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Original Article

Population dynamics and conservation challenges of *Diptychus maculatus* Steindachner, 1866 in the Indus tributary of the Ladakh Trans-Himalayan region, India

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Abstract
The lack of demographic data for many endemic cold-water fishes limits effective conservation planning in the Trans-Himalayan region. This study presents the first comprehensive assessment of the population dynamics and exploitation status of the monotypic cyprinid *Diptychus maculatus* Steindachner, 1866, which inhabits the Indus tributaries of Ladakh, India. Three hundred specimens were analysed for length–weight relationships, growth parameters, and mortality. The species exhibited negative allometric growth (b = 2.89) and a mean condition factor of K (0.91), moderate physiological condition. von Bertalanffy growth parameters (L_∞ = 407.40 mm; K = 0.11 yr^{-1}; ϕ' = 4.26) characterize *D. maculatus* as a slow-growing species, typical of high-altitude schizothoracines. Mortality analysis revealed total, natural, and fishing mortality rates of 0.48, 0.14, and 0.34 yr^{-1}, respectively, with an exploitation rate of 0.71, indicating unsustainable exploitation levels. These findings suggest that *D. maculatus* populations in the Indus River tributaries of Kargil, Ladakh, are adversely affected by external pressures like sand mining, infrastructure development, and damming and face a decline, necessitating effective conservation and restoration strategies.

Keywords: demographics; *Diptychus maculatus*; exploitation rate; growth parameters; Ladakh; mortality; Trans-Himalayan region

1 | INTRODUCTION

The biodiversity of freshwater ecosystems worldwide is drastically declining, and addressing the challenges raised by this crisis requires mobilising significant resources and implementing ambitious goals (Cooke *et al*. 2023; Piczak *et al*. 2023). Freshwater biodiversity includes all freshwa-

ter ecosystems' genes, populations, species, communities, and habitats and offers crucial ecological services necessary for human livelihoods and well-being (Dudgeon *et al*. 2006). Fish inhabit a wide range of aquatic environments; the majority, in terms of species count or abundance, are found in warm environments with moderate temperatures, while others have adapted to cold-water environments. These organisms serve as crucial food resources and indicators of ecological water health. Unfortunately, the deterioration of inland waters is causing a rapid decline in the rich diversity of freshwater fish in the Indian region (Dudgeon *et al*. 2006; Sarkar *et al*. 2010, 2012; Lakra *et al*. 2011). Furthermore, the upland rivers, natural lakes, streams, reservoirs, high and low-altitude lakes, and the Himalayan and peninsular areas of India are home to extensive and diverse cold-water/hill resources for fishing (Mahanta and Sarma 2010). These water bodies exhibit characteristic features such as high-velocity waters, rapid cascades, deep pools, and diverse substrata, supporting rich ichthyofaunal diversity comprising indigenous and exotic fish species (Sehgal 1999; Mahanta and Sarma 2010).

The Himalayan mountains are the world's most magnificent and youngest mountain systems (Hillary 2012). The proportion of endemic taxa is substantial in the entire Himalayan Range, and this ecoregion has been designated a global biodiversity hotspot (Mittermier *et al*. 2004). The Trans-Himalayan landscape is a high-elevation land with an average altitude of about 4000 m above mean sea level. The area is characterised by extreme cold, low precipitation, and rugged mountain terrain. The Trans-Himalayan region encompasses several countries in the midland and highland areas of the Himalayas, Karakoram, and broadly, the Hindu Kush and Pamir. The mountains are characterised by a very low level of human development, with full exploitation or overexploitation of the natural resources. Fisheries are important in providing food and income to the mountain peoples (Abass *et al*. 2024). One of the most important components of the Trans-Himalayan region is its unique animal biodiversity, which includes fish. Sustainable fishery management approaches prioritize age assessment of fish stocks as a fundamental and pivotal metric in population studies. Fish growth significantly influences population dynamics, and understanding the growth patterns is fundamental for studying quantitative changes in fish populations (Zhan 2005). Estimating the age and growth of a fish population is crucial for fisheries management and assessment. Such projections aid in comprehending the age allocation of the harvest, the magnitude in terms of length at maturity during the angling process, and the overall structure of the fish stock. Fish demography provides valuable information about the natural history and population dynamics, which could be useful for fishery development, aquaculture and conservation (Gerber and Heppell 2004; Lorenzen 2005; Denechaud *et al*. 2020). Demographic studies are critical in situations where the fish are facing universal problems like pollution, invasion of alien species and global warming (Scott *et al*. 1986; Denechaud *et al*. 2020), as they severely affect fish development, population dynamics, and are major threats to several native fish species (Strayer and Dudgeon 2010).

The water bodies of Ladakh are comprised of very few streams and rivers fed by Himalayan glaciers. The Trans-Himalayan region of Kargil, Ladakh, serves as a crucial headwater zone for the Indus River system, receiving glacial and snowmelt contributions from several tributaries, including the Zanskar, Suru, and Shingo Rivers. Among these, the Suru and Shingo Rivers play a vital role in shaping the hydrology and ecology of the region (Phartiyal *et al*. 2018; Abass *et al*. 2024). These rivers not only support local biodiversity and aquatic ecosystems but also serve as essential water sources for agriculture, fisheries, and livelihoods in the high-altitude environment of Kargil. Their glacial-fed nature ensures a steady flow of cold, oxygen-rich water, making them significant for the region's ecological studies, fisheries management, and aquaculture development.

The Schizothoracinae subfamily consists of specialised native fish species prevalent in Central Asia's fast-flowing mountain streams, the Himalayas and the Tibetan plateau. These fish are crucial for the sustenance and economic well-being of the human communities residing in these areas. It is believed that Schizothoracinae are ideal models for understanding the processes behind the high-altitude adaptations of animals (Luo *et al*. 2016). The dispersion of these fish species is influenced by environmental factors such as the speed of water currents, the characteristics of the substratum, and the presence of food resources (Shafi and Yousuf 2012). Snow trout primarily feed on litter, adherent plant-like algae, coatings on stones and rocks, and accompanying invertebrate creatures (Bhat *et al*. 2024). *Diptychus maculatus*, a monotypic genus of the subfamily Schizothoracinae (Cyprinidae), is well adapted to high-altitude mountain streams with low temperatures. It primarily occurs in rocky, mountainous streams and lakes and is commonly found in rivers with swift currents. *Diptychus maculatus* holds paramount importance as a flagship species in the context of environmental changes in the Himalayan region. The lack of scientific evidence on the stock status of *D. maculatus* from Ladakh's Trans-Himalayan region has not yet been addressed. The importance of this study lies in the fact that no prior work has been conducted on the fish population of *D. maculatus* in the Trans-Himalayan region, particularly concerning its demographic aspects and management implications. Previous studies on population dynamics have focused mainly on *Schizothorax* spp. from Kashmir (Sabah and Khan 2014; Saba 2016; Magloo 2025; Yousuf *et al*. 2025), highlighting the need for further re-

search on the fish fauna of the Trans-Himalayan region to ensure sustainable fisheries development.

