaiz et al., 2012). It can be found throughout the Himalayan belt in various lentic and lotic systems. In India, this species is reportedly distributed in Himalayan states such as Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Assam, Bihar Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, West Bengal, and Arunachal Pradesh (Nautiyal et al., 2008; Johal et al., 1994).

This species is largely confined to the lotic habitats (rivers and streams) and a few lentic habitats in Uttarakhand. In Uttarakhand, almost all the tributaries between the Yamuna and Saradha rivers inhabit Golden Mahseer, with a distribution record of 300 to 1500m MSL altitudes. As described by Sir H. Ramsay, around 1858, the lakes in Kumaon Himalaya, Bhimtal, and Sathtal were stocked with golden mahseer adults and fingerlings. It has become extinct or rare in Nainital, Nakuchital, and Sathal, and a small population is found in Bhimtal (Johnsingh et al., 2006). In Uttarakhand, golden mahseer thrives in Alakhnanda, Bhagirathi River systems and the Nayyar River in Garhwal, and tributaries of river Ramganga such as the Kosi in Kumaon, Khoh, and Kolhu Rivers in Garhwal (Bhatt et al., 2000). However, as a state with several river systems, several minor and large hydro projects have been springing up in recent years for developmental reasons. Dams and barrages built in the upper reaches of the Ganga are significantly lowering the water flow in the downstream area, with negative consequences for golden mahseer habitats.

Figure i: Distribution record of golden Mahseer (*Tor putitora*) in the Indian subcontinent.

Ecology of Golden Mahseer

The golden mahseer is a rheophilic species that lives in Himalayan hill streams with stony riverbeds (Nautiyal, 2014). It inhabits cooler natural running waterways. It occupies semi-lacustrine waters, particularly in the Himalaya. Large amounts of flowing water have been recorded in their reported habitats. The riverbeds are covered with sand, silt, and small rocks (Bhatt et al., 2016a) (Fig. ii). The feeding grounds of the fish are said to be the Himalayan river's foothill stretches and are characterized by water temperatures in the range of 14–22^{o}C. Dissolved oxygen in these habitats varies from 5.2 to 12.9 mg/L (Bhatt et al., 2004 and 2015). Since golden mahseer moves from the larger rivers to small streams in the upper reaches, these hill streams act as golden mahseer's breeding and spawning habitats. These habitats of the fish are characterized by riverbeds with boulders, cobbles, bedrocks, and gravel and water temperatures varying from 11^{o}C to 30.5^{o}C and dissolved oxygen concentrations of 6.4–11 mg/L (Bhatt et al., 2004; Joshi, 2018). The important spawning habitats are largely distributed across the Himalayan River systems. This habitat provides suitable water equality, migration routes, spawning grounds, feeding sites, resting sites, and shelter from enemies.

Figure ii: Habitat types (upper row) and different substrate categories (lower row) available in mahseer habitat (i) riffle; (ii) pool, (iii) run, (iv) sand; (v) pebbles/gravel, and (vi) cobbles.

Diet and dietary habits

Golden Mahseer's diet and dietary habits contain a high percentage of aquatic insects, i.e., undigested insects' and their chitinous parts (Nautiyal, 2014). As an effect, it is said to be carnivorous. Subsequently, it has been noted that in addition to insect larvae, they also consume green filamentous algae, other water plants, and the slimy substance that covers the rocks (Macdonald, 1948). The insect matter ranked first and was considered the "basic food" of the carni-omnivore's diet of golden Mahseer (Badola and Singh, 1980). However, it has been reported that the dietary components of the mahseer vary among the stocks in a river (Nautiyal, 2014). During the monsoon season, streams' high-water velocity brings more drifted plant materials like broken twigs or branches of riparian plants growing on the stream banks; thus, the fish consume plant matter (Desai, 1992). Because plant debris and fish remain are only consumed during times of starvation, they were also categorized as "obligatory feeders." Thus, adults eat various foods, including insect larvae, higher algae, and diatoms (Pisolkar and Karamchandani, 1981).

Furthermore, the fry and fingerlings of *Tor putitora* primarily feed on plankton, with zooplankton accounting for a greater proportion of the food (Pathani and Das, 1980). The study on food and feeding habits of fingerlings and juveniles inhibiting river Nayyar in Uttarakhand revealed that *Tor putitora* young ones also behave like omnivores (Nautiyal and Lal, 1984a). Nevertheless, from a broad perspective, it has been observed that insects are the major food items. The fish takes such things only based on food availability during stress periods when food is scarce and can opt for other types of food in the existing environment. This "carni-omnivore" nature of golden mahseer has been described in different river stocks (Steven, 1930; Kapoor, 1958; Singh, 1966; Das and Pathani, 1978; and Sharma et al., 2002). There has been reported an evident shift from herbivorous/omnivorous to carnivorous/carni-omnivorous, with a higher proportion of animal products as an essential part of omnivorous diets from the fry to adult stages (Kishor et al., 1998).

Space and habitat utilization

Himalayan streams form a diverse ecosystem with geographical and temporal variations that influence the habitat selection of golden mahseer. These streams are extremely dynamic, with the hydraulic characteristics and species adapted to such changes. Though golden mahseer is distributed in various river systems throughout the Himalayan range, the Western Himalayan riverbeds are mahseers' nourishing, developing, and suitable habitats where they attain sexual maturity and large size (Bhatt et al., 2004). Stream habitat also forms a potential factor to influence species' life history characteristics at the local level. For golden mahseer, stream basins with suitable microhabitat features, water volume, water velocity, and depth, and the presence of large stones, cobbles, pebbles, gravel, silt, sand, and creeks where the fish lays its eggs are some of the distinguishing features of streams that are suitable for the golden mahseer's life history characteristics acts.

Life-history characteristics

The life cycle of golden mahseer varies vividly in size from embryo to adult, associated with the variation in body size. Related to the functionality of different life-history stages, fish use different kinds of habitats at various stages of their life. The golden mahseer lays its eggs beneath stones in shallow water with gravel, pebbles, cobbles, and sand as the substrate (Ogale, 2002). The spawning time is said to be preferably the late-night hours (Pathani and Das, 1979; Shrestha, 1994 A female mahseer stirs up a sand cloud as it moves its caudal fin vigorously over gravel by slapping the tail against the bottom of a shallow river bank to create a nesting site, choosing a perfect spawning den with a diameter of 10 cm (4 inches) made of sand and gravel (Pathani and Das, 1980). External fertilization occurs after the ova and sperm are shed into the water. The eggs do sink to the bottom and swell when exposed to water. Fertilized eggs measure 2.18 to 2.87 mm and are yellow with a hint of orange (Pathani,1983). The incubation period generally lasts 4-7 days in a controlled system (Kulkarni, 1980; Desai, 1970). The eggs mature and hatch and rely on energy entirely from egg yolk. However, this phenomenon has yet to be documented in the wild.

Further, as soon as the embryo phase is complete, the embryo switches to the external source feed; at that stage, they are termed fry (Kishor et al., 2018). After the comprehensive development of the fully formed organ system and fins, the fish is called the fingerling stage (Pathani, 1983) reaches this stage after 12 days of rearing the fry. After the fingerling stage, fish undergo several seasonally favourable periods until they attain sexual maturity, and during this stage, the young ones are called juveniles/sub-adults (Kishor et al., 2018). The golden mahseer has used different habitat conditions at various stages throughout its life.

Spawning of Golden Mahseer

Golden Mahseer migrates in a phased manner in Himalayan streams, according to Nautiyal and Singh (1989). The initial migration begins when the snow meltwater reaches the Himalayan foothills between March and April (Nautiyal et al., 2011). The fish moves from lower to intermediate elevations in Himalayan streams, as there is not enough water to feed the adults until the monsoon rains arrive. As a result, the fish prefers to continue its migration in the main upstream channels and join higher-order tributaries with a permanent water source and low temperatures; this is known as the mahseer's learning behavior (Nautiyal, 1994). The second migration phase happens when the monsoon season begins and the water becomes muddy (Nautiyal, 1994). The turbidity of the water triggers the movement of the mahseers. According to Nautiyal (1994), only adults ascend the Himalayan Rivers to access the tributaries of rain-fed streams. The water of the Alakhnanda River in Uttarakhand gets murky in July due to intensive rain. The monsoonal flow biologically triggers the breeding of fish. For breeding, they travel from deeper waters to shallow stream habitats. This regional movement was first seen when the water became murky in the early shower during April. Adult individuals are likely to move upstream from Rishikesh to the upper reaches of the Ganga before spawning in the Alaknanda and Bhagirathi. The fish begin to spawn in these tributaries after establishing suitable conditions in the breeding grounds. The third migration phase is the movement of brooders and young from smaller upstream streams to bigger ones in the foothills (Nautiyal, 1994). Monsoon is the optimum time for migration because of the water in the river, which allows river channel connectivity and turbidity access in the upstream area (Fig. iii). The environmental clue that causes mahseer to move upstream for spawning is the fresh monsoon flow.

From July to September, the golden mahseer spawns and flows through lengthy rivers and reservoirs at lower elevations to migrate to smaller tributaries to replenish for the next breeding season (Johal et al., 1994). These smaller hill streams serve as golden mahseer spawning and nursing grounds. Riverbeds with boulders, cobbles, bedrock, and gravel are common spawning habitats for this fish. Water temperatures range from 11 to 30.5°C, with dissolved oxygen concentrations ranging from 6.4-11 mg/L, which are the most suitable habitats for mahseer spawning (Bhatt et al., 2004; Joshi et al., 2018). The important breeding habitats of golden mahseer are widely distributed throughout the Himalayan River system. These habitats provide suitable water quality, migratory routes, spawning grounds, feeding sites, resting sites, and shelter from enemies. Moreover, adult individuals prefer large and long rivers or reservoirs in lower altitudes from October to June for wintering (Nautiyal et al., 1989; Nautiyal, 2014; Johnsingh et al., 2006).

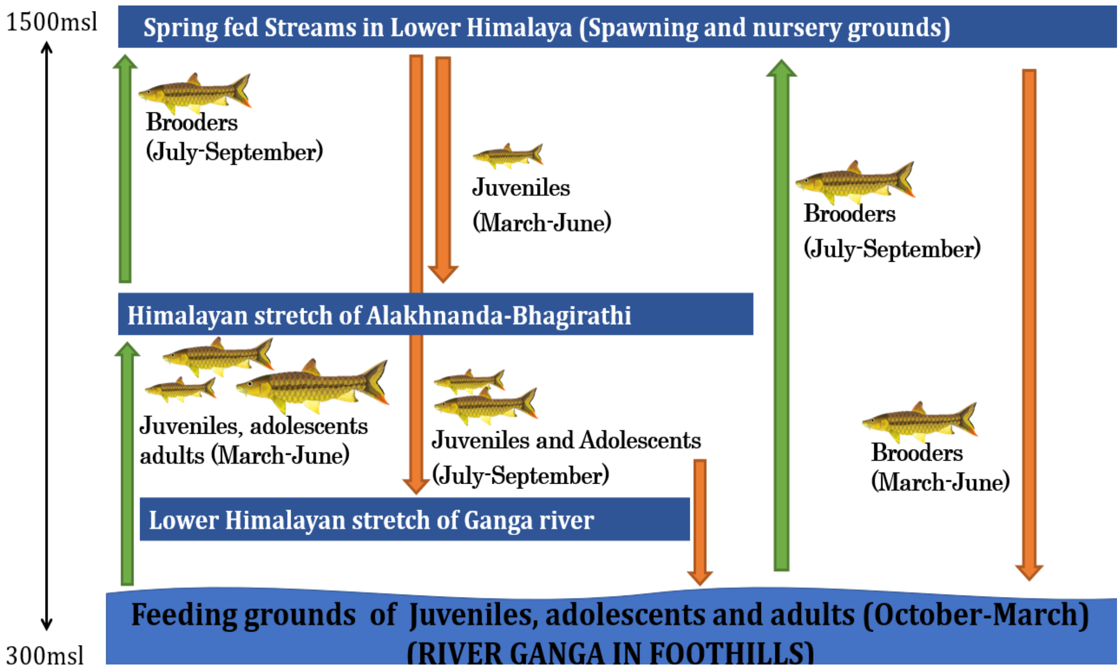


Figure iii: Migration of golden mahseer in river Ganga during different seasons of the year (Nautiyal, 1994).

Threats to Golden Mahseer

Because of the rapid construction of hydropower dams and barrages, indiscriminate fishing, and other anthropogenic activities, the golden mahseer species face a serious threat of extinction (Atkore et al., 2011). Since this fish has several attributes that make it extremely vulnerable to extinction, constructing dams and barrages in the upper segments of the river Ganga is considerably reducing its feeding and breeding habitats (Vinod et al., 2007). It has shown detrimental effects on the physical attributes, such as alteration in feeding behaviour, distribution patterns, and spawning grounds (Sarkar et al., 2012; Rajvanshi et al., 2012; Johnson et al., 2020). Due to modification and altered flow in the Himalayan rivers, this species is threatened to be extinct locally in many regions. However, this charismatic species is more likely to be lost if the actions continue (Jena and Gopalakrishnan, 2012).

Habitat loss and fragmentation due to river valley modifications are other major causes of its population decline. In addition, climate change, illegal/overfishing methods, pollution, development pressure along river banks, and sand/boulder mining contribute to the population decline of the golden mahseer in the Himalayas (Nautiyal, 2014; Bhatt and Pandit, 2016; Pinder et al., 2019). Since this species migrates upstream from the Himalayan foothills for spawning during the pre-monsoon (glacier-fed rivers) and monsoon seasons, numerous river valley changes/developments obstruct their migration paths (Nautiyal, 2014). As a result, the population of golden mahseers has declined in recent years. Besides that, when considering the river basin, whether the

Ganges or the Brahmaputra provides a living for millions of people, various flora and species that rely on the river system should be preserved (Sagir and Dobriyal, 2018).

Furthermore, it inevitably leads to the conservation of species such as golden mahseer, contributing to improved management of rivers and water bodies. Despite their past abundance, the golden mahseers population is dwindling in the current scenario (Gupta et al., 2016; Wangchuk et al., 2022). There needs to be an adequate comparison of its current state in rivers due to the need for precise numerical evaluations of availability and captures.

However, the presence of fish in a river habitat not only contributes to the comprehension of their health but also indicates the overall health of the aquatic system. Even the smallest disruption can disrupt these key variables' functions, impacting fish, their biology, and stream ecosystems (Lakra et al., 2010). Road construction and crossings, riparian tree harvesting, and deforestation are examples of these disturbances (Nautiyal, 2014). Deforestation has caused the most damage in these places, affecting stream ecology and fish assemblages by modifying hydrology and water chemistry. Because habitat is a function of flow, any changes in flow limit the amount and usability of that habitat, and changes in stream hydrology can directly impact fish (Morales-Marin et al., 2019).

Review of Literature

In the literature about the life of golden mahseer is defined by glories. Golden mahseer have revered the pride of the place and the power of the fish in the Himalayan rivers since prehistoric times. It is not surprising that for the descendants or the native inhabitants on the river sides, mahseer continues to possess a cultural significance. Several species of large freshwater carp exist in India, but the golden mahseer has risen to the highest place on the list due to its sporting prowess, strength, beauty, and size. During this study, the previous published literatures were reviewed to understand the history and current scenario of this popular game fish in India that holds a distinguished place among all other carps due to its size and powerful nature. Hamilton's pioneering work on the fish species of river Ganga and its tributaries paved the way for future research on golden mahseer. In 1822, he discovered the mighty golden mahseer, as *Barbus putitora*, now considered a sport fish worldwide (MacDonald, 1948). The first mention of its sporting ability was first reported in the Oriental Sporting Magazine in 1833 (Thomas, 1897). Its game value is described by several different terms of adjectives, including "a fish worth fighting about and fighting against," "unparalleled strength and endurance, and "playing a mahseer" (Dhillon, 2004; Nautiyal 2011). Their biology and ecological studies, were all dispersed throughout a number of publications. This review was put together in an effort to organise all of the information that is presently accessible in Table i.

S.No.	Study Authors	Year	Research Article
1	Hamilton (1822)	*1822*	*An account of the fishes found in the river Ganges and its branches*
2	Beavan (1877)	*1877*	*Handbook of the freshwater fishes of India.*
3	Thomas (1897)	*1897*	*The rod in India: being hints how to obtain sport, with remarks on the natural history of fish and their culture, and illustrations of fish and tackle*
4	Nevil (1915)	*1915*	*The breeding habits of the Mahseer (Barbus tor)*
5	Dhu (1923)	*1923*	*The angler in India or the mighty mahseer.*
6	Hora and Mukherjee (1936)	*1936*	*Fish of the Eastern Doons*
7	Khan (1939)	*1939*	*Study in diseases of fish: Fin-rot—A bacterial disease of fins of fish*
8	Khan (1939)	*1939*	*Study on the sex organ of Mahaseer (Barbus tor)*
9	Hora (1939)	*1939*	*The game fishes of India III: the mahseer or the large scaled barbels of India. 1. The putitor mahseer Barbus (Tor) putitora Hamilton.*
10	Hora (1940)	*1940*	*The game fishes of India IX. The mahseer or the large scaled barbels of India 2. The tor mahseer, Barbus (Tor) tor (Hamilton)*
11	Cordington (1946)	*1946*	*Notes on Indian mahseer.*
12	MacDonald (1948)	*1948*	*Circumventing the mahseer and other sporting fish in India and Burma.*
13	David, (1953)	*1953*	*Notes on the bionomics and some early stages of the Mahanadi mahseer.*
14	Lal (1962)	*1962*	*Morphology of Tor pituitora (HAM.)*
15	Lal and Chatterjee (1962)	*1962*	*Survey of Eastern Doon fishes with certain notes on their biology.*
16	Lal (1963)	*1963*	*Distribution and migration of Tor putitora (Hamilton).*
17	Lal (1964)	*1964*	*The air bladder and weberian ossicles of Tor putitora (Hamilton).*
18	Karamchandani (1972)	*1972*	*Mahseer—a sport fish of India.*
19	Karamchandani et al. (1967)	*1967*	*Biological investigations on the fish and fisheries of Narmada River,*
20	Sehgal et al. (1971)	*1971*	*Observations on fisheries of Kangra valley and adjacent areas with special reference to mahseer and other indigenous fishes. India.*
21	Kulkarni (1971)	*1971*	*Spawning habits, eggs and early development of Deccan mahseer, Tor khudree (Sykes)*

22	Sehgal and Kumar (1977)	*1977*	*Final project report on induced breeding and rearing of mahseer (Tor putitora) seed in running water ponds.*
23	David and Rehman (1978)	*1978*	*Criteria for the selection of cultivable species of fishes in India.*
24	Das and Pathani (1978)	*1978*	*Studies on the biology of the Kumaun Mahaseer (Tor putitora Hamilton)*
25	Tripath (1978)	*1978*	*Artificial breeding of Tor putitora (Ham.)*
26	Kulkarni and Ogale (1978)	*1978*	*The present status of mahseer (fish) and artificial propagation of Tor khudree (Sykes).*
27	Badola and Singh (1980)	*1980*	*Food and feeding habits of fishes of the genera Tor, Puntius and Barilius.*
28	Pathani and Joshi (1980)	*1980*	*On food and feeding habits of fingerlings of the two kumaun mahaseer fishes, Tor tor (Ham.) and Tor putitora (Ham.)*
29	Khuda-Bukhsh (1980)	*1980*	*A high number of chromosomes in the hillstream cyprinid, Tor putitora (Pisces).*
30	Johal and Tandon (1981)	*1981*	*Age growth and length weight relationship of Tor putitora from Gobindsagar Himachal Pradesh. Pb Fish Bull*
31	Kulkarni (1981)	*1981*	*Mahseer in danger needs protection.*
32	Nautiyal and Lal (1981)	*1981*	*Recent records of Garhwal mahseer (Tor putitora) with a note on its present status.*
33	Pathani (1982)	*1982*	*Studies on the spawning ecology of Kumaun mahseer Tor tor (Hamilton) and Tor putitora (Hamilton).*
34	Pathani (1982)	*1982*	*Studies on fecundity of Himalayan Tor mahaseer.*
35	Nautiyal and Lal (1984)	*1984*	*Food and feeding habits of fingerlings and juveniles of mahseer (Tor putitora Ham.) in Nayar River.*
36	Nautiyal (1984)	*1984*	*Natural history of the Garhwal himalayan mahseer Tor putitora (Hamilton) II. Breeding biology.*
37	Joshi (1984)	*1984*	*Artificial breeding of golden mahseer.*
38	Pisolkar and Karamchandani (1984)	*1984*	*Fishery and biology of Tor tor (Hamilton) from Govindgarh lake (Madhya Pradesh).*
39	Nautiyal and Lal (1985)	*1985*	*Fecundity of the Garhwal Himalayan mahseer Tor putitora (Ham.).*
40	Shrestha (1986)	*1986*	*Spawning ecology and behavior of the mahseer Tor putitora in the Himalayan waters of Nepal.*
41	Nautiyal and Lal (1988)	*1988*	*Natural history of Garhwal Himalayan mahseer Tor putitora: racial composition.*

42	Joshi (1988)	*1988*	*Induced breeding of mahseer, Tor putitora (Hamilton)*
43	Johal and Kingra (1989)	*1989*	*Harvestable size of golden mahseer Tor putitora (Hamilton) for its conservation*
44	Nautiyal (1989)	*1989*	*Mahseer conservation: problems and prospects.*
45	Nautiyal (1990)	*1990*	*Natural history of the Garhwal Himalayan mahseer: growth rate and age composition in relation to fishery, feeding and breeding ecology*
46	Shrestha (1990)	*1990*	*Behaviour of the golden mahseer Tor putitora (Ham.) in nature and captivity*
47	Sehgal (1991)	*1991*	*Artificial propagation of Golden mahseer, Tor putitora (Hamilton) in Himalayas.*
48	Pathak (1991)	*1991*	*Growth of tor-putitora (ham) specimen caught from sarju river (kumaun-himalaya).*
49	Talwar and Jhingran (1991)	*1991*	*Inland fishes of India and adjacent countries (Vol. 2). CRC press.*
50	Menon (1992)	*1992*	*Taxanomy of mahseer fishes of the genus Tor Gray with the description of new species from the Deccan.*
51	Dasgupta (1994)	*1994*	*Mahseer of North-Eastern India: A review on the biology.*
52	Pathani (1994)	1994	*Trends of mahseer, snow trout and chital abundance in Kumaun Himalaya. In: Dehadrai*
53	Khan (1994)	1994	*The Himalayan or Putitora mahseer Tor putitora (Hamilton).*
54	Kulkarni and Ogale (1995)	1995	*Conservation of mighty Mahseer.*
55	Nautiyal (1996)	1996	*Spawning ecology and threats to mahseer*
56	Nautiyal (1996)	1996	*Conservation of mahseer in India:*
57	Lakra (1996)	1996	*Cytogenetic studies on the endangered and threatened fishes 1. Karyotypes of three species of mahseer, Tor khudree, Tor tor and Tor putitora (Cyprinidae, Pisces).*
58	Shrestha (1997)	1997	*The mahseer in the rivers of Nepal disrupted by dams and ranching strategies.*
59	Ogale (1997)	1997	*Induced spawning and hatching of golden mahseer. Tor putitora.*
60	Nautiyal et al (1997)	1997	*Assessment of fish food resource in relation to the migratory habits of Tor putitora (Ham.) found in the impounded sections of the river Ganga between Rishikesh and Haridawar.*
61	Mahanta (1998)	1998	*Conservation and rehabilitation of mahseer in India.*
62	Barat and Ponniah (1998)	1998	*Karyotype and nuclear organizer regions (NORs) of golden mahseer, Tor putitora from different populations of north western Himalaya*

63	Pandey et al. (1998)	1998	*Induced spawning of the endangered golden mahseer, Tor putitora, with ovaprim at the state fish farm near Dehradun.*
64	Bhatt et al. (1998)	1998	*Racial structure of Himalayan mahseer, Tor putitora (Hamilton) in the river Ganga between Rishikesh and Hardwar.*
65	Bhatt et al. (1998)	1998	*Comparative study of morphometric characters of Himalayan mahseer Tor putitora (Hamilton) between Ganga and Gobindsagar reservoir stocks*
66	Bhatt and Nautiyal (1999)	1999	*Mortality and Survival of the Himalayan Mahseer Tor Putitora in a Regulated Section of the River Ganga Between Rishikesh and Haridwar.*
67	Johal et al. (1999)	1999	*Age and growth of an endangered cold-water fish-golden mahseer, Tor putitora (Hamilton) from Gobindsagar, Himachal Pradesh, India.*
68	Bhatt et al. (2000)	2000	*Population structure of Himalayan mahseer, a large cyprinid fish in the regulated foothill section of the river Ganga*
69	Johal et al. (2000)	*2000*	*Maturity, fecundity and sex ratio of an endangered coldwater fish, Golden mahseer, Tor putitora (Ham.) from Gobindsagar (HP), India.*
70	Bhatt et al. (2000)	*2000*	*Population structure of Himalayan mahseer, a large cyprinid fish in the regulated foothill section of the river Ganga.*
71	Prasanna et al. (2000)	*2000*	*Cell culture from fin explant of endangered golden mahseer, Tor putitora (Hamilton).*
72	Kapila et al. (2000)	*2000*	*Sex related haematological variations in Himalayan golden mahseer, Tor putitora (Ham.)*
73	Basade et al. (2000)	*2000*	*Changes in muscle composition and energy contents of golden mahseer, Tor putitora (Hamilton) in relation to its spawning cycle.*
74	Ogale (2001)	*2001*	*Multiple breeding in golden mahseer (Tor putitora).*
75	Nautiyal et al. (2001)	*2001*	*The role of ecological factors in governing the direction, time and purpose of migration in Himalayan Mahseer Tor putitora (Ham.).*
76	Dwivedi (2002)	*2002*	*Mahseer" the game fish of Indiaconservation in Madhya Pradesh.*
77	Gurung et al. (2002)	*2002*	*Breeding of pond reared golden mahseer (Tor putitora) in Pokhara, Nepal.*
78	Joshi et al. (2002)	*2002*	*Domestication of wild golden mahseer (Tor putitora) and hatchery operation.*
79	Nautiyal (2003)	*2003*	*Mahseer—the tiger of water in Peril,*
80	Mohindra et al. (2004)	*2004*	*Microsatellite loci to assess genetic variation in Tor putitora.*
81	Dhillon (2004)	*2004*	*The mahseer of Indian Himalayas.*

82	Islam et al. (2004)	*2004*	*Optimization of dietary protein requirement for pond-reared mahseer Tor putitora Hamilton (Cypriniformes: Cyprinidae).*
83	Bhatt et al. (2004)	*2004*	*Status (1993-1994) of the endangered fish Himalayan Mahseer Tor putitora (Hamilton)(Cyprinidae) in the mountain reaches of the river Ganga.*
84	Kiat (2004)	*2004*	*Mahseer in Malaysia and the world.*
85	Mohindra et al. (2004)	*2004*	*Microsatellite loci to assess genetic variation in Tor putitora.*
86	Ranjana (2005)	*2005*	*Molecular characterization of golden mahseer (Tor putitora) for stock identification.*
87	Johal et al. (2005	*2005*	*Length-weight relationship of golden mahseer Tor putitora (Hamilton) from pong dam reservoir, Himachal Pradesh.*
88	Sharma (2006)	*2006*	*Status of fisheries development in Himachal Pradesh.*
89	Lakra et al. (2006)	*2006*	*A new fibroblast like cell line from the fry of golden mahseer Tor putitora (Ham).*
90	Anupama (2007)	*2007*	*Recent catch record of golden mahseer Tor putitora from Garhwal Himalaya.*
91	Nautiyal et al. (2008)	*2008*	*Life-history traits and decadal trends in the growth parameters of golden Mahseer Tor putitora (Hamilton 1822) from the Himalayan Stretch of the Ganga River System.*
92	Gopalakrishnan (2008)	*2008*	*Identification of polymorphic allozyme markers for assessing genetic variability in Golden Mahseer, Tor putitora.*
93	Singh (2009a)	*2009*	*Population distribution of 45S and 5S rDNA in golden mahseer, Tor putitora: population-specific FISH marker.*
94	Singh (2009b)	*2009*	*Extensive NOR site polymorphism in geographically isolated populations of Golden mahseer, Tor putitora.*
95	Mohan et al. (2009)	*2009*	*Performance of chitin incorporated diet on the indigenous Kumaon Himalayan fishes: snow trout, Schizothorax richardsonii (Gray) and golden mahseer, Tor putitora (Hamilton).*
96	Sivaraman et al. (2009)	*2009*	*RNA-DNA ratios as an indicator of fish growth in golden mahseer (Tor putitora).*
97	Dinesh et al. (2010)	*2010*	*Mahseers in India: A review with focus on conservation and management.*
98	Sarma et al. (2010)	*2010*	*Management in seed production of golden mahseer, Tor putitora in hatchery conditions.*
99	Mallik et al. (2010)	*2010*	*Occurrence of fish louse (Argulus sp.) on Indian snow trout (Schizothorax richardsonii) and golden mahseer (Tor putitora) in subtropical Himalayan Lake of Bhimtal, Uttarakhand, India.*
100	Patiyal et al. (2010)	*2010*	*Length–weight relationship of Tor putitora (Hamilton, 1822) from the Ladhiya River, Uttarakhand, India.*

101	Kishore et al. (2011)	*2011*	*Variations in food habit of the Himalayan mahseer-Tor putitora (Ham.) inhabiting the Ganga River system in Garhwal region.*
102	Singh et al. (2011)	*2011*	*Isolation and characterization of 26 polymorphic microsatellite loci in Golden mahseer, Tor putitora (Teleostei, Cyprinidae) and their cross-species amplification in four related species*
103	Sunder et al. (2012)	*2012*	*Preliminary feeding trials on juveniles of golden mahseer, Tor putitora (Ham.) at different stocking densities with artificial dry pellet feeds.*
104	Yasmeen and Madan (2012)	*2012*	*Experimental cage culture of snow trout, Schizothorax richardsonii (Gray) and golden mahseer, Tor putitora (Hamilton) fry and fingerling in a sub-Himalayan Lake Bhimtal, India.*
105	Nautiyal et al. (2013)	*2013*	*Mahseer conservation in India: status, challenges and the way forward, WWF-India,*
106	Langer et al. (2013)	*2013*	*Morphometric and meristic study of golden mahseer (Tor Putitora) from Jhajjar Stream (JandK), India.*
107	Gupta et al. (2013)	*2013*	*Seasonal Variations in Haematological Parameters of Golden Mahseer, Tor putitora.*
108	Akhtar et al. (2013)	*2013*	*Activities of digestive enzymes during oncogenic development of golden mahseer (Tor putitora) larvae.*
109	Arjamand et al. (2013)	*2013*	*Reproductive biology of an endangered Coldwater fish Golden mahseer, Tor putitora (Ham.) from Anji mahseer hatchery Reasi (J&K).*
110	Sahoo et al. (2013)	*2013*	*Isolation and characterization of novel microsatellite markers in endangered mahseer, Tor putitora (Hamilton 1822) (Family: Cyprinidae, Pisces)*
111	Shahi and Mallik (2014)	*2014*	*Recovery of Pseudomonas koreensis from eye lesions in golden mahseer, Tor putitora (Hamilton, 1822) in Uttarakhand, India.*
112	Shahi et al. (2014)	*2014*	*Golden mahseer, Tor putitora—a possible candidate species for hill aquaculture.*
113	Ali et al. (2014)	*2014*	*Study of length-weight relationship and condition factor for the golden mahseer, Tor putitora from Himalayan rivers from India.*
114	Akhtar et al. (2014)	*2014*	*Higher acclimation temperature modulates the composition of muscle fatty acid of Tor putitora juveniles.*
115	Sati et al. (2014)	*2014*	*Complete mitochondrial genome organization of Tor putitora.*
116	Sati et al. (2015)	*2015*	*Genetic characterization of Golden mahseer (Tor putitora) populations using mitochondrial DNA markers*
117	Sarma et al. (2015)	*2015*	*Nutritional Composition of Golden Mahseer (Tor putitora) in Coldwater Himalayan Region of India.*

118	Shahi et al. (2015)	*2015*	*Spermatogenesis and related plasma androgen and progestin level in wild male golden mahseer, Tor putitora (Hamilton, 1822), during the spawning season.*
119	Bhatt and Pandit (2016)	*2016*	*Endangered Golden mahseer Tor putitora Hamilton: a review of natural history.*
120	Kumar et al. (2016)	*2016*	*Pathological findings of experimental Aeromonas hydrophile infection in golden mahseer (Tor putitora).*
121	Sharma et al. (2016)	*2016*	*Histomorphological changes in digestive tract of golden mahseer (Tor putitora) during different developmental stages.*
122	Barat et al. (2016)	*2016*	*De novo assembly and characterization of tissue-specific transcriptome in the endangered golden mahseer, Tor putitora.*
123	Sarma et al. (2016)	*2016*	*Morpho-histological and ultra-architectural changes during early development of endangered golden mahseer Tor putitora.*
124	Barat et al. (2016)	*2016*	*Solute carriers (SLCs) identified and characterized from kidney transcriptome of golden mahseer (Tor putitora) (Fam: Cyprinidae)*
125	Bhagawati et al. (2016)	*2016*	*Effect of dietary zinc on the growth and metabolic enzyme activities of golden mahseer (Tor putitora) fry.*
126	Akhtar et al. (2017)	*2017*	*Reproductive dysfunction in females of endangered golden mahseer (Tor putitora) in captivity*
127	Kumar et al. (2017)	*2017*	*Transcriptome profiling and expression analysis of immune responsive genes in the liver of Golden mahseer (Tor putitora) challenged with Aeromonas hydrophile.*
128	Shahi et al. (2017)	*2017*	*Molecular cloning, characterization and expression profile of kisspeptin1 and kisspeptin1 receptor at brain-pituitary-gonad (BPG) axis of golden mahseer, Tor putitora (Hamilton, 1822) during gonadal development.*
129	Akhtar et al. (2018)	*2018*	*Photo-thermal manipulations induce captive maturation and spawning in endangered golden mahseer (Tor putitora): A silver-lining in the strangled conservation efforts of decades.*
130	Shahi et al. (2018)	*2018*	*Characterization and pathogenicity study of Chryseobacterium scophthalmum recovered from gill lesions of diseased golden mahseer, Tor putitora (Hamilton, 1822) in India.*
131	Joshi et al. (2018)	*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.*
132	Charak (2018)	*2018*	*An Approach for determination of semen quality of golden mahseer (Tor putitora) from central Himalaya.*

133	Akhtar (2020)	*2020*	*Effect of photoperiod and temperature on indicators of immunity and wellbeing of endangered golden mahseer (Tor putitora) broodstock.*
134	Yadav et al. (2020)	*2020*	*Evaluation of the effect of longitudinal connectivity in population genetic structure of endangered golden mahseer, Tor putitora (Cyprinidae), in Himalayan rivers: Implications for its conservation.*
135	Mallik et al. (2020)	*2020*	*The emergence of zoonotic Fusarium oxysporum infection in captive-reared fingerlings of golden mahseer, Tor putitora (Hamilton, 1822) from the central Himalayan region of India.*
136	Kunwar et al. (2021)	*2021*	*Mixed toxicity of chlorpyrifos and dichlorvos show antagonistic effects in the endangered fish species golden mahseer (Tor putitora).*
137	Ciji et al. (2021)	*2021*	*Dietary soy lecithin augments antioxidative defense and thermal tolerance but fails to modulate non-specific immune genes in endangered golden mahseer (Tor putitora) fry.*
138	Akhtar et al. (2021)	*2021*	*Dietary β-glucan influences the expression of testicular aquaporins, antioxidative defence genes and sperm quality traits in endangered golden mahseer, Tor putitora (Hamilton, 1822).*
139	Akhtar et al. (2021)	*2021*	*Molecular characterization of non-specific immune genes of endangered golden mahseer (Tor putitora) and their expression during embryonic and larval development*
140	Kalkhundiya (2021)	*2021*	*Role of dissolved oxygen on behavioural and stress response of golden mahseer, Tor putitora.*
141	Sharma et al. (2021)	*2021*	*Study on the sex-specific seasonality of fatty acid profiles in golden mahseer (tor putitora) collected from a lacustrine ecosystem of Indian Himalaya.*
142	Riar et al. (2021)	*2021*	*Effect of stocking density on growth performance and the survival of golden mahseer, Tor putitora (Hamilton) fry.*
143	Shah et al. (2021)	*2021*	*Evaluation of the acute toxicity of Thymus linearis ethanol extract and its effect on the hemato-biochemical and behavioural response of the Golden mahseer, Tor putitora (Hamilton, 1923).*

Review of Radio telemetry in fish

Globally, the research on freshwater fish telemetry began in the 1950s (Stasko and Pincock, 1977; Mitson, 1978). However, a substantial body of literature has emerged due to this research. It led to various studies on fish migration, distribution patterns, and habitat usage. This understanding has been achieved through telemetry techniques (Nigro and Ward, 1985; Faler et al., 1988; Ward et al., 1995). Tags of various sizes and purposes are used to research multiple ecological characteristics of ecology and fish behavior. In some studies, telemetry was utilized in conjunction with the mark and recaptures study to acquire information on individual fishes, according to Faler et al. (1988). Further, telemetry studies have been widely used to establish the home range of several fishes (Lewis and Flickinger, 1967; Malinin, 1969; Winter, 1977; Doerzbacher, 1980; Ross and Winter, 1981; Mesing and Wicker, 1986).

In India, a radio telemetry study was first reported in 1976 by Mech (1983). The Crocodile Research Centre of the Wildlife Institute of India in Hyderabad conducted the first radio-telemetry study in aquatic ecosystems 1983. The successful tagging of 12 gharials in the Chambal River signalled the beginning of such studies in India (Habib et al., 2014). The first radio tagging of fish in India occurred in 2011, when a whale shark was tagged off the western coast of Gujarat (Habib et al., 2014). Globally, for the freshwater fish species, only recently, in Bhutan, radio telemetry was performed on golden mahseer fish (Fisheries Conservation Foundation and World Wildlife Fund-Bhutan pers. comm. 2018).

Research Hypothesis

The physical structure of the stream, streamflow, water quality, water temperatures, and watershed characteristics are important factors influencing the golden mahseer populations in Himalayan streams. The environmental variables influence the physical habitat structure of streams primary and secondary production, and, as a result, these factors influence the fish population. For my doctoral research, I researched how the environmental variables that affect the river's ecology and ecosystem relate to the golden mahseer's population distribution in aquatic habitats. Furthermore, I studied whether the fish is specific regarding space occupancy and feeding behavior and whether it thrives suitably in resource and habitat classification with other co-existing fish species.

During the monsoon season, golden mahseers are said to migrate upstream to spawn. Environmental cues indicate that the upstream movement will begin during the monsoon season. Moreover, understanding the exercise of golden mahseers connected to generating and breeding behavior is critical for their conservation. I investigated movement and home range studies using radio telemetry techniques for the above research questions. To justify, the following objectives were proposed in this study:

Objectives of the Study:

1. Temporal distribution patterns of the golden mahseer concerning environmental variables

Key Questions:

(a) What are the different fish species associated with golden mahseer?

(b) How do seasons affect the population abundance of the golden mahseer?

(c) How do environmental parameters affect the distribution of golden mahseer?

2. Resource partitioning (space and food resource) of Golden Mahseer with other co-existing fishes

Key Questions:

(a) What are the different food materials in the fish diet?

(b) What are the food and space preferences of the co-occurring species and the golden mahseer?

(c) Is there any niche overlap among the co-existence and segregation of the functional status of associated fish species concerning the golden mahseer?

3. Movement patterns of golden mahseer during spawning and non-spawning period using radio-telemetry techniques

Key Questions:

(a) What are the key routes of the golden mahseer movement?

(b) What are the key characteristics of the movement routes?

(c) How long do they move for the spawning and non-spawning period?

(d) What is the home range pattern of the individuals?

(e) How do water parameters affect golden mahseer's movement among different spawning habitats?

4. Breeding and nursery grounds of golden Mahseer in Kolhu and Kosi rivers.

Key Questions:

(a) What are the different habitat types of spawning grounds of the golden mahseer young ones?

(b) What are the ecological traits and characteristics of these spawning grounds?

(c) Habitat Suitability of young ones of golden mahseer?

Study Area

The state of Uttarakhand, which has a total area of 53,566 $km^{2,}$ is located in the North West Himalayan region between latitude 280 40'-310 29'N and longitude 770 35'-810 5'E (Uniyal et al., 2021). This state has a unique ecosystem and ample water resources in rivers, rivulets, streams, and lakes (Ehrlich and Wilson, 1991; Pandey et al., 2018). The mighty rivers of the Himalaya have unrivaled ecosystems in terms of diversity. Two of the most significant river systems in Uttarakhand originate from them are the Ganga River system from the Gangotri glacier and the Yamuna River system from the Yamunotri glacier, with many rivers, including Alaknanda, Bhagirathi, Ramganga, Yamuna, Saryu, Mandakini and Sharda, as their tributaries (Khanna et al., 2013).

The Ramganga River is a significant tributary of the river Ganga; Western and Eastern Ramganga are two distinct streams that separate at their source and flow separately into the plains. Western Ramganga has its origin in the Kumaon Himalaya. The Namak glacier in the Doodha-Toli ranges in the lower Himalayas of Pauri Garhwal at an altitude of 3,110m (MSL) (Khan et al., 2016). The river enters the plains at Kalagarh, which is on the border of the Garhwal district and where the famous Ramganga dam has been built. After crossing Kalagarh, the river flows southeast to join the Ganga on its left bank close to Kanauj in the Fathehgarh district (Roy and Sinha, 2007). Headwaters of Ramganga, during its course, traverse more than 100km before entering Corbett National Park near Marchula and run through the protected areas, are home to a wide variety of both terrestrial and aquatic (Johnsingh and Williams, 1999). Garhwal-Kumaon hills form the easternmost part of the Western Himalaya, making Uttarakhand's two significant geographical divisions (Gokhale and Pala, 2011). It comprises the lower Himalayan range that lies south of the main or great Himalayan range. In Garhwal and Kumaon, the Shiwalik hills are very well developed, occupying the outer chain of hills more or less parallel to the lower Himalayas (Chauhan et al., 2018). The present doctoral thesis is focused on three freshwater tributaries of the Ramganga River, namely Kosi, Kolhu, and Khoh Rivers. Among these rivers, River Kosi originates from its northmost point near Kausani, district Almora, in the Kumaon region (Atkore et al., 2011) (Fig. iv). River Kolhu and Khoh flow through the Pauri-Garhwal district in the Garhwal area. The aquatic biodiversity of these rivers is structured by diverse geomorphic conditions, thermal regimes, and rapid water currents (Atkore, 2005; Pandey et al., 2018). These together have resulted in the distinctive composition of fish species assemblages (Atkore, 2005; Negi and Mamgain, 2013).

