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From flowing rivers to Himalayan lakes: Comparative growth, condition and environmental drivers of three sympatric snowtrouts

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Abstract
Length–weight relationships (LWRs), condition factor and environmental associations were comparatively examined in *Schizothorax plagiostomus*, *S. esocinus* and *S. curvifrons* from contrasting freshwater habitats of the Kashmir Himalaya. A total of 1,624 specimens collected between October 2023 and September 2025 were analysed. Weight increased strongly with total length in all species (R2=0.935–0.950). Pooled-sex growth was negatively allometric in *S. plagiostomus* (b=2.754) and *S. curvifrons* (b=2.807), whereas *S. esocinus* showed positive allometry (b=3.094). Condition factor differed significantly among species in River Jhelum but not in Dal Lake, indicating stronger interspecific differentiation in the lotic habitat. Species, habitat and their interaction significantly influenced condition factor. Dissolved oxygen showed the strongest positive association with condition in River Jhelum, whereas alkalinity was more strongly associated with condition in Dal Lake; temperature was negatively associated with condition in both habitats. The results demonstrate that growth form and somatic condition in Himalayan snow trouts reflect both species-specific biological traits and habitat-specific physicochemical conditions, providing an integrated baseline for ecological monitoring and conservation of these important cold-water fishes.

Keywords: Allometric growth, condition factor, dissolved oxygen, Dal Lake, River Jhelum, snow trout, *Schizothorax*

Introduction

Length–weight relationships provide one of the most widely used quantitative approaches for describing fish growth, estimating biomass from length measurements and evaluating changes in body form across populations. The relationship is generally expressed as $W=a L^{b}$, where W is body weight, L is fish length, a is the intercept and b is the allometric growth coefficient. Values of b=3 indicate isometric growth, whereas values below or above 3 indicate negative and positive allometric growth, respectively. Froese (2006) [5] demonstrated through a large meta-analysis that the expected range of b for most fishes is approximately 2.5–3.5 and emphasized the importance of interpreting LWRs within the observed size range and ecological context.

The condition factor (K) complements LWR analysis by providing an index of the relative well-being or somatic condition of fish. However, condition is influenced by numerous biological and environmental factors, including food availability, reproductive state, season, body size, habitat and water quality (Le Cren, 1951; Froese, 2006) [5, 7]. Consequently, comparative assessment across sympatric species and contrasting habitats can provide ecological information that cannot be obtained from LWRs alone.

Snowtrouts of the genus *Schizothorax* are among the most characteristic fishes of Himalayan freshwater ecosystems. Previous studies from Kashmir have reported LWRs and biological characteristics of several *Schizothorax* species, including *S. plagiostomus*, *S. esocinus* and *S. curvifrons* (Bhat *et al*., 2010; Khan and Sabah, 2013; Mir *et al*., 2014). Mir *et al*. (2014) [2, 6, 8], for example, reported species-specific LWR variation among Himalayan snowtrouts and emphasized the influence of sampling range and habitat on estimated growth parameters.

Nevertheless, comparatively integrated information combining growth patterns, condition factor and physicochemical characteristics across contrasting lotic and lentic habitats remains limited. River Jhelum represents a flowing, relatively well-oxygenated system, whereas Dal Lake is a shallow lentic ecosystem with relatively higher temperature, alkalinity and hardness.

The present study therefore integrates the three datasets to provide a comparative ecological assessment of *S. plagiostomus*, *S. esocinus* and *S. curvifrons*, linking interspecific growth patterns and body condition with habitat-specific physicochemical characteristics.

Materials And Methods

Study area and sampling

The study was conducted in two contrasting freshwater ecosystems of the Kashmir Himalaya: River Jhelum and Dal Lake. River Jhelum represents a lotic habitat characterized by continuous water movement and relatively high dissolved oxygen, whereas Dal Lake represents a comparatively stable lentic habitat with higher alkalinity and nutrient accumulation.

A combined dataset comprising 1,624 specimens of *S. plagiostomus*, *S. esocinus* and *S. curvifrons* was used. Specimens were collected monthly from October 2023 to September 2025 using cast nets, gill nets of different mesh

sizes and traditional fishing gears. Total length was measured to the nearest 0.1 cm and body weight to the nearest 0.01 g.

Length–weight relationship

The LWR was estimated using:

$$W = a L^{b}$$

and the log-transformed equation:

$$\log W = \log a + b \log L$$

The coefficient of determination (R2) was used to evaluate the strength of the relationship between length and weight. Growth was classified as negative allometric when b<3, isometric when b=3, and positive allometric when b>3.

Condition factor

Fulton's condition factor was calculated as:

$$K = 100W / L^{3}$$

where W is body weight in grams and L is total length in centimetres.

Physicochemical parameters and statistical analysis

Water temperature, dissolved oxygen and pH were measured in situ, while total hardness and alkalinity were determined using standard procedures. Monthly mean values were used to examine associations with fish condition.