2 | METHODOLOGY

2.1 Study area and fish sampling

2.1.1 Study area: The Trans-Himalayan region of Kargil, Ladakh, serves as a crucial headwater zone for the Indus River system, receiving glacial and snowmelt contributions from several tributaries, including the Zanskar, Suru, Shingo and Drass Rivers (Figure 1). These rivers not only support local biodiversity and aquatic ecosystems but also serve as essential water sources for agriculture, fisheries, and livelihoods in the high-altitude environment of Kargil. Their glacial-fed nature ensures a steady flow of cold, oxygen-rich water, making them significant for the region's ecological studies, fisheries management, and aquaculture development. The Suru River, an important tributary of the Indus River, originates from the Panzella Glacier near Pensi La Pass, close to the Drang Drung Glacier, and flows through the Kargil district of Ladakh. Spanning approximately 185 km, the river is a vital watercourse in the region. The Drass River, which the Shingo River feeds, converges with the Suru River at Hardas (Kharal), about 7 km north of Kargil town (Phartiyal *et al.* 2018). The Shingo River is another tributary of the Indus River and flows through the trans-Himalayan region of Gilgit-Baltistan and the Kargil region of Ladakh. The river originates in Gilgit-Batistan, flows into the Kargil district, and then joins the Drass River. The combined river receives the waters of the Suru River and flows into Baltistan again, joining the Indus River near Marol in Pakistan.

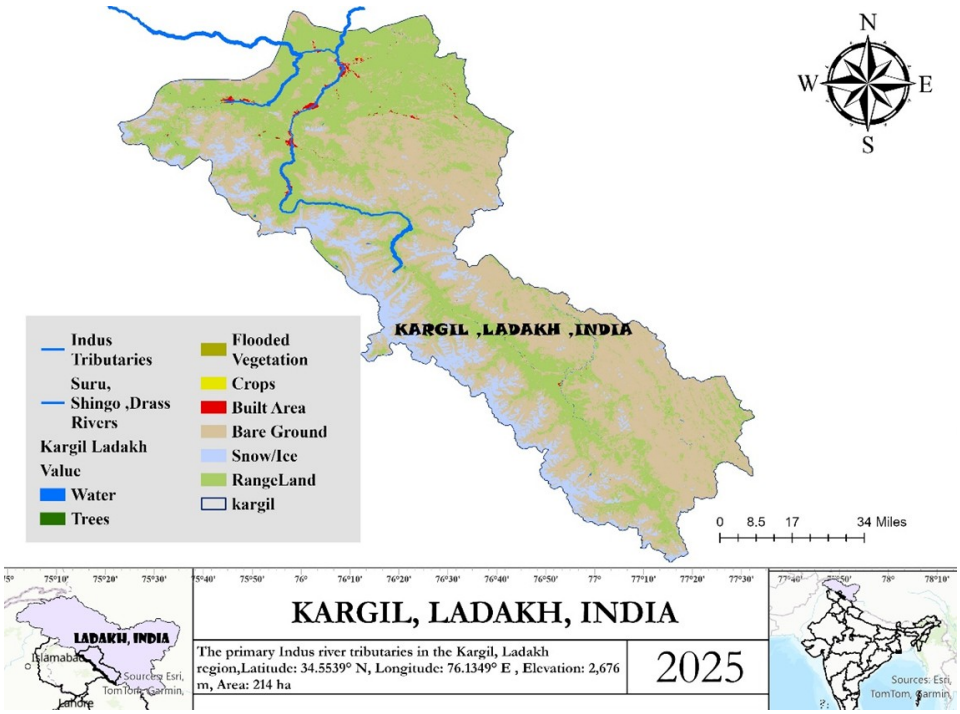


FIGURE 1 Geographical location of the Indus tributaries across the Trans-Himalayan region of Kargil, Ladakh, India.

2.1.2 Fish sampling: Sampling was not conducted in January and February due to severe winter conditions in the Ladakh region, during which rivers were entirely or partially covered with ice, ambient temperatures ranged from −10°C to −18°C, and heavy snowfall severely restricted access to the sampling sites. A total of 300 specimens of *D. maculatus*, ranging in total length from 98.83 mm to 390 mm, were collected monthly between July 2024 and June 2025 (covering a 10-month sampling period). Fish were collected along the river stretches using fishing methods commonly employed by local fishermen, primarily hook-and-line and rod-and-line techniques. Hooks of sizes 3–10 (standard numbering, where smaller numbers indicate larger hooks) were used depending on the size of the target fish and prevailing field conditions. These hooks were baited with natural baits such as earthworms, insects, and fish roe. Hook sizes 3–6 were mainly used for larger adults (>250 mm TL), while sizes 7–10 targeted medium and smaller individuals. This combination enabled collection across a wide size range, despite gear selectivity challenges inherent to high-altitude river sampling.

Alternative sampling methods, including cast netting, were also attempted. However, these proved ineffective and yielded negligible or zero catch because of the high flow velocity, steep channel gradients, shallow water depth, and boulder-dominated rocky substratum characteristic of the study river. These extreme environmental

conditions made it extremely difficult to deploy passive or encircling gears effectively in the fast-flowing Trans-Himalayan tributaries.

2.2 Length classification

In this study of *D. maculatus* population dynamics, 300 fish specimens were analysed for length–frequency estimation. The collected data were further classified into length groups for analysis using FiSAT-II software (FAO-ICLARM Stock Assessment Tools), as proposed by Gayanilo *et al.* (2005). The length–frequency plot was created using MS Excel 2019.

2.3 Data analysis

Length-weight relationships were estimated using the linear regression equation log W = log *a* + *b* log L, where W is the whole-BW (g), L is the TL (mm), and parameters *a* and *b* are the regression parameters (Le Cren 1951; Froese 2006). The condition factor (*K*) was calculated from the equation given by Fulton (1904) as:

$$K = W / L^3 \times 10^5$$

where *W* is the weight in g, *L* is the length in mm, and 10^5 is a factor to bring the value of *K* near unity.