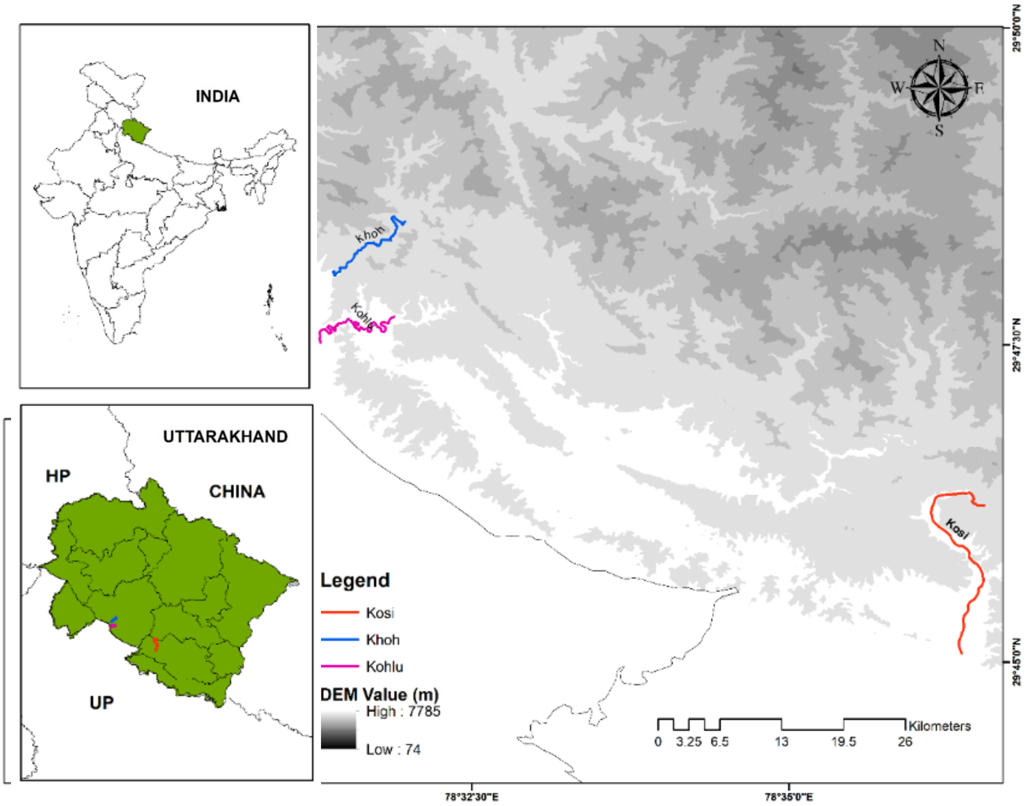


Figure iv: Study area map of the sampled river stretches in Uttarakhand: River Khoh, Kolhu, Kosi (left to right), Ramganga basin, Uttarakhand.

Topography

The area of present research falls under the Terai-Bhabar Shiwalik (Sub-Himalaya). The topography of this area is rugged, characterized by deep valleys and high hills dissected by streams (Negi, 1998; Rawat and Mukherjee, 2005). The Western Himalaya represent a unique set of ecological characteristics over complex systems that incorporate forests, meadows, grasslands, marshes, rivers, wildlife, geology, and several other phytogeographical distinctive peculiarities (Mani,1974). The occurrence of diverse topography and climate factors has resulted in the area's remarkable biodiversity (Singh and Gaur, 2008). Forests dominate phytogeography and constitute the most valuable natural resources. Land use pattern in these areas is strongly governed by elevation, climate, terrain, lithological type, surface hydrology, grazing land, barren land, and human settlement (Karan, 1966). The human settlements are mainly located in the shallower water zones or around the hilly terrain.

Climate

The study area's highly varying topographical features show an equally variegating climatic condition, ranging from hot and sub-humid tropical in the southern tract to temperate in the north (Negi, 2000). The region has a sub-tropical to temperate climate, which remains pleasant throughout the year. Factors such as elevation, slope, forests, mountain peaks and ridges, and direction of mountain ranges give rise to great variations in climatic conditions at the micro and local levels. These attributes determine the temperature range and the distribution of rainfall. However, the southwest monsoon governs the overall climate condition (Ghosh, 1991), extending from June to October. The region's climate is pronounced by three seasons: summer, winter, and monsoon (Sati, 2020). The area experiences an annual average temperature of <5-35 degrees Celsius (Nautiyal, 2010). The hilly terrain with densely forested slopes generally receives adequate rainfall from mid-June to mid-September. About 75% of rain occurs in the zone from June to September, during the monsoon season (Jain et al., 2017). Winter precipitation is associated with the passage of Western disturbances, mostly in the form of snowfall, particularly at higher elevations (Negi, 2000).

Flora and Fauna

There are extensive forests in the lower ranges of Gharwal-Kumaon (Dhar et al., 1997). These forests serve as a base for many industries, local fuelwood needs, fodder resources, and ecological stability. There is a considerable variation in the forest type in the areas because of the variations in altitude, climate, rocks, and soil. Khair-Sisso is a riverine forest in lower elevations (Kaushal et al., 2021). Vegetation in the area includes moist deciduous forests and tropical dry deciduous forests (Champion and Seth, 1968; Rawat, 2017). During the study, along rivers and streams, the dominant trees mainly consisted of *Acacia catechu* (Khair), *Shorea robusta* (Sal), *Dalbergia sisso* (Shesham), and *Bombex ceiba* (Bamboo). Along the banks, there is *Holptelea intergrifolia*, *Murraya koenigii* (a shrub), and *Pogostemon benghalense* (a shrub). *Dalbergia sisso*o and *Acacia catechu* patches were occasionally observed along the river beds. Forests of the Bhabar areas in the region are mainly composed of various deciduous species—*Mallotus philippensis* (Rohini), *Bombax ceiba* (Bamboo), *Adina cordifolia* (Haldu), *Lagerstroemia parviflora* (Queen's crepe), *Cassia fistula* (Amaltas). The main shrubs in the association are *Ziziphus marijuana* (Indian plum), *Ziziphus oenophilia* (wild berries), and *Helicteres isora* (Indian screw tree). The sub-deciduous *Shorea robusta* is the most significant species, generally found up to about 750m (Junjariya and Negi, 2022).

Among others, the widely distributed species are mainly associated with *Anogeissus latifolia* (Dhawa), *Desmodium oojeinense* (Sandan), *Bauhinia roxburghiana* (Kandala), *Terminalia alata* (Saaj), *and Butea monospermic* (Palaash). In most localities along riverbeds, evergreen forests are found up to 800m. The dominant tree species are *Syzygium cumini* (Jamun), *Trewai nudiflora* (Gutel), *Mallotus phillippensis*

(Rohini), *Alstonia scholaris* with *Ardisia solanacea, Murraya koenigii, Adhtoda zeylanica, and Lantana americana* as the main shrub species (Rawat and Mukherjee, 2005).

The Himalayan foothills comprise the Western Himalaya Terai, Bhabar, and Shiwalik regions (Singh and Gaur, 2008). To its south, the region's fauna merges with that range, presenting diverse habitats with levels of variation that are unequaled elsewhere in the world (Nandy et al., 2006). They are home to various mammals, reptiles, and birds. This zoogeographic region is rich in mammalian fauna- *Elephas maximus indicus* (Indian elephant), *Panthera tigris tigris* (Tiger), *Panthera pardus fusca* (Indian leopard), *Axis axis* (Chital), *Boselaphus tragocamelus* (nilgai), *Cervus unicolor* (sambhar), *Muntiacus muntjac* (barking deer), *Axis porcinus* (hog deer), *Sus scrofa* (wild boar), *Canis aureus* (golden jackal) (Rodgers and Panwar, 1988; Johnsingh and Williams, 1999; Harihar et al., 2009) and *Lutrogale perspicillata* (smooth-coated otter) (Basak et al., 2021). This region is also rich in avifauna. There are both resident and migratory, including species of kingfishers, including *Alcedo atthis* (common kingfisher), *Halcyon smyrnensis* (white-throated kingfisher), *Megaceryle lugubris* (crested kingfisher), *Ceryle rudis* (pied kingfisher), *Halcyon capensis* (Stork-billed kingfisher); *Vanellus duvaucelii* (river lapwing), *Tadorna ferruginea* (ruddy shelduck), *Sterna aurantia* (river tern), *Phalacrocorax niger* (little cormorant), *Phalacrocorax carbo* (great cormorant), *Amaurornis phoenicurus* (white-breasted waterhen), *Ardeola grayii* (Indian pond heron). (Ahmed et al., 2019). There is also a large variety of reptiles and amphibians in this area.

Fish biodiversity in Uttarakhand

Fish is an indicator of habitat suitability and health of any aquatic system (Gorman and Karr, 1978). As per the current status, 132 species of fish belonging to 67 genera, 27 families, and 8 orders have been reported (Uniyal et al., 2021). The Himalayan fish fauna is classified under subsistence and commercially important fish groups, i.e., Carps (*Labeo* and *Tor* spp.), barrels (*Barilius* spp.), schizothoracines (*Schizothorax* & *Schizothoraichthys* spp.), carries (*Garra* spp.) and sisorids (*Glyptothorax* & *Glyptosternum* spp.) (Vass, 2009; Atkore, 2005; Atkore et al., 2011). Coldwater species inhabiting the Himalayan rivers belong principally to 5 different families, Salmonidae, Cyprinidae, Cobitidae, Sisoridae, and Mastacembelidae, out of which fishes comprising major commercial fishery belong to Cyprinidae represented by 3 sub-families, i) Cyprinidae-Mahseers and minor carps, ii) Rasborinae-Indian trouts, and iii) Schizothoracinae-Snow trouts (Moza, 2001).

Further, golden mahseer (*Tor putitora*) potentially plays an important role in this region in the ecosystem balance and the livelihoods of local communities (Johnsingh and Negi, 1998; Sarkar *et al*., 2012). The described study areas are considered a key landscape for the conservation of the unique cold-water fish diversity of India, especially for golden mahseer.

Study Sites

River Kosi

Kosi, a perennial river, originates on the southern slope of Dharnapani Dhar in the Baramandal region of district Almora (Kumaon, Uttarakhand) of the Bhatkot-Kausani range (2517, MSL) and flows through Kumaon region of Uttarakhand (Paliwal *et al.*, 2007). It flows through the valleys and the Corbett reserve forests' outer fringes before entering the Uttar Pradesh Terai regions. It enters Bhabar near Ramnagar and covers a basin area of 2101.83 km^2 with a total length of 150 km (Ganie *et al.*, 2022). The current study focused on a 200m reach stretch each upper, middle, and downstream within a 32km stretch from Kunkhet to Ramnagar barrage between latitudes 29°24'2.78" N 79°07'54.41" E and longitudes 29°48'02.62" N 79°12'08.43" E (Fig. v). River Kosi is home to many aquatic animals, including many fish species. Despite being a promising river, urbanization and tourist resorts along the Kosi River banks have significantly affected the river and surrounding landscape in recent years. In addition, gravel and sand mining, overfishing, and resort trash dumping have all impacted in-river ecology to an unknown extent. Amid the scenario of habitat loss, the upper Kosi still has sections of high-quality habitat to support aquatic wildlife. Locals of the Kumaon region use the water of this river for farming and cultivating different crops. Also, this river harbors a wide variety of fish biodiversity and provides a home for notable conservation significant species like golden mahseer and otter.

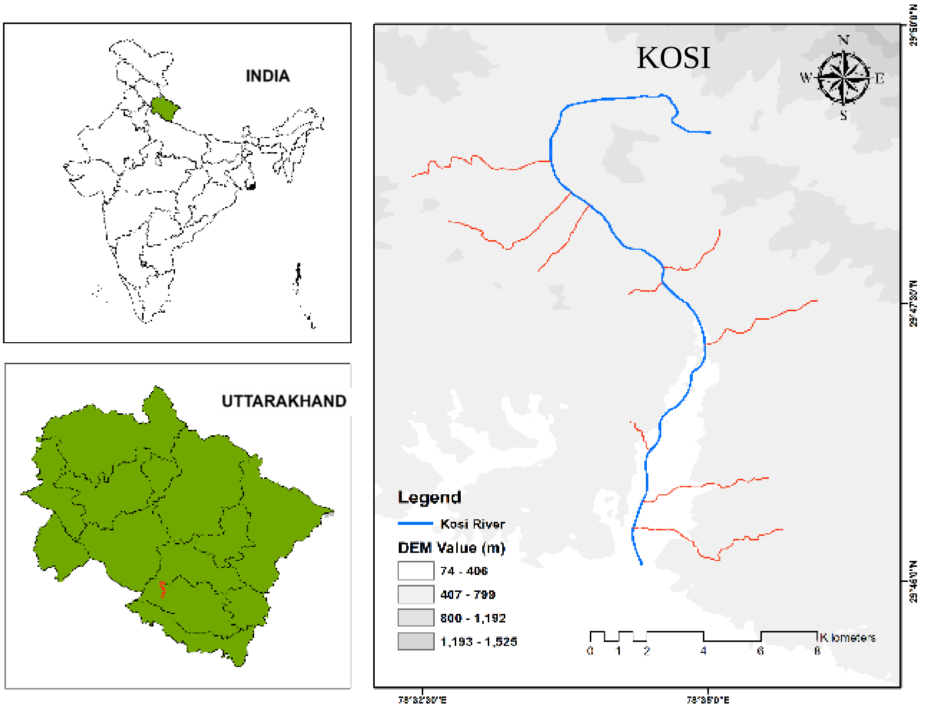


Figure v: Study site map representing the sampling stretch of river Kosi, Ramganga river basin, Uttarakhand.

River Kolhu

Kolhu, on the other hand, originates in the Dungadanda ranges, and it forms from the confluence of two small streams, Noddy and Bhaira, that flow through the reserve forests of Lansdowne (Atkore et al., 2011). River Kolhu (Fig. vi) is reportedly less disturbed than the Kosi since it flows through a protected region. It flows through the Shiwaliks' hilly terrains down to Saneh village near Kotdawar town in Pauri-Garhwal, Uttarakhand, over 16-18 kilometers (315 metres) (Kukreti and Arya, 2022). It joins Khoh and flows downstream to meet river Ramganga on the Uttar Pradesh state border. Between latitudes 29°41'31.2" N 78°31'38.64 "E and longitudes 29°42'58.32" N and 78°35'48.84 "E, segments of 200m each in upper, middle, and down within a total of 16 kilometers of the Kolhu river were chosen for the present study. It is noted to have multiple turns and form S-shaped bends along the stretch. Kolhu is all forested, with a home to a wide variety of mammalian fauna- *Elephas maximus indicus* (Indian elephant), *Panthera tigris tigris* (Tiger), *Panthera pardus fusca* (Indian leopard), *Axis axis* (Chital), *Boselaphus tragocamelus* (nilgai), *Cervus unicolor* (sambhar), *Sus scrofa* (wild boar), *Canis aureus* (golden jackal) (Rodgers and Panwar, 1988).

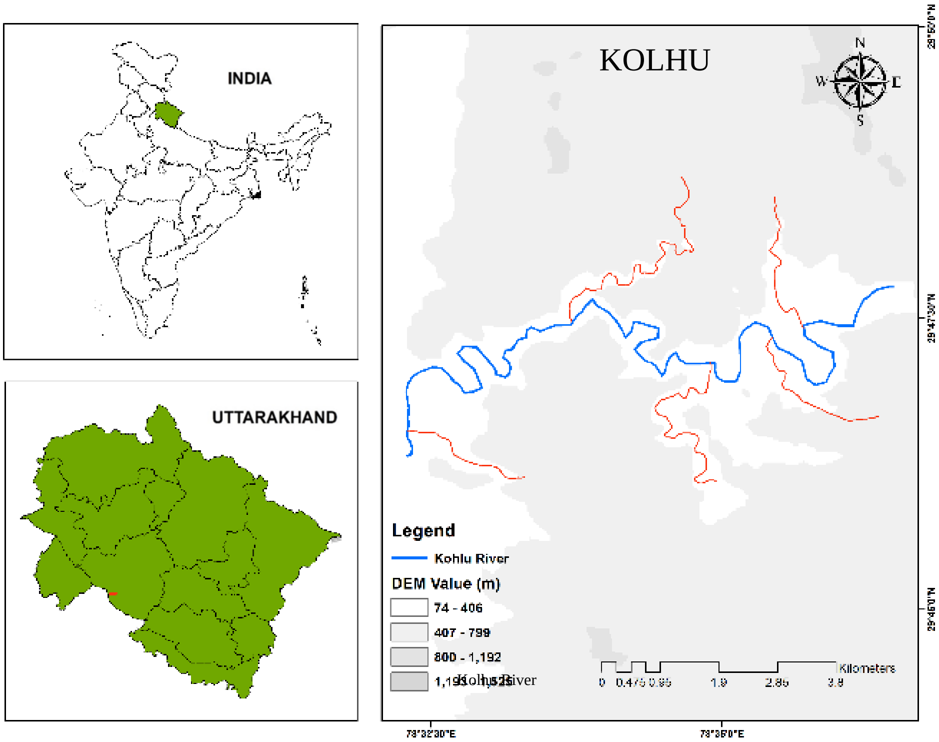


Figure vi: Study site map representing the studied stretch of river Kolhu, Ramganga river basin, Uttarakhand.

Also, the well-developed riparian vegetation of the region includes prominent *Acacia catechu* (Khair), *Shorea robusta* (Sal), *Dalbergia sisso* (Shesham), *and Bombex ceiba* (bamboo). The (smooth-coated otter) *Lutrogale perspicillata* and important birds, including species of kingfishers *Alcedo atthis* (common kingfisher), *Halcyon* *smyrnensis* (white-throated kingfisher), *Megaceryle lugubris* (crested kingfisher), *Ceryle rudis* (pied kingfisher), are the potential fish predators in these areas.

River Khoh

Khoh is another river where the present research work was conducted. River Khoh is a seasonal river that flows north from Dwarikhal and drains through the Shiwalik ranges (Atkore et al., 2007) (Fig. vii). This river originates from the confluence of two rivers, Silgad and Langurgad, near Dugadda in the Pauri district (Atkore et al., 2007). The current study area is located between 29° 45' 27" and 29° 48' 22.1" N and 78° 32' 22.4" and 78° 36' 18.5" E. River Khoh flows 25 km from the forest area and 10 km from Kotdawar. This research site is located in the upper areas of the region before it joins the river Kolhu at Saneh village in Uttarakhand. Later, in Dhampur, near Bijnor, Uttar Pradesh, it merges with the mighty Ganga. The region is home to a wide range of large mammals, such as tigers and leopards, and a sizeable population of elephants. Additionally, mammalian species like the golden jackal, wild boar, chital, nilgai, and sambhar (Rodgers and Panwar, 1988) are found. Kingfishers, herons, and pheasants are among the numerous bird species that can be found in the area. Here, important fish species like snow trout, golden mahseer, loaches, and small fishes are among the fish population. from the upper reaches to the downhill regions.

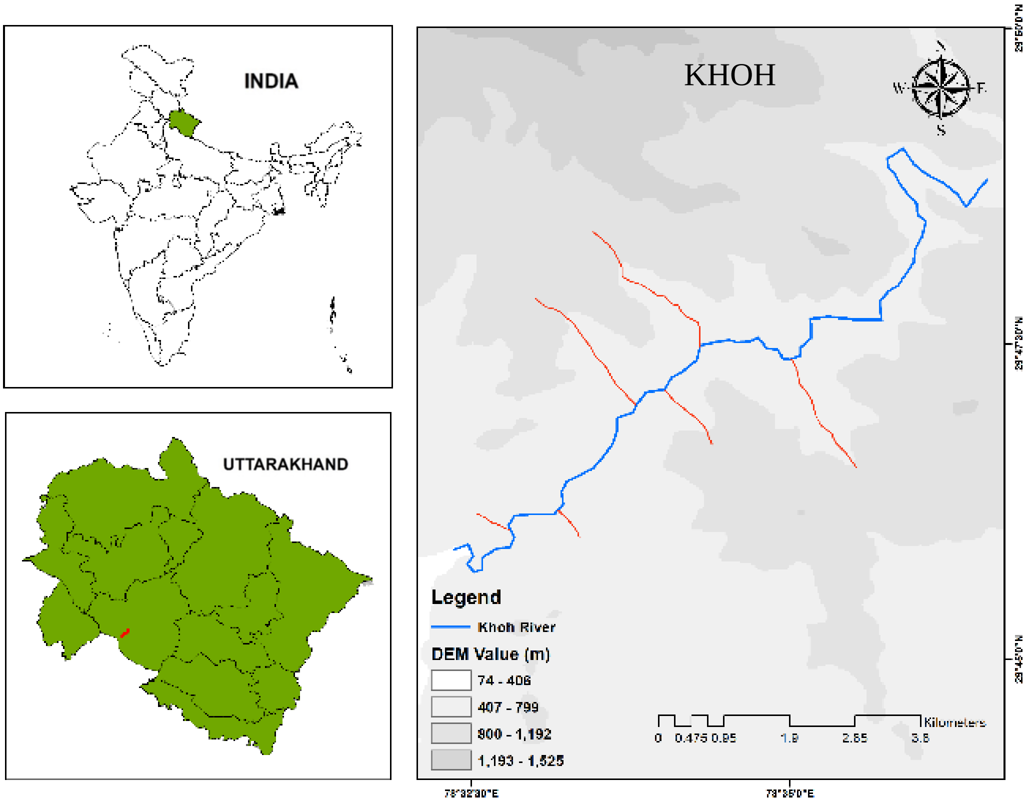


Figure vii: Study site map representing the sampling stretch of river Khoh, Ramganga river basin, Uttarakhand.

Chapter 1

Temporal distribution patterns of the golden mahseer concerning environmental variables

Running title: Factors Governing the Fish Distribution

1.1 Introduction

Water is the planet's lifeline and the thread that ties everything together. Among the world's richest aquatic faunal resources, Indian rivers hold a high diversity (Vass et al., 2009). Several physical and chemical factors, such as the water source, the type of environment, seasons, and anthropogenic activities, play a significant role in determining the faunal community structure in aquatic ecosystems (Parikh and Unadkat, 2021). Fish species composition in the aquatic systems varies due to variations in the altitude, flow rates, environmental parameters, and riparian zones that provide food, shade, and shelter to freshwater ecosystems in rivers, streams, springs, and headwaters (Armantrout, 1990). These components affect the abundance and distribution of aquatic life (Taylor et al., 1993) and provide a suitable space for an organism or species' where they get the conditions necessary to survive, reproduce, feed, and find shelter (Hayes et al., 2018). And any changes to these factors result in changes to the species' community structure (Mohamed, 1998).

Seasonal changes have a significant impact on the composition and abundance of fish species (Sanches et al., 2016), and the difference in environmental variables due to seasonal change influence the species' recruitment, breeding, dietary and feeding patterns (Das et al., 2012; Moyle and Cech, 2000; Smol, 2010). Therefore, it is necessary to comprehend how different complex sets of physical and biological factors interact with the composition of fish in a river over an extensive range of temporal and spatial measurements. As the structure of the physical and biological factors impacts the health of the residing aquatic community, defining a species' natural habitat and conducting habitat evaluation studies also becomes essential (Barbour et al., 1996). Earlier studies have reported species diversity and habitat heterogeneity that depends on various hydrological and environmental parameters (Arunachalam, 2000; Ward et al., 2001; Arrington and Winemiller, 2003; Welcome and Halls, 2003; Johnson and Arunachalam, 2009, 2010; Postel and Richter, 2012).

Freshwater fish species exclusive to South Asia, like *Tor putitora* (golden mahseer), can be found in the snow-fed rivers of the Himalayan water. Being a significant freshwater cyprinid fish and the largest member of its family, it is essential to the aquatic ecosystem and its good health (Nautiyal, 2014). Several studies have examined Himalayan foothill streams' environmental parameters and fish biodiversity (Johnsingh and Negi, 1998; Sarkar et al., 2012; Johnson et al., 2022). However, the present study was conducted after considering the significance of environmental parameters and the suitable habitat characteristics in the study sites with diverse fish communities during different seasons. Further, given the dynamism of freshwater riverine systems, acquiring preliminary data on temporal and spatial fish assemblages, diversity patterns, environmental variables, and conservation status is crucial to developing management strategies that protect environmental integrity while still allowing for long-term development.

This chapter aims to understand the fish community structure of the studied three streams along their conservation status and elucidate the diversity indices during the seasonal studies. This study also determines the relationship between the environmental parameters and further defines the relationships between the fish community and environmental parameters with distinct reference to golden mahseer.

1.2 Materials and Methods

1.2.1 Study area and duration

The study was carried out seasonally, covering pre-monsoon, post-monsoon, and post-winter seasons from 2019 to 2020, during sampling along the three rivers' stretch: Kosi, Kolhu, and Khoh (Fig.1). A detailed site survey was carried out along the rivers to gather information on river habitat types, abundance of fish diversity, environmental parameters, and the distribution status of golden mahseer and co-existing fish species. For this study objective, fish sampling, water quality, and other environmental parameters were measured across 200m of reach in each site's upper, middle, and down areas.

1.2.2 Fish sampling and identification

Fish sampling was performed in three freshwater streams with the assistance of local fishers using monofilament cast nets with varied mesh sizes (10-50mm) and gill nets (15-40mm). The cast net effort lasted about a half-hour and included 10 throws for each sampling. Morphometric characteristics and photographs of the fish samples were obtained before the fish were released back into the rivers. Following Jayaram (2010) and Talwar and Jhingran (1991), the fish specimens were identified up to the species level, and the fish species' conservation status. was determined by the IUCN Red List of Threatened Species,

1.2.3 Measurement of water quality and environmental parameters

The sampling sites' GPS locations (latitude and longitude were collected) and altitude measurements were made using the Garmin 20X GPS, and wetted river width and the river bed were measured using the range finder. Data on various water quality parameters were collected at each sampling site during different seasons. The measurements were all recorded for temperature (thermometer), pH (multimeter-probe), dissolved oxygen (Winkler's technique), electrical conductivity EC (probe), and total dissolved solids TDS (probe). Data measurement for the water quality sample was collected in triplets, and average values were determined. Depth, flow, and substrate type were recorded, measuring the cross-sectional interval data at every 20m and cross-sections at every 1-meter interval. Based on the habitat inventory, the number of each habitat type, pool, run, riffle, and cascade were determined, and instantaneously, habitat depth, velocity, and presence of dominant substrate types were generated. Water velocity and distribution information was developed using a depth finder & a measuring rod, and a hand-held digital flow probe (Johnson et al., 2017). Dominant substrate types: Bedrock (> 200mm), small boulders (150–200mm), cobbles (50–150mm), gravel (5–50mm), sand-silt (1-2mm), and leaflitter were all measured, followed by Bovee, (1982) and Pusey et al., (1993). Fish cover presence was determined using the classification method: overhanging vegetation, bedrock undercut, boulder undercut, rootward/snags, woody debris, and aquatic vegetation. Composition at each substrate and cover type was quantified based on visual observation, and later, proportion values were used for further analysis.

1.2.4 study of fish diversity indices

Shannon's diversity index, Margalef's richness index, and Pielou's evenness index were calculated to elucidate the seasonal diversity of the fishes.

The Shannon diversity index was computed using the formula.

$\boldsymbol{H = -\Sigma i \, ni/N \ln ni/N}$ (Shannon and Wiener, 1949), where H is the diversity index, ni is the relative abundance (S/N), The sample size is expressed as N, S represents the number of species, and N denotes the total number of individuals.

The species evenness index was calculated based on the formula:

$\boldsymbol{J = H/LnS}$ (Ln = The natural logarithm) (Pielou 1966), where H is the Shannon diversity index, and S is the number of species.

Species richness was calculated based on the formula:

$\boldsymbol{D = S-1/Ln\ N}$, where D is Margalef's richness index; the sample size is expressed as N, where N represents all individuals overall, and S represents the number of species.

1.2.5 Data analysis

The percentage of collected fish samples for the fish species from the total samples was measured using MS Excel 2016. Multiple ANOVA tests were used to determine significant differences among seasons from 2019 to 2020 in the fish assemblage patterns in different rivers. One-way ANOVA test analyzed substantial differences in the diversity indices and the environmental parameters at a 5 % significance level. Similarity percentage (SIMPER) analysis (Clarke and Warwick, 1994) was performed to check the percentage contribution, overall average dissimilarity, and dissimilarity among seasons in the three rivers. A dataset comprising all the measured environmental variables was analyzed for their correlation. The Pearson correlation matrix was plotted to check the multicollinearity in the variables (Zuur et al., 2007).

Further, before further analysis, environmental parameters and fish abundance data were standardized by log10 (x=1) transformation. Additionally, principal component analysis (PCA) was performed to reduce the dimensionality of components based on eigenvalues and to obtain a set of variables with high loadings on the first two components in the study data and different rivers. PCA was performed to get the best of the variables in a dataset while retaining the variability in important fish data. The variables related to one another are grouped into factors using PCA.

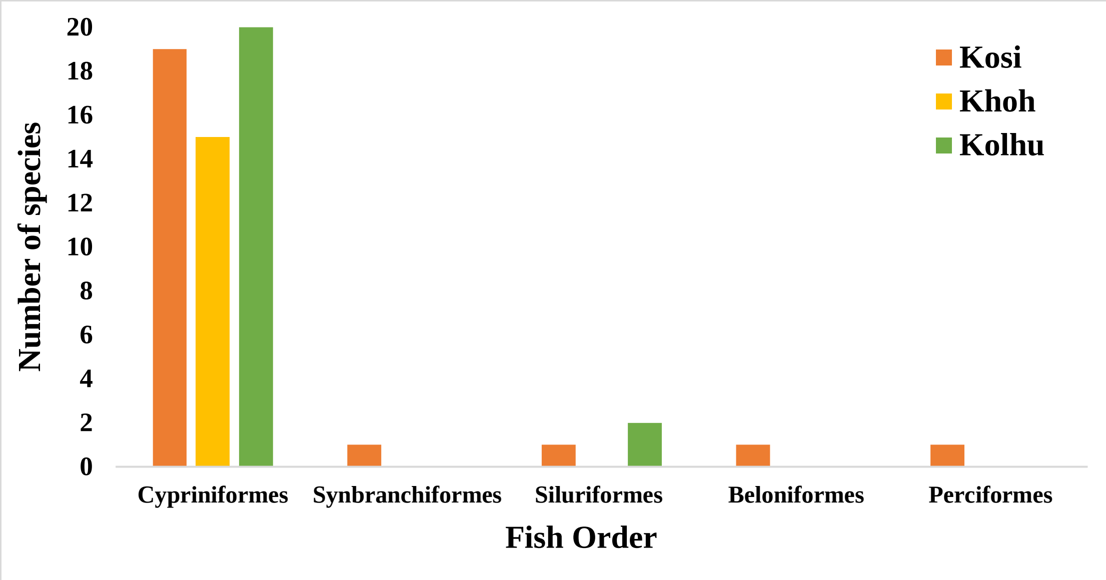
Lastly, after choosing the final predictors, environmental variables with variable loadings > 0.25 were considered important (Chatfield and Collins, 1980). To see the possible relationship between these predictors and the abundance of fish species in the study data, different rivers were evaluated using CCA (Canonical Component Analysis). The statistical significance of the CCA relationship between

the set of all environmental parameters and fish abundance was assessed using the permutation test with 1000 permutations. All the analyses were done using MS Excel 2016, Palaeontological Statistics software version 3, and RStudio version 4.0.2.

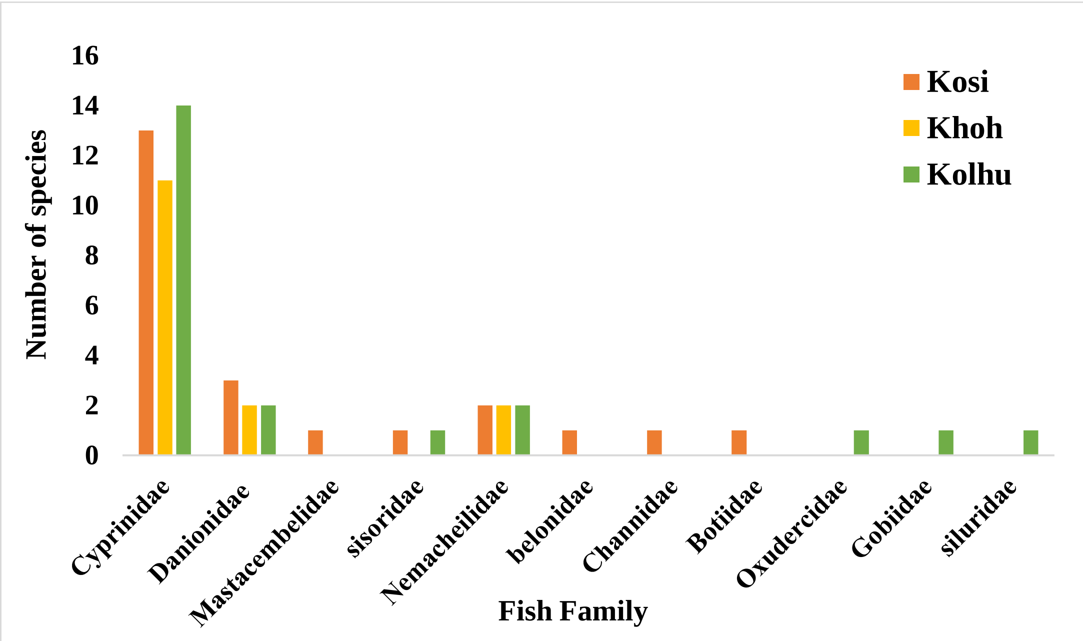
1.3 Results

1.3.1 Fish community structure

The identified fish samples reportedly belonged to 31 different fish species, representing 5 orders, 11 families, and 24 genera, indicating that all three rivers have a diverse fish population. Kosi represents 5 orders, 8 families, 17 genera, and 23 species. Kolhu represents 2 orders, 7 families, 17 genera, and 22 species, and Khoh represents 16 species, 10 genera, 4 families, and one order. Among the fish orders, the most abundant is Cypriniformes, followed by Siluriformes (Fig. 1.1a). Among the studied species, Cyprinidae was the most abundant family reported in all three rivers, following Danionidae, Nemacheilidae, and Sisoridae (Fig. 1.1b). The subsequent ANOVA test for the species sampled revealed a significant ($p = 0.0029$) difference in the abundance pattern during different seasons in three rivers for a 65.33 % difference among the fish species. Overall, a highly effective ($p < 0.005$) higher number of fish individuals were recorded in the post-winter season, followed by the pre-monsoon season. Low was reported during the post-monsoon seasons (2019) and (2020) (Fig. 1.2). SIMPER analysis revealed an overall average dissimilarity of 68.24 % among seasons. It was reported 62.04 % for Kosi and Kolhu, 69.38 % for Kosi and Khoh, and 73.28 % for Kolhu and Khoh during the study.



(a)



(b)

Figure 1.1: Overall Fish diversity representing (a) Order and (b) Family from the study rivers: Kolhu, Khoh, and Kosi, Uttarakhand.

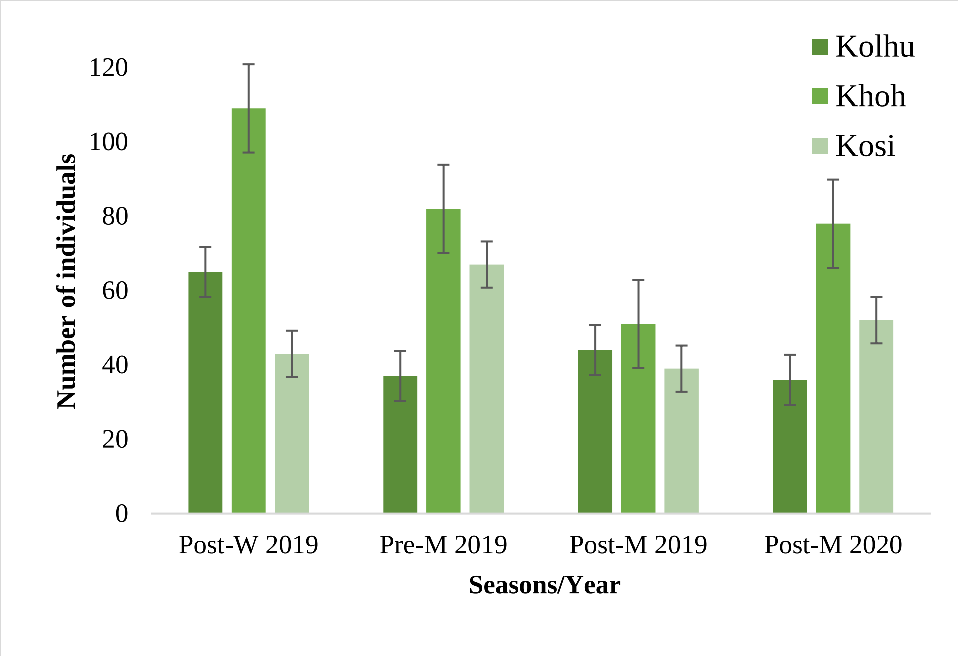


Figure 1.2: Total number of fish recorded in different sampling seasons from the study rivers: Kolhu, Khoh, Kosi, Uttarakhand.

1.3.1.1 Fish assemblage in River Kosi

Cypriniformes are the most dominant order, comprising 82.6% of the Kosi River. At the same time, Siluriformes, Symbrachiformes, and Perciformes contributed low representatives whereas Cyprinidae (54.16 %) was among the most abundant group followed by Danionidae (12.5 %), followed by Sisoridae and Nemacheilidae with 8.33% each (Fig. 1.3). Further, Mastacembelidae, Belonidae, Channidae and Botiidae accounted for 4.16 % each. *Labeo* was the most frequently occurring genus, which accounted for 21.7% of all species. *Tor* and *Opsarius* each accounted for 9%. The results of the subsequent one-way ANOVA test for species in Kosi showed that, except for the post-monsoon season in 2019 and 2020, no significant difference in the abundance pattern between seasons was observed (*p*=0.9933). Pre-monsoon and post-monsoon seasons had an overall highly effective higher ($p < 0.005$) number of fish individuals recorded, while post-winter seasons (2019 and 2020) reported comparatively lower counts. Here, SIMPER analysis showed an overall average dissimilarity of 57% among seasons in the river, with a highest of 62.15% between pre- and post-monsoon and a lowest between post-winter and post-monsoon at 58.5%.

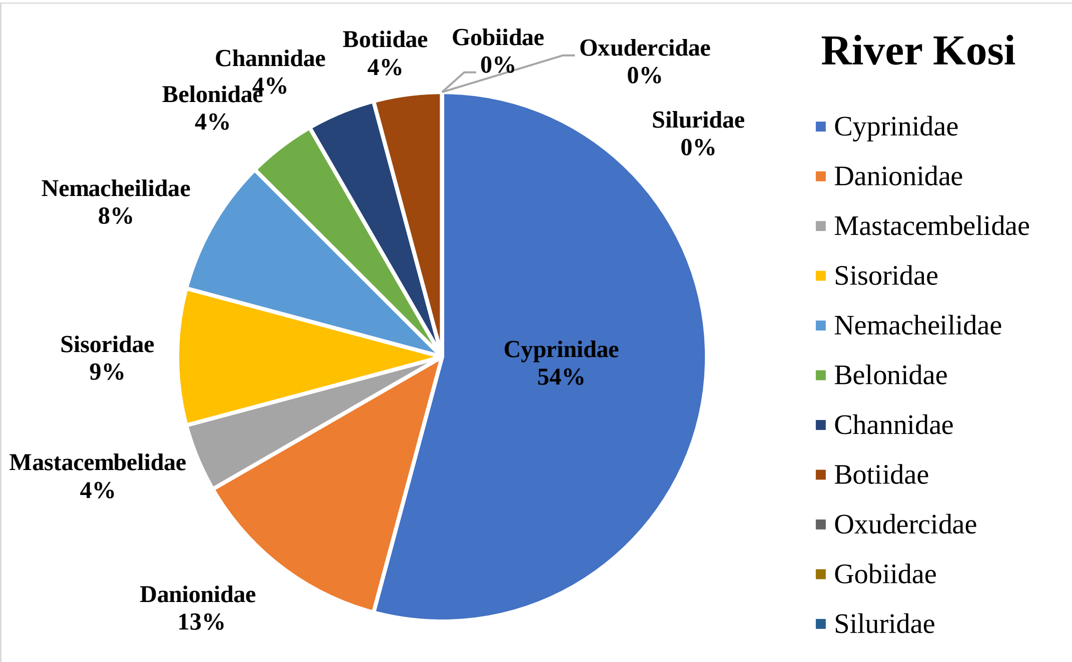


Figure 1.3: Percentage contribution of fish families recorded from Kosi, Ramganga river basin, Uttarakhand.

1.3.1.2 Fish assemblage in River Kolhu

In Kolhu, the order Cypriniformes accounted for 90.9% of the fish composition, whereas Siluriformes made the smallest contribution (9.09%). The most dominant family was Cyprinidae (63.6%), followed by Nemacheilidae and Danionidae (9.09%) each, and Siluridae and Gobiidae (4.54%) each were the least abundant. The most widespread genus was *Labeo* (27.2% among the total 17 genera). The Analysis of Variance (ANOVA) test results for the species diversity in Kolhu showed a significant difference in the abundance pattern between seasons (p<0.005, = 0.0029). Results were reported to be significantly different between seasons in 2019 and 2020 for the post-monsoon season (p = 0.00067), as is also said to be quite different among the three seasons in 2019 (p = 0.00041). Overall, the post-winter season recorded the highest number of fish individuals (p < 0.005), followed by the post-monsoon season. In contrast, the pre-monsoon season had the lowest number of fish individuals (Fig. 1.4). SIMPER analysis found an overall average dissimilarity of 65.33% among seasons in the river, with a highest 64.95% between pre- and post-monsoon and lowest between post-winter and post-monsoon 56.54 %. Following the post-monsoon season in 2019 and 2020, a 65.88% difference in the comparative analysis was reported.

