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Length–weight relationship and condition factor of roach *Rutilus rutilus* in lentic waterbodies of Uzbekistan

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This study investigates the length–weight relationship (LWR) and condition factor of roach, *Rutilus rutilus,* from seven lentic water bodies in Uzbekistan, including reservoirs and drainage lakes in the Syrdarya, Zarafshan, and Surkhandarya river basins. These habitats, formed mainly during the large-scale irrigation developments of the late 20th century, now support abundant roach populations that have become commercially significant since the 2000s. Samples were collected from commercial catches in March–April 2024–2025 using gill nets (mesh 16–50 mm). Total length (TL), standard length (SL), and weight (W) were measured. The LWR was modeled using both power and log-transformed equations, and Fulton's condition factor (K) and relative condition factor (Kn) were calculated. Results revealed strong positive correlations between SL and TL in all stocks. LWR exponents (b) ranged from 2.81 to 3.23, indicating predominantly isometric or slightly positive allometric growth, except for East Arnasay Reservoir (b = 2.81) and Lake Karakir (b = 2.93), which showed slight negative allometry. Fulton's K averaged 1.14–1.26 across sites, suggesting generally good condition, though roach in Lakes Aydarkul and Tuzkan had lower fatness, likely linked to increasing salinity (8–12‰) and reduced freshwater inflow. Kn values averaged around 1.0 for all populations, indicating that observed weights closely matched those predicted by LWR equations and reflecting stable ecological conditions. The findings highlight the adaptability of roach to diverse hydrological conditions, including brackish drainage lakes, and their ability to form sustainable commercial stocks in Uzbekistan's artificial and semi-natural water systems. The data provide the first detailed LWR and condition factor assessments for *R. rutilus* in the region, offering valuable baselines for fisheries management. Differences in growth patterns and body condition among water bodies likely reflect a combination of environmental factors, including salinity, food availability, and hydrological regime stability. From a management perspective, monitoring K and Kn values over time may serve as an effective tool for detecting shifts in fish health related to climate variability, water quality changes, and anthropogenic pressures. Overall, this study expands the understanding of roach biology in arid and semi-arid inland water ecosystems, where climatic extremes and human-modified hydrology shape fish population dynamics. The observed capacity of roach to maintain favorable condition factors in most habitats supports their continued role as a key component of Uzbekistan's inland fisheries, although their declining condition in the more saline lakes signals the need for targeted management actions to sustain productivity.

Keywords: length–weight ratio; condition factor; allometric growth; reservoirs; lakes-accumulators of drainage water; Uzbekistan.

Introduction

In the natural state of the Aral Sea basin (Central Asia), roach, *Rutilus rutilus* (Linnaeus, 1758) (Leuciscinae), inhabited almost all water bodies of the plain part (Berg, 1949; Kamilov, 1973). In the Aral Sea itself, roach was a commercial fish (it disappeared with the increase in water salinity, known as the Aral ecological crisis), but in other water bodies of Uzbekistan it was not included in the commercial fishes, since it did not create noticeable stock accumulations (Kamilov, 1973). As a result of large-scale irrigation construction for the needs of agriculture in the second half of the 20th century, more than 60 reservoirs with a water volume of more than 60 km^3 and an area of more than 310 km^2 and irrigation canals for fresh water on all plain rivers were created in the basin, as well as a developed collector-drainage network and lakes-accumulators of drainage water with an area of more than 7000 km^2, where brackish water is diverted after washing agricultural lands from soil salinization. Roach has demonstrated its high plasticity, naturally penetrated into the reservoirs of the irrigation and drainage system, and in reservoirs and lakes created massive stocks and since the 2000s has entered the list of the most numerous commercial fish, the catch of which in different years is 2–6 thousand tons per year (Kamilov, 2003).

Uzbekistan is located in Central Asia in the south of the temperate zone, it is an arid region with a extremely continental climate. Summer is hot (the average monthly air temperature in July is about 29 °C, during the day it often reaches 35–42 °C and can be higher). Winter is quite cold (the average monthly temperature in January varies from zero to –2 °C, stagnant bodies of water are often covered with ice for up to 1.5 months).

Lakes Aydarkul (about 3000 km^2), Tuzkan (705 km^2) and the Eastern Arnasay Reservoir (200 km^2) form the Aydar-Arnasay Lake System in the middle stream of the Syrdarya; currently this system is the largest system of waterbodies in the Aral Sea basin. The water in Aydarkul and Tuzkan is brackish, in recent years there has been a tendency for the salinity of the water to increase, which has already reached 8–12‰. The water in the reservoir is fresh, coming from the Chardara Reservoir (Fig. 1). The Tudakul Reservoir (200 km^2) is a large reservoir in the lower reaches of the Zarafshan River, fed by water from the middle reaches of the Amu Darya, which is brought by the Amu-Bukhara machine canal. The Uchkizil Reservoir (10.5 km^2) was created in the Surkhandarya River basin. Lakes Zamonbobo (48 km^2) and Karakir (170 km^2) are lakes that accumulate drainage (brackish) water in the lower reaches of the Zarafshan River, created at the turn of the 20th and 21st centuries.

For rational use of fish resources, the study of the relationship between body weight and length of fish, condition factor, characterizing the state of stocks, is widely used, as well as comparing parameters between commercial fish populations in different water bodies (assuming that heavier fish with the same body length are in better condition) (Bagenal & Tesch, 1978; Zafar et al., 2002; Hossain et al., 2006; Gupta et al., 2010; Mansor et al., 2010; Muchlisin et al., 2010; Kamaruddin et al., 2012; Dutta et al., 2021). However, until now, such studies have not been carried out in Uzbekistan, including for roach. The data are of interest, given that formations of semi-anadromous and residential, fast-growing and slow-growing forms are noted in the reservoirs of the republic.