One-way ANOVA was used to compare condition factor among species within habitats. Two-way ANOVA tested the effects of species, habitat and their interaction. Pearson's correlation coefficient was used to evaluate associations between physicochemical variables and condition factor, with significance accepted at $p<0.05$.

Results

Strong relationships between total length and body weight were observed in all three species. The pooled-sex R^2 values were 0.935 for *S. plagiostomus*, 0.950 for *S. curvifrons* and 0.942 for *S. esocinus*, demonstrating that length explained a substantial proportion of variation in body weight (Table 1).

The growth coefficient differed distinctly among species. *S. plagiostomus* exhibited the lowest pooled b value (2.754), followed by *S. curvifrons* (2.807), indicating negative allometric growth. In contrast, *S. esocinus* had a pooled b value of 3.094, indicating positive allometric growth.

Table 1: Comparative pooled length–weight relationship parameters.

Species	Total sample	Growth coefficient (b)	R^2	Growth pattern
S. plagiostomus	624	2.754	0.935	Negative allometric
S. curvifrons	462	2.807	0.950	Negative allometric
S. esocinus	538	3.094	0.942	Positive allometric

Condition factor across species and habitats

Condition factor showed both species-specific and habitat-specific variation. In River Jhelum, mean K was highest in *S. plagiostomus* (1.20 ± 0.13), followed by *S. curvifrons* (1.16 ± 0.12) and *S. esocinus* (1.09 ± 0.11). In Dal Lake, the corresponding values were more similar: 1.15 ± 0.14, 1.12 ± 0.13 and 1.10 ± 0.13, respectively (Table 2).

Table 2: Comparative condition factor in River Jhelum and Dal Lake

Species	River Jhelum, K (mean ± SD)	Dal Lake, K (mean ± SD)	Habitat pattern
S. plagiostomus	1.20 ± 0.13	1.15 ± 0.14	Higher in river
S. curvifrons	1.16 ± 0.12	1.12 ± 0.13	Higher in river
S. esocinus	1.09 ± 0.11	1.10 ± 0.13	Similar

Interspecific differences were significant in River Jhelum ($F=25.937$, $p<0.001$) but not in Dal Lake ($F=1.360$, $p=0.258$). Two-way ANOVA showed significant effects of species ($F=18.07$, $p<0.001$), habitat ($F=14.75$, $p<0.001$) and the species × habitat interaction ($F=5.28$, $p=0.005$). The interaction indicates that habitat did not influence all three snow trout species in the same manner.

Seasonal pattern

Condition factor generally showed seasonal fluctuations. For all three species, relatively higher condition values were commonly observed during spring, particularly around April–May, whereas lower values occurred during summer, particularly July–August. For example, pooled *S. plagiostomus* reached a mean monthly K of 1.218 in May and declined to 0.952 in August. Similar summer reductions were observed in *S. esocinus* and *S. curvifrons*.

This common temporal pattern suggests that seasonal environmental conditions and biological processes may influence somatic condition across the three species.

Physicochemical *relationships*

River Jhelum had a lower mean water temperature (13.8 ± 4.2°C) and higher dissolved oxygen (9.1 ± 1.3 mg L^{-1}), whereas Dal Lake had a higher mean temperature (16.5 ± 5.1°C), alkalinity (156 ± 22 mg L^{-1}) and hardness (172 ± 25 mg L^{-1}).

Condition factor showed habitat-dependent relationships with environmental variables. Dissolved oxygen was positively associated with condition in River Jhelum ($r=0.74$, $p<0.01$). In Dal Lake, alkalinity showed a stronger positive association ($r=0.61$, $p<0.05$). Water temperature was negatively associated with condition in both habitats, ranging approximately from −0.55 to −0.63 (Table 3; Fig 1).

Table 3: Major habitat-specific associations between condition factor and physicochemical parameters

Parameter	River Jhelum	Dal Lake	General interpretation
Temperature	−0.55	−0.63	Negative association
Dissolved oxygen	0.74	Weak/moderate positive trend	Stronger influence in river
Alkalinity	Weak positive trend	0.61	Stronger association in lake

The source analyses also indicate that dissolved oxygen accounted for approximately 52% of variation in condition

factor in the River Jhelum analysis, whereas temperature and alkalinity together explained approximately 46% of variation in Dal Lake (Fig 2).

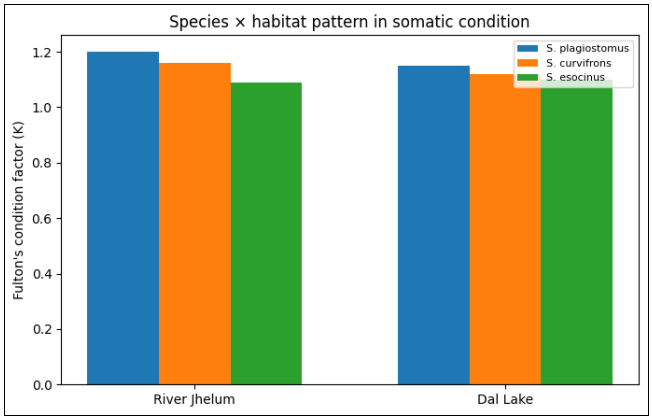

Fig 1: The generated comparative graph highlights the stronger separation among species in River Jhelum and the greater convergence of condition values in Dal Lake.