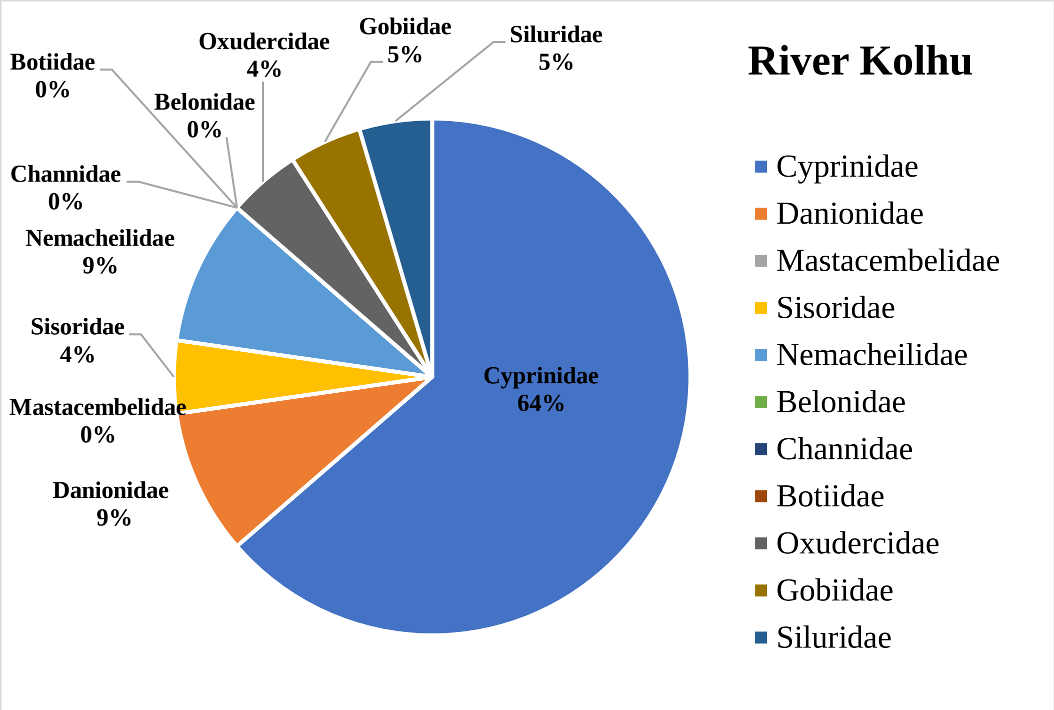


Figure 1.4: Percentage contribution of fish families recorded from Kolhu, Ramganga river basin, Uttarakhand.

1.3.1.3 Fish assemblage in River Khoh

The family Cyprinidae comprised 73.3% of the total fish composition in Khoh, and Nemacheilidae and Danionidae comprised 9.09% each. *Labeo species* with the highest representation (33.3%), *Tor* and *Schizothorax* with 13.3% contributed each, and *Barilius* and *Pethia* with the lowest (3.3%). The abundance pattern in Khoh varied significantly ($p < 0.005$) between seasons, according to the ANOVA test for individual species. The results represented a significant difference during the seasons in 2019 (p=0.001235) and the post-monsoon season in 2019 and 2020 (p=0.0335). Overall, the post-winter season recorded the highest number of fish individuals (p<0.005), followed by the post-monsoon season. In comparison, SIMPER analysis found an overall average difference between seasons in the river of 62.43%, with the highest difference (62.9%) between pre- and post-winter and the lowest difference (48.19%) between pre- and post-monsoon.

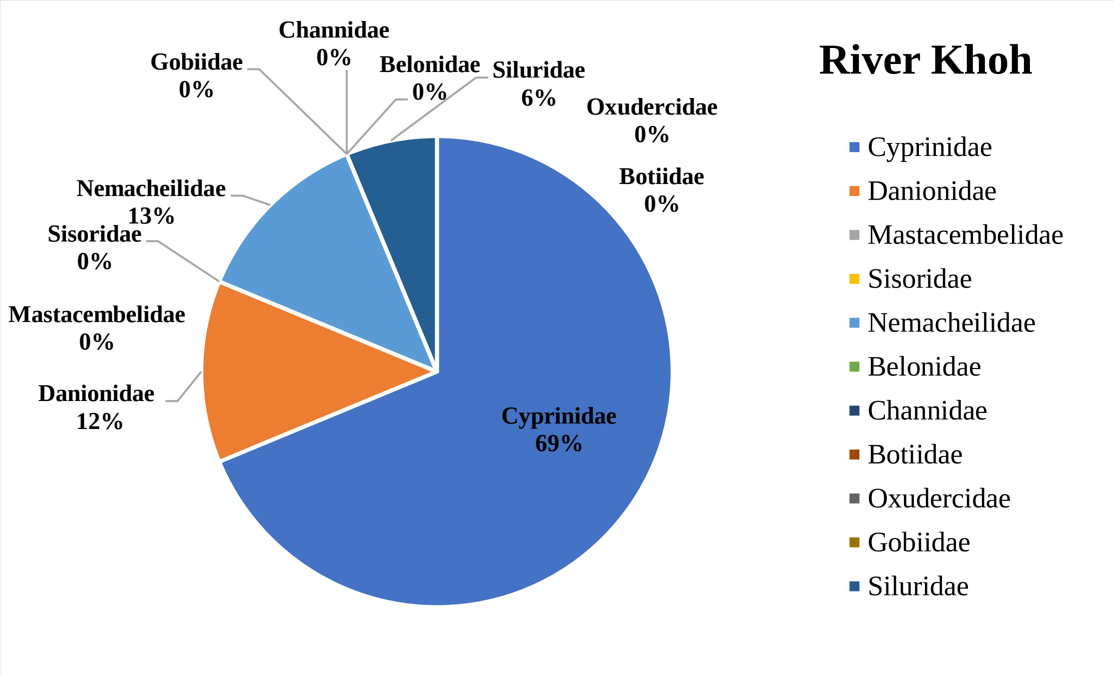


Figure 1.5: Percentage contribution of fish families recorded from Khoh, Ramganga river basin, Uttarakhand.

1.3.2 Conservation status of the fish species

Among the studied species, one endangered species, *Tor putitora*, and two vulnerable species (*Naziritor chelynoides* and *Schizothorax richardsonii*) were reported among the 31 fish species found in the studied rivers, according to the IUCN conservation status (Jha et al., 2008). One was reported near threatened (*Labeo pangusia*) (Fig. 1.6).

The remaining species were listed as least concerned except those not evaluated under the IUCN Red List category. Threats to local fish biodiversity include destructive fishing practices like habitat destruction and fragmentation, which affect the growth and recruitment of many species. Climate change and other anthropogenic factors like damming, altering watersheds, and pollution impact many fish species.

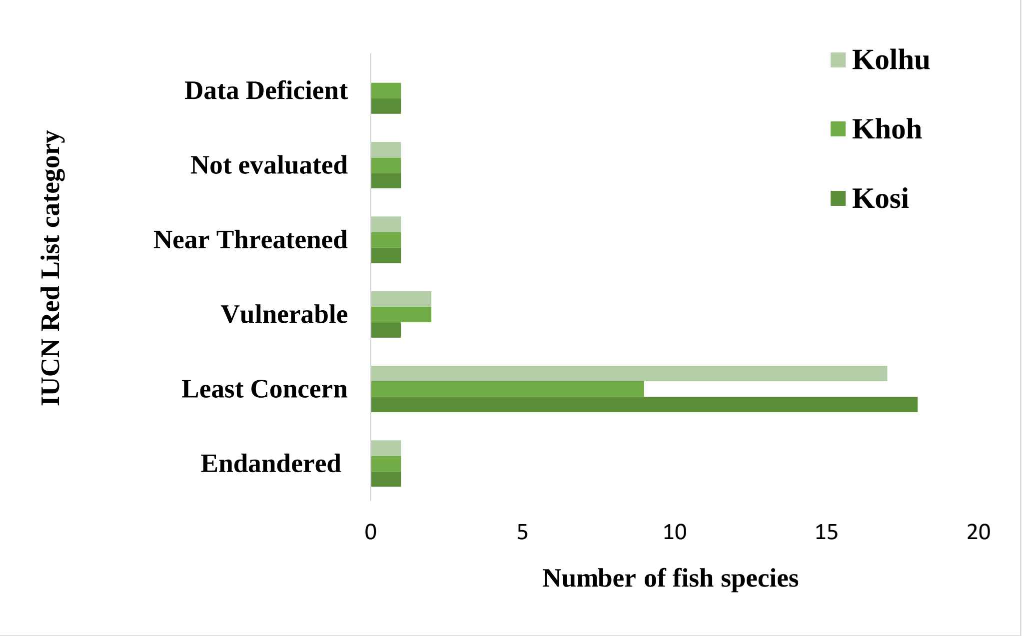


Figure 1.6: Composition of the fish species under different threatened categories in rivers Kosi, Kolhu, and Khoh in Ramganga river basin, Uttarakhand.

1.3.3 Water quality parameters

The water quality parameters represent the aquatic health of the river. In the present study, water quality parameters indicated seasonal and spatial variations. Water temperature is essential since it affects the chemical and biological reactions of water and aquatic organisms (Shrivastava and Patil, 2002). In 2019, water temperature in

Kosi ranged from 22.36°C to 29.45°C, with the minimum in the upper reaches during the post-winter season and maximum in the downstream sites during the pre-monsoon season (Table 1.1). Kolhu ranged from 18°C to 28.1°C, with the highest reported during the pre-monsoon season and the lowest during the post-winter season (Table 1.2). Temperature variations were noted in the various segments, with the upper segment of the stream being slightly cooler. Water temperatures in Khoh ranged from 19.2°C to 28.46°C, with the lowest recorded during the post-winter season and the highest during the pre-monsoon (Table 1.3). Dissolved oxygen is a regulator of organisms' metabolic activities, as well as an indicator of the trophic condition of a water body. Kosi's dissolved oxygen concentration ranged from 7.58 - 9.38 mg/l, with the highest level observed during the post-winter season and the lowest value recorded during the pre-monsoon season (Table 1.1). Similarly, the DO concentration ranged for Kolhu ranged from (8.0-10.5 mg/l) with a high value recorded during the post-monsoon (Table 1.2). In the case of Khoh, the DO value ranged between 8.29 and 10.36 mg/l, with the highest occurring during the pre-monsoon (Table 1.3).

The river water was found to be alkaline throughout the study period. The pH in Kosi ranged from 8.74 to 9.65 (Table 1.1), with the post-winter season having the lowest readings and the pre-monsoon season having the highest value. It was determined to be between (8 and 9.5) in Kolhu, with the pre-monsoon season having the highest maximum and the post-winter season having the lowest (Table 1.2). Throughout the study, TDS concentrations in Kosi ranged from 169.66 to 276.33 ppm (Table 1.1), with the lowest and highest values occurring in the post-monsoon. (222.6 - 299.3 ppm) was the range of values in Kolhu (Table 1.2). The pre-monsoon season had the highest values, while the post-winter season had the lowest. The obtained values in Khoh were reported highest during the pre-monsoon period and lowest during the post-monsoon period (Table 1.3), ranging (from 100- 244.6 ppm). The Kosi River's electric conductivity ranged from (222.33- 196.33 μ/S), with the lowest readings coming after the pre-monsoon and the highest after the winter. The values in Kolhu ranged from 323 to 405 μ/S, with post-winter values being lower and pre-monsoon levels being more elevated. Compared to the other rivers in the study, Kolhu's conductivity levels were higher. The conductivity ranged from 140.1 to 345.6 μ/S in Khoh, with the lowest value recorded in the post-winter season and the highest in the pre-monsoon season (2019). In 2020, the river Khoh had the lowest dissolved oxygen concentration, while the river Kosi had the highest, according to reported temperatures (Table 1.4). During the post-monsoon study in 2022, the pH was reported to be high in Khoh and low in Kolhu. While river Kolhu had the highest concentration of total dissolved solids and river Khoh had the lowest, the Kosi was reported to have the highest electric conductivity.

Further, to understand the distribution patterns of the fish assemblage, the water quality and environmental parameters were measured together to perform further analysis. The factors surveyed in the study for the rivers are listed in (Table 1.5). The table includes the calculated mean values and the range for each parameter.

Table 1.1: Water quality parameters observed during the seasonal study in Kosi River 2019

River Kosi (2019)		Post-Winter		Post-monsoon		Pre-monsoon	
S. No.	***Parameters***	***Range***	***Mean***	***Range***	***Mean***	***Range***	***Mean***
1.	**DO (mg/L)**	7.93-9.38	8.73±0.549	8.90-9.38	9.192±0.2	7.58-8.3	7.99±0.26
2.	**pH**	8.83-9.39	9.122±0.216	8.74-9.46	9.122±0.28	8.89-9.65	9.37±0.32
3.	**W temp (℃)**	22.36-26.53	24.42±1.36	23.66-28.5	26.09±1.56	26.56-29.45	28.011±0.979
4.	**EC (µ/S)**	231.66-296.33	264.75±27.2	248.66-314.33	282.58±21.4	222.33-290	268.46±23.87
5.	**TDS (ppm)**	172-212.33	185.75±14.9	169.66-276.33	208.58±43.9	181.67-262.67	218.75±30.7

Table 1.2: Water quality parameters observed during the seasonal study in Kolhu River in 2019

River Kolhu (2019)		Post-Winter		Post-monsoon		Pre-monsoon	
S. No.	***Parameters***	***Range***	***Mean***	***Range***	***Mean***	***Range***	***Mean***
1.	**DO (mg/L)**	8.1-9.9	9.02±0.91	8.5-10.5	9.32±1.07	8-8.88	8.28±0.25
2.	**pH**	9-9.5	9.13±0.2	8.7-9.27	8.97±0.26	8-8.7	8.34±0.37
3.	**W. temp (℃)**	18-22.1	19.6±2.18	19.6-23.2	21.68±1.89	26-28.1	26.96±0.99
4.	**EC (µ/S)**	323-389	365.55±37	359-395.3	380.66±18.66	382.33-405	393.11±11.47
5.	**TDS (ppm)**	222.6-279.3	257.55±30.5	268-279	275.22±6.3	279.67-299.3	292.67±11.26

Table 1.3: Water quality parameters observed during the seasonal study in Khoh River in 2019

River Khoh (2019)		Post-Winter		Post-monsoon		Pre-monsoon	
S. No.	***Parameters***	***Range***	***Mean***	***Range***	***Mean***	***Range***	***Mean***
1.	**DO (mg/L)**	8.39-10.36	9.18±0.97	8.63-9.36	8.91±0.39	8.29-9.34	8.73±0.45
2.	**pH**	9.23-9.41	9.32±0.09	8.66-9.03	8.91±0.21	8.83-9.55	9.025±0.35
3.	**W. temp (̊C)**	19.2-24.6	21.15±2.41	21.3-21.86	21.48±0.32	26.4-28.46	27.18±0.898
4.	**EC (μ/S)**	140.1-233	190.65±38.52	207.66-229.3	217.22±11.05	321.6-345.6	329.5±11.63
5.	**TDS (ppm)**	100-157.33	137.66±24.54	164.33-175.3	169.2±5.60	232.3-244.6	238.75±5.73

Table 1.4: Water quality parameters observed during the post-monsoon study in all rivers in 2020

Post-monsoon (2020)		Kosi		Kolhu		Khoh	
S. No.	***Parameters***	***Range***	***Mean***	***Range***	***Mean***	***Range***	***Mean***
1.	**DO (mg/L)**	9.03-9.433	9.26±0.21	8.03-8.93	8.51±0.45	8.01-9.26	9.10±0.23
2.	**pH**	8.75-9.08	8.97±0.18	8.3-8.8	8.59±0.291	8.88-9.13	8.98±0.13
3.	**W. temp (̊C)**	17.93-21.73	22.84±1.9	18.2-29.53	23.76±5.66	20.86-22.13	21.5±0.37
4.	**EC (μ/S)**	119.07-254.66	173.137±133	325-369.33	349.1±22.42	138.06-220.6	181.02±21.57
5.	**TDS (ppm)**	164.66-183	173.44±9.19	238.6-260.6	248±11.4	98.2-147	123.17±24.42

Table 1.5: Mean, standard deviation, and range values of water quality and other environmental parameters measured during the study.

S.No.	Variables	Code	Mean ± SD	Range
1	**pH**	**ph**	8.98± 0.33	8.05-9.64
2	**Water Temperature (°C)**	**wt**	23.58± 3.23	18.07-29.53
3	**Total Dissolved Solids (ppm)**	**TDS**	208.74± 56.17	98.20-299.33
4	**Dissolved oxygen (mg/L)**	**do**	8.91± 0.63	7.89-10.53
5	**Electrical conductivity (µS/cm)**	**ec**	281.90± 87.57	19.08-405.33
6	**Salinity (ppm)**	**sal**	146.04± 48.76	67.40-250.33
7	**Altitude (m)**	**alt**	437.48± 124.09	292-725
8	**Bedrock (%)**	**br**	17.50± 13.71	0-70
9	**Small Boulders (%)**	**sb**	18.47± 9.62	0-50
10	**Cobbles (%)**	**co**	20.42± 13	10--60
11	**Gravel (%)**	**gr**	14.86± 6.15	0-30
12	**Sand (%)**	**sd**	23.47± 14.87	0-60
13	**Leaf Litter (%)**	**ll**	5.56± 5.32	0-20
14	**Overhanging vegetation (%)**	**ov veg**	0.08± 0.10	0-.34
15	**Bedrock undercut (%)**	**uc br**	0.31± 0.16	0.09-.74
16	**Boulder undercut (%)**	**uc b**	0.28± 0.17	0-0.66
17	**Rootward/snags (%)**	**rw**	0.07± 0.08	0-0.25
18	**Woody debris (%)**	**wd**	0.10± 0.09	0-0.31
19	**Riparian Vegetation (%)**	**rp veg**	0.15± 0.12	0-0.40
20	**Pool (%)**	**pool**	31.07± 17.24	5--90
21	**Run (%)**	**run**	35.19± 13.56	0.25-65
22	**Riffle (%)**	**rif**	30.05± 14.00	0-61.53
23	**Cascade (%)**	**cas**	2.61± 4,72	0-22.4
24	**Wetted river width (m)**	**wet wd**	25.36± 6.17	13-37
25	**River bed (m)**	**r bed**	62.72± 23.12	35-111
26	**Depth (cm)**	**depth**	43.35± 13.22	18.22-74.59
27	**flow (m/s)**	**flow**	1.10± 0.63	0.07-2.73

1.3.4 Patterns of Fish Biodiversity Indices

The present study considers fish species richness (number of species identified) and abundance, as well as 'fish availability' (total no. of individuals recorded), evaluated between rivers and seasons. Both spatial (river segments) and temporal (seasonal data) biodiversity indices were generated for the three rivers. No significant differences were obtained in the ANOVA test for the diversity indices among seasons in the study streams. Shannon (H') diversity index obtained for Kosi ranged between (1.54 and 1.74 units), with low diversity recorded during the post-winter season and high during the pre-monsoon season (Table 1.6). Kolhu had a high species diversity during the post-monsoon season (1.68), with no significant differences found among seasons. In the case of Khoh, the value ranged from 1.29 to 1.89 units, with the high diversity reported during pre-monsoon and the low during the post-winter, with a significant difference observed as a result of the one-way ANOVA test (p = <0.005). Margalef's index was used to determine maximum species richness, which ranged from 1.04 to 1.96 units in Kolhu, with the minimum recorded during the pre-monsoon and the maximum richness observed during the post-monsoon. It was maximum during pre-monsoon and minimum during post-monsoon in Kosi, ranging from 1.83-2.08 units (Table 1.6). Khoh ranged from 1.42 to 2.49 units, with the maximum richness occurring during the post-winter season and the minimum measured during the pre-monsoon season. In Kosi, evenness among seasons was reported from 0.80 to 0.88 units and was high during post-monsoon and low during post-winter. The Kolhu was reported to have maximum evenness during the post-monsoon-2019 season and minimum during the post-monsoon 2020 season. In Khoh, it was high in the downstream segment after the monsoon and low in the middle pre-monsoon season.

Table 1.6: Diversity indices of the fish species in rivers Kosi, Kolhu, and Khoh of Uttarakhand.

Kosi	**PW-2019**	**PrM-2019**	**PM-2019**	**PM-2020**
Diversity (*H*')	1.54	1.74	1.59	1.57
Richness (D)	1.91	2.08	1.86	1.83
Evenness (*J*)	0.80	0.84	0.88	0.81
Khoh	**PW-2019**	**PrM-2019**	**PM-2019**	**PM-2020**
Diversity (*H*')	1.89	1.31	1.43	1.29
Richness (D)	2.49	1.42	1.77	1.58
Evenness (*J*)	0.74	0.69	0.70	0.67
Kolhu	**PW-2019**	**PrM-2019**	**PM-2019**	**PM-2020**
Diversity (*H*')	1.58	1.07	1.68	1.30
Richness (D)	1.69	1.04	1.96	1.37
Evenness (*J*)	0.87	0.86	0.88	0.85

*PW-Post winter, PrM-Pre-monsoon, PM-Post monsoon

1.3.5 Interaction of environmental parameters

Through PCA, the seasonal and spatial variations in the physiochemical parameters were explained among the study sites. The correlation matrix and network plots indicated highly correlated variables with (>0.80). A significant pattern of limnological studies was found in the principal component analysis of 23 explanatory (environmental and water-quality variables). It produced two main components exhibiting eigenvalues of PC1-5.86 and PC2-2.811 and variances of 21.72% and 10.412% (Fig. 1.7). Among the analyzed water quality parameters, the first axis has higher loadings for TDS, salinity, water temperature, and electric conductivity; depth, aquatic vegetation, and the presence of pools also displayed high loadings throughout the seasons. The second axis produced loadings of high altitude, dissolved oxygen, conductivity, and flow. A significant difference among seasons was found using the MANOVA test, including all habitat variables ($F = 8.67$, $p < 0.05$). Except for the one water-quality parameter and nine other environmental variables that had lower loadings on the components and were thus removed from further analysis (Chatfield and Collins, 1980; Gupta et al., 2012; Rashid et al., 2018). Regarding the seasonal relationship, the rivers Kosi, Kolhu, and Khoh were observed to be related during the post-monsoon season. In contrast, during the post-winter and pre-monsoon studies, only the rivers Kosi and Kolhu were found to be associated in terms of environmental parameters.

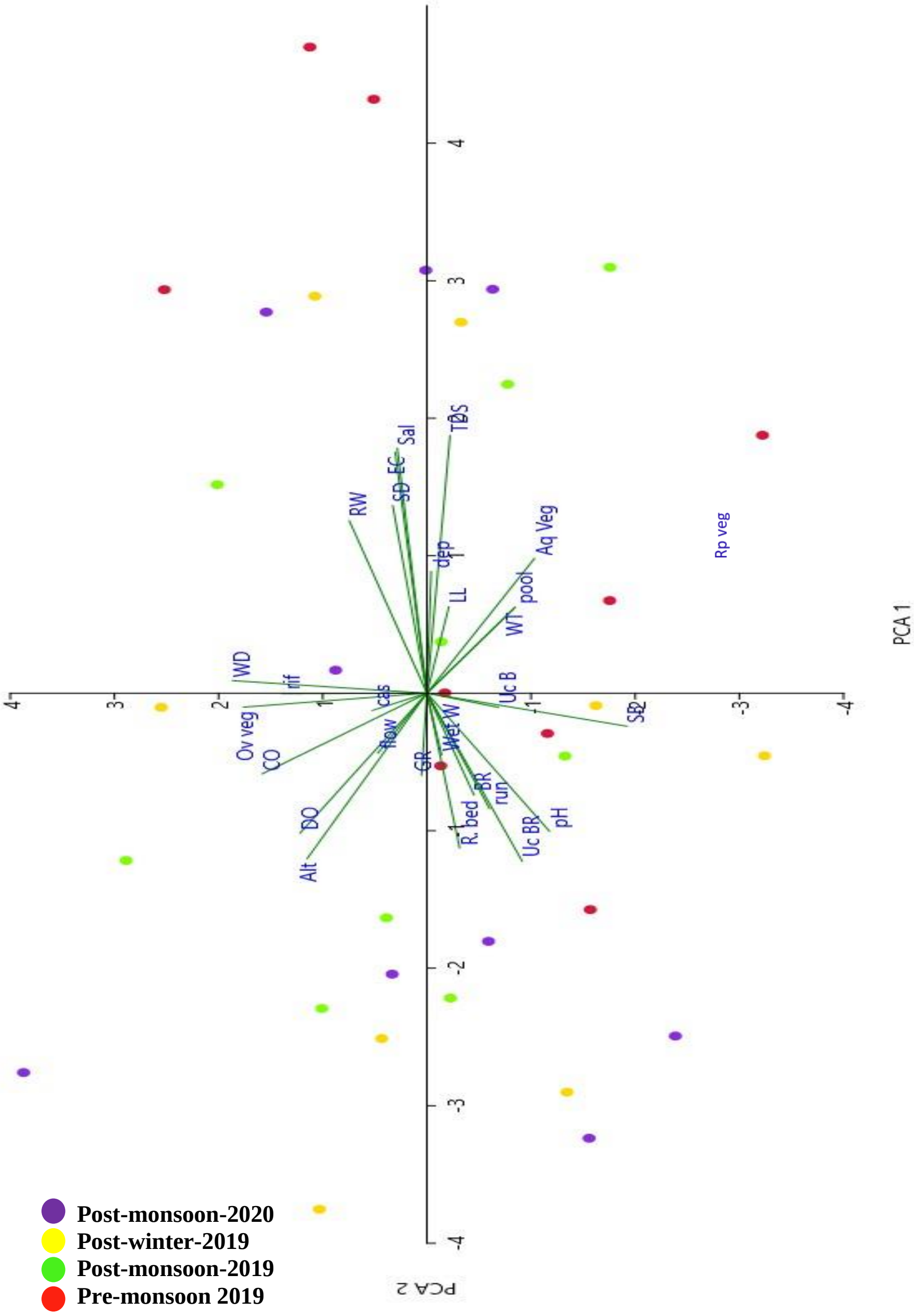


Figure 1.7: The environmental parameters representing the relationship in the studied rivers were analyzed using Principal Component Analysis (PCA).

1.3.7 Interaction between environmental parameters and observed fish species abundance

The canonical correspondence analysis established a significant relationship between fish abundance and the investigated environmental variables. Only 17 out of a total of 27 explanatory variables that significantly contributed to variation in the ordination were retained due to the forward selection procedure for the CCA. Biplots created by the CCA represented the cumulative distribution of various fish species and significant limnological traits. According to the CCA ordination map, the first axis contributed 19.22% of the variance, while the second axis contributed 15.92%. The species and their abundances were significantly correlated (p =0.0059) with the environmental parameters along axes and using a permutation test of the CCA model at the 0.001 level. TDS, EC, riparian vegetation (fish cover), depth, sand, small boulders, and salinity correlated negatively with the first ordination axis.

In contrast, dissolved oxygen, altitude, pH, cobbles (substratum), overhanging vegetation (fish cover), and river bed were correlated positively. The same was true for the second ordination axes, with positive results for dissolved oxygen, altitude, pH, cobbles (substratum), undercut boulders (fish cover), and riffle. It was negatively related to the river bed, depth, sand, small boulders, salinity, aquatic vegetation (fish cover), overhanging vegetation (fish cover), TDS, and EC. The species-environmental variable correlations for each axis were 0.87 (axis 1) and 0.75 (axis 2).

Four groups comprised the species abundance used to analyze the important habitat characteristics. The ten species that made up Group 1 were (*Schizothorax progestins, Schizothorax richardsonii*, *Nemacheilus montanus, Pethia conchonius, Opsarius bendelisis, Garra gotyla, Tor tor, Xenotodon cancila*, *Barilius vagra*, *Schistura* *rupicola*) (Fig. 1.8). Altitude, pH, dissolved oxygen, cobbles, and undercut boulders were the related to the habitat characteristics in this group. Six fish species, including *Bangana dero, Labeo pangusia, Botia almorhae, Labeo calabasu, Glyptothorax pectinopterus, and Chagunius chagunio,* made up the fish community in Group 2, and the only habitat factor associated to the group was the presence of riffles. For group 3, there were eleven different fish species (*Tor putitora, Paracanthogobius, Turquilabeo latius, Glossogobius giurus, Cirrihinus cirrhosis, Labeo bata, Wallago attu, Labeo catla, Mastacembalus armatus, Labeo rohita, Labeo dyocheilus*) with distinct habitat characteristics; salinity, TDS, EC, riparian vegetation, depth and presence of root-wards as fish cover and sandy substrate was present. The remaining group 4, which included five fish species (*Naziritor chelynoides, Barilius barna, Puntius sophore, Channa gachua, and Labeo dyecheilus*), had important habitat variables like a river bed, over-hanging vegetation, and woody debris.

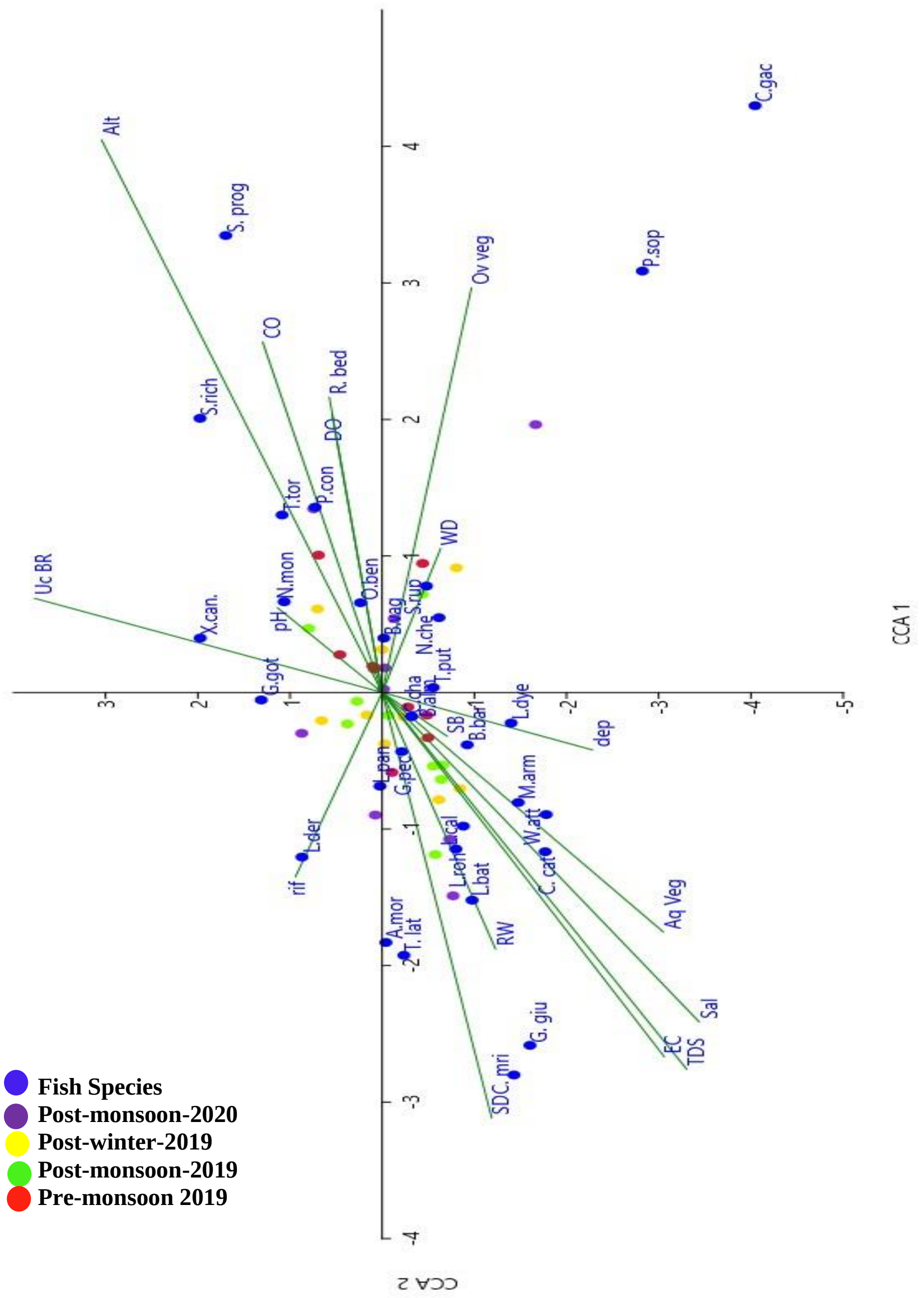


Figure 1.8: Representation of the relation between the environmental parameters and the recorded fish species in the rivers was analyzed using Canonical Correspondence Analysis (CCA).

1.4 Discussion

The habitat's features and environmental parameters significantly influence the aquatic fish assemblage in the river ecosystem (Bio et al., 2011). As a consequence, variations in the habitat characteristics and environmental parameters affect the distributional uniqueness of the aquatic environment as well as the composition of fish assemblages (Gorman and Karr, 1978; Gupta et al., 2012; Hossain et al., 2012; Vega-Cendejas et al., 2013; Akhi et al., 2020). Also, in any aquatic body, sampling attempts and stream accessibility impact the diversity of river fish species obtained (Horwitz, 1978). Besides the stream accessibility, freshwater fish diversity and distribution patterns were connected to various environmental characteristics extensively studied in the streams during the study period. Further, fish assemblage patterns due to the seasonal variations in the streams were reported in several studies (Sarkar et al., 2017; Bhatt et al., 2017; Sandhya et al., 2019). In the present study, Cypriniformes was reported (36.21%) to be the dominant order, which was previously reported to be present abundantly scattered in the tributaries of Ganga (Lakra et al., 2010; Atkore et al., 2011; Gupta et al., 2012, Kamboj et al., 2022).

The fish assemblage composition in the tributaries of the Ganga was found to be widely heterogeneous in the Himalayan foothills, and unique environmental factors govern the composition (Bhatt et al., 2000; Johal, 2002; Negi and Negi., 2010; Dubey et al., 2012; Atkore et al., 2011; Sarkar et al., 2017, Bhatt et al., 2012, Dwivedi et al., 2016; Johnson et al., 2020). However, seasonality influences the environmental variables and the fish assemblages (Kautza and Sullivan, 2012). The present study documented the high species abundance during the post-winter and pre-monsoon seasons and the low during the post-monsoon seasons. This could be because of the decreased water depth in the winters that get reduced to a minimum level due to little rainfall during this period, allowing fishermen to use their gear more efficiently (Akhi et al., 2020). The lower fish abundance in the pre-monsoon season compared to the post-winter season could be attributed to the rise in the river water's TDS, alkalinity, and EC or reduced water levels. The reducing effect of monsoon on the diversity and richness was earlier reported by (Rahman et al., 2015). The study reported higher fish diversity in Kolhu and Kosi, which was found to be related to the water quality during different seasons (TDS, EC, temperature, dissolved oxygen) (Das et al., 2020; Iqbal et al., 2022). Since these rivers flow through protected areas, they may have a higher species diversity than Khoh, which flows along the periphery of a forest but is not protected.

The most critical water-quality parameters associated with fish diversity were reported to be dissolved oxygen, total dissolved solids, and electric conductivity. Apart from them, altitude and pH were two other important parameters that were reported as significant. The study's findings were consistent with that of Galib et al. (2018), in which it was reported that DO and pH can significantly affect the patterns of fish assemblages. The presence of fish cover in the form of overhanging vegetation, undercut boulders, root wards/snags, and woody debris has been reported qualitatively to be significant for the fish diversity presence (Bhatt et al., 2016). Similarly, the presence of the substrate, especially sand, cobbles, and small boulders, is significant in areas with high fish diversity and is relatable to the previous studies (Bhatt et al., 2012; Gupta et al., 2012). The presence of fish cover, undercut boulders, cobbles, and smaller riverbed cover was positively related to increased altitude. Also, pH was reported to be positively associated with DO and altitude but negative with the rivers' TDS, EC, and depth. These studied parameters were found to be negatively correlated with an increase in EC and TDS, which was found to be similar to be reported by (Bhandari and Nayal, 2008; Singh and Akhtar, 2015). This relates to river systems in which, in the lower reaches of the river, the high concentrations of dissolved solids and salts result in high conductance in the water.

In the results, a preference for cyprinids with higher water depth, conductivity, salinity, and TDS was evident in the CCA biplot results. It was found that conductivity was co-related with the other chemical parameters, and we reported this to be positively correlated with the presence of cyprinids, similar to Bhandari and Nayal (2008) and Gupta et al. (2012). Angermeier and Karr (1984) reported earlier that woody debris was the preferred fish cover, but in this study, the presence of riparian vegetation, rootward snags, and undercut boulders along woody debris were reported in abundance in the habitats of cyprinids. The presence of deep pool habitats, riffles, and little water velocity was recorded as the most suitable sites for the cyprinids in the tributaries of Ganga (Lamouroux and Cattaneo, 2006; Sarkar et al., 2017; Bhatt et al., 2012, Dwivedi et al., 2016, Kamboj et al., 2022).

It was reported from the study that abiotic factors such as altitude, dissolved oxygen content, TDS, EC, depth, and pH, along with substrate presence and the fish cover, are important and reflect the level of species richness highly dependent on them. However, the importance of habitat type, pollution levels, and human activities cannot be ruled out. Obtaining information on their habitat requirements and conducting extensive investigations are critical for such significant species.

Chapter 2

Resource partitioning (space and food resource) of golden mahseer with other co-existing fish species

Running title: Resource and Space Use in Cyprinids

2.1 Introduction

Trophic resource partitioning and space use are fundamental means of understanding the co-existence of fish species that influence the community structure (Bovee et al., 1998; Pianka, 1969; Silva et al., 2012). Across zonal gradients in an ecosystem, trophic interactions may vary based on their local habitat characteristics, environmental integrity, as well as physical-chemical parameters (Pianka, 1969; Goulding, 1980; Prejs and Prejs, 1987; Quist et al., 2005; Lappalainen and Soininen, 2006). Also, biological interactions (such as competition and predation) affect the behavior of co-existing species in their habitats (Pearson and Dawson, 2003). In a community, species utilize different categories of available food resources and occupy favorable habitat types (Ross and Mathews, 1985). Challenges in resource partitioning arise when species co-exist with other species and share similar resources like food and space (Pianka, 1969; Schoener, 1982). However, for a given group of fish species in a habitat to fully comprehend resource partitioning, it is important to understand how the fishes select various feeding adaptations and their preferred habitats (Wotton, 1998). According to Ross (1986), partitioning within the community due to space followed by food is the most common in aquatic environments. Therefore, species with similar feeding strategies are grouped in similar tropic guilds in a community.

For a given group of species, to evaluate the dietary share levels in a habitat, niche breadth is determined (Segurado et al., 2011; Sa-Oliveira et al., 2014). Therefore, to classify species groups in a habitat, specialists and generalist groups are based on specialization in exploiting specific resources (Costello, 1990; Winemiller and Pianka, 1990). Species with narrow niche breadth are considered more specialized, whereas species having broad niches are generalist. Surveys on the trophic ecology of important surface dwellers, benthic feeders, and mid-column feeding provide important baseline information for understanding the food-web dynamics (Hayer, 2014). Further, analysis of niche overlap provides data for evaluating communities' structuring, which signifies competition between and within species (Schoener, 1974).

Several studies reported the species feeding behavior in ecological niches and, as a result of which species co-exist in a specific zone (Lucena et al., 2000; Chase and Leibold, 2009; Oscoz et al., 2005; Novakowski et al., 2008; Johnson et al., 2011; Sa-Oliveira et al., 2014). According to Nautiyal and Lal (1984), cyprinids dominate over other fish in terms of biomass and considerably impact trophic interactions in the aquatic systems in the Himalayan streams. Therefore, in this study, we looked at the diet, dietary habits, and habitat suitability to assess how much the cyprinid fishes overlapped in these dimensions. Earlier studies in the tributaries of river Ramganga in India explain the diversity and distribution patterns of significant cyprinid fish species (Atkore et al., 2011; Pandey and Upadhyay, 2016; Ali et al., 2018; Selakoti, 2018; Das et al., 2020; Iqbal et al., 2022). However, to support such studies, it is significant to understand the feeding ecology, resource and space use, and the fish species' trophic organization in river Ramganga's tributaries. Though golden mahseer and other cyprinids have been studied for their feeding habits, diminutive studies are known about their resource partitioning and habitat suitability. In this study, it was hypothesized that these fishes co-exist and utilize various available resources. The study compares the fish species' diets to estimate the niche breadth, overlap, and suitable microhabitat suitability. The study also attempted to test hypotheses that these fishes are generalist feeders and that the co-existence of such sympatric species leads to resource competition.

2.2 Materials and methods

2.2.1 Fish collection and dietary analysis

The fish sampling was performed in the stream reaches, upstream, downstream, and middle streams during the morning hours with the fishers' help. The fish catch was performed using cast nets (15mm, 24mm mesh size) and gill nets (40mm mesh size). All the captured specimens were identified up to the lowest possible taxonomic level, and these specimens were preserved in 10% formalin for gut analysis. The individuals of cyprinid fish were confirmed based on (Jayaram, 2010). The present study investigates the food preferences, feeding strategy, food partitioning, and dietary overlap of six cyprinid species (Family: Cyprinidae) thriving in two important tributaries of the Ramganga river basin. Among the species, *Tor putitora*, *Garra gotyla, Labeo pangusia, Labeo calbasu, Barilius vagra,* and *Opsarius bendelisis* were considered for the gut analysis for the post-monsoon season in 2019 & 2020 in Kosi and Khoh. The fish samples were calculated for their total length (L_T), standard length

(L_S), and body weight (B_W). Diet composition was based on the analysis of the fish individuals' 5 to 10 stomach contents, and the analyses were restricted to adult fishes (Oliveira et al., 2013). To investigate the dietary items, the specimens were dissected for the guts. The guts were then uncoiled and measured to get the gut length (G_T) to the nearest cm and gut-weight (G_T). Fish guts were then opened under a dissecting microscope (5x). The anterior one third of the intestine was dissected as cyprinids lack a distinct stomach (Herder and Freyhof, 2006). The gut content was squeezed out in the glass plates to measure the weight of the gut content.