Fig. 1. Uzbekistan and waterbodies studied with roach:
1 – Lake Tuzkan; *2* – Lake Aydarkul; *3* – East-Arnasay Reservoir; *4* – Uchkizil Reservoir, *5* – Lake Karakir; *6* – Tudakul Reservoir; *7* – Lake Zamonbobo

Studies on the length–weight relationship (LWR) and condition factors of roach are well documented across various parts of its natural range, providing important comparative baselines for the present work. The LWR is most commonly described by the equation $W = a \bullet L^b$ (Le Cren, 1951), with the exponent b typically close to 3, indicating isometric growth, but subject to variation depending on population, environmental conditions, season, and sampling design. For example, in Lake Volvi (Greece), Koutrakis & Tsikliras (2003) reported b values range from 3.653 in males to 3.700 in females, with combined data yielding b = 3.684 and $R^2 > 0.93$, noting seasonal shifts likely linked to reproductive cycles. In Belgium, long-term fish monitoring data from Flanders (Verreycken et al., 2011) showed that roach LWR parameters can vary monthly, with b values around 3.34 in certain months, illustrating the influence of seasonal physiological changes and environmental conditions. Historical datasets from Lake Volvi (Stergiou & Moutopoulos, 2001) also provide sex-specific LWRs and highlight the stability of growth patterns in stable lacustrine habitats. Froese (2006), in a meta-analysis of global LWR data, emphasized the importance of verifying whether b differs significantly from 3 through statistical testing, and of providing confidence intervals to allow robust comparisons across studies.

Condition factors, including Fulton's K and the relative condition factor Kn (Le Cren, 1951), are widely used in conjunction with LWR to assess the well-being of fish stocks. Seasonal fluctuations in K have been reported for roach populations, often reflecting changes in feeding intensity, gonadal development, and environmental stressors. For example, Barnham & Baxter (1998) suggested that K values below 1.00 indicate poor condition, while values above 1.20 suggest moderate to good condition in salmonids, a framework sometimes applied to cyprinids including roach. Gupta et al. (2010) noted that reproductive status can significantly influence K, underscoring the need to interpret this index in the context of life cycle stage and sampling period. Overall, published LWR and condition factor data for *R. rutilus* confirm its adaptability to a wide range of freshwater and brackish habitats, with growth patterns shaped by both intrinsic (age, sex, reproductive status) and extrinsic (temperature, salinity, food availability) factors, making such metrics essential for effective assessment and management of fisheries. The aim of this study was to determine the relationship between the length and body weight of roach in commercial stocks of the specified reservoirs of Uzbekistan.

Material and methods

Study area and sampling design. We examined roach from seven lentic waterbodies distributed across three major basins of Uzbekistan (Syrdarya, Zarafshan, Surkhandarya). Sampling was conducted in March–April of 2024 and 2025 from commercial catches made with set gill nets of 16–50 mm mesh. To reduce mesh-selectivity bias, subsamples were drawn at random from the full range of sizes present in each catch. Fish were processed on the day of capture.

Species identity followed Berg (1949). For each randomly selected roach, we recorded: Total length (TL, cm; tip of snout to end of caudal fin); Standard length (SL, cm; to the posterior margin of the scale cover); Whole body mass (W, g).

Lengths were measured to 0.1 cm using a calibrated ichthyometer; masses were measured to 0.1 g on an electronic balance checked daily with certified weights. Instruments were zeroed before each batch. All measurements were taken by trained personnel to minimize observer error.

Within each waterbody, SL–TL relationships were quantified by ordinary least squares (OLS) linear regression of the form $SL = \alpha \bullet TL + \beta$. We report the Pearson correlation coefficient (r) and coefficient of determination (R^2). Model assumptions were screened via residual diagnostics (normality, homoscedasticity) and visual inspection of fitted vs. residual plots. Where needed, robust standard errors were examined to assess sensitivity to mild heteroscedasticity.

Length–weight relationships (LWR) were modeled as a power function $W = a \bullet TL^b$. Parameters were estimated in two complementary ways: nonlinear fit to the untransformed power model; linear regression on $\log_{10}$-transformed data: $\log_{10} W = \log_{10} a + b \bullet \log_{10} TL$ (Ricker, 1973).

For each stock, we present point estimates and 95% confidence limits (CL) for a and b. To evaluate departure from isometry, we tested H_0 b = 3 using the t-statistic based on the standard error of b from the log-linear fit (Froese, 2006). Because back-transformation of log-fits can introduce bias when predicting on the arithmetic scale, we used predictions from the non-log power model for derived quantities (see below); when predictions from log space were inspected, a smearing estimator was considered in sensitivity checks.

Fulton's condition factor (K) was computed as $K = 100 \bullet W/TL^3$, with W in grams and TL in centimeters (unit consistency verified). The relative condition factor (Kn) was calculated as $Kn = W/W'$, where W′ is the expected mass at length from the site-specific LWR (Ricker, 1973; Borges et al., 2003; Andreu-Soler et al., 2006; Froese, 2006; Veiga et al., 2009). Thus, K reflects "plumpness" conditioned on length via the cube law, whereas Kn standardizes mass to the observed length–weight scaling of each population, facilitating comparisons among sites and seasons.