Three hundred specimens were used to analyse the demographics of *D. maculatus*, and data were arranged in a length frequency table with 10 mm class intervals. Length-frequency distributions were used to study growth patterns, mortality and exploitation level. The various growth parameters like asymptotic length (L_∞), age at zero length (t_0) and growth coefficient (*K*) of von Bertalanffy growth function (VBGF) (von Bertalanffy, 1960) were determined using the equation given below (ELEFAN-I module of FiSAT-II) (Gayanilo *et al*. 2005):

$$L_t = L_\infty [1–e^{–K(t–t0)}]$$

The asymptotic length represents the maximum theoretical length that an individual within a fish population can attain. The growth coefficient indicates the rate at which a fish reaches its maximal length. Age at zero length (t_0) is the age (theoretical) at which the fish length is assumed to be zero, if the growth pattern conforms to the VBGF, and was calculated using the equation given below (Pauly 1979):

$$\log (–t0) = –0.392 – 0.275 \log L_\infty – 1.038 \log K$$

The growth performance index (ϕ) has been reported to be remarkably constant between various populations of a species and is calculated using the equation developed by Pauly and Munro (1984), given below:

$$\phi' = \log K + 2 \log L_\infty$$

Mortality and exploitation were determined. The following formula was used to determine the natural mortality (*M*; Pauly 1980):

$$\log M = –0.0152 – 0.279 \log L_\infty + 0.6543 \log K + 0.463 \log T$$

where *K* is the growth constant, *T* indicates the mean annual ambient temperature (°C) and L_∞ is the asymptotic length.

Fishing mortality (*F*) was obtained by subtracting the *M* from the *Z* ($F = Z – M$), and the current level of exploitation rate (*E*) was obtained from *F/Z* (Gulland 1971). Growth and mortality parameters were used to model virtual population analysis (VPA) and estimate the species' exploitation level. The relative yield per recruit (*Y/R*) and relative biomass per recruit (*B/R*) analysis were calculated using knife selected method which help to understand whether populations are overexploited E_{max} (exploitation rate with maximum yield) and E_{50} (exploitation that retains 50% of the biomass) (Beverton and Holt 1966) using FiSAT II (knife edge function) (Beverton and Holt 1966; Pauly and Soriano 1986).

3 | RESULTS

The summary of the results is presented in Figure 2.

3.1 Length–weight relationship and condition factor (*K*)

The sampled population of *D. maculatus* in the Trans-Himalayan region of Kargil, Ladakh, India, represents the individuals in the 98.83 to 390 mm size range, and the total weight ranged from 12 g to 300 g. The overall mean total length and total weight were reported to be 156 mm and 42 g, respectively. The majority of the fish specimens belonged to the length range of 120 to 160 mm. The LWR equation revealed the values of *a* and *b* to be –4.81 and 2.89, respectively (Figure 3). The mean value of the condition factor (*K*) was reported to be 0.91 ± 0.014. The length-weight relationship analysis revealed a growth exponent (*b*) of 2.89, which was significantly lower than the isometric value of 3 ($p < 0.01$). This indicates a negative allometric growth pattern, where the species exhibits a relatively faster increase in length than in weight as it grows.

3.2 Growth parameters

The analysis of length-class frequency distribution across months revealed that the smallest individual was recorded in December 2024, while the largest individual was observed in April 2025. The attributes of growth, such as L_∞ (asymptotic length) and *K* (growth coefficient), were determined by the ELEFAN technique and assessed to be 407.4 mm and 0.11 year^{-1}, respectively (Figure 4 and 5). The t_0 was valued as − 0.77 years. The growth performance index (ϕ) was estimated as 4.26. The longevity of *D. maculatus* ($t_{max} \approx 27$ years) aligns with the characteristic life-history strategy of schizothoracine fishes, which exhibit extended lifespans, slow somatic growth, and de-

layed maturation as adaptive responses to the cold, oligotrophic, and high-altitude environments of Himalayan and Tibetan Plateau rivers.

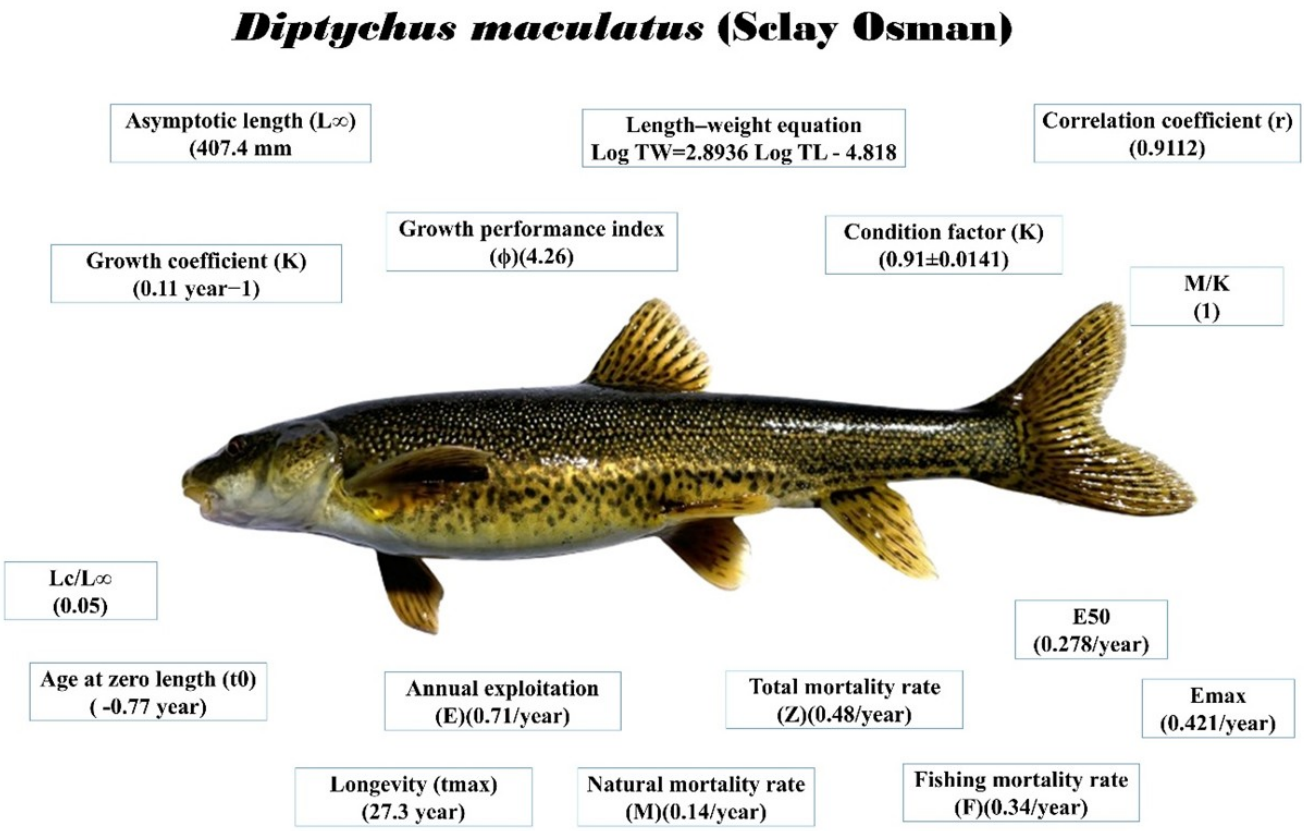


FIGURE 2 Summary of parameters regarding population dynamics of *Diptychus maculatus* in the Trans-Himalayan region of Kargil, Ladakh, India.