Dietary components were measured, counted, and weighed using the Petri plates after separation. Data was obtained to quantify the volume by compressing the food items in small cylindrical graduated tubes to measure the height (ml) and further calculating the water displacement (Sa-Oliveira et al., 2014). The occurrence of each food item was examined by compressing (food items) in a counting glass chamber with a one-mm grid using the optical and stereomicroscope (40X). The study's gut content analysis method was followed using Hyslop (1980), Sa-Oliveira et al. (2014), and Johnson and Arunachalam (2011). The volume proportion of occurrence of each food item was converted to the percentage. Here, we assumed that the results obtained using these methods were similar. Following Hyslop (1980), the frequency of occurrence (O %), % number (N %), and % volume (V %) of food items were calculated. Further, a combination of these parameters was used to calculate the relative weight of each diet category for each fish species using Pianka's (1971) Index of Relative Importance (IRI);

$$\boldsymbol{IRI\ \% = 100((N\ \% + V\ \%)\ O\ \%^{-1})\ (\Sigma\ (N\ \% + V\ \%)\ O\ \%^{-1})^{-1}}$$

The separated food items were identified to have the lowest possible taxonomic levels in the diet composition. The classification with details of the different categories was grouped and was further classified into 11 subcategories with little modifications (Nowakowski et al., 2007; Johnson and Arunachalam, 2011; Sa-Oliveira et al., 2014); **1**-animal matter (including the whole and remains of aquatic and terrestrial insects, fin fish and shellfish); **2**- vegetative matter (including unidentified remains of leaves, flowers, fruits, seeds, and algae); **3**- detritus (including organic debris at different stages of decomposition); and **4**- unidentified matter (unknown remains of non-fish vertebrates). The technique for gut content analysis was followed (Hyslop, 1980; Johnson and Arunachalam, 2011; Sa-Oliveira et al., 2013). The diet composition was analyzed based on research to understand the preferences of the different fish species. A one-way ANOVA test was measured to check for significant differences in the relative percentage of each food category in the fish's diet for two years. Further, the trophic groups were established through cluster analysis using the data of relative weight of food categories with the Euclidean distance and UPGMA method (Vidotto-Magnoni and Carvalho, 2009; Johnson and Arunachalam, 2011).

2.2.2 Trophic Niche Breadth

To determine the diet specialization of each species, niche breadth (*Bi*) was calculated using Levin's index (1968);

$$B_i = (\Sigma^n{}_i \, p_{ij}{}^2)^{-1}$$

where *pij* represents the proportion of food items of predator I on prey *j* and *n* represents the total number of food items in the diet. Levin's measure (Krebs, 1999) was calculated using individual prey number data to determine the niche breadth of each species.

2.2.3 Niche Overlap

Analysis of species feeding overlap between the species was calculated using Pianka's index (Pianka, 1973), which ranged between 0 to 1, with 1 indicating complete overlap. The analysis of niche overlap between the two species was based on Pianka's index derived from the different species' diet composition (%):

$$O_{jk} = \frac{\sum_{i}^{n} p_{ij} p_{ik}}{\sqrt{\sum_{i}^{n} p_{ij}^2 \sum_{i}^{n} p_{ik}^2}}$$

Where '*Ojk*' is Pianka's index of niche overlap between species '*j*' and '*k*,' '*pij*' is the proportion of the *ith* resource in species *j's* diet, *pik* is the proportion of the *ith* resource in species *k's* diet, and '*n*' is the total number of items. The Pianka index values were classified using the Grossman (1986) and Novakowski et al. (2008) methods. Here, the assumption was that different dietary resources available as a resource are equally accessible to all species (Sa-Oliveira et al., 2013). Further, data were analyzed for indices of both nice breadth and overlap using the one-way analysis of variance (ANOVA) where ($p < 0.05$) significance level was considered.

2.2.4 Microhabitat Use and Availability

For the space use analysis, field surveys were performed during the post-monsoon (mid-October), post-winter (February-March), and pre-monsoon (May-June) seasons in the years 2019-2020. The reach was selected down, middle, and upstream, and the habitat availability data of micro-habitats was collected. Data collection and micro-habitat features were quantified using the transects within each study stream and carried out in the selected reach length (Pusey et al., 1993). At every 20m, the data on streamflow, depth, and substrate available were recorded (Bovee, 1982) using a measuring rope (1m cross-section), and the flow velocity was measured using a hand-held digital flow probe (3.7-6', Model: FP111, Global Water Instrumentation). The major substrate types were measured: bedrock (> 200mm), small boulders (150–200mm), cobbles (50–150mm), gravel (5–50mm), sand-silt (1-2mm), and leaflitter (Bovee, 1982; Pusey et al., 1993). Wetted width was measured at 20m intervals along stream banks every season. Measurements of the habitat structure were followed using (Gorman and Karr, 1978; Arunachalam, 2000; Johnson et al., 2020) with few modifications based on the physiographic conditions of Himalayan streams. The spatial habitat (depth, water column velocity, and substrate availability) of physical locations occupied or used by the cyprinids were studied to understand their suitability. Microhabitat available and use data of depth and water velocity were classified into eight depth classes (0.1-0.3, 0.3-0.6, 0.6-1.0, 1.0-1.2, 1.2-1.5, 1.5-1.8,1.8-2.0 and >2.0 m) six water velocity class (0-0.3, 0.3-0.6, 0.6-0.9, 0.9-1.0, 1.0-1.2 m/s) as per the methods of Johnson et al. (2017). The relative frequencies were measured for each depth and water velocity classification. To calculate preference for each class interval, based on availability and use, ‘$Pi = Ui/Ai$’ was used, where ‘Pi’ is the relative preference value, ‘Ui’ is the proportion of utilization of a specific interval, and ‘Ai’ is the proportion of a particular interval of the measured variables when fish were sampled. The preferences were normalized using the formula ‘$Pn = Pi/max\ P$’ and were normally calculated on a scale of 0 to 1, from not used to optimal utilization. In the range of the variable *Pi, Pn* is the normalized index of preference, and *max P* is the highest index of preference. For the study sites, the depths and water velocities of cyprinids were measured, and habitat suitability criteria curves (HSCs) were created (Hayes and Jowett, 1994; Bovee et al., 1998; Jowett and Davey, 2007; Johnson et al., 2017). Habitat suitability was displayed as continuous curves implying the suitability of the target habitat variables, the most important of which are depth and flow velocity (Santos et al., 2008; Boavida et al., 2013; Rivaes et al., 2017).

2.3 Results

2.3.1 Diet composition

The six studied species' body size and gut length are given in (Table 2.1). The relative composition of the different food items in the stomachs of all the investigated fishes was calculated based on volumetric analysis (V%), numeric method (N%), and occurrence method (O%), and they are documented in Tables 2.2 and 2.3, respectively. It was found that fishes fed upon the macro-vegetation, insects (aquatic and terrestrial), other small fishes, and detritus materials. However, variation has been observed in different food items in the fish species. Here, the results showed that the *Tor putitora* is primarily an insectivore, consuming a variety of aquatic and terrestrial insects, fin- and shellfish. The main diet components were Diptera, Isoptera, and Trichoptera. IRI% (Index of relative importance) results showed that animal matter (aquatic insects) is the main food source for *Opsarius bendelisis*. Similarly, *Barilius vagra* feeding habits were also characterized by a high content of animal matter (the presence of aquatic insects' body parts). As per the results, *Labeo* species (*Labeo pangusia and Labeo* *calbasu*) were found to be herbivores in nature. The proportion of the fish's preferred food item was vegetative matter (preferably fallen leaves and algae) and was reported to be dominant in their diet. Considerably higher ratios of detritus matter and unidentified gut content were also reported in their diets. The presence of vegetative matter, primarily algae and detritus material, including most of the sediments in *Garra gotyla*, indicated the fish was an algal feeder. Further, fishes had significant differences in their relative percentage for each food category (p=0.00064, df = 21.75, F=5.193 and p=0.0036, df = 21.6 and F= 8.426) during the two years. And, in terms of digested and undigested matter, fish species mostly had >40% of digested food content (Fig. 2.2). In the case of *Tor putitora*, it was reported that the fish hindgut contained most of the digested matter, fish scales, insect parts, and sand.

Table 2.1 Body sizes and gut length and weight of cyprinid fishes recorded from the study area

S.No.	Fish species	Total length (cm)	Standard size (cm)	Body weight (g)	Gut length (cm)	Gut weight (g)
1	***T. putitora***	25.73 ±11.81	21.56 ± 10.35	248.93 ± 185.1	64.65 ± 31.94	10.51 ± 8.81
2	***O. bendelisis***	13.96 ± 2.85	11.88 ± 2.92	22.24 ± 8.30	17.84 ± 5.70	1.80 ± 0.455
3	***B. vagra***	11.98 ± 0.59	9.98 ± 0.59	17.45 ± 1.77	15.40 ± 3.13	1.10 ± 0.28
4	***G. gotyla***	11.18 ± 1.92	9.40 ± 1.70	20.28 ± 11.62	13.17 ± 5.02	1.83 ± 0.71
5	***L. pangusia***	24.17 ± 9.69	19.60 ± 7.96	173.71 ± 146.24	284.33 ± 238.3	19.50 ± 20.64
6	***L. calbasu***	25.02 ± 11.31	20.46 ± 9.36	237.66 ± 203.49	279.23 ± 237.08	17.27 ± 17.30

Table 2.2.: Relative weight (%) of diet items recorded in cyprinids during the post-monsoon season 2019

2019	***T. putitora***	***O. bendelisis***	***B. vagra***	***G. gotyla***	***L. pangusia***	***L. calbasu***
Animal Matter						
1. Aquatic insects	24.66	18.15	18.94	0	1.12	1.86
2. Terrestrial insects	7.57	2.59	1.14	0	1.34	0.67
3. Fin fish	9.64	0	2.16	0	0	0
4. Shellfish	10.16	0	0	0	0	0
Vegetative Matter						
1. leaves	6.01	1.25	1.69	9.06	21.02	21.14
2. Flowers	0.00	0	0	2.02	2.53	1.13
3. Fruits	3.42	0	0	0	0	0
4. Seeds	5.49	0	0	0	3.61	3.07
5. Algae	8.08	5.25	6.2	32.31	26.39	28.16
Detritus (g)	15.33	13.32	12.14	29.56	19.44	22.9
Unidentified (g)	9.64	36.11	32.76	24.7	17.88	18.31

Table 2.3: Relative weight of the diet items recorded in cyprinids during the post-monsoon season 2020

2020	**T. putitora**	**O. bendelisis**	**B. vagra**	**G. gotyla**	**L. pangusia**	**L. calbasu**
Animal Matter						
1. Aquatic insects	14.08	17.49	19.34	0	1.07	0.38
2. Terrestrial insects	7.28	2.48	3.53	0	1.74	1.76
3. Fin fish	14.08	0	0	0	0	0
4. Shellfish	11.65	0	0	0	0	0
Vegetative Matter						
1. leaves	10.68	0.35	0.34	3.9	30	17.01
2. Flowers	0.00	0	0	2.67	1.42	1.62
3. Fruits	5.83	0.78	0	0	1.42	0
4. Seeds	6.80	0.15	0	0	5.4	1.62
5. Algae	9.71	1.06	1.84	20.7	15.24	24.12
Detritus (g)	11.65	13.5	17.46	33.04	19.57	27.42
Unidentified (g)	8.25	39.77	34.46	36.69	18.72	24.49

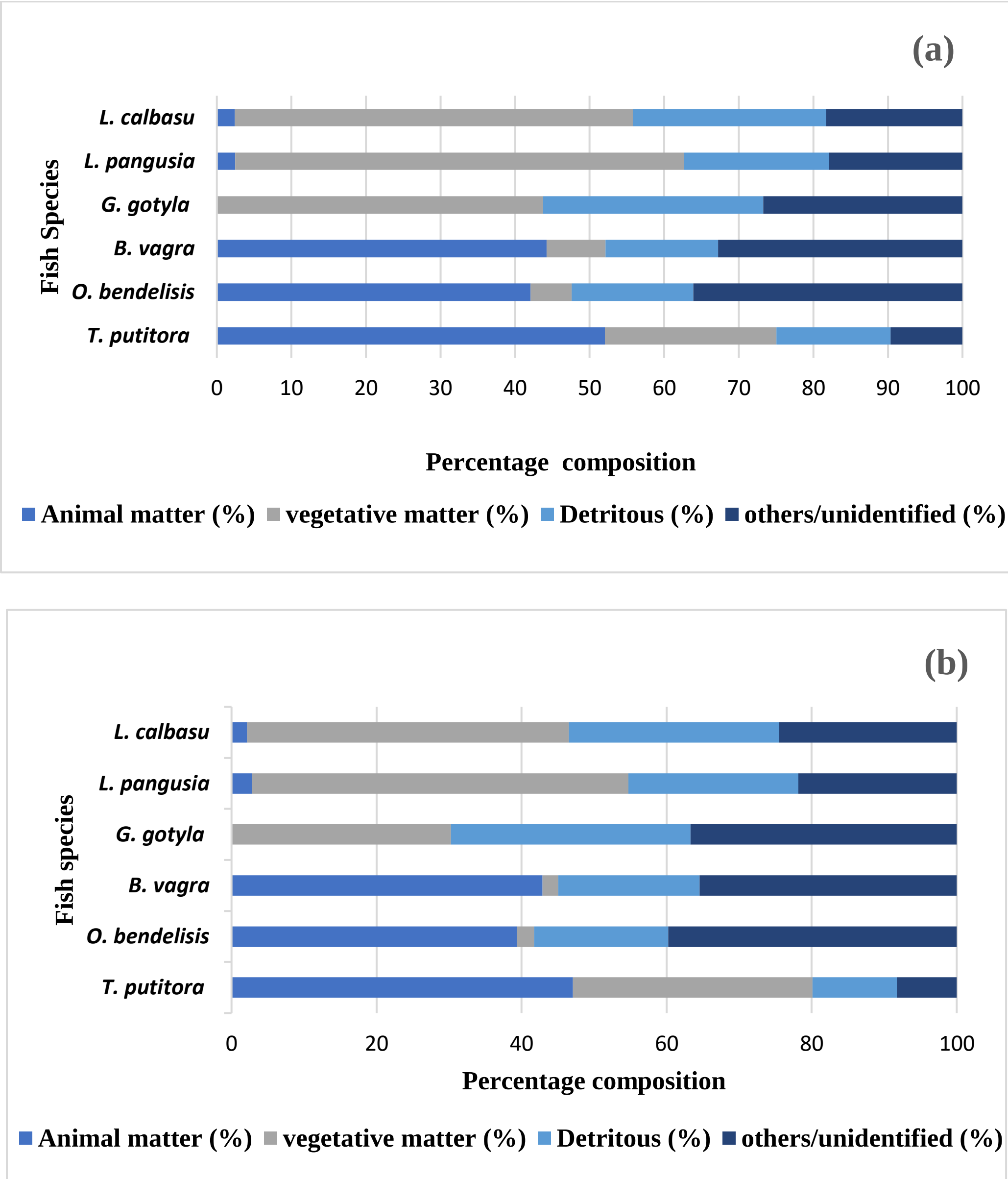


Figure 2.1: Relative percentage composition of diet components in the gut of fish samples in (a) 2019 and (b) 2020 during the post-monsoon season.

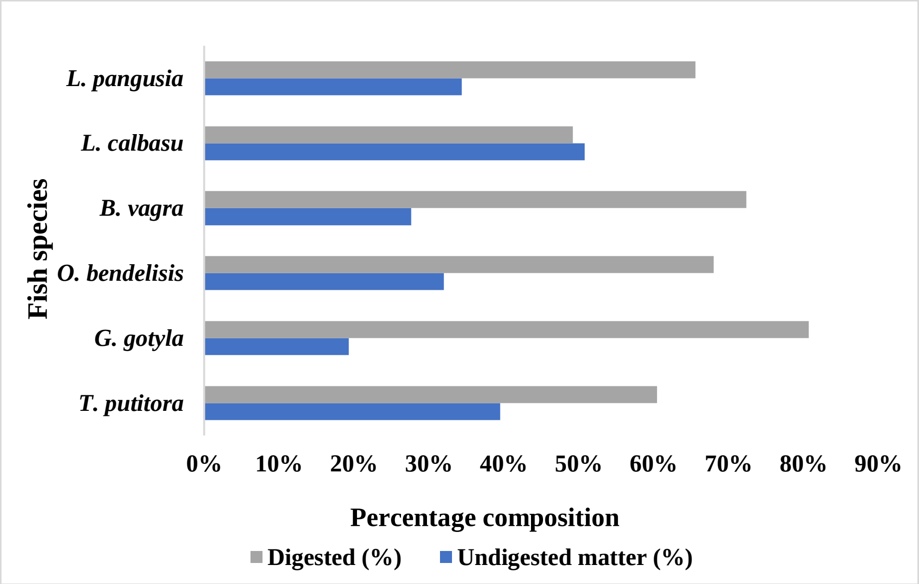


Figure 2.2 Digestive and undigested material reported in the gut content analysis of fish samples.

2.3.2 Niche Breadth

For both years, the value of niche breadth was studied for the fish species (Table 2.4). The present study's Niche Breadth (*Bi*) values ranged from 0.90 to 4.90. The study found that accounting for more than half of the species displayed niche breadth between (1.90-2.75) for the specialist species' diet. The fish species *L. calbasu* (1.96), *L. pangusia* (1.91), *O. bendelisis* (2.62), *G. gotyla* (2.19), and *B. vagra* (2.16) were found to have specialized diets in 2019 while *T. putitora* was found to have a larger niche breadth that falls between a specialist and a generalist with more inclination to be a generalist in nature with a niche breadth of 4.90 (Fig. 2.3).

Table 2.4: Standardised Levin's niche breadth measured during post-monsoon season 2019 and 2020

Seasons/Year	*O. bendelisis*	*B. vagra*	*T. putitora*	*G. gotyla*	*L. calbasu*	*L. pangusia*
Post Monsoon 2019	**2.62**	**2.16**	**4.90**	**2.19**	**1.96**	**1.91**
Post Monsoon 2020	**2.75**	**2.36**	**4.37**	**1.90**	**1.88**	**1.67**

According to the study, all species except *T. putitora*, which had a high value (4.37) in 2020, have been classified as a generalist feeder. The diet analysis showed that the *Labeo* species, including *L. calbasu*, which has a narrower niche breadth of (1.88), and *L. pangusia*, which is (1.67), are highly specialized in nature. Here, it was determined that the *O. bendelisis* (2.75), *B. vagra* (2.36), and *G. gotyla* (1.90) are specialists in their feeding behavior (Fig. 2.3). According to the ANOVA test, there were no significant difference was reported between seasons in terms of diet breadth.

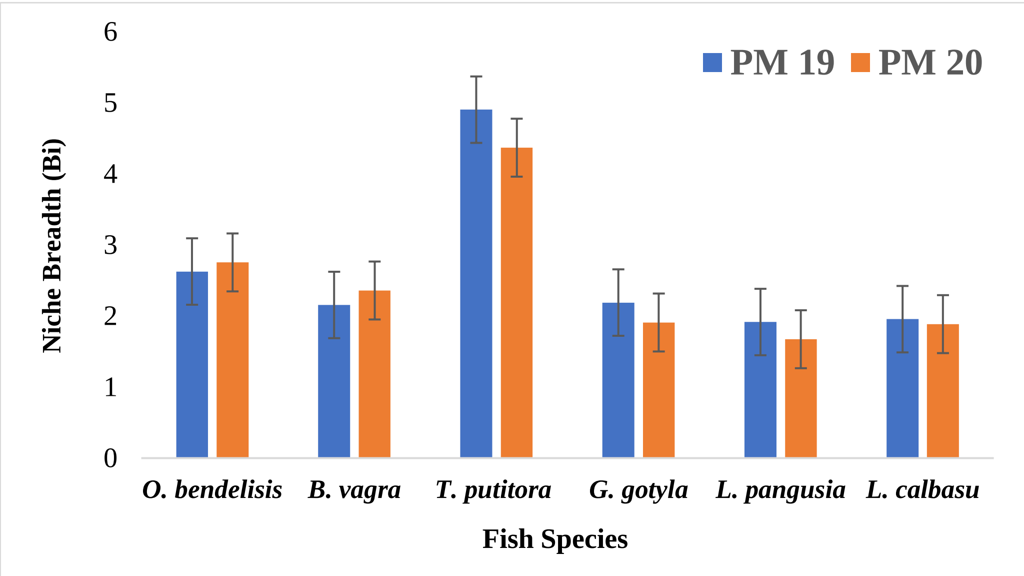
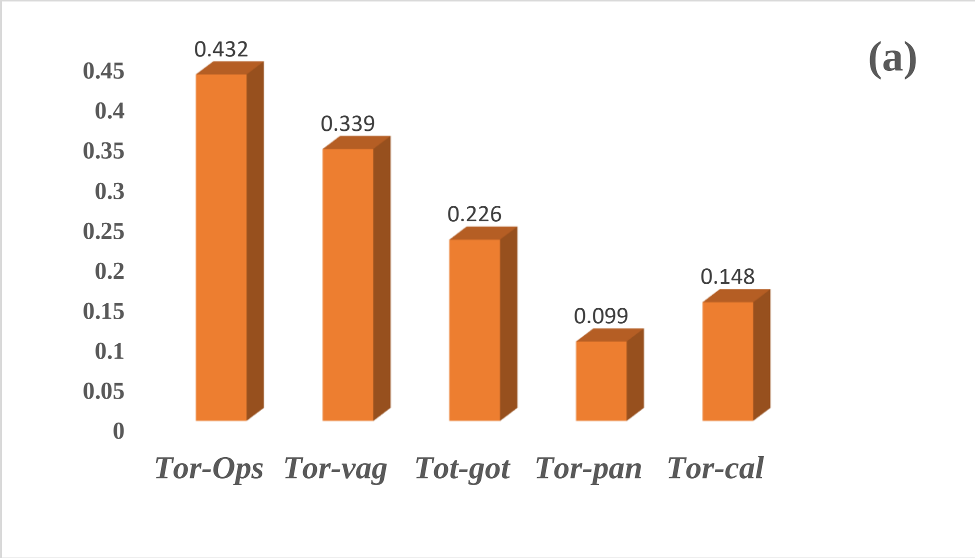


Figure 2.3: Levin's niche breadth measured for 2019-2020.

2.3.3 Niche Overlap

The diet overlaps results from Pianka's overlap index reported that the species co-existing along *T. putitora* revealed intraspecific similarities in some species' diets and interspecific relations (Fig. 2.4a). The *O. bendelisis* (0.432) showed high overlap with the diet of *T. putitora,* followed by *B. vagra* (0.339). During the post-monsoon 2019, the other three cyprinids, *L. calbasu* (0.148), *L. pangusia* (0.09), and *G. gotyla* (0.226), reported low diet overlap with *T. putitora*.

In 2019, data from 2022 showed that the *Labeo* species *L. calbasu* (0.116) and *L. pangusia* (0.134) had a low diet overlap with *T. putitora*. The intermediate or moderate overlap was reported for *G. gotyla* (0.237) and *O. bendelisis* (0.356) with *T. putitora* (Fig. 2.4b). However, compared to *B. vagra*, which reported moderate overlap intensity during 2019, the overlap value was significantly higher (0.35). The fish was reportedly found to overlap with *T. putitora* and changes in the availability of resources during that season could be the reason.



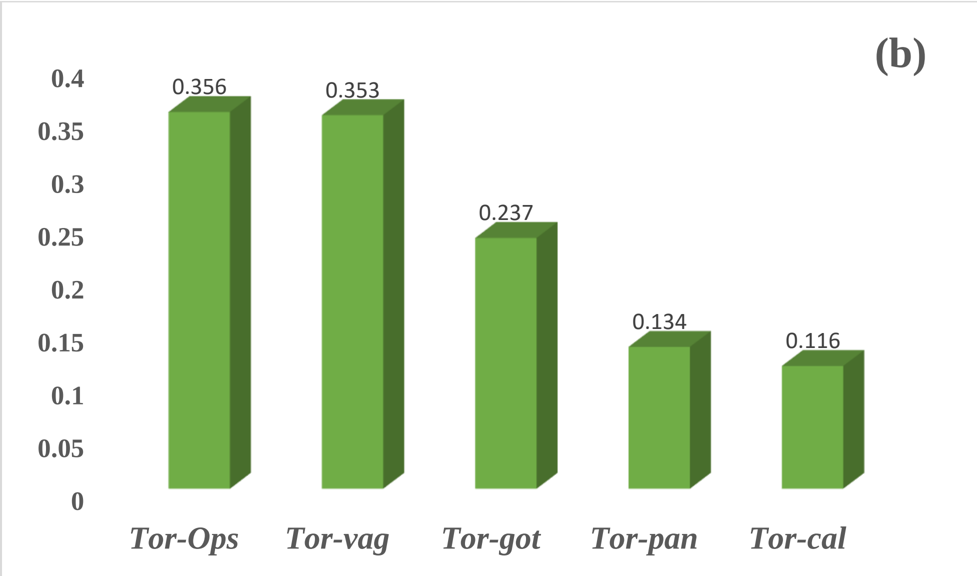


Figure 2.4: Pianka's Niche overlap measured during the post-monsoon season (a) 2019 and (b) 2020.

**Tor-Ops (Tor putitora- Opsarius bendelisis); Tor-vag (Tor putitora-Barilius vagra); Tor-got (Tor putitora-Garra gotyla); Tor-pan (Tor putitora-Labeo pangusia); Tor-cal (Tor putitora-Labeo calbasu).*

In the gut content analysis concerning food categories, since no significant differences were found among the various food categories, we attempted to establish a relationship between the species based on the foods consumed. The similarity dendrogram based on food items ingested by fishes during the post-monsoon season in 2019 and 2020 (Fig. 2.6) showed the occurrence of four trophic groups, and they were reported as (I) OMNIVOROUS, which included species that primarily consumed terrestrial and aquatic insects and occasionally consumed animal matter, vegetative matter and detritus. This category consists of one species, *T. putitora*. Following this, (II) INSECTIVOROUS, which includes the two cyprinids *B. vagra* and *O. bendelisis*, which feed primarily on insects, algae, and sediment particles, were classified under this group. (III) HERBIVOROUS consisted of *Labeo* species, *L. pangusia*, provided on a variety of fallen leaves and other vegetative matter, and (IV) ALGAL FEEDER, represented by two species, *L. calbasu* and *G. Gotyla*, which was found to consume a variety of algae and detritus material.

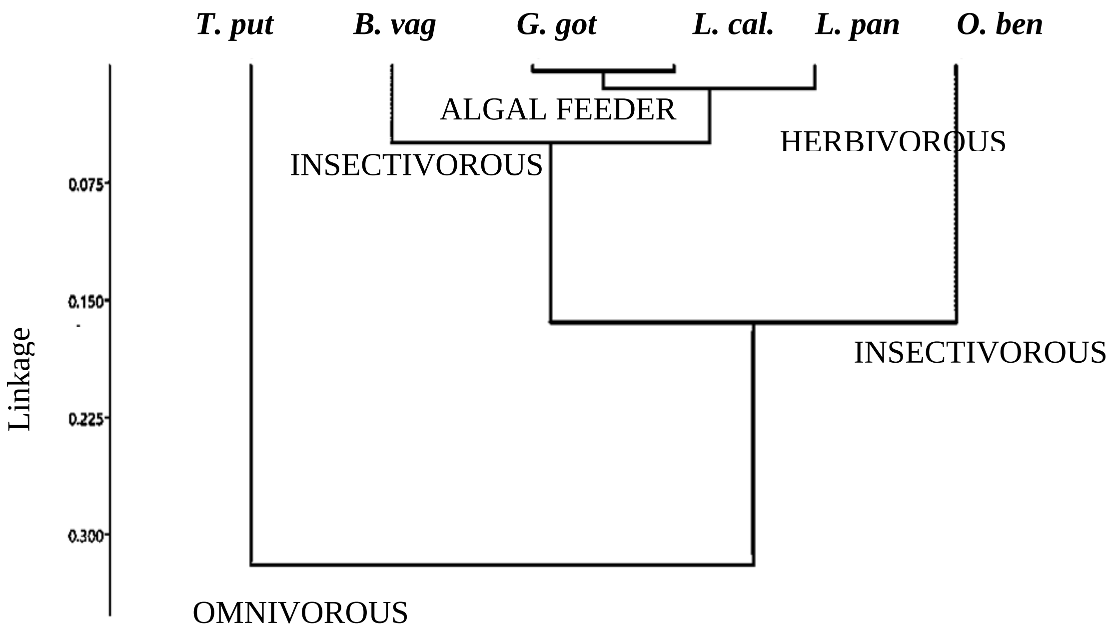


Figure 2.5: Dendrogram of the main cyprinid fishes' main trophic groups as given by Kosi and Khoh's linkage distance. *T. put (Tor putitora); B. vag (Barilius vagra); G. got (Garra gotyla); L. cal (Labeo calbasu); L. pan (Labeo pangusia); O. ben (Opsarius bendelisis).*

2.3.4 Habitat partitioning in cyprinids

The study's habitat variables were typically those of a sandy-rocky bottom with reported gentle to turbulent flow during pre-monsoon and post-monsoon, respectively. The depth ranged from (0.3-6.5m) throughout seasonal surveys, and the most frequent depth observation was between (1-1.5m) in the post-monsoon, (0.6-1.2m) was observed during post-winter and in the pre-monsoon, it was observed ranged between (0.1-0.6m) (Fig. 2.6 a). The measured water column velocity ranged between (0.0- 2.4 m/s). During the post-monsoon, it was reported to be frequent between (0.6-1.2m/s); during post-winter, it was (0.3-0.6m/s), and in the pre-monsoon, it ranged between (0-

0.3m/s) (Fig. 2.6 b). Here, water velocities were reported higher only during the post-monsoon season of the study period.

The spatial segregation of species was reported along gradients of depth (vertical height in the water column) and flow velocity. *T. putitora*, being the important key species of the study, was frequently encountered, and it was reported that adult fish used a range of (0.6-2m), although it varied during the seasonal study where it was found thriving between (1-1.5m) during the post-monsoon, (0.6-1.2m) during post-winter and less frequent during pre-monsoon (0-0.6m). The water velocity was higher in the post-monsoon and post-winter seasons than in the pre-monsoon season. *G. gotyla* was the second most observed species in the study. It was observed that individuals of *G. gotyla* were mostly found in shallow water areas in association with the depth range between (0-0.6m) in post-monsoon and (0-0.3m) during post-winter and pre-monsoon (Fig. 2.7). Water velocity associated with *G. gotyla* ranged 0 and 0.3m/s during different seasons. In the habitat partitioning, *G. gotyla* reportedly thrived in the shallower water areas with moderate flow velocity compared to *T. putitora*, which was found in the deeper water areas with medium to high-velocity use.

For *Barilius vagra*, the depth ranged between 0.1 and 0.6m, and the velocity ranged between 0 and 1m/s (Fig. 2.8). For *Opsarius bendelisis*, the depth varied between 0.6 and 1m. During the post-monsoon, it was between (0.3 and) for the post-winter season, and it was reported high between 0.1 and 0.6m in the post-winter. Water velocity for *Opsarius bendelisis* was found between 0.3 and 1m/s during the post-monsoon. It ranged between (0-0.6m/s) and (0-0.3m/s) during post-winter and pre-monsoon, respectively (Fig. 2.9). In the habitat partitioning in *O. bendelisis* and *B. vagra* with *T.*

putitora, both have observed to be thriving in mid-column area. Still, *bendelisis* was also observed to thrive in shallower areas during different seasons (Fig. 2.9).

The optimal depth preference of adult *L. pangusia* was reportedly found in-depth ranged between (1-1.5m) during post-monsoon, and they were reported deeper during the post-winter season in depth range between (1.2-1.8m) and were observed comparatively in the shallower areas during pre-monsoon season (0.3-1m). The associated water velocity was between (0-0.6m/s) during post-monsoon and winters and less during pre-monsoon. In the habitat partitioning in *O. bendelisis* and *B. vagra* with *T. putitora*, both have been observed thriving in mid-column areas. Still, *bendelisis* was also observed to be thriving in shallower areas (Fig. 2.10). For *L. calbasu*, depth was reported in association with moderately deeper open-channel regions of the river. It was written between 0.6 and 1.8m. It was reported that water velocity ranged between (0-0.6m/s) during different study periods. Among them, they have been observed to be thriving in deeper areas with low water velocity.

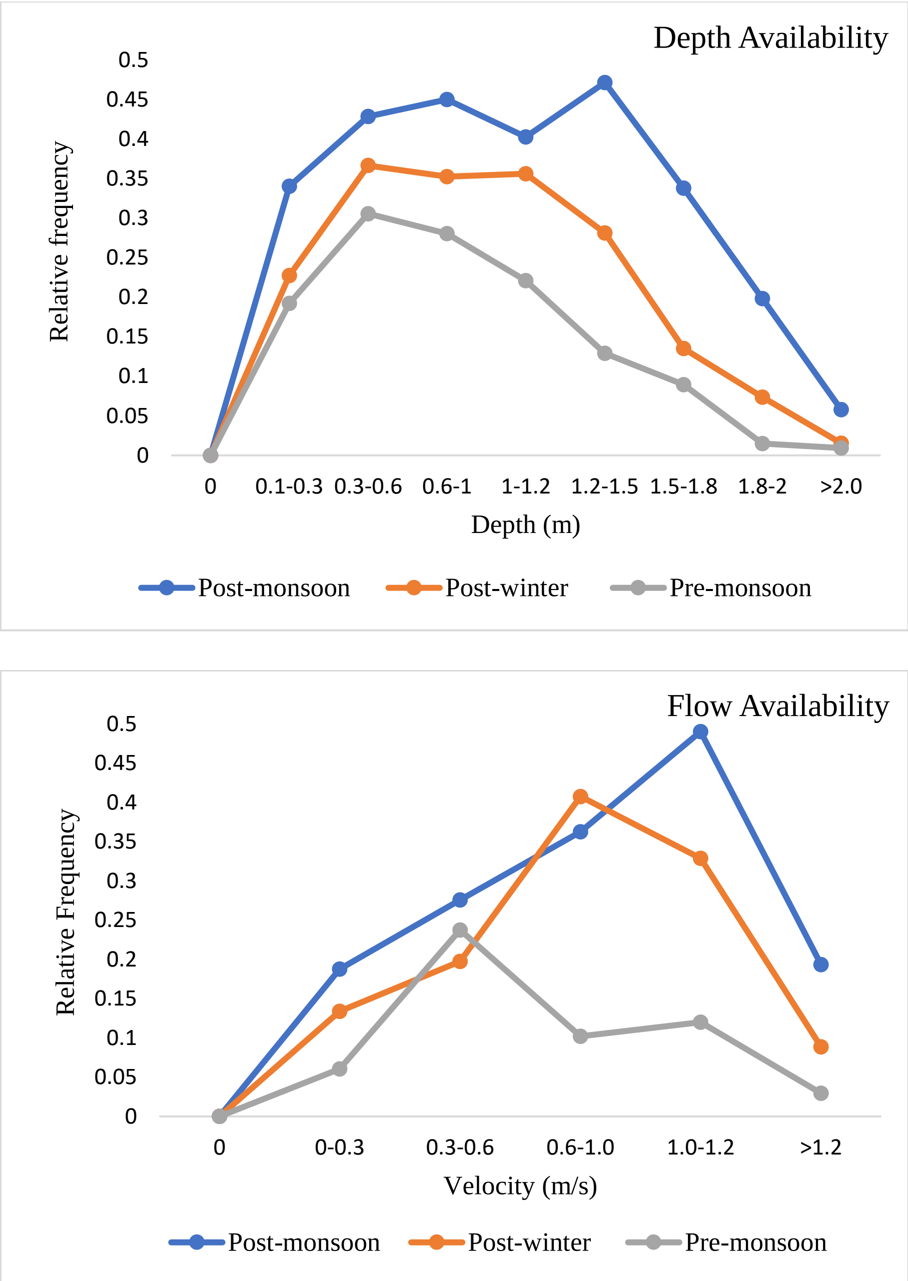


Figure 2.6: Relative frequency of available depth and water velocity in fish habitats in the studied rivers representing (a) depth availability, (b) water velocity availability.

Figure 2.7: Habitat partitioning (depth and velocity) in *Tor putitora* and *Garra gotyla* during different seasons in the studied river.

(*PW-Post winter, PM-Post Monsoon, PreM-Pre-Monsoon)

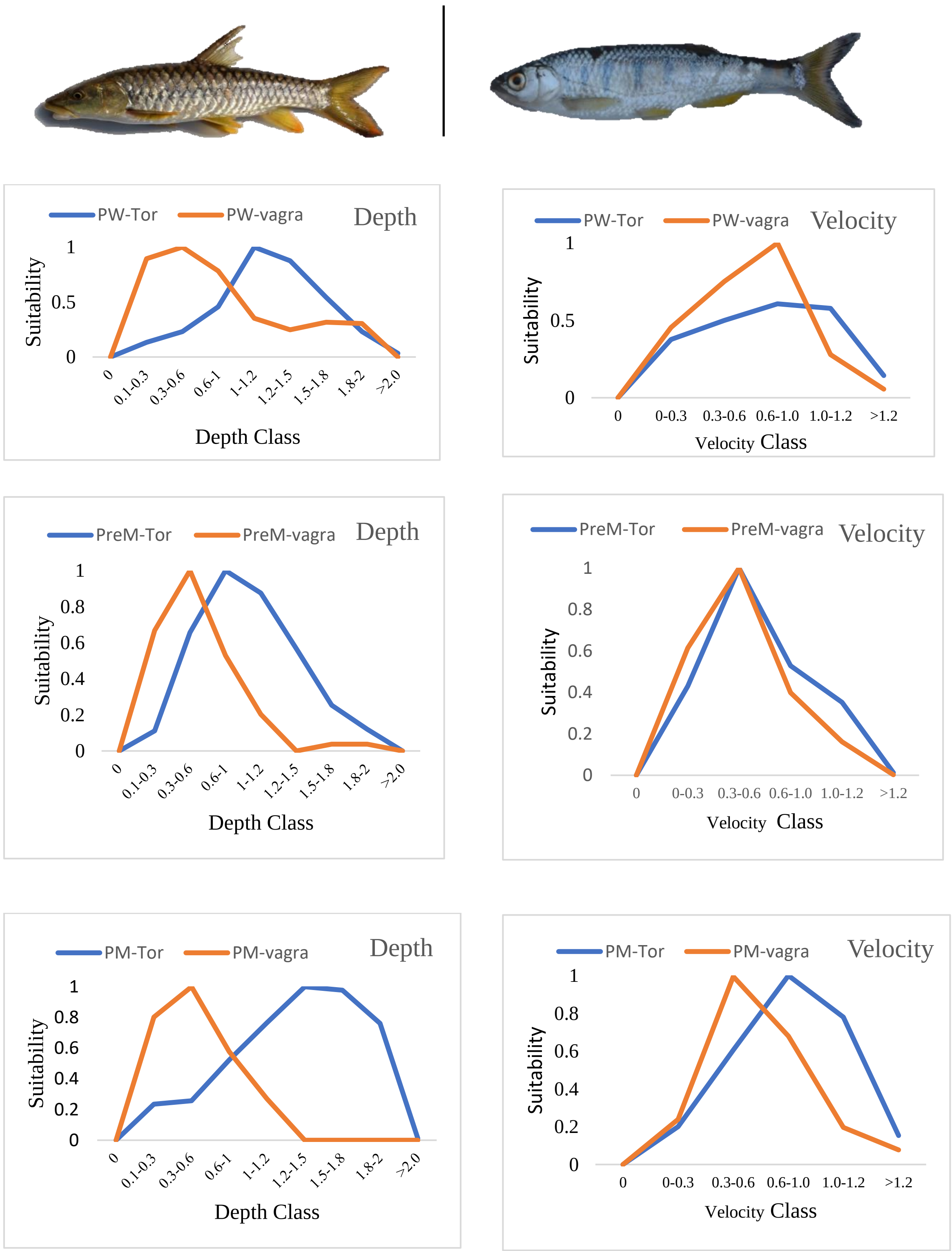


Figure 2.8: Habitat partitioning (depth and velocity) in *Tor putitora* and *Barilius vagra* during different seasons in the studied rivers.

(*PW-Post winter, PM-Post Monsoon, PreM-Pre-Monsoon).