All analyses were conducted separately for each waterbody to avoid pooling across potentially distinct growth environments. Outliers were screened using leverage and Cook's distance in the log-linear fits; no observations were removed solely on statistical grounds without a biological rationale (e.g., measurement error). Parameter uncertainty is expressed as 95% CL; statistical significance was assessed at P = 0.05. When comparing parameters among stocks, primary inferences relied on the overlap (or non-overlap) of confidence intervals rather than multiple pairwise tests, recognizing the sensitivity of b to sampled length ranges and gear selectivity.

Results

Our samples consisted of individuals included in the roach fisheries capture in each of the water bodies studied (Table 1). In all the water bodies, there was a very strong positive linear dependence of the indicators between the standard and total body length of roach (Table 2), which was reliably expressed by the linear regression equation; the determination coefficient (R^2) was higher than 0.95 in all stocks.

Table 1 presents the minimum and maximum values of total length (TL), standard length (SL), and body weight (W) of roach from the studied water bodies. These data reflect the size structure of the commercially exploited stocks and provide an initial comparison of growth potential across habitats with differing hydrological and ecological characteristics.

The largest individuals in terms of TL and body weight were recorded in the Tudakul Reservoir (TL up to 31.0 cm; W up to 440 g) and Lake Zamonbobo (TL up to 31.5 cm; W up to 370 g). This indicates favourable feeding conditions and/or lower exploitation pressure in these water bodies, allowing fish to reach larger sizes. In contrast, the smallest maximum TL values were observed in Lake Tuzkan (22.3 cm) and Lake Karakir (23.0 cm), suggesting either higher fishing intensity, more limited food resources, or environmental conditions constraining growth.

Table 1
Size parameters of roach in the studied water bodies (min–max)

Waterbody	TL, cm	SL, cm	W, g
Lake Tuzkan	16.3–22.3	13.0–18.1	43–130
Lake Aydarkul	16.1–22.8	13.3–18.7	45–134
East Arnasay Reservoir	13.0–24.0	11.0–20.0	23–170
Uchkizil Reservoir	13.0–29.0	11.5–23.8	29–320
Lake Karakir	13.0–23.0	11.0–18.8	23–159
Tudakul Reservoir	11.6–31.0	9.6–26.0	15–440
Lake Zamonbobo	10.5–31.5	8.7–26.5	10–370

Variation in standard length (SL) closely followed the patterns seen in TL, reflecting consistent body proportions among populations. The lower minimum TL values in Lake Zamonbobo (10.5 cm) and the Tudakul Reservoir (11.6 cm) may indicate the presence of younger cohorts in the catch, possibly due to recruitment pulses or seasonal fishing that includes sub-adult individuals.

Body weight showed considerable variability both within and between water bodies. The wide range of weights in some sites, such as the Uchkizil Reservoir (29–320 g) and Tudakul Reservoir (15–440 g), suggests the coexistence of multiple year classes and differences in growth rates within the same habitat.

From a fisheries management perspective, these size distribution patterns are valuable for assessing stock structure and productivity. The presence of larger, older individuals in certain water bodies indicates higher growth potential and could reflect less intensive fishing pressure, while smaller size ranges may signal the need for regulation of fishing intensity to prevent growth overfishing.

Table 2
Standard length and total body length relationship of roach in the studied water bodies and the value of the correlation coefficient

Waterbody	Regression equation	r
Lake Tuzkan	SL = 0.7747 * TL + 0.686	0.97
Lake Aydarkul	SL = 0.8062 * TL + 0.907	0.98
East Arnasay Reservoir	SL = 0.7709 * TL + 1.0546	0.98
Uchkizil reservoir	SL = 0.8132 * TL + 0.2468	0.99
Lake Karakir	SL = 0.7584 * TL + 1.2114	0.97
Tudakul Reservoir	SL = 0.8282 * TL - 0.0522	0.99
Lake Zamonbobo	SL = 0.8397 * TL - 0.0228	0.99

Table 2 summarises the results of linear regression analysis between standard length (SL) and total length (TL) of *R. rutilus* in each of the studied water bodies, accompanied by the corresponding correlation coefficients (r). The obtained regression equations take the form SL = a•TL + b, where the slope (a) reflects the proportional increase in SL relative to TL, and the intercept (b) indicates the theoretical SL value at zero TL.

Across all populations, a very strong positive correlation was recorded, with r values ranging from 0.97 to 0.99 and coefficients of determination (R^2) exceeding 0.95 in all cases. Such consistently high values confirm the stability of body proportions in roach across diverse hydrological and ecological settings, including both freshwater and brackish environments. This stability suggests that morphometric relationships in the species are robust to environmental variation within the studied range.

The variation observed in slope coefficients between water bodies, though small, is biologically meaningful. Lower slope values, such as those found in the East Arnasay Reservoir (0.7709) and Lake Karakir (0.7584), may be indicative of a slightly more elongated body form in these populations. Such morphological tendencies can arise from environmental pressures including reduced prey abundance, hydrodynamic conditions favouring streamlined shapes, or resource competition influencing growth allocation. Conversely, higher slope values, as in the Tudakul Reservoir (0.8282) and Lake Zamonbobo (0.8397), point to proportionally greater standard lengths for the same total length, which may be associated with favourable feeding conditions, lower competition, or habitat structures that select for deeper-bodied fish.

The regression intercepts (b) also varied among sites, reflecting subtle differences in initial growth patterns during early life stages. While these differences are minor, they can provide insight into early juvenile development conditions, which are often sensitive to temperature regimes, prey availability, and nursery habitat quality. From a fisheries biology perspective, the robustness of the SL–TL relationship across all studied stocks means that either metric can be used with confidence to estimate the other, facilitating field data collection when measuring both parameters is impractical. Furthermore, consistent monitoring of this relationship over time can serve as an indicator of morphological shifts in response to environmental changes, fishing pressure, or stock density.