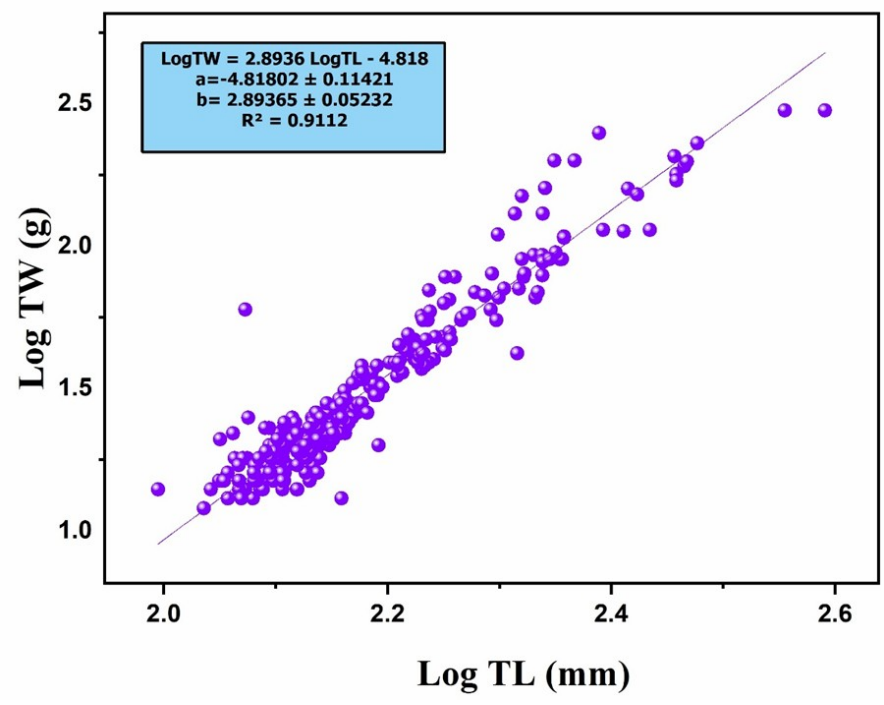


FIGURE 3 Scatter diagram depicting the length-weight relationship of *Diptychus maculatus*.

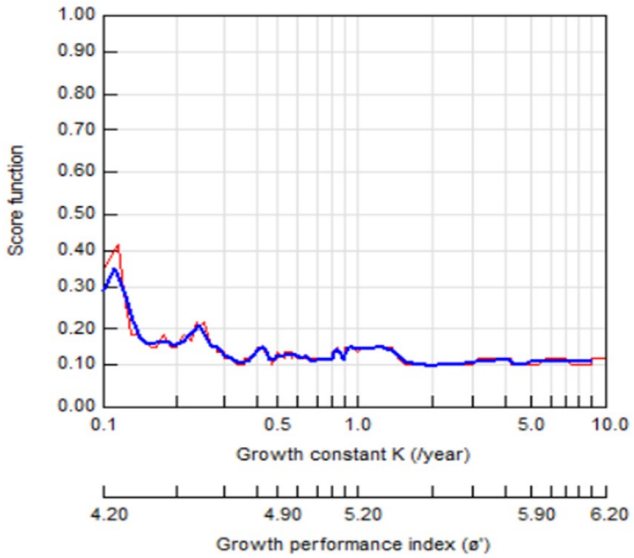


FIGURE 4 K-scan routine graph also showing growth performance index for *Diptychus maculatus* obtained from the ELEFAN-I programme of FiSAT-II.

3.3 Mortality rates (*Z*, *M* and *F*) and exploitation ratio (*E*)

The total mortality (*Z*) was estimated from the length-converted catch curve (Figures 6 and 7). The total mortality (*Z*) was determined to be 0.48 yr^{-1}, considering the average annual surface water temperature of the tributaries of the Indus in the Trans-Himalayan region of Kargil, Ladakh, 12°C. In comparison, natural mortality (*M*) and fishing mortality (*F*) were 0.14 yr^{-1} and 0.34 yr^{-1}, respectively. The fishing mortality (0.34) for *D. maculatus* is more than double the value of natural mortality (0.14) and the annual exploitation rate (0.71), indicating that the species is being heavily exploited in the river.

3.4 Virtual population analysis, yield-per-recruit / biomass-per-recruit and recruitment

The comparative yield per recruit (*Y'/R*) as well as biomass per recruit (*B/R*) of *D. maculatus* were estimated utilising the FiSAT-II based analysis using the knife-edge selection technique (Figure 8). The data for these calculations were values of L_C/L_∞ (0.05) and *M/k* (1). The assessed values of E_{max}, $E_{0.1}$, and $E_{0.5}$ by the (*Y/R*) investigation were 0.421, 0.355 and 0.278, respectively. The current valuation indicates that the optimum yield for *D. maculatus* would be achieved at an *E* value (0.421). Additionally, when *E* = 0.278, 50% (half) biomass might be attained as a harvest, as depicted by the red portion of Figure 8. The parameters utilised for VPA were L_∞ = 407.40, *k* = 0.11 $year^{-1}$, *M* = 0.14 $year^{-1}$, *a* = − 4.81, and *b* = 2.89 from the weight and length analysis in g and mm. Angling mortality for *D. maculatus* in the Trans-Himalayan region of Ladakh was substantially larger among length groups of 120 mm to 160 mm, according to the virtual population analysis. The FiSAT-derived recruitment pattern for *D. maculatus* shows that the species recruits throughout the year, with a strong peak in mid-year and smaller pulses before and after (Figure 9). This indicates a prolonged and adaptive spawning strategy characteristic of cold-water schizothoracines, ensuring population resilience in unpredictable high-altitude riverine ecosystems.