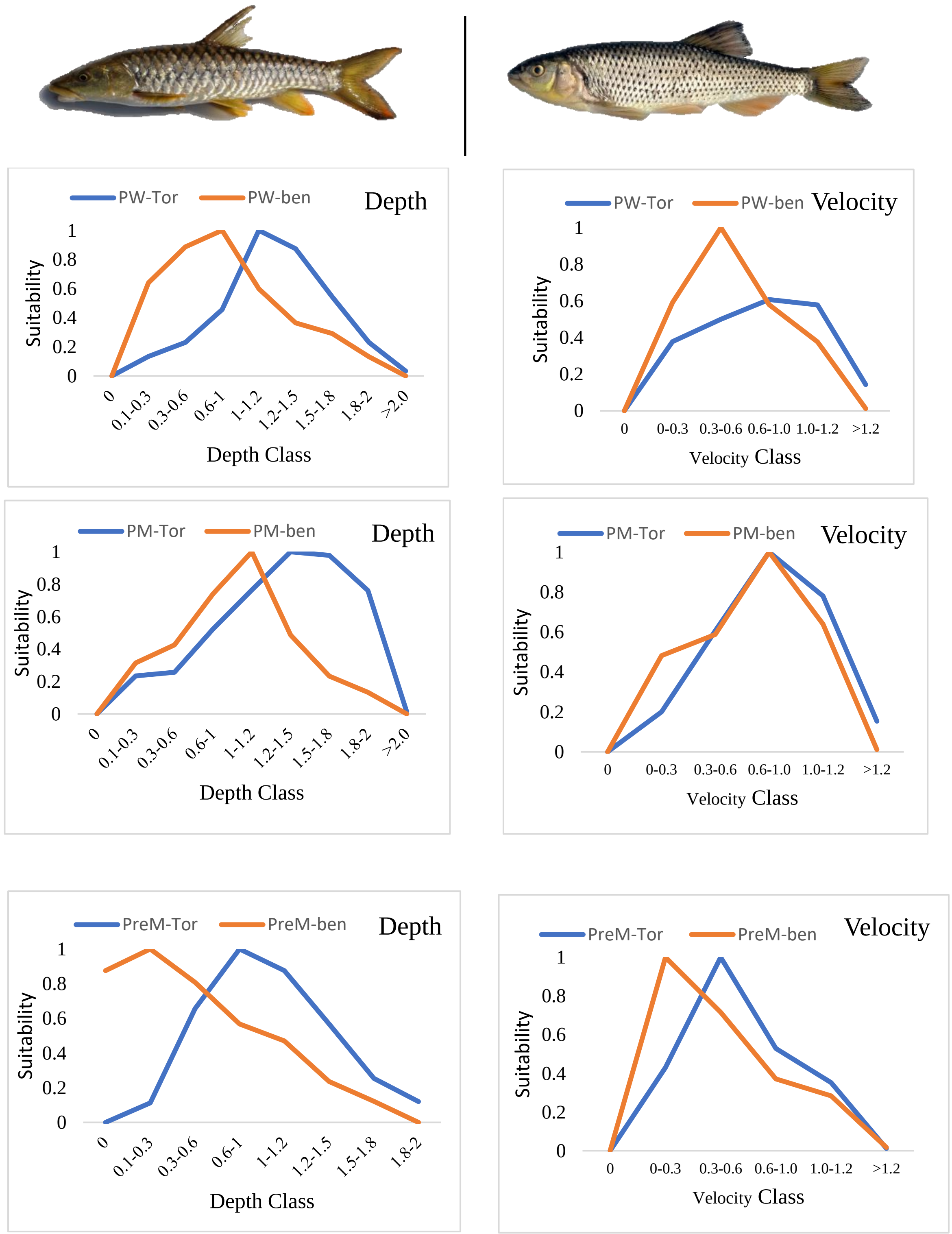


Figure 2.9: Habitat partitioning (depth and velocity) in *Tor putitora* and *Opsarius bendelisis* during different seasons in the studied rivers

(*PW-Post winter, PM-Post Monsoon, PreM-Pre-Monsoon)

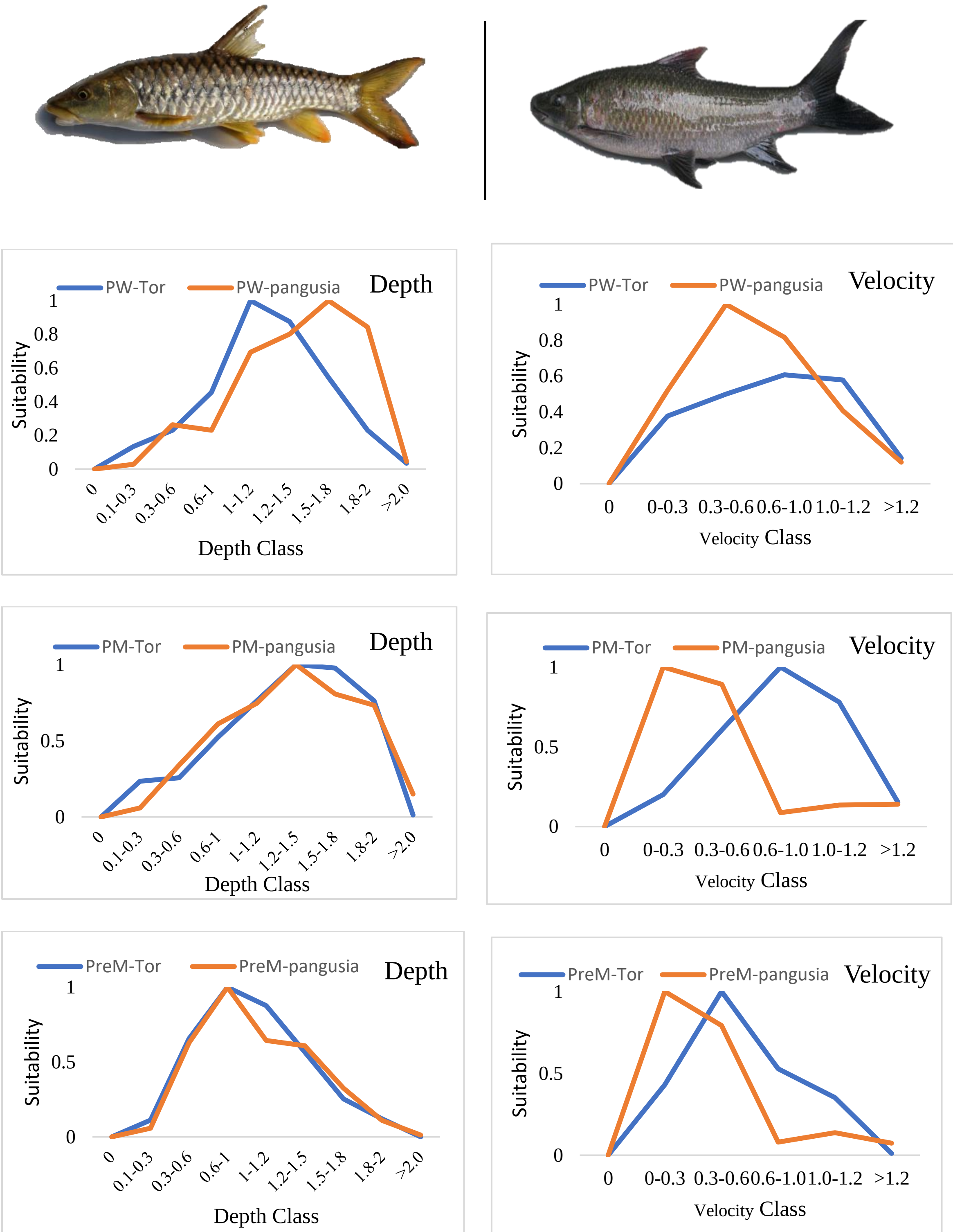


Figure 2.10: Habitat partitioning (depth and velocity) in *Tor putitora* and *Labeo pangusia* during different seasons in the studied rivers.

(*PW-Post winter, PM-Post Monsoon, PreM-Pre-Monsoon).

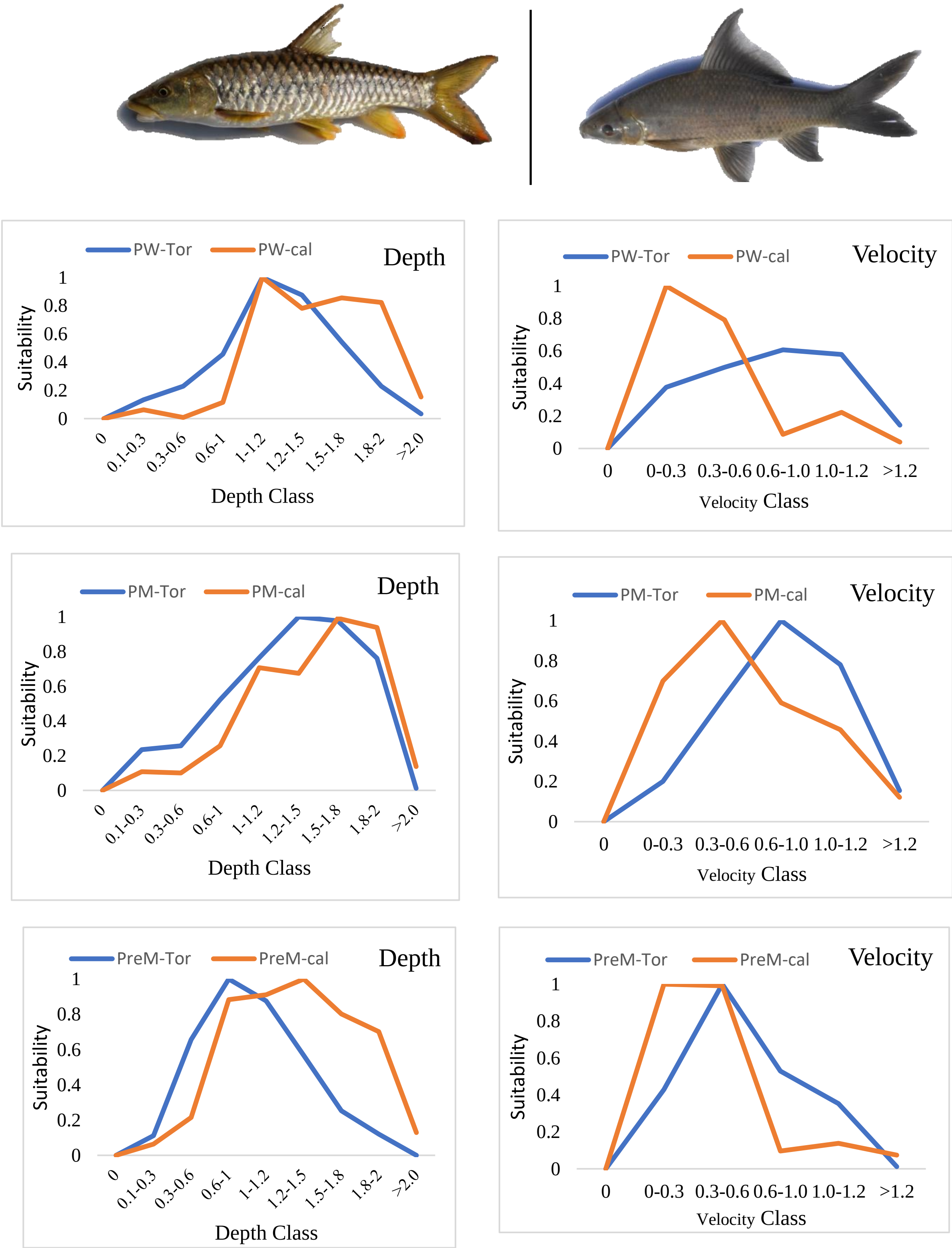


Figure 2.11: Habitat partitioning (depth and velocity) in *Tor putitora* and *Labeo calbasu* during different seasons in the studied rivers.

(*PW-Post winter, PM-Post Monsoon, PreM-Pre-Monsoon).

2.4 Discussion:

Ramganga River is one of the important headwater tributaries of the Ganga, inhabiting a unique assemblage of cyprinid fishes (Jayaram, 2010; Atkore et al., 2011). It is a widely accepted phenomenon that stream fishes are opportunistic in their feeding habits because of the highly variable nature of habitat types and resource availability (Lowe McConnell, 1987; Degerman et al., 2000). In this study, the fish fauna used different food items, both terrestrial and aquatic food resources, which corroborate the dietary pattern described in the literature for the tropical streams (Casatti, 2002; Borba *et al*., 2008; Brandao-Goncalves *et al*., 2010; Mazzoni *et al*., 2010b; Tófoli *et al*., 2010; Schneider *et al*., 2011). The study observed and reported variations in the diet patterns among species of different trophic groups, such as algal feeders, herbivorous, insectivorous, and omnivorous. The riparian vegetation, present abundantly along aquatic streams, provides seeds, flowers, fruits, and filamentous algae and is responsible for the presence of plant material in the diets of several species (Barthem and Goulding, 1997). Also, the Himalayan streams, having a rich diversity of insect fauna in the form of aquatic and terrestrial insects, provide a great resource source to the stream fishes (Winemiller et al., 2008; Mishra et al., 2013). Similar resource utilization patterns have been reported in Himalayan streams, and the variation in feeding habits and resource partitioning among the fish communities is very common in tropical Asian streams (Singh et al., 1993; Dudgeon, 1999; Nautiyal and Negi, 2004; Singh and Aggarwal, 2014).

Further, the present study reported a small variation in the cyprinids' niche breadth values. The small overlap in the species resulted from the species' varied foraging strategies and dietary preferences due to the availability of various food resources.

However, the present study reported that *G. gotyla, O. bendelisis, and B. vagra* were among the specialist groups of the species. The devising strategy of *O. bendelisis* was described in a study similar to the previously reported ((Nautiyal and Negi, 2004). Also, we said the *Labeo* species is highly specialist among the fish species. The niche breadth results revealed that the generalist feeding behavior of golden mahseer in streams was reported and observed previously (Shrestha, 1997; Negi, 1994). Also, this species is usually a trophic opportunist and may change its diet according to the spatial variations and interactions during the change in the season.

The niche overlapping has focused on the resource share of co-existing cyprinids with *T. putitora*. We reported an intermediate overlap of *T. putitora* with *G. gotyla, O. bendelisis, and B. vagra*. This might be because they have different feeding intensities and feeding preferences, their niche does not highly overlap, and there is less competition among them. This is mainly due to the availability of food resources in the streams (Singh, 2014). This also relates to the study that fishes co-exist in the riverine environment and use separate water columns to survive and thrive (Grossman and Freeman, 1987; Rice, 2005). They fed on their preferred food items, such as terrestrial and aquatic insects, small fishes, and plant matter readily available on the surface and mid-column areas. Our analyses of dietary overlap showed that food resource partitioning is well-defined, with a low overlap in the community for both years. However, a higher overlap was observed for the pairs *T. putitora*, *O. bendelisis*, and *B. vagra*, and it is mainly due to the occurrence of insects (aquatic and terrestrial) in the diets of these fish species. However, the suitability of *T. putitora* was reported in shallower to deep areas with moderate to high velocity. The suitability of *O. bendelisis* has been documented in the shallower areas. These species forage on aquatic insects and other planktivorous species in the shallower to mid-column regions of the stream, where they primarily use surface resources as part of their feeding strategy (Nautiyal and Nedi, 2004). *O. bendelisis* was, therefore, described as an insectivore surface-mid column feeder. According to the study, *B. vagra* was an insectivore surface dweller found in shallow water areas with moderate to low water velocity, eating mostly insects and other detritus. Similarly, the *Labeo* species were categorized as herbivorous benthic dwellers in the present study as *L. calabasu* and *L. pangusia* have been identified preferably in the benthic habitats in streams and specifically consuming similar food resources, i.e., the submerged aquatic plants, algae, and other vegetation (Das et al., 2020). Likewise, *G. gotyla*, which has a dorsoventrally flattened body, lives in shallower areas with moderate flow velocity and has suctorial or adhesive mouth parts to scrape algae off of rocks are surfaces are benthic-herbivorous (Koundal et al., 2016).

This study on the diet and resource overlap is mainly due to the variation and availability of food and space sources in the Himalayan streams. But, at the same time, inter-specific and intra-specific competition was less in the study species as they were segregated because of the preferable use of microhabitats (Pusey and Bradshaw, 1996). Additionally, this study reported the stream channel bottom in the examined area was sandy and mixed with silt. Because it was the combination of substrate availability for the cyprinids, it was found rocky with sand and gravel, and the suitability of the substrate was reported together.

Chapter 3

Chapter 3

Movement patterns of golden mahseer during spawning and non-spawning period using radio-telemetry techniques

Running title: Movement ecology of golden mahseer

3.1 Introduction

Movement is an essential feature that living organisms exhibit to meet their biological needs. As an aquatic living form, fish move longitudinally and laterally through their habitats to locate and access resources and places crucial to complete their reproductive cycle (Cooke et al., 2016). Hence, understanding such crucial life process is essential in explaining the species' ecology and behavior, and this can be achieved by obtaining information on an animal's space use within its habitat (Alp et al., 2018; Farrae et al., 2019; Habib et al., 2014; McDowall and Taylor, 2000). Electrofishing and field observation methods from above and below the water surface have generated spatial biological data for fish (Furey et al., 2013). However, electronic tagging has allowed scientists to expand their understanding of fish behavior and environmental requirements (Cooke and Cowx, 2004; Cooke and Bunt, 2001). It also generates extensive information on fish ecology, a prerequisite for developing appropriate conservation plans and managerial perspectives.

Golden mahseer migrates in phases during different seasons (Bhatt et al., 2004; Nautiyal, 2014), characterised by water currents and optimal water quality conditions.

The field observation by Nautiyal et al. (1994, 2001) revealed that the movement of the fish gets triggered by water temperature, water velocity and turbidity during the monsoonal flow, and the mature adult fish ascend the Himalayan river's lower tributaries in rain-fed rivers. The rain-fed rivers provide a protective cover for fish and their fertilized eggs. They also meet their other biological needs by providing a large volume of water, high turbidity, high discharge, and a low number of visual predators (Bhatt et al., 2004). Aquatic habitat features such as water velocity, depth, temperature, and other physio-chemical parameters are essential for golden mahseer movement and distribution in these rivers (Nautiyal and Lal, 1984). These physico-chemical parameters strongly influence the aquatic community structure in the Himalayan River system. However, very little is known in this regard; being a sensitive fish, even modest disturbances in the golden mahseer habitat might cause the population to decline. As a result, despite several efforts of conservation measures, its distribution in the Indian Himalayan stretch is getting limited. Climate change, overfishing, pollution, habitat modification, sand and boulder mining, and the establishment of hydroelectric power plants have been reported to contribute to the population decline of the golden mahseer in the Himalayan rivers (Atkore et al., 2011; Everard et al., 2019; Gupta et al., 2013; Nautiyal, 2014; Sharma et al., 2015). Therefore, understanding the spatio-temporal ecology related to habitat characteristics is pertinent for effective conservation planning.

Thus, in the present objective of the study, the use of radio telemetry technique to understand the fish species' spatial ecology and their habitat preferences concerning physio-chemical parameters in two potential riverscapes; Kosi and Kolhu, in the tributaries of Ramganga river basin, India. The tagging of fishes was carried out in the monsoon and post-monsoon seasons (late June to mid-October) to research the golden mahseer's movement patterns and home range. The primary goals of this objective were to evaluate the movement patterns and home ranges of golden mahseer in the Himalayan rivers and parameterize environmental variables at the site of their habitat utilization. In the present study, it is hypothesized that the golden mahseer migrates upstream during monsoon, and variations in water velocity, volume, and physico-chemical parameters of water influence their movement behavior.

3.2 Materials and Methods

3.2.1 Study area

The study was carried out in the two tributaries of the Ramganga River basin, Kosi and Kolhu rivers in Uttarakhand (Fig. 3.1).

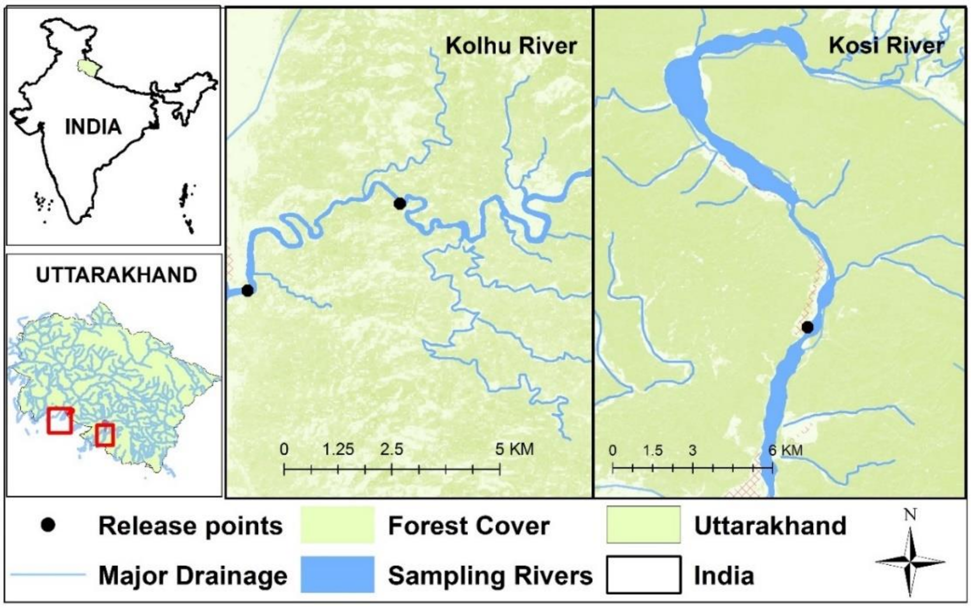


Figure 3.1: Study area map showing stretches of Kolhu and Kosi rivers of Ramganga River basin, Uttarakhand, India (Black dots representing the release locations of the golden mahseer tagged individuals).

3.2.2 Field methods

3.2.2.1 Telemetry tagging

The telemetry tagging was carried out during the last week of June (pre-monsoon season), early in the morning hours till afternoon, at the selected sites along the Kosi (n = 5) and Kolhu rivers (n = 6). (Fig. 3.1). Individuals of the golden mahseer were captured using the gill net (10 cm X 10cm); only the adult individuals were captured and kept in a nylon net bag and then brought into shallow water to perform tagging exercises. Cylindrical-shaped VHF radio transmitters (Lotek Wireless Inc., Canada, Model MCFT3-L-TP) 80 mm long, 15 mm wide, and 20 g weight in the air were used (Fig. 3.2). The mass of these transmitters represented <2 % of the fish's body mass ($\bar{x}$ = 2.69978 ± SD=1.245 kg). The tag's weight to the fish's weight varied from 0.0062 to 0.0263 ($\bar{x}$ = 0.0088 units ± SD=0.071). Each transmitter was used at a frequency of 150.00 MHz with a unique code for individual identification. However, the battery life of the transmitter was programmed to ~ 600 days for "on" for 12 hours and "off" for 12 hours with a signal transmission at an interval of every 2 seconds. A total of eleven telemetry transmitters were externally affixed to the golden mahseer individuals, ranging from 48.0 cm (760.0 g) to 95.0 cm (4500.0 g) in size and 5+ to 12 years of age in June 2019 (Table 3.1). The tags were attached at the dorsal side of the body, close to the dorsal fin area, with the help of a needle, piercing the muscle nearby (Fig. 3.3). The overall tagging exercise took 2-3 minutes per individual. After tagging, the fish were examined for any physical injury. We also ensured that, after being released, all the fish were healthy and able to move smoothly.

During the tagging, scale samples of the tagged individuals were collected from their bodies' lateral line area and later analyzed in the lab to estimate their age. In addition, body measurements and sex determination were also carried out. For further analysis, individuals tagged in Kolhu were named KL1, KL2, KL3 and KL4, whereas those tagged in Kosi were assigned KS1, KS2, KS3, KS4 and KS5.

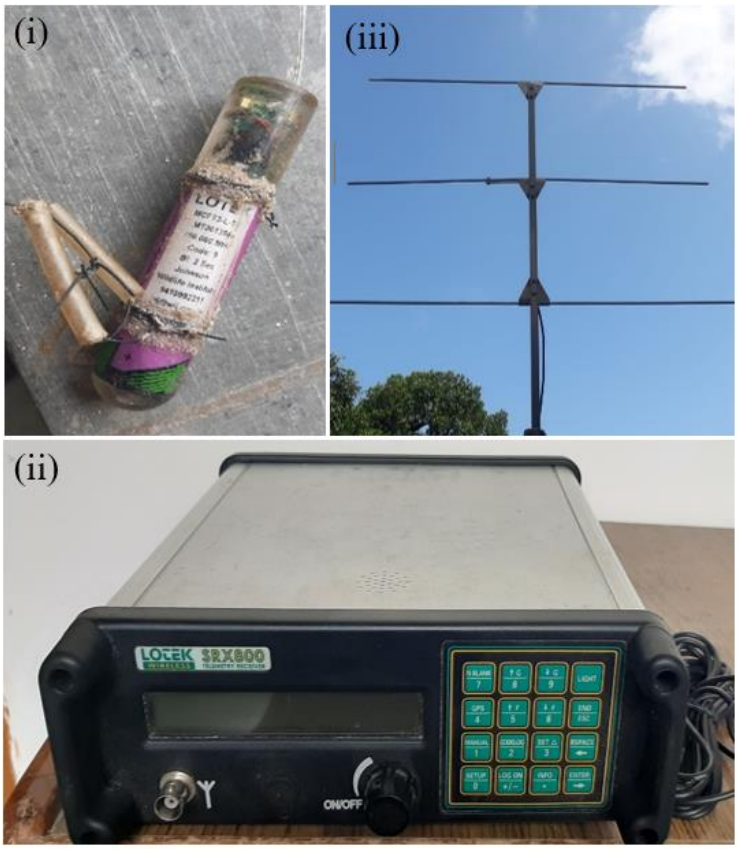


Figure 3.2: Radio Telemetry equipment's (i) Radio telemetry tag (20g) (ii) Receiver (iii) Manual antenna

3.2.2.2 Post release manual tracking

Tracking of tagged golden mahseer individuals started in late June 2019 and continued till October 2019. After 12–16 hrs of the post-release, detections were made to account for the acclimation period. Individuals were tracked from the bank of the river using an "H" shaped hand-handle antennae and receiver (N = 1, Lotek Company, Canada; Model SRX400) (Fig. 3.2). The detection range of the receiver was around <50m radius. Tracking was conducted every fortnight during the study period, upstream and downstream of the rivers, to locate all the tagged individuals. Since the rivers flow through the protected areas and there were other large mammals such as elephants and tigers, all tracking exercises were performed during the daylight. Fish locations were collected using the receiver's automatically recorded latitude and longitude coordinates and a geographic positioning system (GPS; Garmin etrex, 20X, USA).

Figure 3.3: Telemetry fixing process; fish catch, determining weight and length of fish, tracing tagging position to fix tag externally, release of fish, manual tracking of fish to get the location data.

3.2.2.3 Physio-chemical parameters

Critical microhabitat features and water quality parameters were assessed during the tracking exercises to define the environmental factors associated with the preferred habitats. We generated nine ecological variables through tracking surveys. The river depth, water velocity, and presence of substrate type were measured at each recorded location of the fish. The telemetry receiver, a depth rod, and a velocity metre were used to record the individuals' water depth and velocity. The composition of each substrate type was quantified based on visual observation. The size classification was done as bedrock (> 200mm), small boulders (150–200mm), cobbles (50–150mm), gravel (5–50mm), sand-silt (1-2mm), and leaflitter, followed by Bovee (1982) and Pusey *et al.* (1993).

Additionally, the water temperature was also recorded on the receiver for each fish habitat. At the same time, total dissolved solids (TDS), pH, salinity (S), and electric conductivity (EC) were measured using a hand-held probe (Eutech PCS Tester 35 multi-parameter probe). Dissolved oxygen (DO) content was measured for the locations using Wrinkle's method (once per week). It was essential to characterize depth, surface water velocity, and physio-chemical parameters during the telemetry monitoring period to investigate the hydrological data concerning the fish location in the studied rivers.

3.2.3. Analytical methods

3.2.3.1 Movement behavior

The collected fish locations (coordinates) were considered for the analysis. With the help of Microsoft Excel 2016, the GPS locations of the golden mahseer individuals were arranged in order and then imported into the software ArcMap 10.5 (Alp et al., 2018; Gilroy et al., 2010). Individual distances travelled by golden mahseers were determined by measuring the distance between two consecutive locations. The total distance travelled was calculated by considering all the daily distances travelled. Also, total displacement was estimated in both upstream and downstream directions as the straight-line distance between the starting point of release and the last observed position of the individuals. We used Arc GIS (10.5) to create trajectories to better understand the downstream and upstream movement patterns. Correlation analysis was performed to identify relations between the movement pattern and sex of the individuals and individuals tagged in both rivers.

3.2.3.2 Home Range

Out of the 11 tagged and released golden mahseer individuals, two were lost just two days after the release. Of the lost individuals, one was found floating dead on the water's surface, and another was found eaten by the otter (bones were found). Thus, only nine individuals were tracked after that and were considered for analysis. We used the concept of the linear home ranges (Alp et al., 2018; Bolden, 2001; Dahl and Patterson, 2020; Hardy and Taylor, 1980) and kernel density home range estimates (Barry and McIntyre, 2011; Cantrell et al., 2018; Downs and Horner, 2012; Vokoun, 2003) for our study in the riverine habitat because the MCP (minimum convex polygon) calculated for different individuals overlapped mostly in the terrestrial habitat. The kernel density home range estimates (95%, 75%, and 50%) were used to determine the habitat utilization by golden mahseer. To understand the home range of golden mahseer in this study, 95% (KDE) was considered as the total home range of the individuals and 50% (KDE) as the core area. ArcMap 10.5 software created the home range map and calculated the size.

3.2.3.3 Habitat Preference and water quality

To understand the habitat preference of the golden mahseer individuals, the locations were looked inside the 95%, 75%, and 50% KDE in the studied rivers. Seaman and Powell (1996) used Kernel density estimates to explain the home ranges and habitat use of individual species in their habitats. To define the association of the physicochemical parameters with the preferred habitat, six important physico-chemical parameters, i.e., water temperature, presence of total dissolved solids, presence of hydrogen ions, electric conductivity, salinity, and dissolved oxygen, and three habitat parameters, i.e., water depth, velocity, and substrate type were looked in. Regression analysis was performed to assess the relationship between habitat selection of stream sites and the water quality data about habitat preference. Regression analyses were performed in R software version 4.1.1 to elucidate the relationship.

3.3 Results

3.3.1 Movement behavior

The nine tagged individuals were located during the tracking. Only four times (1.17 %) of the individuals were spotted near shallow water out of all the sites observed. The tagged individuals showed dispersion between 74.53m and 1369.19m ($\bar{x}$ = 347.74m ± SD 41.274). The total mean distance travelled for golden mahseer individuals differed significantly (t =2.519, p = 0.0193). Four of the nine individuals, KL2, KL4, KS3 and KS4, travelled long distances ($\bar{x}$ = 4927.88m ± SD 1182.24) (Table 2). Similarly, three individuals with code ids KL1, KL5 and KS5 travelled short distances ($\bar{x}$=497.96m ± SD 53.82), and two individuals, KS1 and KS2, ($\bar{x}$ =287.05m ± SD 63.34) exhibited site fidelity behavior. Individuals with ids KS3 travelled the longest distance upstream (5721.35m), whereas KS4 travelled the maximum distance downstream (6119.11m) (Table 3.1, Fig 3.4). The average daily distance travelled by female golden mahseer individuals was ($\bar{x}$ =324.06m ± SD= 197.4), and for male golden mahseer, the distance was $\bar{x}$ = 108.12m ± SD= 29.3. It is observed that the average total distance travelled by females was larger ($\bar{x}$ =1938.22m ± SD= 226.39) than males ($\bar{x}$ =169.22m ± SD=20.126) during the study period. The individuals in the Kosi travelled the longest, KS4 ($\bar{x}$ =1369.19m ± SD= 234.65) and the shortest, KS1 (74.53m ± SD= 9.02) distance out of the total tagged golden mahseer individuals. While considering the upstream and downstream specific movements, a significant difference (p = 0.0012) was recorded between female and male individuals and between different sites. Since the study was conducted during the monsoon period, the results reflect the seasonal movement pattern. During the study period, tagged individuals moved more actively in the early and evening hours in shallow water in Kosi.

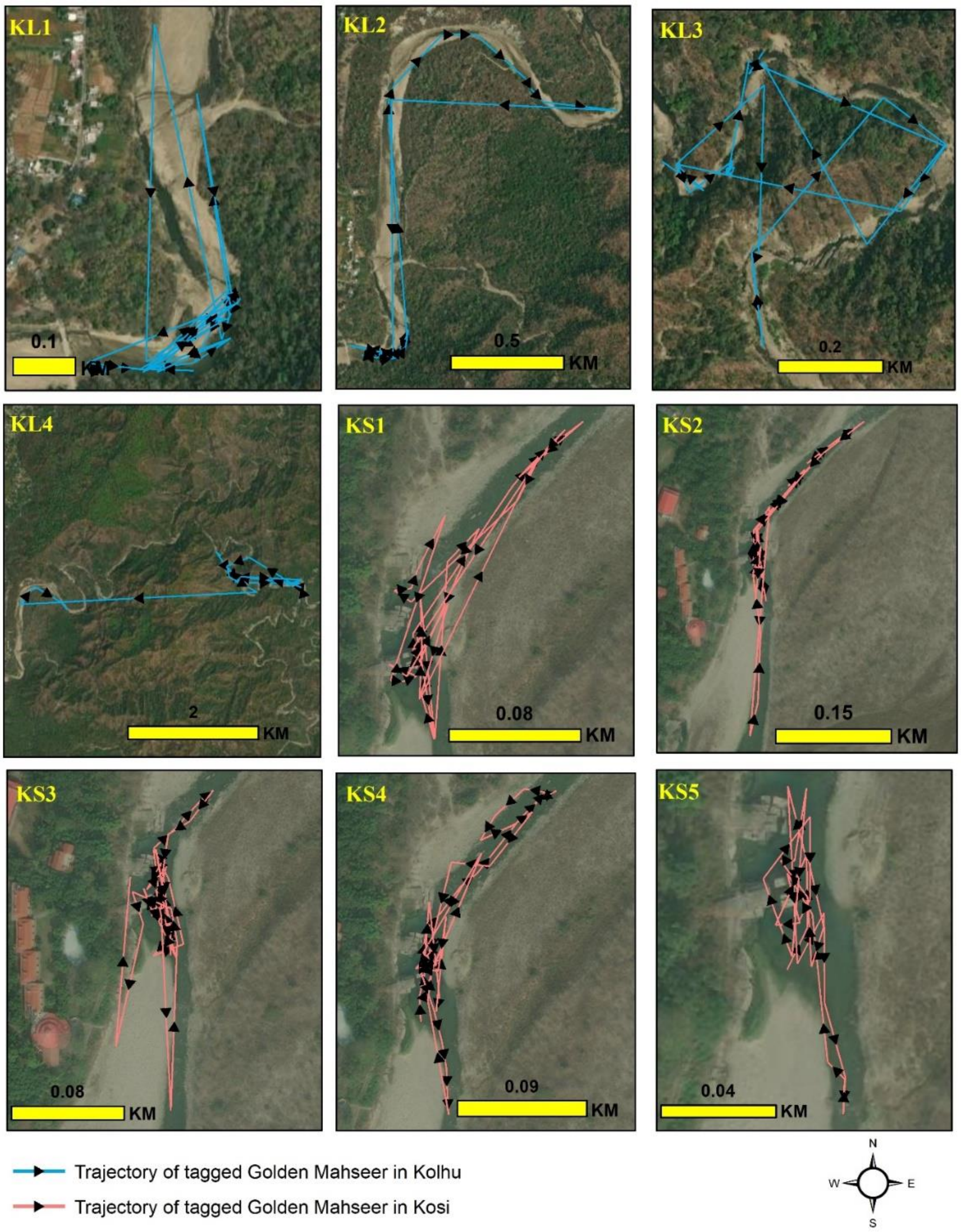


Figure 3.4: Representation of the movement trajectories (colored lines); the upstream and downstream movement (arrow directions) of radio-tagged golden mahseers (n = 9) [KL1 to KL4 – represent tagged individuals from Kolhu river; KS1 to KS5 - represent tagged individuals from Kosi River].

Table 3.1: Information on the transmitters, tagged fish and release points (GPS locations) in each site during radio telemetry.

Fish Id	Date	Stream	Latitude	Longitude	Fish length (cm)	Fish gender	Fish weight (g)	Fish age (years)
KL1	20.6.2019	Kolhu	29.6916583	78.5272701	95	male	4500	12
KL2	20.6.2019	Kolhu	29.69168611	78.52666667	80	female	4430	6+
KL3	21.06.2019	Kolhu	29.70986111	78.5577778	66	female	2350	5+
KL4	21.06.2019	Kolhu	29.70939722	78.55861111	58	female	1538	7+
KS1	22.06.2019	Kosi	29.45196667	79.14602222	70	male	3100	7
KS2	22.06.2019	Kosi	29.45209444	79.14589444	72	female	3220	7+
KS3	22.06.2019	Kosi	29.45222222	79.14589444	55	female	2100	6+
KS4	22.06.2019	Kosi	29.45207778	79.14586389	61	female	2300	9+
KS5	22.06.2019	Kosi	29.45209167	79.14587778	48	female	760	5+
Mean					67.22		2699.78	
Max					95.00		4500.00	
Min					48.00		760.00	
SD					14.18		1245.98	

3.3.2 Home Range

The radio-tracking of golden mahseer produced linear and kernel density estimates of their home range. The average linear home range of the tagged individuals was 347.44 ± SD=41.374 m. The linear home range for individuals was reported to be significantly different (t =2.519, p = 0.035). The individual KS4 occupied the largest linear home range, and the smallest linear home range was reported in KS2 (74.53m) (Table 3.2). A female individual, KL4 (length = 58cm; weight = 1538g) (Table 3.2), had the largest estimated total kernel density home range (2.168 km^2), followed by KL2 and KL3 (0.2074 km^2 and 0.1066 km^2), respectively. In the Kolhu River, the mean core area of the tagged individuals was estimated as 0.0599 km^2 ± SD=0.095, while in the Kosi River, it was calculated as 0.00155 km^2 ± SD=0.00108. Individuals of the river Kolhu, with an area of (0.24 km^2) had a higher percentage of 50% KDE (core area home range) than those of the Kosi (0.0077 km^2). Furthermore, individuals' core home ranges varied significantly (t= 1.25, p = 0.0039). Given the smaller number of males present during the study period (n = 2), we could not identify any sex-related changes in the home range. The spatial distribution of each individual with 95%, 75%, and 50% home range analysis is illustrated in (Fig 3.5).

Table 3.2: Description of each tagged individual movement pattern and home range.

Code of transmitter	Number of recorded locations	Longest travelled distance (m)	Meantime (days) of track	Linear Home Range (m)	Home range (km^2)		
					95% KD area	75% KD area	50% KD area
KL1	39	541.10	54	128.84	0.0216	0.0090	0.0039
KL2	40	4231.23	57	264.04	0.1295	0.0507	0.0272
KL3	33	437.64	63	139.6	0.0817	0.0181	0.0069
KL4	33	3639.81	71	568.56	1.4416	0.5248	0.2017
KS1	38	240.14	57	87.39	0.0100	0.0033	0.0014
KS2	42	333.96	56	74.53	0.0143	0.0062	0.0019
KS3	46	5721.35	60	338.28	0.0003	0.0011	0.0032
KS4	48	6119.11	63	1369.19	0.0090	0.0029	0.0009
KS5	30	515.15	45	156.53	0.0023	0.0011	0.0004
Mean	38.78	2419.94	58.44	347.44	0.1900	0.0686	0.0275
Max	48	6119.11	71	1369.19	1.4416	0.5248	0.2017
Min	30	240.14	45	74.53	0.0003	0.0011	0.0004
SD	6.06	2488.53	7.18	413.74	0.4714	0.1718	0.0659

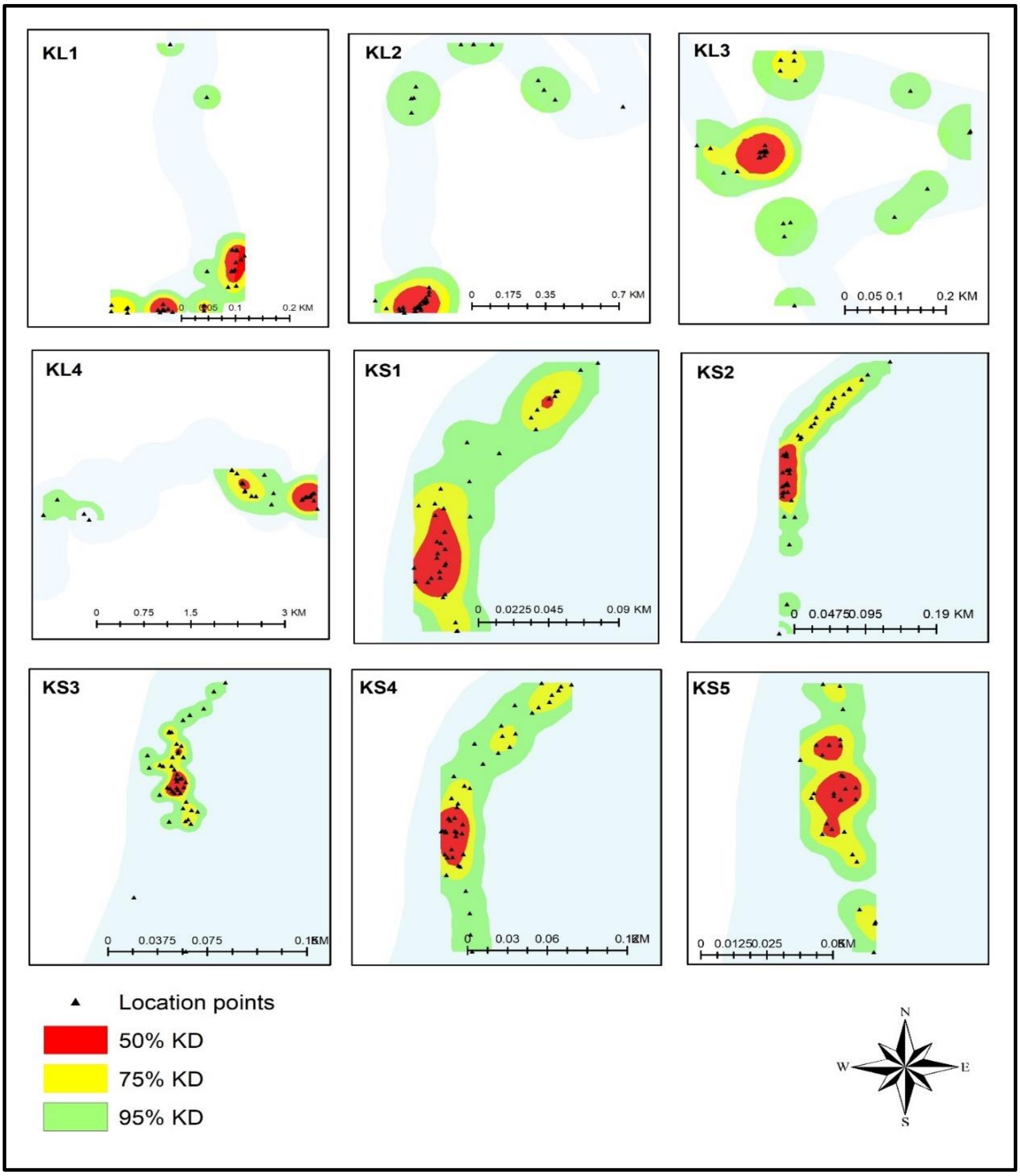


Figure 3.5: Tracking data and Kernel Density Home Ranges (KD HR) of radio-tracked golden mahseers (n = 9) [KL1 to KL4 – represent tagged individuals from Kolhu River; KS1 to KS5 - represent tagged individuals from Kosi River; KD - Kernel Density].