Roach is a relatively small size commercial fish, which is caught in the lakes of Uzbekistan at the age of 3–4 years. Due to the above (that roach does not reach large body length indicators), the dependence of the total body weight on the total body length is reliably characterized by a linear regression, in all cases the determination coefficient was higher than 0.87. However, for fish, the regression equation in the form of a power function is more correct. These data are shown in Figure 2 and Table 3.

Table 3
The number of specimens (N) and estimated parameters of length – weight relationship for roach populations studied (‘a’ – intercept of regression line, ‘b’ – exponent in an equation, CL – confidence level, R^2 – coefficient of determination)

Waterbody	N	*a*	95% CL of *a*	*b*	95% CL of *b*	R^2
Lake Tuzkan	78	0.0088	–194.956 to –148.433	3.0927	12.108 – 14.468	0.881
Lake Aydarkul	78	0.0058	–200.253 to –160.342	3.2289	12.658 – 14.671	0.919
East Arnasay Reservoir	78	0.0218	–160.078 to –128.057	2.8052	11.427 – 13.075	0.936
Uchkizil Reservoir	78	0.0990	–261.816 to –207.741	3.0784	15.909 – 18.464	0.938
Lake Karakir	78	0.0143	–162.085 to –129.258	2.9335	11.242 – 12.966	0.937
Tudakul Reservoir	78	0.0063	–281.291 to –217.019	3.2253	16.618 – 19.650	0.954
Lake Zamonbobo	78	0.0108	–235.703 to –184.622	3.0502	1.552 – 1.795	0.977

Table 3 presents the sample size (N), estimated parameters of the length–weight relationship (LWR), and the corresponding 95% confidence limits for the intercept (a) and exponent (b) for *R. rutilus* populations in the studied water bodies. The parameter a represents the intercept of the regression line, reflecting the condition factor when fish length approaches zero, while b is the scaling exponent describing the type of growth:

– b ≈ 3.0 indicates isometric growth (proportional increase in weight and length),

– b < 3.0 suggests negative allometric growth (fish become more elongated with size),

– b > 3.0 indicates positive allometric growth (fish become deeper-bodied with size).

In most studied water bodies, b values were very close to 3.0, indicating nearly isometric growth and balanced body proportions. Slight deviations were observed: in the East Arnasay Reservoir (b = 2.8052) and Lake Karakir (b = 2.9335), growth was slightly negative allometric, suggesting that fish tend to be more elongated, possibly due to hydrodynamic conditions or foraging behaviour in open-water habitats. Conversely, in Lake Aydarkul (b = 3.2289) and the Tudakul Reservoir (b = 3.2253), positive allometric growth was recorded, reflecting a tendency towards deeper-bodied morphology, potentially associated with favourable feeding conditions and reduced predation pressure.