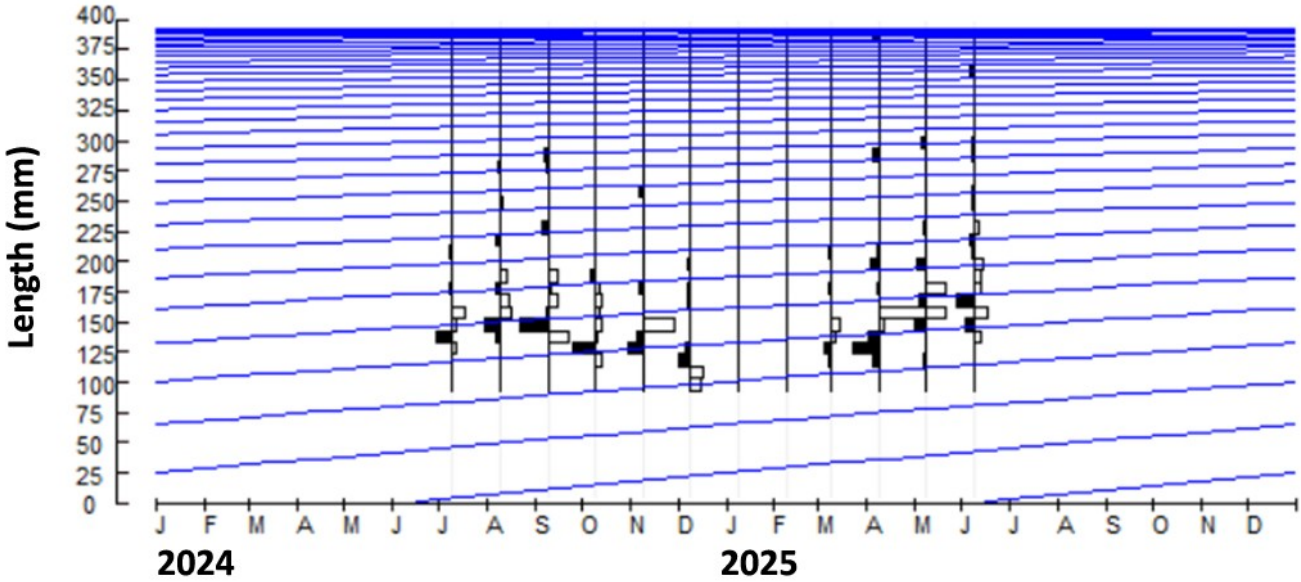


FIGURE 5 Length–frequency distribution output obtained from FiSAT-II for *Diptychus maculatus* from the Trans Himalayan Region of Kargil, Ladakh, using ELEFAN I (with parameters L_∞ = 407.40 mm and *k* = 0.110 $year^{-1}$),

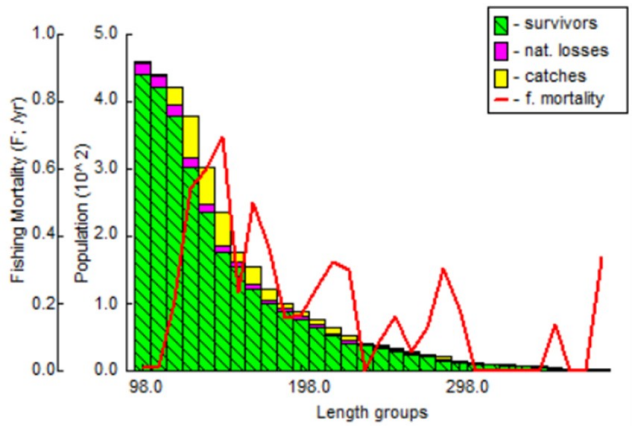


FIGURE 6 Length structured VPA output for *Diptychus maculatus* in the Trans-Himalayan Region of Kargil, Ladakh, India.

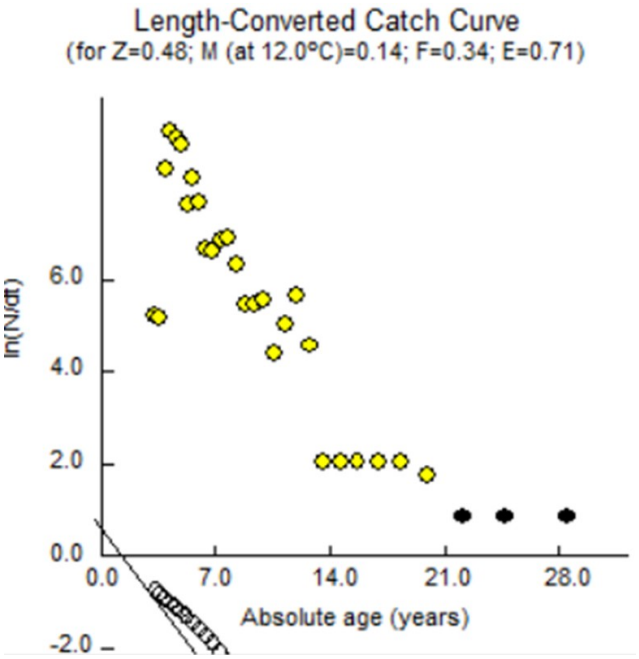


FIGURE 7 Length converted catch curve for the estimation of mortality of *Diptychus maculatus* in the Trans-Himalayan Region of Kargil, Ladakh, India.

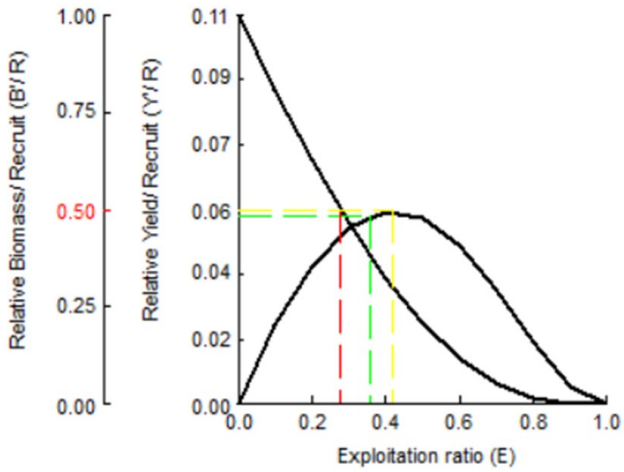


FIGURE 8 Relative yield per recruit (Y/R) and relative biomass per recruit (B/R) plots of *Diptychus maculatus* in the Trans-Himalayan Region of Kargil, Ladakh, India. (E_{max}—maximum yield per recruit, E_{10}-exploitation that retains 10% of the biomass, E_{50}—exploitation that retains 50% of the biomass.