3.3.3 Habitat preference

Both rivers' ecosystems comprise mesohabitats like pools, run, and riffles. Most individuals were observed in the pool areas of the study stretch. The depth usage by tagged fishes were ranged between 0.4 to 2.43m, and the average depth at which the individuals were located in the rivers was ($\bar{x}$ =1.81m ± SD=0.495). Throughout the study period, the river flow was reported to vary between 0 m/s and 2.09 m/s and the mean preferred velocity was reported to be ($\bar{x}$ =1.167 m/s ± SD=0.62). The preferred habitat's river bed was mostly sandy with large boulders. The average temperature recorded was 25.171 ^{o}C ± SD=0.795; average pH was measured to be 8.48 ± SD= 0.20, mean electrical conductivity was 280.80 µS cm^{-1} ± SD= 28.70 and average total dissolved solids, TDS was found 200.1 ppm. ± SD=38.55

Similarly, the average salinity and dissolved oxygen were measured to be 128.47ppm ± SD= 25.91 and 8.833 mg/l ± SD= 0.29 mg/l, respectively. The regression model results revealed that water velocity (flow), TDS, and salinity were positively related to mahseer habitats among the studied parameters. In contrast, electric conductivity (EC) was negatively related to golden mahseer habitats during the study period. The final selected regression model, including estimates and standard errors for each water quality indicator, is given in (Table 3.3).

Per week average distance travelled by the fish individuals in the rivers Kosi and Kolhu (Fig. 3.6) exhibited maximum movements between week 7 and week 12 (early August – mid-September). This suggests that environmental factors play role in the movement of the fish individuals. After the set of monsoons from mid of July, the rivers got flooded with water. This relates to how changed environmental parameters might have made the individuals move long-distance.

Table 3.3: Estimates and statistics for the regression model predicting the relation of water quality parameters and tagged golden mahseer individuals.

Predictor	Estimate	S.E.	*z*-value	*p*-value
Intercept	-3.458750	0.653873	-5.290	1.23e-07
Flow	0.143468	0.079048	1.815	0.06953
TDS	0.008342	0.002836	2.941	0.00327
EC	-0.003612	0.002131	-1.695	0.09010
Salinity	0.007683	0.003033	2.533	0.01130

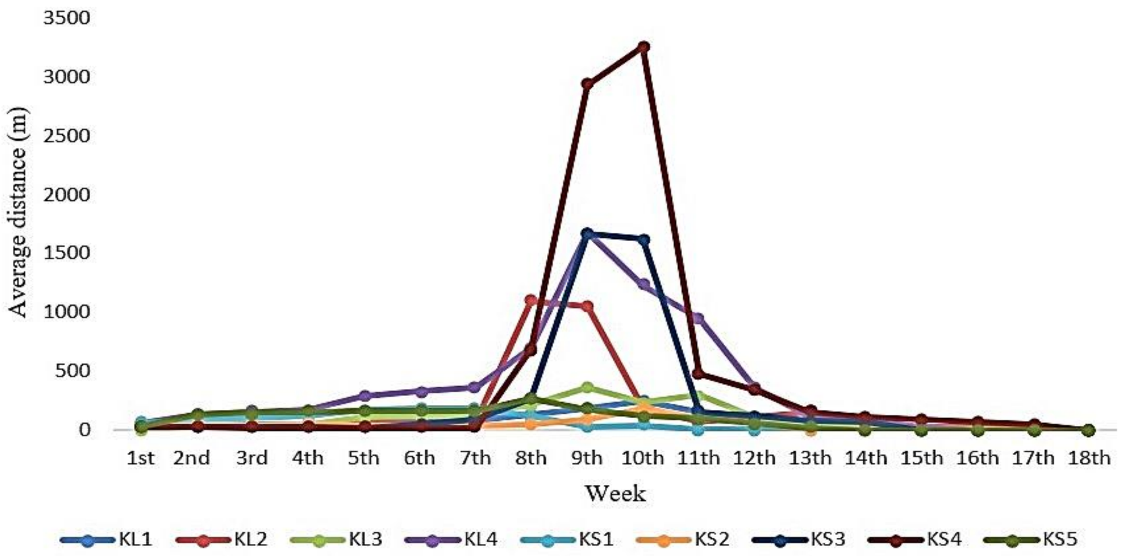


Figure 3.6: Graphical representation of the weekly distance travelled by radio-tagged individuals during the monitoring period [KL1 to KL4 – represent tagged individuals from Kolhu river; KS1 to KS5 - represent tagged individuals from Kosi River].

3.4 Discussion

In this study, we observed the movement patterns of golden mahseer individuals for over an average of 60 days (considering the total number of days tracked and the individuals monitored) after their release into the rivers. We observed initiation movements by the individuals soon after their release and after the rain commenced. The movement pattern of golden mahseer concerning the monsoonal rain is a common phenomenon where it has been observed that monsoonal rains induce the onset of breeding and spawning, and displacement was observed more frequently (Nautiyal and Lal, 1984; Nautiyal et al., 2001). Variations in the movement pattern between the individuals were also observed. Not every individual made long-distance movements during the rise in the water, and some showed small movements during our study period. We also found that female golden mahseer individuals travelled longer distances than males. Variations in the movement patterns at the individual level have been observed earlier by several studies (Stamps and Swaisgood, 2007; Lang and Whitaker, 2010; Kemp et al., 2012; Klinard et al., 2014, 2020).

Golden mahseer is a rheophilic species that generally migrates during the monsoon and breeds and spawns in the upstream areas (Nautiyal *et al.*, 2001). In a recent study conducted in Bhutan, the distance travelled by golden mahseer was reported to be >50 km in 48 hours (Fisheries Conservation Foundation and World Wildlife Fund-Bhutan pers. comm., 2018). This study also reported the utilization of warmer tributaries for spawning and homing instinct behavior of golden mahseer individuals. However, in the present study, we have reported a maximum movement of < 10 km in the foothills of the Western Himalayas. The reason might be that the movement of individuals in their habitats can be influenced by several factors, including habitat connectivity, water availability and other environmental factors (Barry and McIntyre, 2011; Cantrell *et al.,* 2018). Hence, we believe this difference in the movement pattern of golden mahseer in the Western Himalaya could be an artefact of difference in the river's physiographic conditions or the environmental parameters. Also, suitable spawning and nursery grounds and resource availability along rivers Kosi and Kolhu might have provided potential spawning habitats for the individuals, and they only migrated briefly. Moreover, these two rivers are mostly fed by monsoonal rains and groundwater discharge. Thus, the water remains warmer in these rivers than in the typical Himalayan rivers. This could be another reason for not searching long distances for spawning grounds. However, future telemetry studies on the cold-water Himalayan rivers will give a better answer if there is a migrating and resident population of golden mahseer. Furthermore, such a difference in the movement pattern could be attributed to the individual's ability or resource availability, which either did not allow such a long-distance movement or facilitated the individuals in a smaller area by satisfying all their resource needs (Chateau and Wantiez, 2007). Golden mahseers are also considered sensitive to environmental recognition (Nautiyal et al., 2001). This could be why some individuals, after their release, stay near the site while others travel a significant distance to find a suitable habitat. Also, the intra and interspecific competition influences such variation in the movement at the individual level. The dominants generally occupy suitable habitats near the release site, and the subordinates are driven out.

Regarding sex-biased movement, females in most aquatic habitats generally move longer distances to locate suitable breeding and spawning grounds (Marshell et al., 2011; Zeller, 1998). They often need a comparatively safer site with less competition and abundant resources, which increases their breeding success. I also observed an intra-specific coalition of golden mahseer during the monsoon rains, where individuals prefer to stay together. There were frequently observed phenomena such as where other non-tagged individuals were spotted along with the tagged ones. The study believed that such associations correlate with their breeding successors and might be a defensive behavior against predators.

Following that, physically tagging fish and releasing them into the habitat puts them under stress, and it takes time to acclimate. Such occurrences are frequently impacted by the suitable surrounding environment and quality, which help recuperation. In our situation, the predator of the golden mahseer (smooth-coated otter, *Lutrogale perspicillata*) ate up an individual during the telemetry tracking time phase, and we lost the individual due to its slow movement. Our findings on golden mahseer movements in the studied rivers uphold the previous ecological observations that have shown ample evidence of behavioral responses to the availability of suitable habitats and biotic factors (Nautiyal et al., 2001; Bhatt and Pandit, 2016).

3.4.1 Home range

The estimated golden mahseer's home range in the Kolhu and Kosi rivers is difficult to compare because to date no similar studies on fresh water fish species have used Kernel density estimates to determine the home ranges. However, we find sufficient rational ground to use Kernel density estimates in our study. KDE generates a smooth and can increase the information content of home range estimation; it is also widely accepted and recommended, particularly in lotic systems, which we chose to use in our study due to the limited study time (Kern et al., 2017; Kernohan et al., 2001; Vokoun, 2005; Worton, 1989). However, we reported the individuals' core home ranges which have some significance on the species' ecology, which could be significant for the species' future conservation. In both rivers, we discovered that the home ranges of the individuals overlapped. Almost every individual's core area (50 % KDE) was in the area of the released site. Similar to the movement trend, variations in the home range size were observed at the individual level and were sex-biased. Females tended to establish a larger home range (95% KDE) than males. Linking to the movement pattern justification, the intrinsic factors, such as searching for a safer site for breeding and spawning, might lead female individuals to establish a larger home range than male individuals. The larger and smaller home ranges in the Kosi and Kolhu rivers are attributable to several reasons, including habitat preferences, inter-and intra-specific competition, and anthropogenic disturbances in individuals (Berger and Saltz, 2014).

3.4.2 Habitat preference

Tagged individuals were observed using all different habitat types simultaneously. Since the home ranges were comparatively smaller, the wide variations in the physicochemical parameters in the habitat types were reported not to vary significantly. Hence, present study has summarised a few parameters, such as water velocity, TDS, and salinity as the environmental parameters to link them with the preferred habitats. Deep-water pools characterised the core area (50% KDE) with an average depth (>1.4m). In contrast, the total home range (95% KDE) includes the different riverine habitats characterised by cobbles, sand beds, and secondary water channels that connect to the golden mahseer's core area. The core zone of the golden mahseer individuals in the Kosi was restricted to the released site, which had deeper depth and good cover. Fewer anthropogenic disturbances also characterise the released area as it is well-protected in the Kolhu River and by the resort security along the riverbank in Kosi River. The presence of sandy bed ponds with large rocks and cobbles characterises the golden mahseer's aquatic habitats in Kosi and Kolhu rivers. The water velocity was medium, with a high enough flow velocity to convey the fish to their destination during monsoon. The habitat locations of golden mahseer were shown to be favourably associated with the measured physio-chemical and habitat characteristics. Larger areas are essential for the survival of different groups of individuals because, in general, larger fish prefer deeper water, while smaller ones prefer shallower water. The observed water velocity and temperature were closely associated with earlier studies and comparable with the study in Bhutan. Thus, the findings of the study related to habitat preference further strengthen the existing literature on habitat characteristics critical for the survival of golden mahseer. In the present study, we reported maximum movement of the fish from early August to mid-September. This suggested that the observations represented are natural rather than the random movements of potentially compromised individuals.

Despite the small sample size and limited time frame, this study provides valuable insights into the golden mahseer movement patterns, home-range parameters, and habitat preferences. It demonstrated the significance of individual behaviour and the differences in fish habitat selection. This information is valuable and should be considered while formulating the conservation measurements and management plans for the golden mahseer individuals.

Chapter 4

Chapter 4

The breeding and nursery grounds of golden mahseer in Kolhu and Kosi rivers

Running title: Habitat Suitability of young ones of golden mahseer

4.1 Introduction

Habitat suitability is an important aspect of the life-history traits of fish. Several intrinsic and extrinsic factors favour the fish's suitable habitat (Santos et al., 2008). During the early stages of ontogeny, fish undergo various developmental processes in which small-sized young fish are relatively vulnerable to high water velocity and variations in the volume of water (Lake et al., 2007). To overcome such hurdles, young fish find suitable microhabitats in the small river channels to get nutrient-rich refuge areas with a good cover complex (Pusey and Arthington, 2003). These channels are suitable habitats for the young fish before joining the main river channel during the monsoonal rains. Many fish species, concerning their life histories, may necessitate different environments during their development periods (Fausch et al., 2002; Curtis et al., 2017). This method of microhabitat quantification has been proposed to promote species distribution, growth rates, resource exploration, and predator avoidance (Rosenberger and Angermeier, 2003; Skyfield and Grossman, 2007).

Habitat suitability describes how suitable a certain habitat and environmental conditions are for a given size or life-history stage of fish (Midway et al., 2010; Bain and Jia, 2012). Addressing species-habitat interactions and habitat suitability is crucial to fish ecology and conservation (Bovee et al.,1998; Munoz-Mas et al., 2012; Boavida et al., 2013). Based on the observations of an individual's presence or absence in different habitats, it is determined for fishes and their life-history phases in various habitats (Jowett and Davey, 2007). The variables such as depth, water velocity, and substrate composition are the most suitable, and for habitat suitability, they are represented as continuous curves (Santos et al., 2006; Boavida et al., 2013; Rivaes et al., 2017).

Golden mahseer (*Tor putitora*) is one of the iconic endangered fish species in the rivers of the Himalayan foothills. Recent studies revealed that the species had lost almost 50% of its population in the recent past and is predicted to decline by more than 80% in the future if the current trend of habitat loss continues (Bhatt et al., 2004; Sharma et al., 2015; Bhatt and Pandit, 2016). River characteristics and dynamics are critical for fish survival (Malakar et al., 2014); however, gradual changes in the environmental variables can alter their life cycle (Piffady et al., 2013). Studies dealing with their life history stages and ecological requirements are paramount in the current scenario (Lake et al., 2007). Inevitably, taking the necessary measures for their conservation and management through a scientific approach is imperative. However, several studies are available on the aspect of habitat suitability of fishes in the aquatic ecosystems of the Indian region; (Arunachalam, 2000; Sivakumar, 2008; Johnson et al., 2017) the Ganges and Brahmaputra basins (Lakra et al., 2010; Malakar et al., 2014). However, to our knowledge, studies have yet to be conducted on the habitat use, availability, and suitability of young golden mahseer in the Himalayan streams. The ecological characteristics and habitat requirements of young golden mahseers need to be better understood compared to adults. Therefore, the study was performed on young golden mahseer to assess size-related microhabitat suitability.

Furthermore, the present study aimed to fill the research gap by documenting habitat availability and the use by golden mahseer. It was also hypothesised that the habitat suitability criteria of golden mahseer young ones vary across the seasons. To test this hypothesis, the present study was carried out covering three seasons: the post-monsoon (mid-October 2018), post-winter (February-March), and pre-monsoon (May-June) seasons in the year 2019.

4.2 Materials and Methods

4.2.1 Study area

The present study was conducted in two important streams (Kosi and Kolhu) of Ramganga river basin, which flow through the state of Uttarakhand in the Western Himalaya. These streams are considered one of the important mahseer habitats (MacDonald, 1948). The streams' headwaters run through significant protected areas of the Corbett Tiger Reserve in India.

4.2.2 Inventory of nursery grounds

Field surveys were undertaken during the three seasons, including post-monsoon, post-winter and pre-monsoon in 2018-2019. The nursery grounds were identified throughout the stretch through visual observations of the fish. The locations were recorded using Garmin global positioning systems (GPS; etrex 10X, Garmin International, Inc., Switzerland, United States). During the study, young ones were classified into two size classes; fingerlings (1.5-10 cm) and juveniles (10-30 cm) (Desai, 2003) and their potential habitats in the river channel were mapped as backwater pools (BWP), secondary channels (SC), run habitats (RH), associated stream habitats (AS), isolated pools (IP), and confluence point (CP) areas (Pusey et al., 1995) (Table 4.1). In the study, backwater pools are the areas with a moderate to deep depth, a sandy substratum with exposed rocks, and very low to zero water velocity. Run habitats have a shallower depth, moderate flow with hydraulic leaps, and a uniform substratum composition of bedrock, cobbles, and gravel. Secondary channels are formed when rivers are flooded with rainwater and join the main river channel, forming the confluence points. Isolated pools are generated when the main river channel is cut off during the dry season, including small units with almost limited flow, sediments and nutrient exchange. After mapping the habitats, fish shoals along the river channel were noted, and in the present study, young ones of golden mahseer of two size classes were studied.

4.2.3 Fish sampling

Primarily, visual count of young ones associated with pool habitats since the habitats were shallow (5-60cm depth), and the bottom was visible in bright sunshine. The fish sampling was performed (Johnson et al., 2017) with slight modifications to account for channel morphology. First, for backwater and isolated pools, two persons stood on the banks of streams at different points using an aqua scope to count fish in channels. It was observed that the fish for at least a minute to see if they were moving or feeding in a particular location and then took an average count at that site. Second, the young ones were counted by underwater snorkelling in the runs and associated stream habitats with less flow and shallower depths (10-100cm depth). Third, a bottom-set monofilaments gill net (10m long, 2m wide with two mesh sizes, 10mm and 20mm) was used to sample the golden mahseer young ones in a run and secondary channel.

After a one-hour effort at the sites, the number of fish was recorded, and the respective size class were noted down before releasing them back into the water. The observations were all made in the morning (8:00-11:00). Ten efforts for each sampling technique were followed throughout all sampling locations and seasons for studied reach. The average young one's count was measured for each habitat and then used in the subsequent analysis. Later, a one-way ANOVA test was used to determine if there was a significant relationship between the numbers of young ones in different habitats during different seasons.

4.2.4 Measurements of microhabitat availability and use

Cross-stream transect was measured at 1-meter intervals for microhabitat availability. The habitat inventory was conducted to take measurements of habitat depth, water velocity, and the presence of dominant substrate types on each transect (Bovee, 1982). For microhabitat use, after sampling the fish, three microhabitat variables were measured at each fish position as described (Bovee, 1982; Santos and Ferreira, 2008). A hand-held digital flow probe (3.7-6', Model: FP111, Global Water Instrumentation Inc., California) with a graduated scale was used to monitor the water velocity and depth. Bedrock (> 200mm), small boulders (150–200mm), cobbles (50–150mm), gravel (5–50mm), sand-silt (1-2mm), and leaf litter were all measured, followed by Bovee (1982) and Pusey et al. (1993). The stream habitat characteristics were measured (Table 4.1).

Table 4.1 Recorded mean depth, water velocity and dominant substrates for different habitat types of young ones of golden mahseer in rivers Kosi and Kolhu.

Habitat Type (Number in Kosi and Kolhu)	Mean depth (m)		Mean Water velocity (m/s)		Dominant Substrates	
	Kosi	Kolhu	Kosi	Kolhu	Kosi	Kolhu
Backwater Pool (70, 32)	1.2	0.78	0.4	0.6	Sand/Cobble	Cobble/Sand
Run Habitat (75, 26)	0.9	0.60	2.5	1.4	Sand/Gravel	Bedrock/Sand
Secondary Channel (46,10)	1.10	0.43	2.5	1.3	Cobble/boulder	Sand/ Bedrock
Isolated Pool (34,13)	1.50	0.47	0.2	0.2	Sand/Bedrock	Sand/Gravel
Associated Stream (8,12)	0.56	0.56	1.8	1.6	Sand/ Gravel	Sand/Bedrock
Confluence Point (9,10)	0.89	0.22	1.8	1.6	Sand/ Bedrock	Sand/Bedrock

4.2.5 Quantification of water quality parameters

During the study, along with the microhabitat measurements, water quality parameters were assessed across the diverse habitat types in each season's sampling zone. Water temperature (°C), pH, electric conductivity (EC, µS cm^{-1}), and total dissolved solids (TDS, ppm) were measured using a hand-held probe (Eutech PCS Tester 35 multi-parameter probe, Thermo Fisher Scientific, Inc. Massachusetts, USA). Also, Winkler's method was used to quantify dissolved oxygen (DO, mg/L) content.

4.2.6 Data analysis

To generate the estimates of HSCs for fingerlings and juveniles, the available microhabitat and use data for depth and water velocity were analysed for three seasons for every reach. The data set was classified into depth classes (0.1, 0.3, 0.6, 1.0, 1.2, 1.5, 1.8, 2.0 and >2.0 m), six water velocity classes (0.2, 0.3, 0.5, 0.6, 0.9, 1.2 m/s) as per the methods of (Johnson et al., 2017). The relative frequencies were measured for each available habitat and use by young fish for depth and water velocity classification. To calculate preference for each class interval, based on availability and use by fingerlings and juveniles, $Pi = Ui/Ai$ was used, where Pi is the relative preference value, Ui is the proportion of utilisation of a specific interval, and Ai is the proportion of a particular interval of the measured variables when fish were sampled. The preferences were normalised using the formula $Pn = Pi/max\ P$ and were calculated on a scale of 0 to 1, from not used to optimal utilisation. In the range of the variable Pi, Pn is the normalised index of preference, and $max\ P$ is the highest index of preference. For the study streams, the depths and water velocities of golden mahseer fingerlings and juveniles were analysed, and habitat suitability criteria curves (HSCs) were created (Hayes and Jowett, 1994; Bovee et al., 1998; Jowett and Davey, 2007; Johnson et al., 2017) for golden mahseer fingerlings and juveniles. To assess the relationship between water quality and the golden mahseer young ones, an analysis of 15 explanatory variables was performed. The correlation matrix plots indicated highly correlated variables from which variables with lower loadings were removed for further analysis. Water quality and habitat parameters were the dependent variables, and the abundance of young mahseer 9in the studied rivers was the independent variable. The relationship between the young ones and the retained water quality parameters within each stream was assessed using generalised linear modelling (GLM) (McCullagh and Nelder, 1989). The count data set was analysed using Poisson distribution to determine the best data distribution, and the best-fit models were selected using Akaike's Information Criteria (AIC) (Arnold, 2010). The co-efficient values were compared to the fitted and explanatory variables to validate the model. All models that fall within an AIC delta of less than two units from the best model were selected for model averaging (Zurr et al., 2007). All the statistical analysis in the study was performed using MS Excel 2016 and RStudio ver. 4.0.2 (R Core Team, 2013) with the "MASS", "vegan", "MuMIn", and "ggplot2" packages used to carry out the data analysis and interpretation, and ArcMap 10.5 was used to create the maps. Here, box and whisker plots were used to explore the relationship between golden mahseer abundance with associated environmental variables. These tools were used to study the effect of variables on the habitat preference of fingerlings and juveniles in the studied streams.

4.3 Results

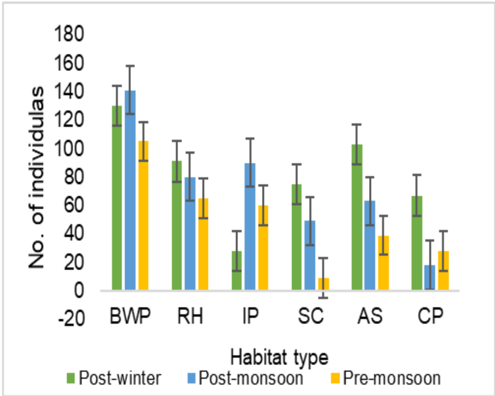
4.3.1 Fish data

In the Kosi stream, a significant difference in habitat uses by juveniles (59%; $F=8.008$, d.f. = 7.845 and $p < 0.012$) and fingerlings (41%; $F=6.228$, d.f. = 7.621 and $p < 0.024$) in the described habitat types (Fig.4.1) during different seasons was reported. However, in Kolhu, habitat use by juveniles and fingerlings (51 % and 49 %, respectively), and particularly the presence of juveniles, showed to be significant during the post-monsoon season ($F=1.89$, d.f. = 9.77, and $p < 0.020$). They were found across rivers in different habitats but were most abundant during the post-monsoon, followed by the post-winter season. Except for fingerlings in Kolhu, the results of one-way ANOVA showed a significant relationship between habitat types and the presence of young ones (Table 4.2).

Table 4.2 One-way ANOVA results for the effects of season and habitat type on the microhabitat use by the fish size-class (young) in Kosi and Kolhu.

Size-class/ River	Source of variation	F-value	d.f.	p-value
Fingerlings, Kosi	Seasons x Habitat types	6.228	7.621	0.0249
Juveniles, Kosi	Seasons x Habitat types	8.008	7.845	0.012
Fingerlings, Kolhu	Seasons x Habitat types	1.251	9.923	0.327
Juveniles, Kolhu	Seasons x Habitat types	1.89	9.77	0.0202

*d.f.: degree of freedom



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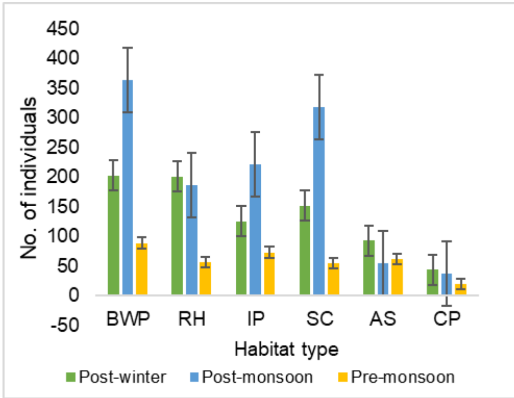

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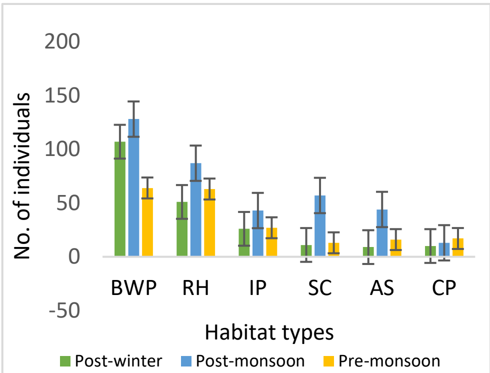

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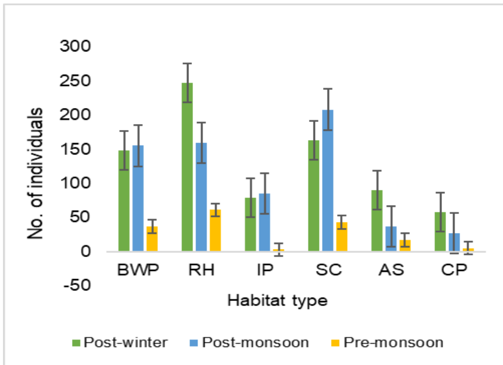

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Figure 4.1: Recorded number of fingerlings in different habitats (a) Kosi; (b) Kolhu and (c) Khoh and juveniles and (d) Kosi during different seasons

*BWP-Backwater pool, RH-Run habitat, SC-Secondary channel, IP-Isolated pool, AS- Associated stream and CP-Confluence point

4.3.2 Microhabitat – availability and use

Among the nursery ground habitat types, BWP, RH, and SC were the most commonly occupied habitats of golden mahseer young ones in both river stretches, followed by IP, AS, and CP. The distribution of these nursery ground habitats was mapped based on the inventory (Fig. 4.2). In the present study, 242 nursery ground habitats of golden mahseer young ones were recorded in the Kosi River, including BWP accounting for 28.9%, RH 31%, SC 19%, IP 14%, AS 3%, and CP 3.7%. In Kolhu, 103 nursery ground habitats with golden mahseer young ones were recorded, which included BWP accounted for 33%, RH 25%, SC 10%, IP 13%, AS 13%, and CP 3.7%. Overall, the available microhabitats, depth and water velocity for the fingerlings and juveniles range from (0 to 1.2m and 0 to 1.2m/s) and (0 to 1.5m and 0 to >2.0 m/s) respectively (Fig. 4.3a-d) and substrate was mainly composed of small boulders (15%), bedrock (10%), cobbles (25%), gravels (20%), and sand-silt (30%).

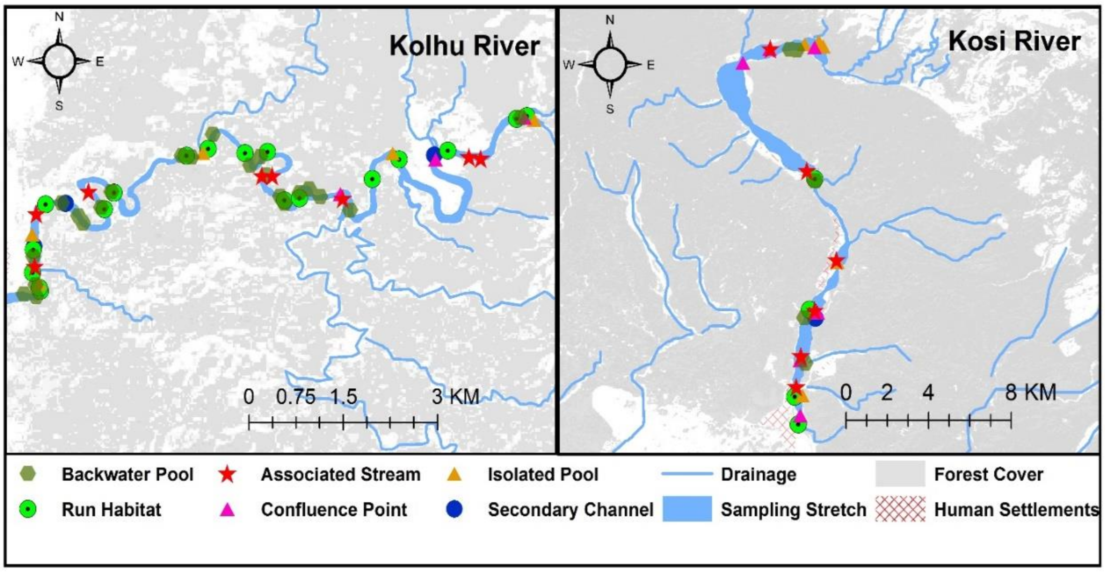
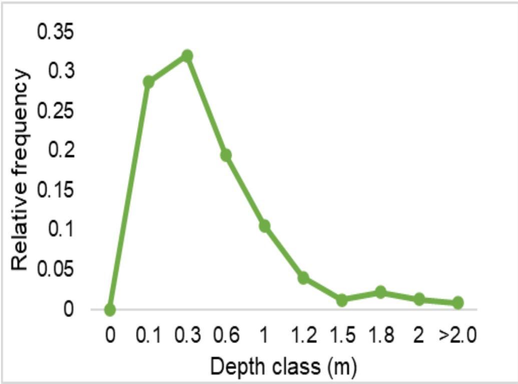


Figure 4.2: Marked habitat locations of golden mahseer young (juveniles and fingerlings) in river Kolhu and Kosi.



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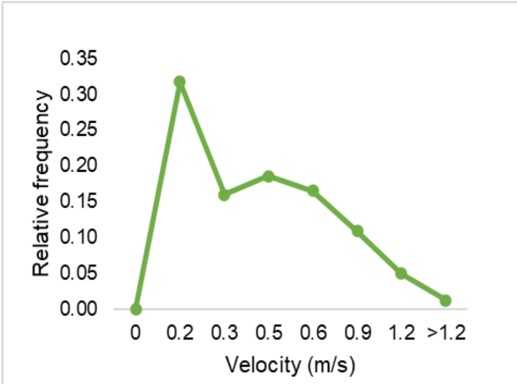

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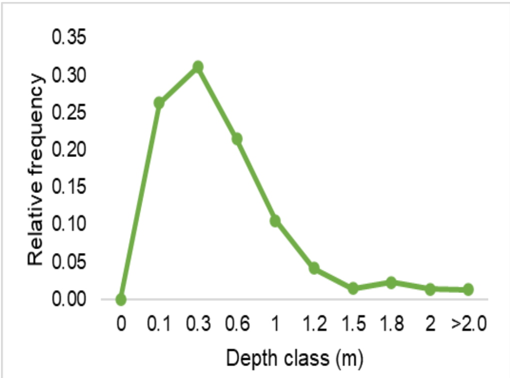

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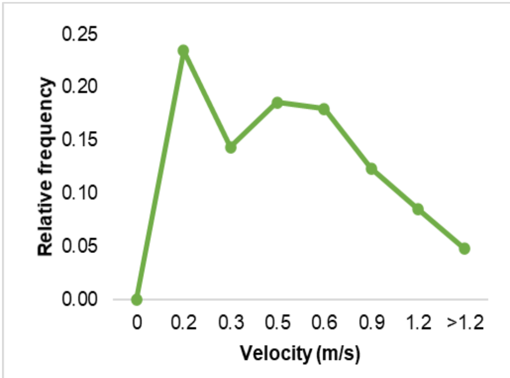

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Figure 4.3: Relative frequency of available depth and water velocity in nursery habitats in the studied rivers representing (a) depth availability in fingerlings, (b) water velocity availability in fingerlings; (c) depth availability in juveniles, (d) water velocity availability in juveniles.

4.3.3 Generation of habitat suitability criteria curves

Habitat suitability criteria curves (HSC) were developed for golden mahseer young ones for the Kosi and Kolhu (Fig. 4.4 and 4.5). The results showed that fingerlings varied across depth ranges throughout different seasons, with the preferred depth values of 0.1-0.3m being used in Kolhu (Fig. 4.5a) and 0.1-0.6m in Kosi (Fig. 4.4a) during the post-monsoon. Most preferred water velocity for fingerlings in Kosi was reported to be zero m/s during the post-winter and the pre-monsoon. However, an increased water velocity was found during the post-monsoon (0-0.2 m/s) in Kosi (Fig. 4.4b). In Kolhu, the preferred water velocity was 0-0.2m/s during the post-monsoon and post-winter seasons. Water velocity was found to be around zero for the fingerlings' used pool habitats during the pre-monsoon in Kolhu (Fig. 4.5b). Although the juvenile’s depth ranged from 0.1-1.5m in Kosi (Fig. 4.4c) and 0.1-1.2m in Kolhu (Fig. 4.5c), the most suitable water column depth ranged between 0-0.6m during the studied seasons in both rivers. It was high during the post-monsoon, (0.1-1.1m) in Kolhu and (0-0.6m) in Kosi during the post-winter. In both the rivers, the most suitable water velocity value was found at (0.1- 0.5m/s) during the post-monsoon, and the lowest was measured during the pre-monsoon 0.1-0.2m/s. However, juveniles and fingerlings were located in a selected depth and water velocity range in their preferred habitats throughout the study period. They have been found to thrive together in groups in the streams.

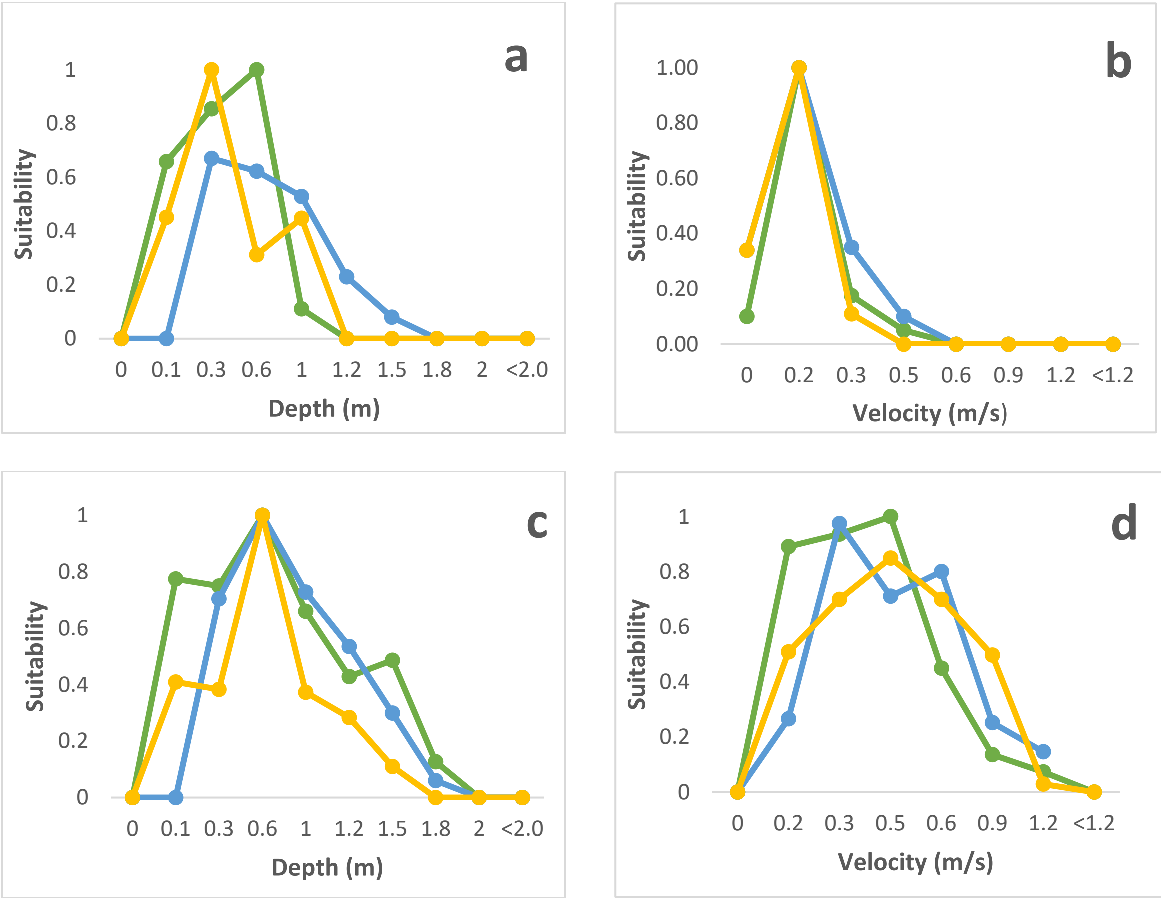


Figure 4.4: Suitability curves of depth and water velocity for fingerlings and juveniles in River Kosi representing (a) depth suitability fingerlings, (b) water velocity suitability fingerlings, (c) depth suitability juveniles, (d) water velocity suitability juveniles

*Color representation: green=post-monsoon, blue=post-winter, yellow=pre-monsoon

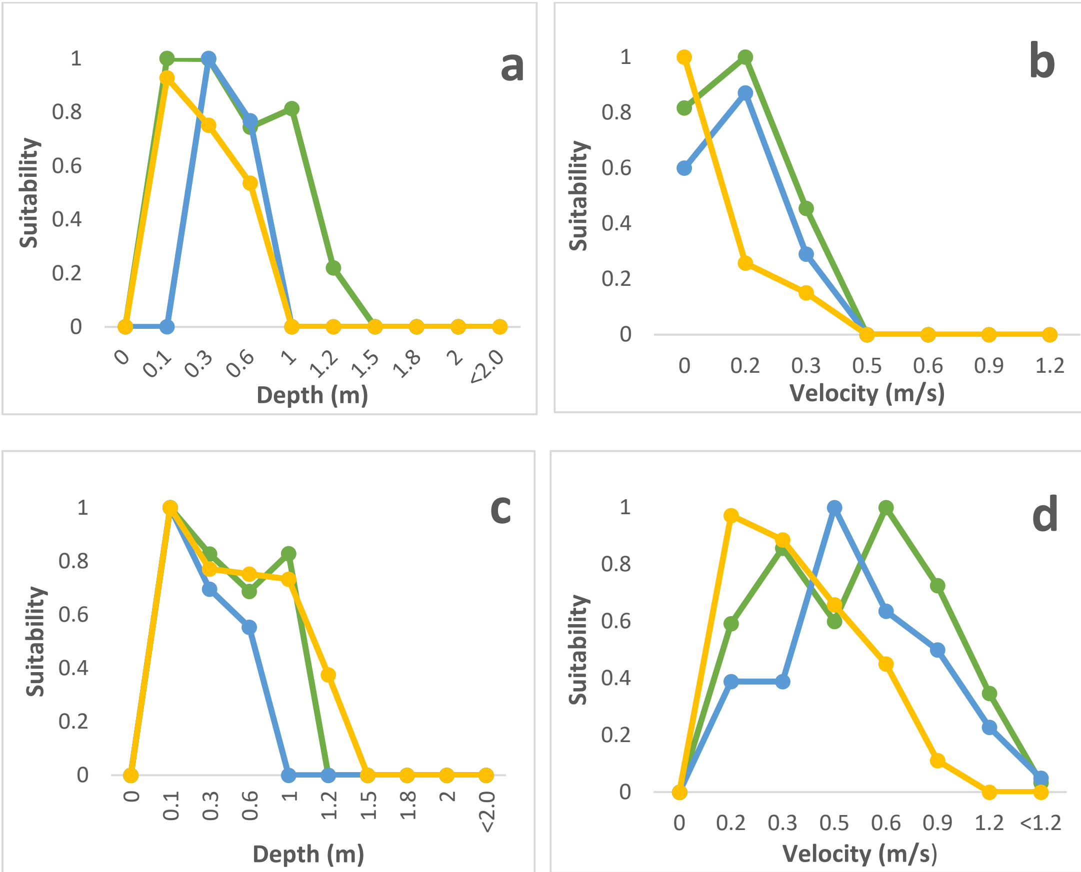
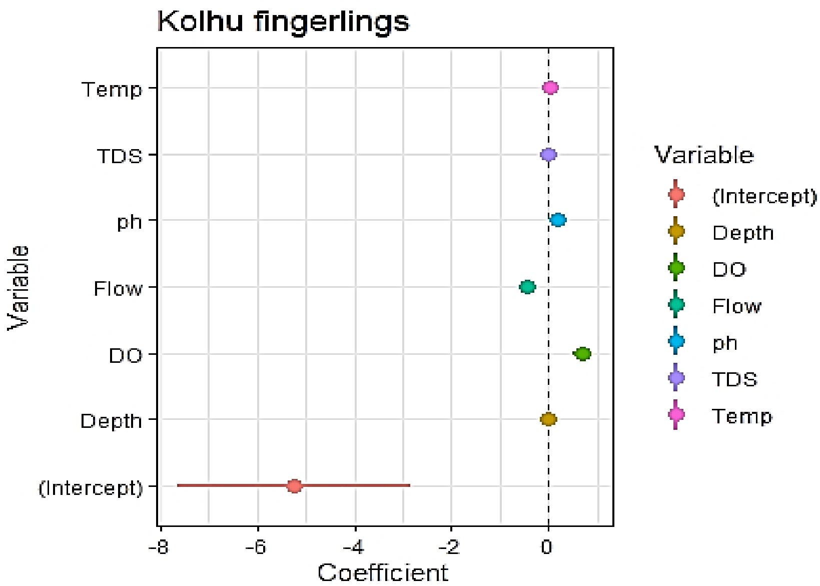


Figure 4.5: Suitability curves of depth and water velocity by fingerlings and juveniles in River Kolhu representing (a) depth suitability fingerlings, (b), water velocity suitability fingerlings, (c) depth suitability juveniles, (d) water velocity suitability juveniles

*Color representation: green=post-monsoon, blue=post-winter, yellow=pre-monsoon

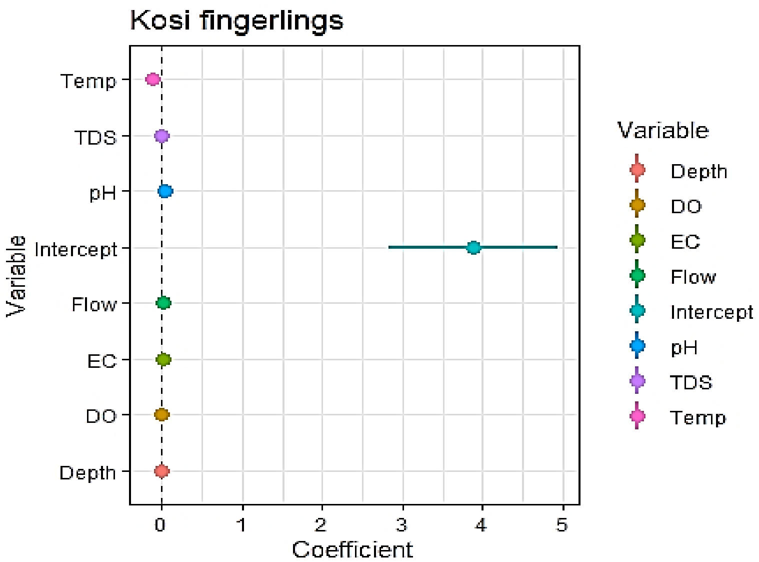
4.3.4 Associated environmental parameters

GLM explained the abundance of mahseer young ones impacted by dissolved oxygen (DO), electric conductivity (EC), pH and temperature (Table 4.3a). They were reported to influence the presence of fingerlings positively. Apart from TDS and depth, which did not affect the presence of fingerlings in Kolhu, the flow rate negatively affected their presence (Fig. 4.6a). In Kosi, the fingerlings were positively influenced by temperature (Fig. 4.6b). Water velocity positively influenced the presence of juveniles in Kosi and Kolhu (Fig. 4.6c, d). The optimal GLM model obtained by successively removing the explanatory factors for fingerlings from the full models led to a result of flow, pH, temperature, DO and electrical conductivity (EC) (Table 4.3b). In the case of juveniles, depth, flow and EC were found to be significant explanatory variables (Table 4.3c).