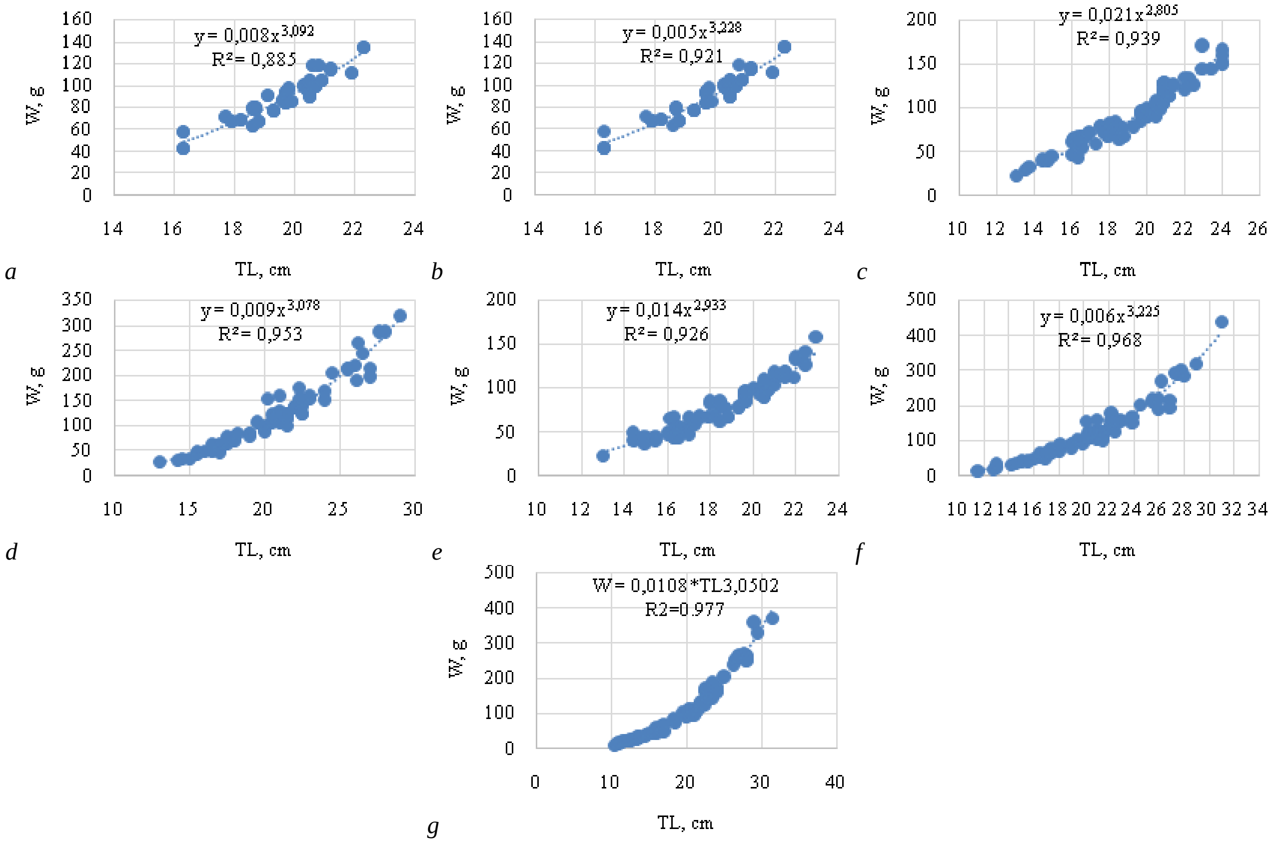

Fig. 2. Length–weight ratio of roach from populations studied: *a* – Lake Tuzkan, *b* – Lake Aydarkul, *c* – East Arnasay Reservoir, *d* – Uchkizil Reservoir, *e* – Lake Karakir, *f* – Tudakul Reservoir, *g* – Lake Zamonbobo

The coefficient of determination (R^2) values ranged from 0.881 to 0.977, indicating a high degree of fit for all regression models. The highest R^2 was recorded in Lake Zamonbobo (0.977), reflecting a very strong length–weight relationship and low variability in body condition among individuals. This may be due to a relatively homogeneous age structure or stable environmental conditions. In contrast, the lowest R^2 was observed in Lake Tuzkan (0.881), possibly indicating more heterogeneous stock composition or seasonal fluctuations in feeding intensity.

From a fisheries biology perspective, these LWR parameters are crucial for biomass estimation, stock assessment, and growth modelling. The proximity of b to the theoretical value of 3.0 in most stocks suggests that these populations are in generally good condition, with balanced energy allocation between somatic growth and other physiological needs. As shown in Figure 2, a very strong relationship between length (SL) and length (TL) was observed at all sites (r = 0.97–0.99), while length-weight (b) indices and condition indices (K, Kn) varied depending on hydrology and salinity. Roach from Tuzkan Lake (Aydar-Arnasay system, Syr Darya basin; ~705 km²; brackish water) showed moderate size range (TL 16.3–22.3 cm; W 43–130 g); close to isometric LWR (b = 3.0927); lower average K (1.16) and Kn ≈ 1.00, consistent with increased salinity and low food supply.

Roach from Lake Aydarkul (Aydar-Arnasay; ~3000 km²; brackish water, 8–12‰ in recent years) showed length 16.1–22.8 cm; width 45–134 g; positive allometry (b = 3.2289), but moderate K (1.14); Kn ≈ 1.15, indicating that individuals sometimes exceed the expected mass-for-length despite salt stress. Roach from East Arnasay Reservoir (Aydar-Arnasay; ~200 km²; mainly freshwater tributary from Chardara) showed length 13.0–24.0 cm; width 23–170 g; negative allometry (b = 2.8052), i.e. thinner fish; average K = 1.24 and Kn ≈ 1.01. Roach from Uchkizil Reservoir (Surkhandarya basin; 10.5 km²; fresh water) showed length 13.0–29.0 cm; width 29–320 g; nearly isometric LWR (b = 3.0784); high K (1.26) and Kn ≈ 1.00, indicating favorable feeding conditions. Roach from Lake Karakir (lower Zarafshan; 170 km²; endorheic/brackish) showed TL 13.0–23.0 cm; W 23–159 g; slightly negative allometry (b = 2.9335); K = 1.18; Kn ≈ 1.01, consistent with hydrological and trophic constraints. Roach from Tudakul Reservoir (lower Zeravshan; ~200 km²; freshwater inflow via the Amu-Bukhara Canal) showed TL 11.6–31.0 cm; W 15–440 g; positive allometry (b = 3.2253) and high K values (1.26); Kn ≈ 1.01; wide size range suggests a multi-cohort structure. Roach from Lake Zamonbobo (lower Zeravshan; 48 km²; drained / brackish water) showed total length (TL) 10.5–31.5 cm; width (W) 10–370 g; nearly isometric LWR distribution (b = 3.0502) with best fit (R^2 = 0.987); K = 1.26; Kn ≈ 0.97.

High salinity basins (Aydarkul, Tuzkan) tend to have lower mean K values, while freshwater reservoirs (Tudakul, Uchkizil) have higher K, with b > 3 in Tudakul. Site-level differences in b and K/Kn are consistent with the hydrological regime and inferred production fields, supporting the study's conclusion that environmental context influences growth form and state. Since many data on the size-weight dependence for fish populations are given after logarithmizing the data, we will also provide the corresponding calculations in Tables 4, 5.