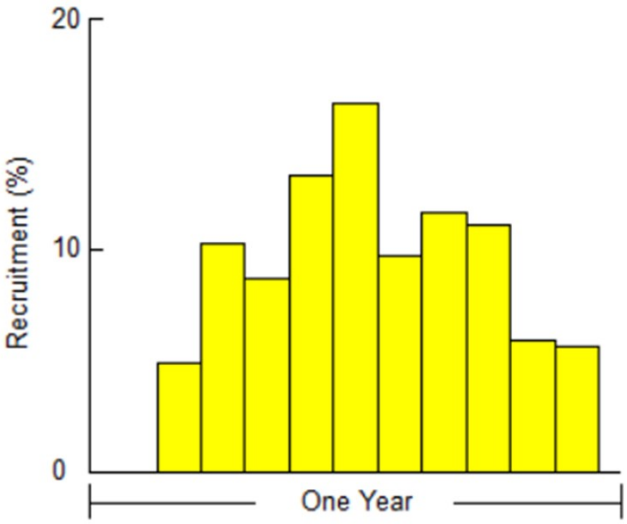


FIGURE 9 Recruitment pattern obtained from FiSAT-II for *Diptychus maculatus* in the Trans-Himalayan Region of Kargil, Ladakh, India.

4 | DISCUSSION

Information on growth patterns, mortality rates, exploitation levels, and the interactions among these parameters is crucial for understanding and effectively managing freshwater fisheries (Raghavan *et al*. 2018). However, only a limited number of studies have examined the population dynamics of *Schizothorax* species in the Trans-Himalayan region (Hussain 2011; Sabah and Khan 2014; Saba 2016; Magloo 2025; Yousuf *et al*. 2025). In this context, investigating the population dynamics of the monotypic species *D. maculatus* is particularly important for its conservation and sustainable management.

4.1 Length–weight relationship (LWR) and condition factor

LWR analysis is a valuable tool for assessing growth patterns in fish species by evaluating the allometric coefficient "*b*," which can indicate isometric growth (*b*=3), positive allometric growth (*b* > 3), or negative allometric growth (*b* < 3) (Jobling 2002; Morey *et al*. 2003). In isometric growth, all body dimensions increase proportionally; in positive allometry, the body becomes relatively deeper or bulkier as length increases; whereas in negative allometry, the fish becomes more elongated as it grows

(Jobling 2002).

The present study observed a strong and highly significant linear relationship between length and weight in *D. maculatus*. The estimated *b* value was 2.89, which falls within the expected biological range of 2.5–4 (Froese 2006) but is slightly lower than the isometric value of 3 ($p < 0.0001$). This indicates a negative allometric growth pattern, meaning the species shows a relatively faster increase in length than in weight. These findings are consistent with previous reports on other schizothoracine fishes. Bhat *et al*. (2010) reported a *b* value of 2.94 for *Schizothorax plagiostomus* in the Lidder River. Similarly, Khan and Sabah (2013) documented *b* values of 2.86 for *S. plagiostomus*, 3.08 for *S. esocinus*, 2.64 for *S. labiatus*, and 2.69 for *Schizopyge curvifrons* in the Jhelum River. Arafat and Bakhtiyar (2022) also found comparable values in the Vishav Stream, ranging from 2.85 to 3.09 across species. Xia *et al*. (2025) reported a higher *b* value of 3.32 for *D. maculatus* from Xinjiang, China. The discrepancy between their result ($b = 3.32$; $n = 35$) and the present study ($b = 2.89$; $n = 300$) can be attributed to several biological, ecological, and methodological factors. This study's larger sample size and extended 10-month sampling period likely provide a more representative picture of population growth. In contrast, seasonal bias may have affected a smaller sample, especially if collected during spawning, when increased gonadal weight can elevate b values. Environmental factors, including differences in water flow, temperature, and food availability, may further explain these variations. Typically, streamlined species such as *D. maculatus* inhabiting fast-flowing rivers exhibit negative allometric growth, whereas populations in slower or nutrient-rich habitats tend to show positive allometry. Differences in size range, life stage structure, and sampling methodology also contribute to variability in *b* estimates.

The condition factor (*K*) is the indicator of general fitness, being the index of the well-being of a fish population (Froese 2006). It is the reflector of the overall physiological health of a fish (Nikolsky 1969). Fish in poor health have condition factor values below 1, whereas fish in excellent health have condition factor values over 1 (Mir *et al.* 2012). The condition of a fish population is mainly affected by factors such as feed availability, the maturity status of the fish, parasitism, and diseases (Le Cren 1951). The mean condition factor (*K*) value of 0.91 observed in the present study is close to the baseline value of 1, which typically indicates that the fish are in moderate physiological condition. These findings are consistent with previous reports on other Schizothoracine fishes in the Himalayan region (Shafi and Yousuf 2012; Tyagi *et al*. 2014; Arafat and Bakhtiyar 2022; Philip *et al*. 2023).

4.2 Growth parameters

The growth parameters, namely the asymptotic length (L_∞) and the growth coefficient (*K*) of the von Bertalanffy growth function (VBGF), are essential in fisheries science. The *K* parameter is strongly linked to a fish's metabolic rate; higher *K* values indicate faster metabolism, leading to earlier maturation in terms of both age (T_m) and size (L_m), which are relatively larger compared to their asymptotic length (L_∞) (Qasim 1973).

Using the K-scan technique of ELEFAN-I, the asymptotic length (L_∞) for *D. maculatus* was estimated to be 407.40 mm. This value is consistent with reports for other Schizothoracine fishes from various Himalayan and Trans-Himalayan water bodies (Table 1). The annual growth coefficient (*K*), which reflects a fish population's lifespan and mortality characteristics, is a critical parameter for evaluating the risk of overexploitation (Musick 1999). This study estimated the *K* value for *D. maculatus* at 0.110, indicating a slow growth rate. Comparable low *K* values have also been documented in other Schizothoracine species by Saba (2016) and Sabah and Khan (2014) (Table 1). This finding suggests that *D. maculatus* is a slow-growing species, similar to other cold-water fishes. The growth performance indices generally fall within the range of 2.77 to 7.15 (Kindong *et al*. 2018). The growth performance index (ϕ) was estimated to be 4.26, reflecting a satisfactory growth rate for *D. maculatus*. This value is comparable to that reported for *Schizopygopsis younghusbandi* by Han *et al*. (2025), which ranged from 4.41 to 4.43 in four tributaries of the Yarlung Zangbo River, Tibet. Such a value indicates that the species exhibits a moderate growth potential, consistent with other cold-water cyprinids inhabiting similar high-altitude environments. The estimated longevity of *D. maculatus* ($t_{max} \approx 27$ years) reflects the typical life-history strategy of Schizothoracine fishes, characterised by long lifespans, slow growth, and delayed maturity, adaptations to the cold, oligotrophic, high-altitude rivers of the Himalayas and Tibetan Plateau. Similar patterns occur in *Schizothorax pseudaksaiensis* (23 years; Wang *et al*. 2023) and *S. o'connori* (40 years; Ma *et al*. 2010). Comparative studies confirm that extended longevity and low growth rates are common among these cold-water cyprinids, shaped by short growing seasons and low metabolic rates (He *et al*. 2023). This longevity indicates the species' life-history vulnerability and underscores the need for cautious management to avoid recruitment overfishing. Mortality forms an essential parameter in fish population dynamics because it is the factor that reveals the fraction of individuals a given population is going to lose (Pope *et al*. 2010). Mortality is related to growth, since the fish become more susceptible to fishing and predation during their growth, leading to mortality (Allen and Hightower 2010).