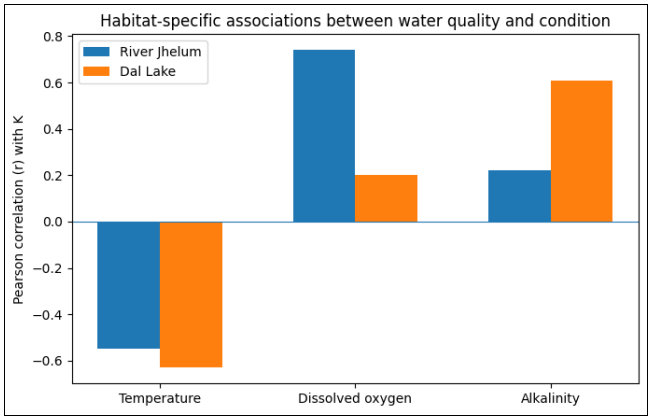

Fig 2: The comparative correlation graph illustrates a strong positive dissolved oxygen–condition relationship in the river, a stronger alkalinity–condition association in the lake, and consistently negative temperature associations.

Discussion

The comparative analysis of 1,624 snow trout specimens demonstrates that *S. plagiostomus*, *S. esocinus* and *S. curvifrons* differ not only in their growth trajectories but also in their responses to contrasting freshwater environments. The high R^2 values obtained for all three species confirm a strong length–weight association and indicate that body weight can be reliably predicted from total length within the observed sampling range.

The pooled *b* values reveal a clear interspecific contrast. Negative allometry in *S. plagiostomus* (b=2.754) and *S. curvifrons* (b=2.807) suggests that increases in length were proportionally greater than increases in body mass, whereas the positive allometry of *S. esocinus* (b=3.094) indicates a relatively greater increase in body mass with length. These estimates fall within the broad range reported by Froese (2006) [5] for fish LWRs.

The observed interspecific differences are also broadly consistent with earlier work on Himalayan snow trouts. Mir *et al.* (2014) [8] reported substantial variation in LWR parameters among *Schizothorax* species and noted that differences among studies may result from habitat, sample size and observed length range. Similarly, Bhat *et al.* (2010) and Khan and Sabah (2013) [2, 6] reported species-specific growth coefficients from Kashmir waters, supporting the interpretation that allometric responses in snow trouts are not uniform across habitats or populations.

The present study adds an ecological dimension by demonstrating that growth differences occur alongside habitat-dependent differences in somatic condition. *S. plagiostomus* consistently showed the highest mean condition factor, particularly in River Jhelum, while *S. esocinus* displayed the lowest mean riverine condition despite its positive allometric growth. This finding illustrates an important distinction: a higher LWR slope does not necessarily imply a higher Fulton condition factor because the two indices capture different aspects of body growth and condition.

The significant species × habitat interaction further indicates that environmental effects were not uniform among the three species. The stronger interspecific separation in River Jhelum may reflect ecological differentiation under flowing, oxygen-rich conditions, whereas the convergence of K values in Dal Lake suggests a relatively more homogeneous environmental influence. This interpretation is consistent with the ecological basis of condition indices described by Le Cren (1951) [7] and the methodological recommendations of Froese (2006) [5], who emphasized that condition must be interpreted in relation to body size and environmental context.

The positive association between dissolved oxygen and condition factor in River Jhelum is particularly noteworthy. Dissolved oxygen may influence aerobic metabolism, feeding activity and energy allocation, thereby contributing to differences in somatic condition. The higher oxygen concentration recorded in the river, together with its flowing nature, provides a contrasting environment to Dal Lake.

Conversely, the stronger relationship between alkalinity and condition in Dal Lake suggests that lentic environmental productivity and water chemistry may have a relatively greater influence on fish condition in that system. However, these associations should not be interpreted as evidence of direct causation because condition factor is also influenced by season, feeding, maturity and size composition.

The negative association between temperature and condition in both habitats deserves particular attention. The summer reduction in condition factor observed across the three species corresponds with the general negative temperature relationship reported in the source dataset. Seasonal temperature increases may increase metabolic costs, alter dissolved oxygen availability and interact with feeding and reproductive cycles. Similar environmental sensitivity is particularly important for cold-water Himalayan fishes, which may experience physiological constraints under changing thermal conditions.

Overall, the present analysis improves upon earlier single-parameter assessments by integrating growth, condition and environmental relationships within one comparative

framework. Previous studies such as Bhat *et al*. (2010), Khan and Sabah (2013) [2, 6] and Mir *et al*. provide important baseline information on LWRs of Himalayan snowtrouts, while the present combined analysis demonstrates that these relationships are best interpreted alongside habitat-specific variation in fish condition and water quality.

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