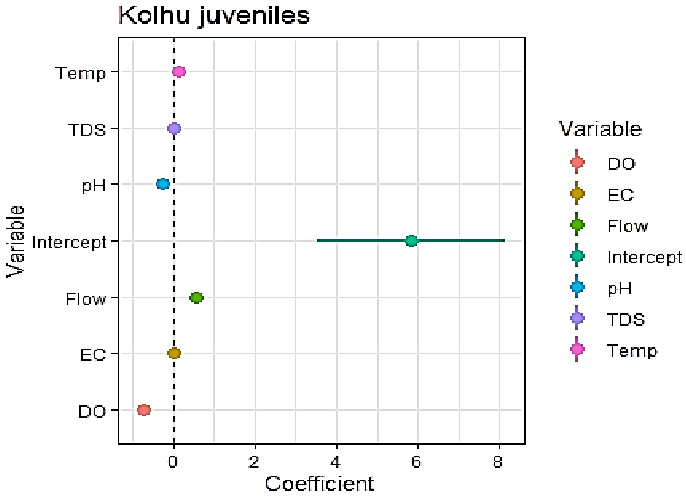
Kolhu fingerlings
Temp
TDS
ph
Flow
DO
Depth
(Intercept)
Variable
-8
-6
-4
-2
0
Coefficient
Variable
(Intercept)
Depth
DO
Flow
ph
TDS
Temp

(a)

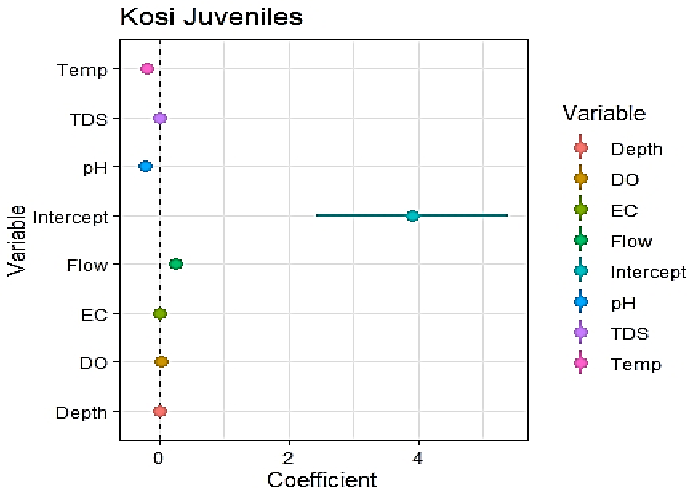


Kosi fingerlings
Temp
TDS
pH
Intercept
Flow
EC
DO
Depth
Variable
0
1
2
3
4
5
Coefficient
Variable
Depth
DO
EC
Flow
Intercept
pH
TDS
Temp

(b)



(c)



(d)

Figure 4.6: Relation of the variables and presence of young golden mahseer through generalized linear modelling, GLM in Kosi, Kolhu rivers

*DO: Dissolved oxygen, TDS: total dissolved solids, EC: electrical conductivity, Temp: temperature, pH: presence of hydrogen ions.

Table 4.3 (a) The best fit model results for the Generalised linear model (GLM) using depth, temperature (temp), electric conductivity (ec), water velocity (flow), dissolved oxygen (do), ph, total dissolved solids (TDS) as independent variables and (b) using Poisson distribution parameter estimates of the best model for fingerlings (c) for Juveniles

(a)			
Size-class/ River	**Best fit model**	**AIC**	**DF**
Fingerlings, Kosi	~ depth + temp + ec	1331.3	99
Juveniles, Kosi	~flow + temp + ph + do + ec	1887.4	236
Fingerlings, Kolhu	~ depth + ec + temp	1335.9	99
Juveniles, Kolhu	~flow + temp + ph + do + ec	1887.4	236

(b)	**Coefficients**	**Estimate**	**Std. Error**	**z value**	**p**
	Intercept***	3.53	0.75	4.66	3.06e-06
	flow***	0.24	0.03	8.37	< 2e-16
	Temp***	-0.17	0.02	-9.35	< 2e-16
	pH***	-0.21	0.06	-3.66	0.00025
	DO	0.08	0.057	1.47	0.13985
	EC***	0.02	0.001	8.50	< 2e-16

(c)	**Coefficients**	**Estimate**	**Std. Error**	**z value**	**p**
	Intercept	1.023	0.80	1.27	0.2030
	depth***	-0.009	0.002	-3.97	7.11e-05
	Temp*	0.044	0.022	2.0	0.0455
	EC*	0.002	0.001	2.55	0.0107

Akaike information criterion (AIC) and degrees of freedom (DF) are provided. The scores for the significant variables in each step are ********p* **< 0.001; *****p* **< 0.01; ****p* **< 0.05**
Temp-temperature; ec- electric conductivity; do- dissolved oxygen

4.4 Discussion

Microhabitat use in riverine ecosystems, particularly in the streams, is important because they reflect the hydraulic conditions that allow fish to grow and survive. In between several available measured microhabitats, water depth, water velocity, and stream bed substrate are widely regarded as the prominent factors influencing habitat use by fish (Gibson, 1993; Lake et al., 2007; Santos et al., 2008). In the present study, fingerlings were found preferably in shallow habitats with low water velocity. Their preferred habitats were reported to be the flowing refuge regions of an active river channel, which were not directly connected to the mainstream channel. They prefer these habitats to protect themselves from predators and seek shelter (Rosenberger and Angermeier, 2003; Santos et al., 2008; Malakar et al., 2014). However, juveniles were reported in shallow to deep locations with moderate to high water velocity. Their preference for secondary channels and run habitats was related to their need for adequate shelter and feeding. Nevertheless, the study findings related to varying habitat suitability by young fishes contradict Braaten et al. (1997), which reported an equitable distribution of fish microhabitat usage across different environmental conditions and no evidence of change in habitat use. It was found that young golden mahseer did not use stream habitat randomly but selected suitable instream conditions. The GLM results revealed that dissolved oxygen content and water velocity affect the presence of young golden mahseers at various growth stages, and that these variables also affect their presence during the seasons. The microhabitat preferences in fishes have been demonstrated in several studies where the habitat use was influenced due to modification in association with benthic organisms and substrate presence (Moore et al., 2020; Valles and Kramer, 2021). This study reported microhabitat use preferences at different life history stages of young golden mahseers and marked the first study to examine habitat suitability criteria.

Streamflow systems suitability functions as biological inputs, making them effective tools for stream managers to implement flow regimes (Rosenfeld, 2012). In general, as the behaviour of fish changes with an increase in their size to attain maturity, young ones generally prefer fast-flowing water with an increase in size (Solstorm et al., 2018; Yoon et al., 2018). Similarly, the juvenile and fingerling of golden mahseer were found to inhabit low to moderate-velocity microhabitats. Cobbles, sand, small boulders, and gravel were present as substrates in the preferred habitats of the young golden mahseer. Juveniles preferred cobbles and gravel, while sand was reported for fingerlings.

Further, the habitat suitability study results revealed a seasonal pattern of habitat use by the young ones. During the monsoon rains, young ones move to secondary and associated streams when the water level rises after the dry season (Giller and Malmqvist, 1998). With the rising water level, they prefer to spread out to find suitable areas with good shelter, safe from predators and abundant food resources. Our findings correspond to the hypothesis that young fish confine themselves to standing pools in the main channel by the end of the rain (Godinho et al., 2007). Throughout the research study, it was noticed that the population of young fish fluctuated as the water flow changed.

One of the pertinent findings of the study demonstrated the significance of environmental parameters in influencing fish habitat use throughout their lives. Dissolved oxygen, temperature, and pH were the major ecological parameters associated with the young fish habitats. Being one of the most important environmental variables, temperature affects the presence of fish in a particular habitat (Shrivastava and Patil, 2002; Gupta et al., 2011, 2012). In the study, water temperature in the preferred habitats of juveniles and fingerlings was found to be a little cooler in comparison with the other areas of the stream. Compared to the post-winter season (19.6±2.18 ^{o}C), when temperatures were high (28.01±0.97 ^{o}C) in the pre-monsoon, here it was that reported fewer juvenile individuals. This was found to be comparable with Bhatt and Pandit (2016). Also, the pH is crucial in determining water quality since it impacts other chemical properties of the water (Fakayode, 2005). The observed pH range of the preferred habitats the ideal range for spawning grounds of golden mahseer (Bhatt and Pandit, 2016). As Gupta et al. (2011) reported, the dissolved oxygen concentration in flowing water is high and is highest during winter. Our study also observed an increased dissolved oxygen concentration with a fall in temperature with the seasonal change. The lowest value of dissolved oxygen was measured during the pre-monsoon season (7.99 mg/l), and the highest value (9.32 mg/l) was recorded during the post-winter season. These differences might be due to the increasing water temperatures and decreased water currents. Importantly, microhabitats have been highlighted as a critical directing force for the survival and existence of biological communities in their ecosystems (Schoener, 1974). The rivers in the western Himalaya range in Uttarakhand are the potential habitats for the golden mahseer (Nautiyal, 2014). Throughout their life cycle, they grow large and use various habitat types. Meanwhile, due to the implementation of several hydro projects followed by the subsequent changes in river physiography, the golden mahseer is expected to endure habitat loss, fragmentation, and degradation in the future as sand/boulder mining is the most critical threat in Western Himalaya (Nautiyal, 2014; Lima et al., 2016). Though not quantified in the study, smooth-coated otters and kingfishers have been identified as the young golden mahseers' main predators in the study.

The results of the study presented here not only aid in gaining a better understanding of the habitat requirements of the young of the endangered golden mahseer but should be considered while planning for the conservation management of its habitats. Also, understanding the habitat suitability of young golden mahseer enhances the previous studies on adult golden mahseer and their habitat characteristics in similar riverine systems (Gorman and Karr, 1978; Nautiyal et al., 2001; Gupta et al., 2011; Bhatt and Pandit, 2016). The findings of the study are valuable in illuminating the restoration strategies that should be undertaken to conserve the nursery habitats, which are critical for maintaining a self-sustaining population of golden mahseer in the Himalayan Rivers. In the study, it was recommended that managers consider the study in protecting this endangered mahseer species in its natural habitats in the Himalayan regions.

Fish habitat suitability varies across the river's capes. This study helps to understand potential interactions between the species and its habitat's intrinsic and extrinsic characteristics. The findings suggest that the habitat suitability criteria of young golden mahseer are significant for a better understanding of their habitat requirements. The study also reported that environmental variations, such as temperature and dissolved oxygen influence the young fish's presence. Furthermore, the habitat availability and use-based approach could be employed to identify the significant fish species' preferred microhabitats. This would help in long-term development decisions and have conservation implications.

Conclusion

Golden mahseer was reportedly found throughout the lower belt of the Ganga and the Brahmaputra basin during the 19th century (Nautiyal, 2014; Bhatt and Pandit, 2016), but it has faced a drastic decline in its population size and distribution (including local extinctions) due to various developmental and the anthropogenic pressures (Khan and Sinha, 2000; Sinha and Khan, 2001; Sodhi et al., 2013). Because of these threats, it is considered globally an endangered species on the IUCN list, and its population is declining rapidly in the freshwater systems, including the tributaries of river Ramganga, Uttarakhand (Jha et al., 2018; Nautiyal, 2014). The most damaging factors in these tributaries are illegal fishing practices, pollution, habitat modification, and fragmentation (Atkore, 2005; Bhatt et al., 2017; Nautiyal, 2014). However, strong conservation and management initiatives since the last 1900s have resulted in population control in the wild (Gupta et al., 2014; Baruah and Sarma, 2018; Sarkar et al., 2020; Dutta et al., 2020). Nevertheless, habitats of golden mahseer have been fragmented largely in the Himalayan streams (Nautiyal, 2006). Apart from the concerns mentioned above, increasing demand for fish consumption, sedimentation falls, and irrigation weirs have led to illegal fishing practices (Gupta et al., 2014; Nautiyal, 2014). Therefore, the existing wild population is in a threatened situation.

Meanwhile, obstructions have been observed in species' breeding and spawning routes in the fast-flowing rivers (Nautiyal, 2001; Bhatt et al., 2004; Baruah, 2023). Therefore, considering the situations mentioned above and their long-term conservation, the rational planning of developmental activities such as upcoming hydro projects in these regions and a better understanding of the distribution, habitat requirements, and movement patterns of golden mahseer in the Himalayan rivers is consequently imperative. Despite a relatively long history of population distribution and effective management efforts, more information was needed on the movement and routes to the upstream and downstream areas often observed in the wild populations. As a result, this doctoral research was aligned towards understanding the current distribution status of golden mahseer and its ecology along with other co-existing species in the tributaries of river Ramganga. Golden mahseers' movement for breeding has been severely damaged by practices like habitat modification and fragmentation, leading to understanding the factors important for golden mahseer upstream routes and their breeding and nursery grounds. However, a study has been carried out in Bhutan with radio-telemetry tagging to study the movement and migration of golden mahseer (Fisheries Conservation Foundation and World Wildlife Fund-Bhutan pers. comm. 2018). The current work marks the first assessment of learning and understanding the movement of a freshwater fish species in India. Also, this study explains the environmental variations, such as temperature and dissolved oxygen, that influence the presence of different life-history stages of golden mahseer fish. Another study objective discusses the dietary overlap, trophic partitioning, food preferences, and feeding patterns of six fish species (Order- Cypriniformes) that thrive in these rivers. Furthermore, this study suggests the habitat availability and use-based approach that could be employed to identify the species' preferred microhabitats. This study documented the suitable nursery grounds and habitats of golden mahseer young ones that facilitate the conservation of their habitats. Consequently, the present doctoral study is believed to be significant for the short and long-term development decisions related to aquatic fish species and have conservation implications. The key findings from this doctoral thesis are discussed below:

7.1 Factors governing the golden mahseer distribution

- The objective explains the fish community structure in the study sites, their conservation status, and the governing environmental parameters of the three rivers.
- The results of fish community structure showed a significant relationship between the resulting environmental parameters and fish assemblages.
- Fish assemblage patterns in the Kosi, Kolhu, and Khoh rivers have resulted in responses to various environmental factors during the seasonal studies.
- The fish community observed a pattern of increasing species richness, diversity, and abundance from upstream to downstream,
- Abiotic components reflected golden mahseer's distribution, including altitude, dissolved oxygen content, TDS, EC, depth, pH, and cobbles, boulders, sand, and gravel as substrates.
- The presence of woody debris, undercut boulders, root wards/snags, and overhanging vegetation was qualitatively significant for the distribution of golden mahseer.

7.2 Resource and space use in carps

- The study showed that *Tor putitora* was reportedly found to be an insectivore that consumed a variety of aquatic and terrestrial insects. The main diet components were Diptera, Isoptera, and Trichoptera.

- *Labeo. calbasu*, *Labeo. pangusia*, *Opsarius. bendelisis*, *Garra gotyla*, and *Barilius vagra* were found to have specialists, while *Tor putitora* was found to have a range between specialist and generalist.
- Habitat suitability for depth for *Tor putitora* adult individuals preferred a range of 0.6 to 2m. Habitat suitability curve of water velocity ranged from 0.3 to 1m/s.
- *Garra gotyla* were mostly found in shallow water areas with a depth range between 0 and 0.6m and a velocity range between 0 and 0.3 m/s.
- *Barilius vagra*, the suitability of depth ranged between 0.1 and 0.6m, and the velocity ranged between 0 and 0.3m/s.
- *Opsarius bendelisis* showed that the depth ranged between 0.6 and 1.2m and water velocity was between 0.3 and 1m/s.
- The optimal depth preference of *Labeo pangusia* was reportedly found to range between 1 and 1.5m, and the water velocity associated was between 0 and 0.6 m/s.
- In *Labeo calbasu*, depth was reported in association with moderately deeper open-channel areas of the river.

7.3 Movement ecology of golden mahseer

- It was reported that the individuals were dispersed, with the maximum recorded distances in the Kosi and Kolhu rivers being 4231.23 m and 6119.11 m, respectively.
- While females and smaller individuals traversed long distances and established wider home ranges, males and larger individuals showed released side fidelity with smaller home sizes. The study also described how golden mahseer individuals used warmer tributaries for their homing instincts and spawning.

- Females were found to utilize the majority of aquatic habitats and to travel longer distances in search of ideal areas for nesting and breeding.
- In addition, compared to males, females tend to establish a larger home range (95% KDE).
- The present study reported that the maximum movement of the fish was from early August to mid-September.
- The study results are valuable and should be considered while formulating the conservation measurements and management plans for the golden mahseer individuals.

7.4 Habitat suitability of young ones of golden mahseer

- The last chapter of the thesis discusses the habitat suitability of young ones (fingerlings and juveniles). The presence of juveniles showed to be substantial during the post-monsoon season. They were found across rivers in different habitats but were most abundant post-monsoon, followed by the post-winter season.
- For the fingerlings and juveniles, the range of available microhabitats, depth, and water velocity was 0 to 1.2 m and 0 to 1.2 m/s, and 0 to 1.5 m and 0 to >2.0 m/s.
- The primary constituents of the substrate included small boulders, bedrock, cobbles, gravel, sand, and silt.
- Sand, gravel, and small cobbles were the most common substrates used by fingerlings, who preferred a depth range of 0.1 to 0.6 m with water velocity ranging from 0 to 0.2 m/s.

- Sand, bedrock, and cobbles dominated the juveniles' habitats, ranging in depth from 0.1 to 1.5 m and water velocity from 0.1 to 0.5 m/s.
- The three main variables affecting habitat selection were temperature, water velocity, and dissolved oxygen; dissolved oxygen positively influenced fingerlings. On the other hand, water velocity had a significant impact on juveniles.

Key concerns and recommendations

- The environmental and ecological parameters of the riverine system should be monitored closely and regularly as they indicate any change in the river's health. This would help comprehend the effects of anthropogenic pressure, climate change, river conditions, and other factors.

- Fishing should only be open to licensed sport fishermen in the streams from October to May (non-breeding season). Destructive or illegal fishing practices such as dynamiting and poisoning should be prohibited.

- Efforts should be made to check the sediment flow by extensive plantation of native trees, shrubs, etc., on the riverbank and adjoining catchment area.

- Since the local communities and fishermen are the ones who ensure the wild population of fish thriving in the rivers is safe, they need to be made more aware of the ecological significance of fish species like golden mahseer and the effects of illegal fishing practices.

- Many societies have already started to define what makes up essential fish habitat (EFH) (Rosenberg et al., 2000) with local communities, which includes guiding the waters and substrates required for these fish species' spawning, feeding, and maturation. Therefore, it is suggested that the golden mahseer species in the Himalayan streams be protected with these actions. Furthermore, this can serve as a guide for conserving significant mahseer-like fish species in danger of extinction.

- Before starting any hydro projects, a comprehensive environmental assessment should be done to better understand the fish habitats in the upper and lower stretches of the Ganges River. Fish conservation strategies must consider migratory fish species' migration routes and habitat requirements.

- Using modern satellite telemetry to collect more fine-scale data on such endangered species movement patterns for the long term should be highly encouraged.

- More research efforts on generating information on the life history of threatened fishes are necessary for their successful conservation. An ecosystem approach (Garcia and Cochrane et al., 2005) to fish conservation is a new management of fish communities in many countries. Therefore, information on the role of species diversity in the functioning of ecosystems should be incorporated into comprehensive environmental management policies of the large Indian rivers.

- Successful strategies such as raising awareness, controlling illegal fishing, protecting fish breeding grounds, creating best practices like no-go zones, ensuring e-flows for the ecological integrity of ecosystems, and ongoing stakeholder consultation are suggested as successful ways to conserve the fish for the long term.

In summary, this doctoral thesis establishes a strong baseline for long-term ecological research on the movement ecology of the wild existing endangered golden mahseer species in the Himalayan stretch. This work has helped to understand the distribution of golden mahseer and other important fish species in the tributaries of river Ramganga in the Western Himalaya. Despite many studies on the ecology of golden mahseer, this study shed light on the resource and habitat utilization of significant fish species, showing the application of inter-specific competition among the considerable fish species. This study has resulted from a combination of both field and laboratory approaches. Significantly, this research led to the nation's first study into radio-telemetry tagging of freshwater fish species. This work forms a base for understanding further detailed investigations on the population assessment, performing fish tagging, and planning scientific studies to assess the impacts of changing climatic conditions on the population of golden mahseer and other significant conservation species.

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ANNEXURE-I

Permits and ethical clearance:

Data generated in this study is part of a collaborative programme title, "Ecology and migratory patterns of golden mahseer (*Tor putitora*) in river Ganga using radio telemetry technique in Uttarakhand rivers". The fish sampling from all the three tributaries was permitted by Ministry of Environment, Forests and Climate Change (MoEF&CC), Government of India (Letter No. 470/5-6) was received.

ANNEXURE-II

MAKE INDIA CLEAN AS WELL AS CLEANING UP TECHNOLOGIES

5th International Conference on Environment and Ecology

Hosted by: Christ College, Pune, Maharashtra
In Association with: International Foundation for Environment and Ecology, Kolkata
In Collaboration with: Confederation of Indian Universities, New Delhi

ICEE 2019

Certificate of Appreciation

The Conference Organising Committee do hereby confer upon BHAWNA DHAWAN.

of Wild life Institute of India, Dehradun.

BEST PRESENTATION AWARD (~~Oral~~ / Poster) for the topic Status of Golden Mahseer (Tor putitora) in River Kosi, Uttarakhand, India.

in the "5th International Conference on Environment and Ecology" held on 18-19-20 February 2019 at Christ College, Pune, Maharashtra.

Dr (Fr) Sony J. Chundattu, Director/Principal, Christ College - Pune
Dr P. R. Trivedi, President, CIU, New Delhi
Dr Tridip Bandopadhyay, President, IFEE

20th February 2019 Pune, Maharashtra, India

The International Mahseer Conference

CERTIFICATE

presented to

Bhawna Dhawan

On behalf of the Program Committee of the International Mahseer Conference, this certificate recognizes that **Bhawna Dhawan** presented the scientific paper "*Distribution Status of Golden Mahseer, Tor putitora, in Uttarakhand India and Way Forward*" during the International Mahseer Conference held at the Zhiwa Ling Heritage in Paro, Bhutan, December 2-8, 2018.

Date: December 8, 2019

Julie Claussen,
Program Co-Chair,
International Mahseer Conference
Fisheries Conservation Foundation

INTERNATIONAL MAHSEER CONFERENCE
DECEMBER 2018

CONFERENCE HOSTS

Certificate of Appreciation

This certificate is presented to

Bhawna Dhawan

in honor and appreciation for oral presentation

Habitat use by young golden mahseers (*Tor putitora*) in Kosi and Kohlu rivers of Uttarakhand, India

on the occasion of

"2nd International Mahseer Conference"
held by Maejo University, Chiang Mai, Thailand
on 11th -15th February 2020

Assoc. Prof. Apinun Suvarnaraksha, Ph.D.
Director of 2nd International Mahseer Conference

Asst. Prof. Jongkon Promya, Ph.D.
Dean, Faculty of Fisheries Technology and Aquatic Resources

Assoc. Prof. Weerapon Thongma, Ph.D.
President, Maejo University

Certificate of Participation

Bhawna Dhawan

participated and presented paper/poster paper in International Conservation Conference held at Aligarh Muslim University, Aligarh, U.P., India during 21st to 23rd October 2019. The title of the presentation was

Plan for development or conservation....? Indeed ...... to be Concerned about Tiger of Freshwater Ecosystem

DR. AFIFULLAH KHAN
Conference Director

DR. ORUS ILYAS
Conference Co-ordinator

Organized by
Department of Wildlife Sciences, AMU
and
Wildlife Institute of India, Dehradun

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RESEARCH ARTICLE

WILEY

Habitat suitability of golden mahseer young ones (*Tor putitora*, Hamilton 1822) in Himalayan waters, India

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Wildlife Institute of India, Ministry of Environment, Forest and Climate Change

Abstract

Habitat suitability refers to the mechanism that enables organisms to choose suitable habitats to survive. In the present study, we studied the habitat suitability of young golden mahseer (fingerlings and juveniles) in the streams of the Ramganga River, one of the prominent rivers of the western Himalaya. Different habitat types and micro-habitat features were documented. Habitat suitability was evaluated by generating habitat suitability criteria curves in response to varying habitat availability and use by young golden mahseer during different seasons. Generalised linear modelling (GLM) was used to analyse environmental characteristics responsible for selecting golden mahseer habitats. We studied mahseer based on body size into two main classes, that is, fingerlings (1.5–10 cm) and juveniles (10–30 cm). Golden mahseer fingerlings preferred mean depth (0.1–0.6 m) and mean stream velocity (0–0.2 m/s) at stream reach dominated by diverse substrate compositions such as sand, gravel, and small cobbles. Similarly, juveniles preferred mean depth (0.1–1.5 m) and mean water velocity (0.1–0.5 m/s), with cobbles, bedrock, and sand dominating their habitats. The GLM results indicated that dissolved oxygen, temperature, and water velocity were the significant factors influencing habitat suitability. High dissolved oxygen positively influenced fingerlings, whereas moderate to high water velocity affected juveniles the most. Therefore, to understand the flow requirement for threatened species like golden mahseer, it is essential to characterise critical habitats and develop criteria based on habitat suitability curves.

KEYWORDS
fish conservation, GLM, habitat use, microhabitats, Ramganga River, western Himalaya

1 | INTRODUCTION

Habitat suitability is an important aspect of the life-history traits of fish. Several intrinsic and extrinsic factors favour the fish's suitable habitat (Santos et al., 2008). During the early stages of ontogeny, fish undergo various developmental processes in which small-sized young fish are relatively vulnerable to high water velocity and variations in the volume of water (Lake et al., 2007). To overcome such hurdles, young fish find suitable microhabitats in the small river channels to get nutrient-rich refuge areas with a good cover complex (Pusey & Arthington, 2003). These channels are suitable habitats for the young fish before joining the main river channel during the monsoonal rains. Many fish species, concerning their life histories, may necessitate different environments during their development periods (Curtis et al., 2017; Fausch et al., 2002). This method of microhabitat quantification has been proposed to promote species distribution, growth rates, resource exploration, and predator avoidance (Rosenberger & Angermeier, 2003; Skyfield & Grossman, 2007).

Habitat suitability describes how suitable a certain habitat and environmental conditions are for a given size or life-history stage of fish (Bain & Jia, 2012; Midway et al., 2010). Addressing species–habitat interactions and habitat suitability is crucial to fish ecology and conservation (Boavida et al., 2013; Bovee et al., 1998; Muñoz-Mas et al., 2012). Based on the observations of an individual's presence or absence in different habitats, it is determined for fishes and their life-history phases in various habitats (Jowett & Davey, 2007). The variables such as depth, water velocity, and substrate composition are the most suitable, and for habitat suitability, they are represented as continuous curves (Boavida et al., 2013; Rivaes et al., 2017; Santos et al., 2006).

Golden mahseer (*Tor putitora*) is one of the iconic endangered fish species in the rivers of the Himalayan foothills. Recent studies revealed that the species had lost almost 50% of its population in the recent past and is predicted to decline by more than 80% in the future if the current trend of habitat loss continues (Bhatt et al., 2004; Bhatt & Pandit, 2016; Sharma et al., 2015). River characteristics and dynamics are critical for fish survival (Malakar et al., 2014); however, gradual changes in the environmental variables can alter their life cycle (Piffady et al., 2013). Studies dealing with their life-history stages and ecological requirements are paramount in the current scenario (Lake et al., 2007). Inevitably, taking the necessary measures for their conservation and management through a scientific approach is imperative. However, several studies are available on the aspect of habitat suitability of fishes in the aquatic ecosystems of the Indian region (Arunachalam, 2000; Johnson et al., 2017; Sivakumar, 2008) and the Ganges and Brahmaputra basins (Lakra et al., 2010; Malakar et al., 2014). However, to our knowledge, studies have yet to be conducted on the habitat use, availability, and suitability of young golden mahseer in the Himalayan streams. The ecological characteristics and habitat requirements of young golden mahseers need to be better understood compared to adults. Therefore, the study was performed on young golden mahseer to assess size-related microhabitat suitability.

Furthermore, the present study aimed to fill the research gap by documenting habitat availability and the use by golden mahseer. We also hypothesised that the habitat suitability criteria (HSC) of golden mahseer young ones vary across the seasons. To test this hypothesis, the present study was carried out covering three seasons: the post-monsoon (mid-October 2018), post-winter (February–March), and pre-monsoon (May–June) seasons in the year 2019.

2 | MATERIALS AND METHODS

2.1 | Study area

The present study was conducted in two important streams (Kosi and Kolhu) of the Ramganga basin, which flows through Uttarakhand in the western Himalaya (Figure 1). These streams are important golden mahseer habitats (Atkore et al., 2011; MacDonald, 1948). The

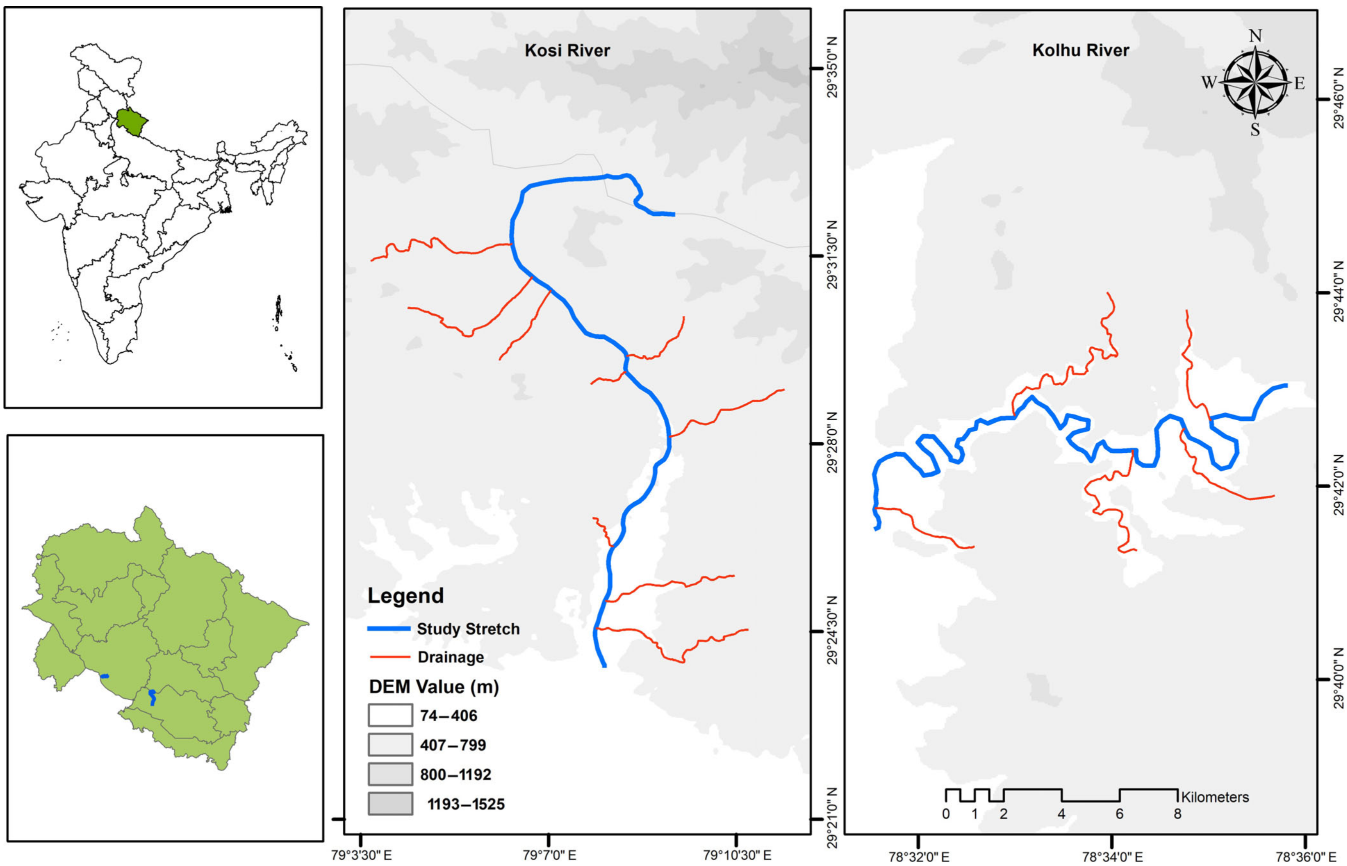

FIGURE 1 Study area map of the sampled river stretches in Uttarakhand; rivers Kosi and Kolhu. [Color figure can be viewed at wileyonlinelibrary.com]

streams' headwaters run through significant protected areas of India's Corbett Tiger Reserve and Lansdowne Forest Division. Kosi, a fifth-order stream, flows through one of the fine Shivalik forests between the Corbett Tiger Reserve and the Ramnagar Forests Division (reserve forest area). It is home to a diverse range of aquatic wildlife, such as smooth-coated otters (*Lutrogale perspicillata*), mugger crocodiles (*Crocodylus palustris*), turtles (*Nilssonia gangetica*), and gharials (*Gavialis gangeticus*), including many fish species such as *Tor putitora*, *Tor tor*, *Labeo rohita*, *Chagunius chagunio*, *Mastacembelus armatus*, etc. (Khwairakpam et al., 2023). Despite being a promising water channel, urbanisation along the Kosi banks has significantly affected its habitats and wildlife (Mondal & Zhang, 2018). Amid the habitat loss scenario, Kosi's upper stretch sections still have high-quality habitats supporting aquatic wildlife. The stream reach of 200 m focusing on each upper, middle, and downstream, was selected within a 32 km stretch (29°24′2.78″ N, 79°07′54.41″ E and 29°48′02.62″ N, 79°12′08.43″ E) with elevation 410 m, mean sea level (msl).

Unlikely, Kolhu is a rain-fed third-order stream that rises from the confluence of two lesser streams, Noddy and Bhaira, which flow through the Lansdowne Forests Division (Atkore et al., 2011). It flows (16–18 km) through the Shivalik Himalaya area down to Kotdawar town in Pauri-Garhwal, Uttarakhand, where it joins the river Khoh at Saneh village (29°41′31.2″ N, 78°31′38.64″ E and 29°42′58.32″ N, 78°35′48.84″ E, 315 m, msl) and flows downstream to meet the river Ramganga. The stream reach of 200 m each in the upper, middle, and down parts of 16 km of the Kolhu were selected for the present study. The research sites were forested with tropical dry deciduous forests (Champion & Seth, 1968), with well-developed riparian vegetation that included prominent *Acacia catechu* (Khair), *Shorea robusta* (Sal), *Dalbergia sissoo* (Shesham), *Bombex ceiba* (bamboo), etc. The potential fish predators in these areas were the smooth-coated otter and important birds such as kingfishers, greater egrets, and little egrets. Kolhu is less disturbed than the Kosi stretch since it flows through a well-protected Lansdowne Forest Division situated between Rajaji National Park and the Corbett Tiger Reserve.

2.2 | Inventory of nursery grounds

Field surveys were undertaken during the three seasons, including post-monsoon, post-winter, and pre-monsoon in 2018–2019. The nursery grounds were identified throughout the stretch through visual observations of the fish. The locations were recorded using Garmin global positioning systems (GPS; etrex 10X, Garmin International, Inc., Switzerland, USA). During the study, young ones were classified into two size classes: fingerlings (1.5–10 cm) and juveniles (10–30 cm) (Desai, 2003) and their potential habitats in the river channel were mapped as backwater pools (BWP), secondary channels (SC), run habitats (RH), associated stream habitats (AS), isolated pools (IP), and confluence point (CP) areas (Pusey et al., 1995) (Table 1). In the study, backwater pools are the areas with a moderate to deep depth, a sandy substratum with exposed rocks, and very low to zero water velocity. Run habitats have a shallower depth, moderate flow with hydraulic leaps, and a uniform substratum composition of bedrock, cobbles, and gravel. Secondary channels are formed when rivers are flooded with rainwater and join the main river channel, forming the confluence points. Isolated pools are generated when the main river channel is cut off during the dry season, including small units with almost limited flow, sediments, and nutrient exchange. After mapping the habitats, fish shoals along the river channel were noted, and in the present study, young ones of golden mahseer of two size classes were studied.

2.3 | Fish sampling

Primarily, we did a visual count of young ones associated with pool habitats because the habitats were shallow (5–60 cm depth) and the bottom was visible in bright sunshine. The fish sampling was performed as Johnson et al. (2017) with slight modifications to account for channel morphology. First, for backwater and isolated pools, two persons stood on the banks of streams at different points using an aqua scope to count fish in channels. We observed the fish for at least a minute to see if they were moving or feeding in a particular location and then took an average count at that site. Second, we counted the young ones by underwater snorkelling in the runs and associated stream habitats with less flow and shallower depths (10–100 cm depth). Third, a bottom-set monofilaments gill net (10 m long, 2 m wide with two mesh sizes, 10 and 20 mm) was used to sample the golden mahseer young ones in a run and secondary channel. After an hour effort at the sites, the number of fish was recorded, and the respective size classes were noted down before releasing them back

TABLE 1 Recorded mean depth, water velocity and dominant substrate for different habitat types of young ones of golden mahseer in rivers Kosi and Kolhu.

	Mean depth (m)		Mean water velocity (m/s)		Dominant substrates	
Habitat type (number in Kosi and Kolhu)	Kosi	Kolhu	Kosi	Kolhu	Kosi	Kolhu
Backwater pool (70, 32)	1.2	0.78	0.4	0.6	Sand/Cobble	Cobble/Sand
Run habitat (75, 26)	0.9	0.60	2.5	1.4	Sand/Gravel	Bedrock/Sand
Secondary channel (46, 10)	1.10	0.43	2.5	1.3	Cobble/boulder	Sand/Bedrock
Isolated pool (34, 13)	1.50	0.47	0.2	0.2	Sand/Bedrock	Sand/Gravel
Associated stream (8, 12)	0.56	0.56	1.8	1.6	Sand/Gravel	Sand/Bedrock
Confluence point (9, 10)	0.89	0.22	1.8	1.6	Sand/Bedrock	Sand/Bedrock

into the water. The observations were all made in the morning (8:00–11:00 AM). Ten efforts for each sampling technique were followed throughout all sampling locations and seasons for studied reach. The average young one's count was measured for each habitat and then used in the subsequent analysis. Later, a one-way analysis of variance (ANOVA) test was used to determine if there was a significant relationship between the numbers of young ones in different habitats during different seasons.