4.3 Mortality rates (*Z, M* and *F*) and exploitation ratio (*E*)

In the present study, the total, natural, and fishing mortality rates for *D. maculatus* were estimated at 0.48 year^{-}

^{1}, 0.14 year^{-1}, and 0.34 year^{-1}, respectively, indicating that fishing mortality exceeded natural mortality. Similarly, for *Schizothorax niger* in Manasbal Lake, the total mortality rate (*Z*) was reported as 1.43 year^{-1}, based on an average annual surface water temperature of 16.2°C. Within this, the natural mortality (*M*) was 0.56 year^{-1}, while the fishing mortality (*F*) reached 0.87 year^{-1} (Yousuf *et al*. 2025). In comparison, total mortality values of 0.453, 1.066, 1.67, and 0.69 year^{-1} were observed for *Schizopygopsis younghusbandi* across four tributaries of the Yarlung Zangbo River, Tibet (Han *et al*. 2025). The VPA results indicate high natural mortality among younger individuals (< 98 mm) and elevated fishing mortality in larger size groups. The high natural mortality in juveniles is likely driven by factors such as predation, disease, and pollution. The study further shows that the fishing mortality rate (*F* = 0.34) for *D. maculatus* is more than twice the natural mortality rate (*M* = 0.14), with an exploitation rate (*E*) of 0.71. This level of exploitation is significantly higher than the optimum, as the maximum sustainable exploitation rate (E_{max}) is 0.42 and double the E_{50} value, which preserves 50% of the spawning biomass. For effective conservation, it is essential to maintain at least half of the spawning stock and reduce the current exploitation level from 0.71 to around 0.42. According to Gulland (1971), in a sustainably exploited fishery, fishing mortality should be approximately equal to natural mortality (*F*=*M*), corresponding to an exploitation rate (*E*) of 0.5.

TABLE 1 Growth parameters (L_∞, *K*, t_o, and ϕ) of *Schizothorax* species estimated by various researchers across different water environments.

Species	Region	L_∞ (cm)	*k*	t_o	References
Schizothorax niger	Dal Lake, Kashmir	46.599	0.07 yr^{-1}	− 0.18 yr	Hussain (2014)
	Nigeen Lake, Kashmir	43	0.4 yr^{-1}	− 0.05 yr	Saba (2016)
	Manasbal lake, Kashmir	46.05	0.30 yr^{-1}	− 0.493 yr	Yousuf *et al.* (2025)
	Kashmir waters	44.8	0.255 yr^{-1}	− 1.42 yr	Sabah and Khan (2014)
Schizothorax curvifrons	Kashmir waters	49.8	0.263 yr^{-1}	− 0.34 yr	Sabah and Khan (2014)
	Jhelum River, Kashmir	49.3	0.091 month^{-1}	0.007 yr	Qadri *et al.* (2018)
Schizothorax esocinus	Kashmir waters	66.6	0.278 yr^{-1}	− 0.34 years	Sabah and Khan (2014)
Schizothorax plagiostomus	River Jhelum, Kashmir	38.85	0.160 yr^{-1}	-	Magloo *et al.* (2025)
Schizothorax o'connori	Yarlung Tsangpo River, China	49.24	0.1133 yr^{-1}	− 0.5432 yr	Yao *et al.* (2009)
Schizothorax waltoni	Yarlung Tsangpo River, China	58.62 (male) 64.43 (female)	0.084 yr^{-1}	− 0.5432 yr	Zhou *et al.* (2017)
Schizopygopsis younghusbandi	Yarlung Zangbo River, Tibet	38.7877 and 41.4535	0.154 to 0.174 yr^{-1}	-	Han *et al.* (2025)
Schizothorax o'connori, Oxygymnocypris stewartii, and Ptychobarbus dipogon	Duoxiong Zangbo River, Tibet	59.1233, 50.7557, and 51.5292	0.098, 0.122, and 0.118	-	Han *et al.* (2025)
Schizothorax wangchiachii	Yalong River, China	64.29 (male) 59.43 (female)	Female: 0.0579 yr^{-1}; Male: 0.0683 yr^{-1}	Female: −0.3318 year^{-1}; Male: −0.3031 year^{-1}	He *et al.* (2023)
	Jinsha River, China	62.21 (female) 57.41 (male)	Female: 0.0637 yr^{-1}; Male 0.0559 yr^{-1}	Female: −0.2203 year^{-1}; Male: −0.7094 year^{-1}	He *et al.* (2023)
Schizopygopsis younghusbandi	Yarlung Zangbo River in Tibet, China	44.27 (male) 47.14 (female)	Male 0.0738 yr^{-1} Female 0.0789 yr^{-1}	Male: −1.4 yr Female: 0.2 yr	Chen *et al.* (2007)
Diptychus maculatus	Trans-Himalayan Region of Kargil, Ladakh, India.	40.74	0.11 yr^{-1}	− 0.77 yr	Present study