Table 4
Size-weight dependence in roach of the studied water bodies after logarithmizing the indicators

Waterbody	Regression equation	R^2
Lake Tuzkan	$\log_{10}(W) = 3.0927 * \log_{10}(L) – 2.0568$	0.885
Lake Aydarkul	$\log_{10}(W) = 3.2289 * \log_{10}(L) – 2.2400$	0.921
East Arnasay Reservoir	$\log_{10}(W) = 2.8052 * \log_{10}(L) – 1.6609$	0.939
Uchkizil Reservoir	$\log_{10}(W) = 3.0784 * \log_{10}(L) – 2.0058$	0.954
Lake Karakir	$\log_{10}(W) = 2.9335 * \log_{10}(L) – 1.8448$	0.926
Tudakul Reservoir	$\log_{10}(W) = 3.2253 * \log_{10}(L) – 2.1991$	0.968
Lake Zamonbobo	$\log_{10}(W) = 3.0502 * \log_{10}(L) – 1.9662$	0.987

Table 4 presents the length–weight relationships for roach (*Rutilus rutilus*) populations in the studied water bodies after logarithmic transformation of both body length (L) and weight (W) data. This transformation, expressed in the form $\log_{10}(W) = b \cdot \log_{10}(L) + \log_{10}(a)$ is widely applied in fisheries biology to linearize the power function describing fish growth, enabling straightforward estimation of the scaling exponent (b) and intercept ($\log_{10}(a)$) using linear regression techniques.

Across all water bodies, the b values obtained from the log-transformed regressions were identical to those in the non-transformed analysis (Table 3), confirming the stability and reliability of parameter estimation. The high coefficients of determination (R^2), ranging from 0.885 in Lake Tuzkan to 0.987 in Lake Zamonbobo, indicate that length explains the vast majority of weight variation in all studied populations. The slightly lower R^2 in Lake Tuzkan may reflect greater individual variability in body condition, possibly due to fluctuating food availability or mixed age structure in the catch.

Populations from Lake Aydarkul (b = 3.2289) and the Tudakul Reservoir (b = 3.2253) again demonstrated positive allometric growth, consistent with the untransformed analysis, while East Arnasay Reservoir (b = 2.8052) and Lake Karakir (b = 2.9335) exhibited slightly negative allometric growth. This pattern suggests that habitat-specific environmental factors, such as prey type, water flow, and competition, exert a measurable influence on body shape and mass accumulation. The use of log-transformed LWR equations has practical significance for fisheries science, as it allows straightforward conversion between length and weight data in population assessments. Furthermore, the consistency of b values and the high R^2 across both transformed and untransformed datasets validate the robustness of the results, making them suitable for comparative studies with other roach populations across different regions.

Table 5 summarises the welfare indicators of roach (*Rutilus rutilus)* populations from the studied water bodies, including actual weight (W actual), theoretical weight (W theoretical) derived from the length–weight relationship, Fulton's condition factor (K) and the relative condition factor (Kn). For each parameter, both the range and the mean ± standard error are presented.

Table 5
Roach welfare indicators in the studied water bodies
(above the line – limits, below the line – mean and error of the mean)

Waterbody	W actual	W theoretical	Fulton condition factor	Relative condition factor (Kn)
Lake Tuzkan	43.0 – 135.0	49.4 – 130.1	0.99 – 1.36	0.86 – 1.17
	89.60 ± 2.27	89.60 ± 2.13	1.16 ± 0.01	1.00 ± 0.01
Lake	43.0 – 135.0	41.0 – 112.9	0.99 – 1.34	1.02 – 1.41
Aydarkul	89.90 ± 2.33	77.94 ± 1.95	1.14 ± 0.01	1.15 ± 0.01
East Arnasay	23.0 – 170.0	29.1 – 162.3	0.99 – 1.57	0.78 – 1.24
Reservoir	91.83 ± 3.76	91.42 ± 3.70	1.24 ± 0.01	1.01 ± 0.01
Uchkizil	29.0 – 320.0	26.6 – 314.4	0.92 – 1.88	0.74 – 1.50
Reservoir	124.23 ± 6.98	124.21 ± 6.98	1.26 ± 0.02	1.00 ± 0.01
Lake Karakir	23.0 – 159.0	26.5 – 141.2	0.94 – 1.61	0.79 – 1.34
	83.12 ± 3.33	82.73 ± 3.17	1.18 ± 0.01	1.01 ± 0.01
Tudakul	15.0 – 440.0	17.1 – 406.9	0.88 – 1.88	0.75 – 1.52
Reservoir	128.31 ± 8.81	127.63 ± 8.77	1.26 ± 0.02	1.01 ± 0.01
Lake	10.0 – 370.0	14.6 – 417.2	0.86 – 1.49	0.68 – 1.14
Zamonbobo	129.04 ± 10.93	133.52 ± 11.27	1.26 ± 0.01	0.97 ± 0.01

Across all water bodies, mean actual and theoretical weights were highly consistent, with minimal differences, indicating that the regression-derived length–weight relationships accurately represent the body mass of the sampled fish. The close match between W actual and W theoretical also confirms the robustness of the estimated growth parameters in Tables 3 and 4.

Fulton's condition factor (K), which reflects the general 'plumpness' or energy reserves of the fish, ranged from 0.86 (Lake Zamonbobo) to 1.88 (Tudakul Reservoir). Mean K values were generally above 1.14 in all populations, indicating a satisfactory to good nutritional state, with the highest mean values recorded in Uchkizil, Tudakul, and Zamonbobo lakes (all 1.26).

The relative condition factor (Kn), which accounts for deviations from the expected weight based on length, showed that most populations were close to or slightly above the theoretical optimum (Kn ≈ 1.0). The highest maximum Kn values were observed in Lake Aydarkul (1.41) and Tudakul Reservoir (1.52), suggesting that individuals in these habitats occasionally exceeded the expected body mass for their length. Conversely, the lowest minimum Kn was found in Lake Zamonbobo (0.68), indicating that some individuals there were noticeably below average condition, possibly due to seasonal food limitations or intra-specific competition.