2.4 | Measurements of microhabitat availability and use

Cross-stream transect was measured at 1-m intervals for microhabitat availability. The habitat inventory was conducted to take measurements of habitat depth, water velocity, and the presence of dominant substrate types on each transect (Bovee, 1982). For microhabitat use, after sampling the fish, three microhabitat variables were measured at each fish position as described (Bovee, 1982; Santos & Ferreira, 2008). A hand-held digital flow probe (3.7-6′, Model: FP111, Global Water Instrumentation Inc., California) with a graduated scale was used to monitor the water velocity and depth. Bedrock (>200 mm), small boulders (150–200 mm), cobbles (50–150 mm), gravel (5–50 mm), sand-silt (1–2 mm), and leaf litter were all measured, followed by Bovee (1982) and Pusey et al. (1993). The stream habitat characteristics were measured (Table 1).

2.5 | Quantification of water quality parameters

During the study, along with the microhabitat measurements, water quality parameters were assessed across the diverse habitat types in each season's sampling zone. Water temperature (°C), pH, electric conductivity (EC, μS/cm), and total dissolved solids (TDS, ppm) were measured using a hand-held probe (Eutech PCS Tester 35 multi-parameter probe, Thermo Fisher Scientific, Inc. Massachusetts, USA). Also, Winkler's method was used to quantify dissolved oxygen (DO, mg/L) content.

2.6 | Data analysis

To generate the estimates of HSCs for fingerlings and juveniles, the available microhabitat and use data for depth and water velocity were analysed for three seasons for every reach. The data set was classified into depth classes (0.1, 0.3, 0.6, 1.0, 1.2, 1.5, 1.8, 2.0, and >2.0 m), six water velocity classes (0.2, 0.3, 0.5, 0.6, 0.9, and 1.2 m/s) as per the methods of (Johnson et al., 2017). The relative frequencies were measured for each available habitat and use by young fish for depth and water velocity classification. To calculate preference for each class interval, based on availability and use by fingerlings and juveniles, $Pi = Ui/Ai$ was used, where Pi is the relative preference value, Ui is the proportion of utilisation of a specific interval, and Ai is the proportion of a particular interval of the measured variables when fish were sampled. The preferences were normalised using the formula $Pn = Pi/\max P$ and were calculated on a scale of 0–1, from not used to optimal utilisation. In the range of the variable Pi, Pn is the normalised index of preference, and $\max P$ is the highest index of preference. For the study streams, the depths and water velocities of golden mahseer fingerlings and juveniles were analysed, and HSC curves were created (Bovee et al., 1998; Hayes & Jowett, 1994; Johnson et al., 2017; Jowett & Davey, 2007) for golden mahseer fingerlings and juveniles. To assess the relationship between water quality and the golden mahseer young ones, an analysis of 15 explanatory variables was performed. The correlation matrix plots indicated highly correlated variables from which variables with lower loadings were removed for further analysis. Water quality and habitat parameters were the dependent variables and the abundance of young mahseer in the studied rivers was the independent variable. We assessed the relationship between the young ones and the retained water quality parameters within each stream using generalised linear modelling (GLM) (McCullagh & Nelder, 1989). The count data set was analysed using Poisson distribution to determine the best data distribution, and the best-fit models were selected using Akaike's information criteria (AIC) (Arnold, 2010). The coefficient values were compared to the fitted and explanatory variables to validate the model. All models that fall within an AIC delta of less than two units from the best model were selected for model averaging (Zuur et al., 2007). All the statistical analysis in the study was performed using MS Excel 2016 and RStudio version 4.0.2 (R Core Team, 2013) with the 'MASS,' 'vegan,' 'MuMIn,' and 'ggplot2' packages used to carry out the data analysis and interpretation, and ArcMap 10.5 was used to create the maps. We used box and whisker plots to explore the relationship between golden mahseer abundance with associated environmental variables. These tools were used to study the effect of variables on the habitat preference of fingerlings and juveniles in the studied streams.

3 | RESULTS

3.1 | Fish data

In the Kosi stream, we observed a significant difference in habitat use by juveniles (59%; $F = 8.008$, $df = 7.845$, and $p < 0.012$) and fingerlings (41%; $F = 6.228$, $df = 7.621$, and $p < 0.024$) across the different habitat types and different seasons (Figure S1). However, in Kolhu, the habitat use by young ones, specifically the juveniles, showed to be significant during the post-monsoon season ($F = 1.89$, $df = 9.77$, and $p < 0.020$). The findings revealed that the golden mahseer young ones were found across rivers in different habitats and they were most abundant during the post-monsoon, followed by the post-winter season. The results of one-way ANOVA showed a significant relationship between habitat types and the presence of young ones (Table 2); however, in Kolhu river, the fingerlings association with habitat types were not significant.

TABLE 2 One-way ANOVA results for the season and habitat-type effects on the microhabitat use by the fish size class (young ones) in Kosi and Kolhu.

Size-class/river	Source of variation	*F*	df	*p*
Fingerlings, Kosi	Seasons × Habitat types	6.228	7.621	0.0249
Juveniles, Kosi	Seasons × Habitat types	8.008	7.845	0.012
Fingerlings, Kolhu	Seasons × Habitat types	1.251	9.923	0.327
Juveniles, Kolhu	Seasons × Habitat types	1.89	9.77	0.0202

Abbreviation: df, degree of freedom.

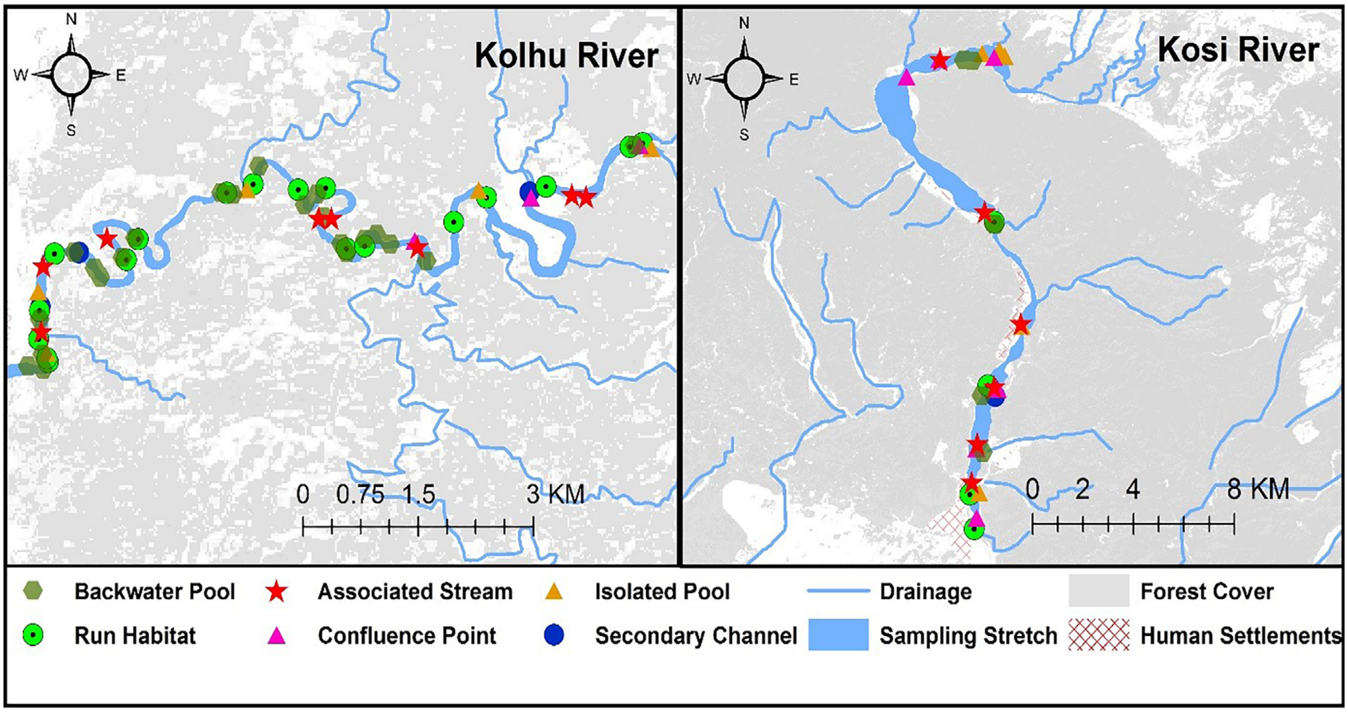

FIGURE 2 Marked habitat locations of golden mahseer young ones (juveniles and fingerlings) in Kolhu and Kosi. [Color figure can be viewed at wileyonlinelibrary.com]

3.2 | Microhabitat: Availability and use

Among the habitat types, BWP, RH, and SC were the most occupied habitats of golden mahseer young ones in both river stretches, followed by IP, AS, and CP. The distribution of these nursery ground habitats was mapped based on the habitat inventory (Figure 2). In the present study, we recorded 242 nursery ground habitats of golden mahseer young ones in the Kosi River, including BWP accounting for 28.9%, RH 31%, SC 19%, IP 14%, AS 3%, and CP 3.7%. In Kolhu, 103 nursery ground habitats with golden mahseer young ones were recorded, which included BWP accounting for 33%, RH 25%, SC 10%, IP 13%, AS 13%, and CP 9.7%. Overall, the available microhabitats, depth, and water velocity for the fingerlings and juveniles range from 0 to 1.2 m and 0 to 1.2 m/s and 0 to 1.5 m and 0 to >2.0 m/s, respectively (Figure 3a–d), and substrate was mainly composed of small boulders (15%), bedrock (10%), cobbles (25%), gravels (20%), and sand-silt (30%).

3.3 | Generation of HSC curves

HSC curves were developed for golden mahseer young ones for the Kosi and Kolhu (Figures 4 and 5). The results showed that fingerlings varied across depth ranges throughout different seasons, with the preferred depth values of 0.1–0.3 m being used in Kolhu (Figure 5a) and 0.1–0.6 m in Kosi (Figure 4a) during the post-monsoon. Most preferred water velocity for fingerlings in Kosi was reported to be 0 m/s during the post-winter and the pre-monsoon. However, an increased water velocity was found during the post-monsoon (0–0.2 m/s) in Kosi (Figure 4b). In Kolhu, the preferred water velocity was 0–0.2 m/s during the post-monsoon and post-winter seasons. Water velocity was found to be around zero for the fingerlings' used pool habitats during the pre-monsoon in Kolhu (Figure 5b). Although the juveniles depth ranged from 0.1–1.5 m in Kosi (Figure 4c) and 0.1–1.2 m in Kolhu (Figure 5c), the most suitable water column depth ranged between 0 and 0.6 m during the studied seasons in both rivers. It was

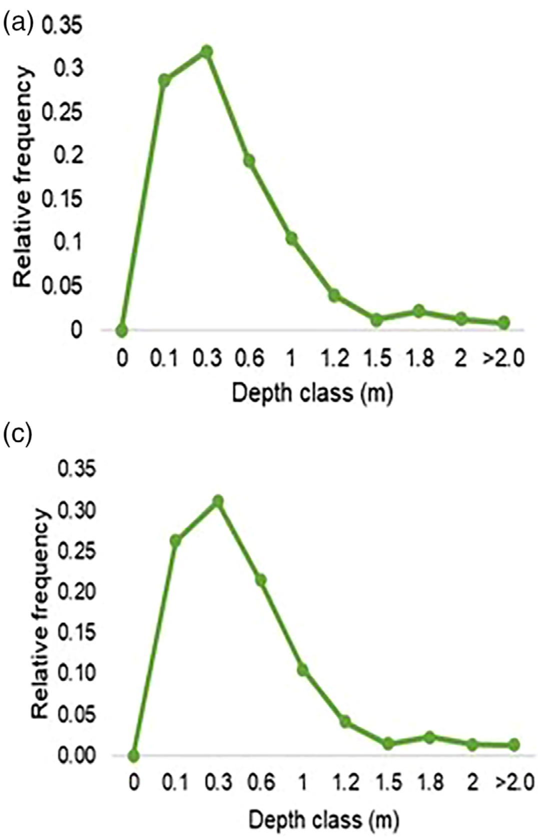

FIGURE 3 Relative frequency of available depth and water velocity in nursery habitats in the studied rivers representing; (a) depth availability for fingerlings, (b) water velocity availability for fingerlings, (c) depth availability for juveniles, and (d) water velocity availability for juveniles. [Color figure can be viewed at wileyonlinelibrary.com]

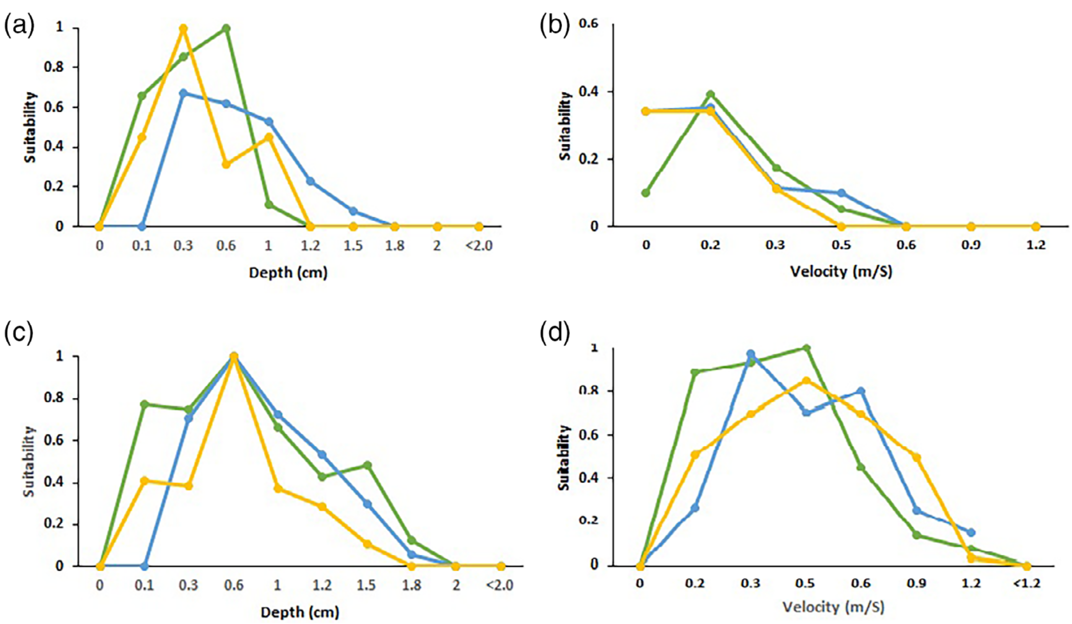

FIGURE 4 Suitability curves of depth and water velocity for fingerlings and juveniles in River Kosi representing (a) depth suitability, (b) water velocity suitability for fingerlings, (c) depth suitability, and (d) water velocity suitability for juveniles. Colour representation: green, post-monsoon; blue, post-winter; yellow, pre-monsoon. [Color figure can be viewed at wileyonlinelibrary.com]

high during the post-monsoon in Kolhu (0.1–1.1 m) and during the post-winter in Kosi (0–0.6 m). In both the rivers, the most suitable water velocity value was found between 0.1 and 0.5 m/s during the post-monsoon, and the lowest was measured during the pre-monsoon (0.1–0.2 m/s). However, juveniles and fingerlings were located in a selected depth and water velocity range in their preferred habitats

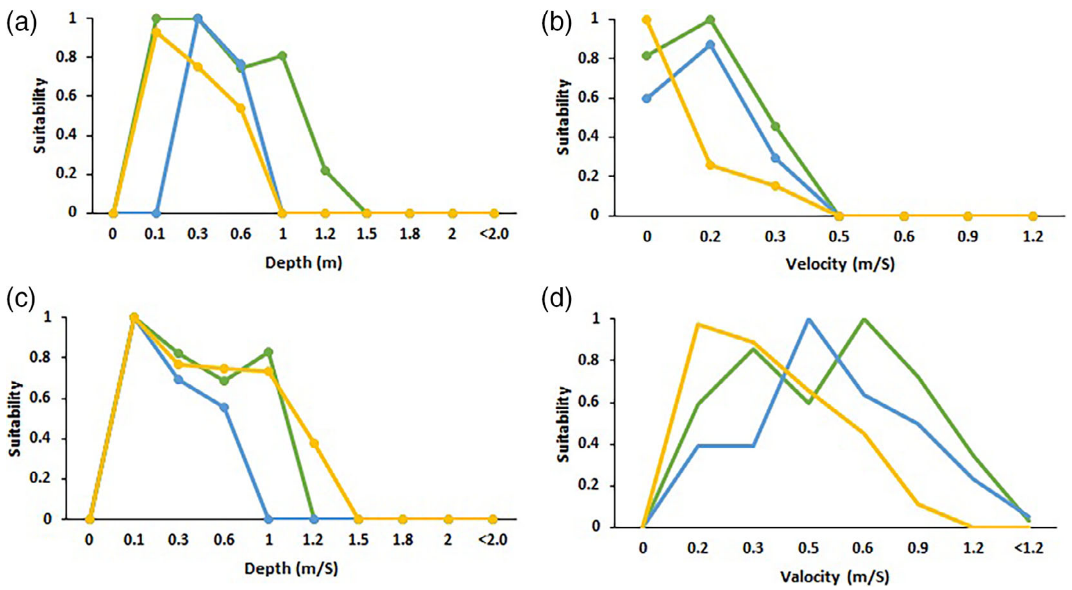

FIGURE 5 Suitability curves of depth and water velocity by fingerlings and juveniles in River Kolhu representing (a) depth suitability, and (b) water velocity suitability for fingerlings, (c) depth suitability, and (d) water velocity suitability for juveniles. Colour representation: green, post-monsoon; blue, post-winter; yellow, pre-monsoon. [Color figure can be viewed at wileyonlinelibrary.com]

throughout the study period. They have been found to thrive together in groups in the streams.

3.4 | Generalised linear modelling

GLM explained the abundance of mahseer young ones impacted by DO, EC, pH, and temperature (Table 3a). They were reported to influence the presence of fingerlings positively. Apart from TDS and depth, which did not affect the presence of fingerlings in Kolhu, the flow rate negatively affected their presence (Figure 6a). In Kosi, the fingerlings were positively influenced by temperature (Figure 6b). Water velocity positively influenced the presence of juveniles in Kosi and Kolhu (Figure 6c,d). The optimal GLM obtained by successively removing the explanatory factors for fingerlings from the full models led to a result of flow, pH, temperature, DO, and EC (Table 3b). In the case of juveniles, depth, flow, and EC were found to be significant explanatory variables (Table 3c). Also, the results of the GLM with the season and environmental factors as predictors for fingerlings and juveniles revealed that depth, flow, gravel, and small boulders influenced the presence of young golden mahseer. The results are presented with the corrected AIC value and degree of freedom in Tables S1a and S1b.

4 | DISCUSSION

Microhabitat use in riverine ecosystems, particularly in the streams, is important because they reflect the hydraulic conditions that allow fish to grow and survive. The microhabitats feature such as water depth, water velocity, and stream bed substrate are widely regarded as the prominent factors influencing habitat use by fish (Gibson, 1993; Lake et al., 2007; Santos et al., 2008). In the present study, fingerlings were found preferably in shallow habitats with low water velocity. Their preferred habitats were reported to be the flowing refuge regions of an active river channel, which were not directly connected to the mainstream channel. They prefer these habitats to protect themselves from predators and seek shelter (Malakar et al., 2014; Rosenberger & Angermeier, 2003; Santos et al., 2008). However, juveniles were reported in shallow to deep locations with moderate to high water velocity. Their preference for secondary channels and run habitats was related to their need for adequate shelter and feeding. Nevertheless, the study findings related to varying habitat suitability by young fishes contradict Braaten et al. (1997), which reported an equitable distribution of fish microhabitat usage across different environmental conditions and no evidence of change in habitat use. We found that young golden mahseer did not use stream habitat randomly but selected suitable instream conditions. The GLM results revealed that DO content and water velocity affect the presence of young golden mahseers at various growth stages, and that these variables also affect their presence during the seasons. The microhabitat preferences in fishes have been demonstrated in several studies where the habitat use was influenced due to modification in association with benthic organisms and substrate presence (Moore et al., 2020; Vallès & Kramer, 2021). This study reported microhabitat use preferences at different life-history stages of young golden mahseers and marked the first study to examine HSC.

Streamflow systems' suitability functions as biological inputs, making them effective tools for stream managers to implement flow regimes (Rosenfeld, 2017). In general, as the behaviour of fish changes with an increase in their size to attain maturity, young ones generally prefer fast-flowing water with an increase in size (Solstorm

TABLE 3 The best fit model results for the generalised linear model (GLM) using depth, temperature (temp), electric conductivity (ec), water velocity (flow), dissolved oxygen (do), and pH as independent variables (panel A) and using Poisson distribution parameter estimates of the best model for fingerlings (panel B) and for juveniles (panel C).

Panel A			
Size-class/river	**Best fit model**	**AIC**	**df**
Fingerlings, Kosi	~depth + temp + ec	1331.3	99
Juveniles, Kosi	~flow + temp + pH + do + ec	1887.4	236
Fingerlings, Kolhu	~depth + ec + temp	1335.9	99
Juveniles, Kolhu	~flow + temp + pH + do + ec	1887.4	236

Panel B				
Coefficients	**Estimate**	**SE**	***Z***	***p***
Intercept***	3.53	0.75	4.66	3.06e-06
Flow***	0.24	0.03	8.37	<2e-16
Temp***	−0.17	0.02	−9.35	<2e-16
pH***	−0.21	0.06	−3.66	0.00025
DO	0.08	0.057	1.47	0.13985
EC***	0.02	0.001	8.50	<2e-16

Panel C				
Coefficients	**Estimate**	**SE**	***Z***	***p***
Intercept	1.023	0.80	1.27	0.2030
Depth***	−0.009	0.002	−3.97	7.11e-05
Temp*	0.044	0.022	2.0	0.0455
EC*	0.002	0.001	2.55	0.0107

Note: Akaike's information criterion (AIC) and degrees of freedom (df) are provided. The scores for the significant variables in each step are ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$.

et al., 2018; Yoon et al., 2019). Similarly, the juvenile and fingerling of golden mahseer were found to inhabit low- to moderate-velocity microhabitats. Cobbles, sand, small boulders, and gravel were present as substrates in the preferred habitats of the young golden mahseer. Juveniles preferred cobbles and gravel, while sand was reported for fingerlings.

Further, the habitat suitability study results revealed a seasonal pattern of habitat use by the young ones. During the monsoon rains, young ones move to secondary and associated streams when the water level rises after the dry season (Giller & Malmqvist, 1998). With the rising water level, they prefer to spread out to find suitable areas with good shelter, safe from predators, and abundant food resources. Our findings correspond to the hypothesis that young fish confine themselves to standing pools in the main channel by the end of the rain (Godinho et al., 2007). Throughout the research study, we noticed that the population of young fish fluctuated as the water flow changed.

One of the pertinent findings of the study demonstrated the significance of environmental parameters in influencing fish habitat use throughout their lives. DO, temperature, and pH were the major ecological parameters associated with the young fish habitats. Being one of the most important environmental variables, temperature affects the presence of fish in a particular habitat (Gupta et al., 2011, 2012; Shrivastava & Patil, 2002). In the study, water temperature in the preferred habitats of juveniles and fingerlings was found to be a little cooler in comparison with the other areas of the stream. Compared to the post-winter season (19.6 ± 2.18°C), when temperatures were high (28.01 ± 0.97°C) in the pre-monsoon, we reported fewer juvenile individuals. This was found to be comparable with Bhatt and Pandit (2016). Also, the pH is crucial in determining water quality because it impacts other chemical properties of the water (Fakayode, 2005). The observed pH range of the preferred habitats is the ideal range for spawning grounds of golden mahseer (Bhatt & Pandit, 2016). As Gupta et al. (2011) reported, the DO concentration in flowing water is high and is highest during winter. Our study also observed an increased DO concentration with a fall in temperature with the seasonal change. The lowest value of DO was measured during the pre-monsoon season (7.99 mg/L), and the highest value (9.32 mg/L) was recorded during the post-winter season. These differences might be due to the increasing water temperatures and decreased water currents. Importantly, microhabitats have been highlighted as a critical directing force for the survival and existence of biological communities in their ecosystems (Schoener, 1974). The rivers in the western Himalaya range in Uttarakhand are the potential habitats for the golden mahseer (Nautiyal, 2014). Throughout their life cycle, they grow large and use various habitat types. Meanwhile,

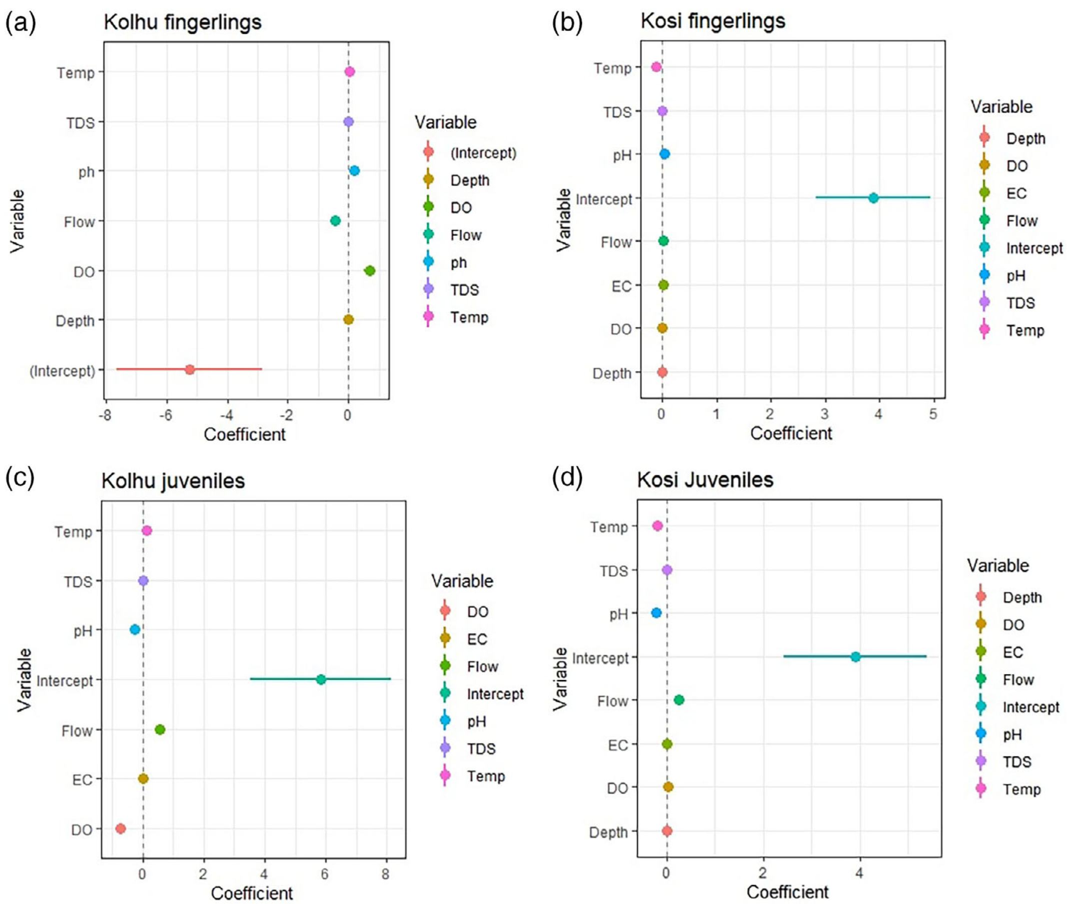

FIGURE 6 Generalised linear modelling (GLM) of the variables and the presence of young golden mahseers. (a) Fingerlings in Kosi River; (b) fingerlings in Kolhu river; (c) juveniles in Kosi River; (d) juveniles in Kolhu river. DO, dissolved oxygen; TDS, total dissolved solids; EC, electrical conductivity; Temp, temperature; pH, the presence of hydrogen ions. [Color figure can be viewed at wileyonlinelibrary.com]

due to the implementation of several hydro projects followed by the subsequent changes in river physiography, the golden mahseer is expected to endure habitat loss, fragmentation, and degradation in the future as sand/boulder mining is the most critical threat in western Himalayas (Lima et al., 2016; Nautiyal, 2014). Though not quantified in the study, smooth-coated otters and kingfishers have been identified as the young golden mahseers' main predators in the study.

The results of the study presented here not only aid in gaining a better understanding of the habitat requirements of the young of the endangered golden mahseer but should be considered while planning for the conservation management of its habitats. Also, understanding the habitat suitability of young golden mahseer enhances the previous studies on adult golden mahseer and their habitat characteristics in similar riverine systems (Bhatt & Pandit, 2016; Gorman & Karr, 1978; Gupta et al., 2011; Nautiyal et al., 2001). The findings of the study are valuable in illuminating the restoration strategies that should be undertaken to conserve the nursery habitats, which are critical for maintaining a self-sustaining population of golden mahseer in the Himalayan Rivers. We recommend that managers consider the study in protecting this endangered mahseer species in its natural habitats in the Himalayan regions.

5 | CONCLUSIONS

Fish habitat suitability varies across the river's capes. This study helps to understand potential interactions between the species and its habitat's intrinsic and extrinsic characteristics. The findings suggest that the HSC of young golden mahseer are significant for a better understanding of their habitat requirements. The study also reported that environmental variations, such as temperature and dissolved oxygen content influence the young fish's presence. Furthermore, the habitat availability and use-based approach could be employed to identify the significant fish species' preferred microhabitats. This would help in long-term development decisions and have conservation implications.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests related to this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ResearchGate at https://www.researchgate.net/publication/358211615, reference number DOI: 10.13140/RG.2.2.30906.06084.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Preliminary study on the movement behaviour and home range of golden mahseer (*Tor putitora,* Hamilton 1822) inhabiting Himalayan waters, India

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Abstract

The present study aimed to document the movement behaviour and habitat use of golden mahseers (*Tor putitora*) inhabiting Himalayan waters. A total of nine adult golden mahseers (two males and seven females) were fitted with a VHF radio. Individuals dispersed with the maximum recorded distance of 4231.23 m and 6119.11 m in the Kosi and Kolhu rivers, respectively. Home ranges for males (0.0245 km^2) and larger individuals (0.0697 km^2) exhibited released side fidelity whereas females (0.361 km^2) and smaller individuals (0.459

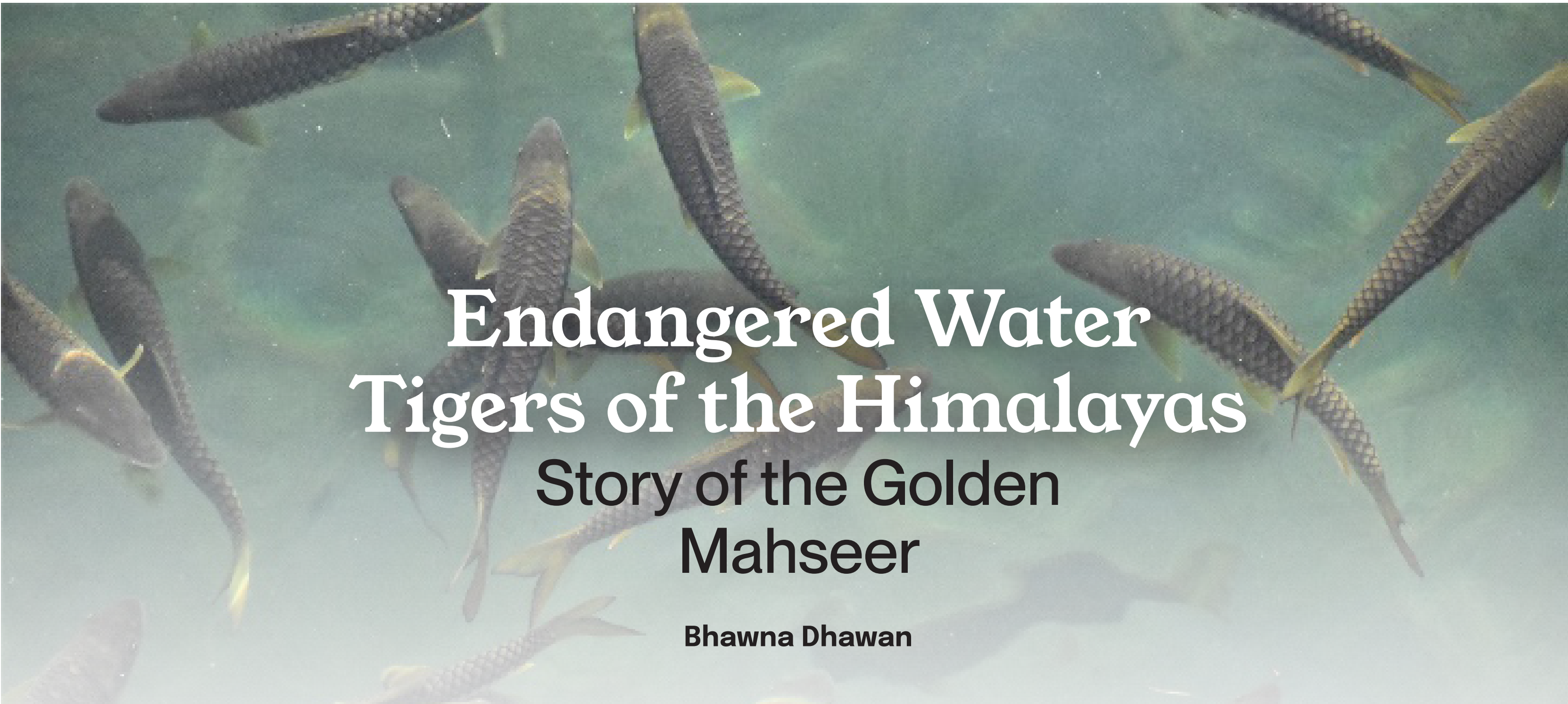
km^2) moved long distances. The research results successfully identify golden mahseer movements and spatial ecology knowledge, to conserve the fish habitats.

Key Words: Habitat preference, Kernel density, Radio-telemetry, Ramganga river, Spatial ecology.

Introduction

Movement is an essential feature that living organisms exhibit to meet their biological needs. As an aquatic living form, fish move longitudinally and laterally through their habitats to locate and access resources and places crucial to complete their reproductive cycle[1]. Hence, understanding such a crucial life process is essential in explaining the species' ecology by obtaining information on an animal's space use within its habitat [2,3,4,5]. Electrofishing and field observation methods from above and below the water surface have generated spatial biological data for fishes[6.] However, electronic tagging has allowed scientists to expand their understanding of fish behaviour and environmental requirements[7,8].

The golden mahseer, *Tor putitora*, is an emblematic species among the 16 reported species in the genus *Tor*[9.] It has a distribution record in South Asian countries, from Pakistan in the west to India, Nepal, Bhutan, and Myanmar in the east[10,9,11]. In India, this species predominantly occurs in the natural running rivers of the Himalayan foothills, up to 1500 m of altitude[12,10,13]. Being a large-sized fish with gaming qualities, the golden mahseer is the most intensively studied among all the "*Tor*" species[14,15,16].



Endangered Water Tigers of the Himalayas

Story of the Golden Mahseer

Bhawna Dhawan

RIVERS are the foundation of humanity. One such Indian river system, which is the epitome of our cultural and religious beliefs, is the holy Ganges. It is home to many life forms, including humans. It is also home to a legendary fish species, the tiger of the Ganga — 'The Golden Mahseer'.

The Golden Mahseer (*Tor putitora*) is one of the largest freshwater fishes in the Himalayan rivers. This fish has been popular since its discovery in the colonial era. In 1822, the avid English angler Hamilton introduced the fish to the world, as it offered all the thrills of a European salmon. Since then, the desire to see one has always piqued the interest of anglers from around the world. And eventually, the golden mahseer became an integral part of the Himalayan River ecosystem. But the golden scales are not the only interesting part of the species!

As a budding researcher, I was lured by this fish, which has swum its way into local narratives, research discussions and debates. With time, I was greeted by several fascinating stories when I first stepped into the simplicity of the Ramganga basin hill streams to study the golden mahseer.

"*Once, there was a local fisherman who lived in the wilderness of river Kosi. Galloping through the Himalaya to meet the mighty Ganges, Kosi moved fiercely. As the sun shone brightly and the call from the wild became increasingly louder, he would go out on a fishing quest. But unlike others, his pursuit was special. In the river full of many fishes, his eyes would look out for only one! The one with the big golden scales!*

The 'tiger' of Himalaya — The Golden Mahseer!

His love for this fish was unrivalled, not only for of its attractive golden colour but also because of its elusiveness and intelligence."

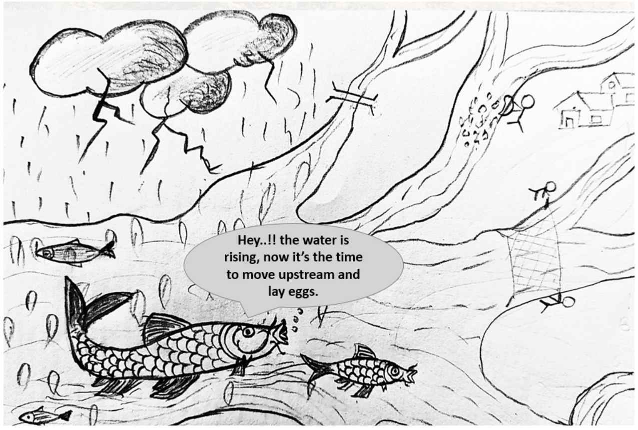
Stories like these sparked in me a curiosity to interact more closely with the local communities, and explore the chilled waters of the rivers Kosi and Kolhu in the Western Himalaya to find this fish with shiny golden scales.

The Journey

As the course of my community interactions moved from 'knowing the fish', to 'tell me more about it' I came across multiple oral narratives, which truly marked the beginning of my doctoral work. The local fisherfolk shared how at times they were overwhelmed to see huge numbers of the golden mahseer populations in their neighbouring quintessential streams throughout winters and early summers. But then, with the beginning of the monsoon, there would be fewer of them. As if something would just make the fish appear and then disappear, with a magic wand.

They then shared something that their ancestors had passed on about the unique behaviour of the Golden Mahseer!

"*With the onset of monsoon in the Himalaya, this fish moves upstream in the small streams in search of safe homes in rivers to give birth to their children. Rivers become murky due to the sediments that rain brings down, allowing fish to safely move in the Ganges waters. Being a great swimmer, the golden mahseer swims against the water flow to find suitable places for their young ones to emerge safely and grow.*"



The Golden Mahseer during the onset of monsoon in the Himalayas

After listening to this story, I began researching the literature to learn more about the Golden Mahseer's migratory behaviour. And learnt that this fish makes occasional upstream movements to the hill streams in the Himalayas during the pre-monsoon and monsoon seasons to find suitable places to lay their eggs. And, after spawning, they come back to the main channels.

But how much did we truly know about this migrating behaviour beyond local narratives?

I realised that, to our knowledge, the seasonal migration of the Golden Mahseer was never confirmed by any scientific study from India. And here, the significance of researching such stories becomes crucial in wildlife science. Where we need to provide scientific evidence to phenomena that cannot be understood by listening to stories unless they are supported by strong field observations.

Story of Golden Mahseer's Migration

Thus, we began a new chapter of our research work on the Golden Mahseer. A first of its kind freshwater fish tagging study in India to understand the unique migration behaviour of the species. All with the help of a tiny machine with inbuilt sensors to locate fish and sense the surrounding temperature (VHF radio tag), attached to their bodies. This machine became a shadow of the individuals that carry them and a treasure hunt game for us. It alerted us to every move, turn, dive and halt the tagged fish made.

In India, the great Himalayan range drains three major river basins as the distributional range of the Golden Mahseer, with the river Indus serving as the Westernmost and the river Brahmaputra as the Easternmost. The Ganges and its tributaries are the most suitable home and breeding ground for this fish as it is present abundantly here. We started our tagging experiments on river Kolhu, followed by river Kosi.

In the morning of winter, the picturesque Kolhu River

On 21 June 2019, a bright sunny day, we started our tagging experiment. When I held the Golden Mahseer for the first time, I was both awestruck by its beauty and thrilled. Knowing that the male and female Golden Mahseer release their sperm and eggs into the water to get fertilised, our team successfully captured both male and female individuals and attached the tags to their bodies. We used a hand-held antenna to understand the course our tagged individuals were taking. To verify and validate the seasonal movements of the individuals, as mentioned by the locals, we began following the tagged individuals every day.

The monitoring work continued throughout the season (pre and post-monsoon), against all odds, despite being chased by elephants or fearful of meeting tigers and leopards on the way.

Our Eureka Moments!

Our findings were overwhelming! We found scientific evidence to corroborate the local narratives. We observed that the fish made the initiation movements during the pre-monsoon season. And, with the monsoon's onset, the Golden Mahseer were found dispersed in the river systems. Our tagged individuals were moving both upstream and downstream of the rivers.

We found differences in the movement of male and female individuals. Further, while males and larger individuals moved less, the female Mahseers and the smaller individuals moved much farther in the streams. In addition, we detected that not every individual moved far when the water level rose; some moved a very short distance.

Also, we observed that the individuals were very careful while choosing their homes upstream and downstream. They required a suitable water depth, temperature and water velocity. The selected homes were mostly sandy with large and small boulders. This also indicated that any change in the characteristics of the river system will further impact this behaviour of the Golden Mahseer.

When Danger Lies Ahead

Lately, the tide in the Himalayas has been changing. Ruthless development is turning the course of the Ganges away from normalcy. And hence the fate of the Golden Mahseer as well. A species which behaviourally has been moving through the course of the rivers and streams will not be able to perform the migration if barrages and dams block their routes or if activities such as fragmentation of river routes, mining of sand and boulders, and water pollution continue.

Also, as shared by the locals, the catch size of the Golden Mahseer is much smaller than in the good old times, indicating their pre-harvesting. This highlights a strong need to sensitise the local communities towards community-based conservation.

Our study is the first attempt from India to provide insights into the movements of the Golden Mahseer through radio-tagging. This research can be used to secure optimum habitat requirements for the Golden Mahseer in India. We believe a huge scope of tagging has been broadened through this work, giving a new beginning to the Mahseer's migration research in India.

An adult Golden Mahseer and its young swimming serenely in the Kosi River

Gurgling river Kosi traversing by the Corbett tiger reserve and the Ramnagar forests

(Pictures/Artwork credits: Bhawna Dhawan)

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