4.4 Virtual population analysis, yield-per-recruit / biomass-per-recruit and recruitment

Relative yield per recruit (*Y′/R*) and biomass per recruit (*B′/R*) analyses, based on knife-edge selection, estimated the exploitation rate at 0.71 higher than the recommended 0.5, indicating excessive fishing pressure on this *D. maculatus*. This high exploitation rate is largely due to the harvesting of mature individuals across three major length groups, which reduces recruitment and subsequently affects yield per recruit. External pressures also contribute to overexploitation, including habitat degradation, food availability changes, sand mining, dam construction, and infrastructure development (Roads), all of which degrade feeding and breeding habitats. Additionally, the use of non-selective fishing gears, such as pole and line, disregards length at first capture, further increasing fishing mortality. Even in the absence of commercial fisheries, these factors collectively drive-up fishing mortality and exploitation rates of *D. maculatus* in the Trans-Himalayan region. Keskar *et al*. (2017) documented comparable trends for the spiny loach *Lepidocephalichthys thermalis* in the northern Western Ghats, where exploitation rates at several sites exceeded E_{50}, and in high-impact areas characterised by urbanisation, pollution, and invasive species rates reached more than 86% of E_{max}. These parallels suggest that overexploitation is a common issue in freshwater fish populations inhabiting regions subjected to increasing human activity and habitat alteration. The subfamily Schizothoracinae is characterised by restricted distributions, slow growth rates, low fecundity, and late maturity, which may result from their surrounding rigorous environment (Chen and Cao 2000). These life-history characteristics make them more vulnerable to intense exploitation (Buxton 1993). These species have been subjected to intensive anthropogenic pressures such as indiscriminate fishing, habitat modification resulting from dam construction, and biological invasions (Huo *et al*. 2012). Han *et al*. (2025) reported exploitation rates of 0.54 for *Schizothorax o'connori*, 0.75 for *Oxygymnocypris stewartii*, and 0.71 for *Ptychobarbus dipogon*, indicating substantial fishing pressure across these species Duoxiong Zangbo River Tributary of the Yarlung Zangbo River, Tibet. He *et al*. (2023) observed in *Schizothorax wangchiachii* a higher female mortality rate (0.65 year^{-1}) compared to males (0.45 year^{-1}), along with an overall exploitation rate (*E*) of 0.69 year^{-1} in the Yalong River and the upper reaches of the Jinsha River, China. According to the rule of thumb ($E > 0.5$), this suggests the stock is experiencing overfishing. Similarly, Xiang *et al*. (2025), using otolith annulus analysis, also reported an exploitation rate of 0.69 year^{-1}, indicating the species is slightly overfished in Nansi Lake, China. The FiSAT-based recruitment analysis for *D. maculatus* indicates continuous recruitment throughout the year, with a prominent peak during mid-year and smaller pulses occurring before and after. This pattern reflects the species' prolonged and flexible spawning strategy, a common trait among cold-water schizothoracines, which supports population stability in unpredictable high-altitude river environments. Pauly and Morgan (1987) emphasise that FiSAT recruitment patterns are essential for understanding spawning cycles and assessing stock sustainability. Himalayan schizothoracines typically exhibit extended breeding seasons, with peak spawning during spring and summer when warmer temperatures and increased river discharge create optimal conditions for reproduction (Jhingran 1991; Mir *et al*. 2013). The occurrence of multiple recruitment pulses within a single year is considered an adaptive mechanism to enhance survival under fluctuating environmental conditions (Sparre and Venema 1998). The snow trout (subfamily Schizothoracinae), once abundant in Himalayan rivers, is now in rapid decline due to human activities. These include relentless hydropower and infrastructure development, overfishing, the introduction of exotic species, and habitat degradation. To effectively conserve Schizothoracinae, we urgently need policies developed in collaboration with multiple stakeholders: government, research agencies, local communities, and NGOs. Key priorities should include creating protected conservation zones, building hatcheries, ensuring minimum river flows, banning exotic species introductions, and establishing mid-elevation refuges for in-situ conservation (Bhatt and Manish 2023; Sarma *et al*. 2024).

Despite gear selectivity challenges inherent to high-altitude river sampling, the present study provides the first comprehensive assessment of population dynamics of snow trout *D. maculatus* in the understudied Trans-Himalayan region of Ladakh. Sampling was conducted exclusively using hook-and-line and rod-and-line methods traditionally employed by local fishermen, as alternative gears such as cast nets and gill nets proved ineffective owing to the extreme hydrological and geomorphic features of the study rivers (high flow velocity, steep gradients, shallow depths, and boulder-dominated rocky substrate). Although a broad size range (98.83–390 mm TL) was successfully obtained with a large sample size (n = 300) over 10 months, hook-and-line gear is inherently more selective towards larger and more active individuals. This may introduce some bias in length-frequency distributions and, consequently, in the estimated growth, mortality, and exploitation parameters.

Furthermore, the absence of long-term temporal data restricts the assessment of interannual variation in population dynamics. Future research should aim to incorporate complementary sampling approaches during optimal seasons, validate the length-based parameters through direct ageing methods such as otolith analysis or mark-recapture experiments, and integrate environmental, reproductive, and genetic data. Nevertheless, given the considerable difficulties of conducting fisheries re-

search in this remote and challenging environment, the present dataset offers a robust and valuable baseline for understanding the population status and informing conservation strategies for *D. maculatus*.

5 | CONCLUSIONS

The conservation of endemic and exploited fish species in the Ladakh Trans-Himalayan region faces significant challenges due to the limited availability of demographic data, which hinders the development of effective management strategies. This study provides a foundational investigation into the population dynamics and exploitation patterns of the monotypic cyprinid *D. maculatus*, offering critical insights for its sustainable management and long-term conservation in this ecologically sensitive region. The fragile aquatic ecosystems of Ladakh are under increasing pressure from rapid anthropogenic changes, including infrastructure development, unregulated sand mining, and river damming, notably the Chutuk Hydroelectric Project on the Suru River. These activities disrupt natural flow regimes, alter sediment transport, and degrade spawning, migration, and feeding habitats, posing severe threats to *D. maculatus* and other high-altitude schizothoracines by fragmenting populations and reducing habitat connectivity. To ensure the survival of this unique Trans-Himalayan biodiversity, science-based fisheries management is essential, incorporating measures such as legal catch size limits, seasonal closures during spawning periods, and strengthened environmental regulations to mitigate ecosystem degradation. Embracing ecosystem-based fisheries management, fostering active community participation, and prioritizing future research are vital steps toward protecting these threatened species and sustaining the region's fisheries resources for future generations.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHORS' CONTRIBUTION

Zaheer Abass: Conceptualization, investigation, data curation, and writing – original draft; Tasaduq Hussain Shah: Methodology, validation, and supervision; Farooz Ahmad Bhat: Conceptualization, resources, project administration, and funding acquisition; Karankumar Kishorkumar Ramteke: Formal analysis, software, and visualization; Ishrat Mohd: Data curation and investigation; Syed Talia Mushtaq: Formal analysis and writing – original draft; Rinkesh Nemichand Wanjari: Conceptualization, writing – review and editing, visualization, and overall supervision; Sabina Iqbal Darve: Data curation and methodology; Adil Hussain Magloo: Investigation and formal analysis; Junaid Ahmad Khan: Validation and review; Tabish Farooq: Writing – review and editing; Inab Majeed Bala: Data curation and visualization.

AI-USE STATEMENT

During the preparation of this manuscript, AI-assisted tools were used for language improvement and structural editing. All scientific content, data analyses, interpretations, and final revisions were performed and verified by the authors, who take full responsibility for the integrity and accuracy of the work.

DATA AVAILABILITY STATEMENT

The datasets generated during the current study will be available from the corresponding author on reasonable request.

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