Overall, the consistently high mean K and Kn values across most habitats reflect stable feeding conditions and a generally favourable ecological status for roach populations in the studied lakes and reservoirs. However, the broader range of K and Kn in certain water bodies (e.g., Tudakul, Uchkizil) suggests more heterogeneous population structures, possibly influenced by variable age composition, prey availability, and environmental conditions.

Discussion

In this study, a multi-waterbody assessment of the length–weight relationship (LWR), length–length relationship, and condition indices of *R. rutilus* in Uzbekistan was conducted for the first time. By integrating data from seven lentic systems differing in size, salinity, and hydrological connectivity, the results reveal both the general features that define the species' growth form in arid/semi-arid inland waters and site-specific deviations driven by local environmental factors. Across all sites, the linear relationship between standard length (SL) and total length (TL) was exceptionally strong ($r = 0.97$–0.99; $R^2 > 0.95$), indicating stable body proportions within populations despite contrasting ecological conditions. LWR exponents (b) ranged from 2.8052 (East Arnasay Reservoir) to 3.2289–3.2253 (Aydarkul and Tudakul), pointing to predominantly isometric or slightly positive allometric growth, with slight negative allometry in two stocks. Fulton's condition factor (K) averaged 1.14–1.26, and the relative condition factor (Kn) hovered around 1.0, jointly indicating generally favorable nutritional status and habitat suitability. These patterns confirm the well-known ecological plasticity of roach and its capacity to exploit new water bodies created by irrigation infrastructure.

The very tight SL–TL association in all stocks demonstrates morphological constancy of body proportions, a feature often observed in cyprinids with a generalized body plan. Minor differences in regression slopes (e.g., lower slopes in East Arnasay and Karakir versus higher slopes in Tudakul and Zamonbobo) are biologically meaningful. Lower slopes may indicate comparatively more elongated individuals at a given TL, potentially reflecting a shift toward pelagic zooplanktivory, hydrodynamic selection for streamlined shapes in wind-exposed basins, or prey fields that favor active cruising. Conversely, higher slopes imply proportionally greater SL for the same TL, consistent with deeper-bodied morphotypes. In mixed fisheries, such morphological shifts can be amplified by gear selectivity (set gill nets) that differentially retain body shapes. Given the strength of the SL–TL regressions, SL can reliably serve as a proxy for TL (and vice versa) in field monitoring, reducing processing time when rapid measurements are needed.

The central conclusion from the LWR analyses is the dominance of isometric growth in six of seven stocks, supported by b values near 3.0 and high model fits in both raw and log-transformed spaces (R^2 up to 0.987). This aligns with canonical expectations for cyprinids inhabiting productive lentic environments in temperate climates (Bagenal & Tesch, 1978; Froese, 2006). Positive allometry in Aydarkul and Tudakul ($b \approx 3.23$) indicates mass increases slightly faster than length – a pattern often observed where prey availability, thermal regime, and hydrological stability favor energy accumulation and somatic growth. In contrast, negative allometry in East Arnasay (b = 2.8052) and Karakir (b = 2.9335) suggests relatively leaner fish for their length, plausibly due to constraints on prey diversity/quantity, elevated metabolic costs (e.g., from increased salinity or temperature extremes), or density-dependent competition. Because b is sensitive to length range, mesh selectivity, and season (Ricker, 1973; Froese, 2006), the March–April sampling window should also be considered: pre-spawning hypertrophy can increase the mass of mature females, whereas post-winter energetic deficits can reduce mass in fish that have depleted reserves.

Equivalence of b estimates between untransformed and log-transformed regressions (Tables 3 and 4) strengthens confidence in the inference. Log transformation linearizes the power function (W = a•L^b) and stabilizes variance, but it introduces a well-known back-transformation bias if predictions are naively exponentiated. Here the goal was parameter estimation rather than predicting biomass from log space; consequently, agreement between modeling approaches underscores the structural robustness of the length–weight signal. In applied settings, when biomass must be predicted for management, a correction factor (e.g., a smearing estimate) should be used during back-transformation, especially under heteroscedasticity (Froese, 2006).

Fulton's K and the relative condition factor Kn integrate the outcomes of energy acquisition (feeding), allocation (growth versus reproduction), and expenditure (locomotion, osmoregulation, thermoregulation). Mean K values ranged from 1.14 to 1.26, indicating moderate to good condition across water bodies, with the highest means observed in Uchkizil, Tudakul, and Zamonbobo. Meanwhile, mean Kn was ≈1.0 across stocks, indicating observed masses are consistent with expectations for individuals of a given length. Interpreting these indices requires nuance: K is sensitive to gonad mass (Le Cren, 1951; Barnham & Baxter, 1998; Gupta et al., 2010), hence March–April sampling (near the spawning period for temperate cyprinids) may elevate K in gravid females. By contrast, Kn adjusts for length-based expectations and is especially useful for comparisons among populations; values near unity indicate no systematic nutritional deficit.

The Aydar–Arnasay system (Aydarkul–Tuzkan–East Arnasay) provides a natural laboratory for disentangling hydrological and salinity effects. Elevated salinity (8–12‰ reported in recent years in Aydarkul and Tuzkan) has two main implications for freshwater cyprinids: (i) higher osmoregulatory costs that divert energy from somatic growth, and (ii) restructuring of lower trophic levels (phytoplankton/zooplankton) that can alter prey fields. The present results are consistent with these mechanisms: Aydarkul and Tuzkan show somewhat lower mean K than other water bodies, while East Arnasay, despite hydrological connectivity, exhibits negative allometry (b = 2.8052), consistent with leaner fish. Conversely, in freshwater-fed systems (e.g., Tudakul via the Amu–Bukhara Canal, Uchkizil in the Surkhandarya basin), higher K and b > 3 were observed in several cases, indicating favorable energy landscapes. These patterns echo cross-system observations that increased salinity and hydrological instability degrade condition in freshwater taxa even when populations remain abundant.

The spatial mosaic captured here–from small reservoirs (Uchkizil, 10.5 km²) to very large lakes (Aydarkul ≈ 3000 km²)–illuminates scale-dependent constraints on growth. Large, wind-exposed lakes typically exhibit stronger fetch, deeper mixing, and more heterogeneous plankton distributions, factors that can increase foraging costs for visual planktivores and zoobenthivores. In contrast, moderate-sized reservoirs with regular freshwater inflow often show more predictable nutrient balances and foraging grounds. Wider weight ranges in Uchkizil (29–320 g) and Tudakul (15–440 g) indicate multi-cohort representation and potentially stronger habitat heterogeneity, which can be beneficial by providing dietary niches and refugia for different size classes. Narrower maxima in Tuzkan and Karakir are consistent with either ecological constraints (e.g., salinity, turbidity) or more intensive exploitation shaping the upper tail of size distributions.

Because all samples were derived from commercial gill-net catches (mesh 16–50 mm), selectivity effects must be explicitly acknowledged. Gill nets disproportionately retain certain combinations of length and body depth; thus, stocks with deeper-bodied morphs may appear heavier at a given length solely due to gear interaction. Moreover, length selectivity narrows the effective size range used to fit LWRs; the exponent b is sensitive to the sampled length domain (Ricker, 1973). The high R^2 reported here reflect strong within-sample fit, but extrapolation beyond observed length ranges should be conservative. Confidence intervals for a and b, as reported, are informative, although formatting artifacts (e.g., negative values shown for the confidence limits of a in one table) require cautious interpretation. Future sampling should consider stratified designs (by habitat zone and season) and multi-gear panels to reduce selectivity bias and cover a fuller size spectrum.

Roach in Uzbekistan reach maturity at about two years (TL 10–11 cm; mass 30–45 g), with commercial catches dominated by ages 3–4. The March–April sampling coincides with pre-spawning / spawning for many regional cyprinids. Gonadal development increases total mass and can elevate K, especially in females. After spawning, post-ovulatory mass loss and energy reallocation to recovery can reduce K and temporarily depress Kn even when prey is adequate. This timing effect can generate cross-system variability if reproductive phenology is not perfectly synchronized among water bodies. Thus, while mean K and Kn indicate favorable conditions, seasonal panels would clarify the relative contributions of reproductive state versus trophic environment to the indices at each site.

Condition indices are emergent properties of food-web structure. Systems with abundant mesozooplankton (e.g., *Daphnia* spp.) and accessible benthos (chironomids, amphipods) favor energy accumulation. Conversely, shifts toward cyanobacteria-dominated phytoplankton or low-quality zooplankton depress fish condition. Habitat structure also matters: littoral macrophyte beds can harbor rich invertebrate communities that subsidize juveniles and subadults. If water-level fluctuations reduce macrophyte cover, the resulting loss of benthic prey and refuge can depress condition metrics. Relatively high K in Uchkizil and Tudakul is consistent with prey-rich, structurally diverse littoral zones, whereas lower K in Tuzkan and Aydarkul is compatible with plankton communities and salinity regimes that reduce prey quality/quantity. Although diet data were not collected, these mechanistic pathways are well supported in the literature (Bagenal & Tesch, 1978; Froese, 2006) and align with the observed indices.

The direction and magnitude of deviation from isometry (b ≠ 3) can diagnose environmental pressure. Slight negative allometry (b < 3) implies that length increases are not matched by proportional mass gains, consistent with elevated metabolic costs (osmoregulation in brackish water, high temperatures), suboptimal prey fields, or chronic disturbance. Slight positive allometry (b > 3) indicates energy surplus sufficient for mass accrual. Here, site-level divergence mirrors salinity and hydrological context: East Arnasay and Karakir skew leaner; Aydarkul and Tudakul skew heavier; Zamonbobo is close to isometric. Monitoring b through time thus offers a comprehensive, low-cost early-warning signal when coupled with environmental data (temperature, conductivity, nutrients) and fishery-effort records.

European and Russian studies report roach b values commonly between 2.8 and 3.3, with departures driven by trophic status, temperature, and life-history strategy. Contemporary b and K values in Uzbekistan fall squarely within this envelope. Higher b and K in some reservoirs match patterns from eutrophic or mesotrophic lakes with abundant prey. Negative allometry elsewhere echoes findings from habitats with lower trophic support or higher pollutants/salinity. This concordance suggests that despite the arid region's peculiarities (extreme summer heat, winter ice cover up to ~1.5 months, high evaporation), the species follows the general LWR rules documented elsewhere (Bagenal & Tesch, 1978; Froese, 2006; Verreycken et al., 2011; Kamaruddin et al., 2012; Dutta et al., 2021).

Projected warming and altered precipitation/inflow regimes in Central Asia may amplify stressors already implicit in the dataset. Higher summer temperatures shorten the window of thermal optimum, potentially curtailing feeding during peak heat and elevating metabolic costs. Increased evaporation without compensatory inflow raises salinity in closed or weakly flushed basins, compounding osmoregulatory burdens. Under such scenarios, we anticipate downward drift in K and Kn and more frequent b < 3 in vulnerable waters (especially large, interconnected lakes with limited freshwater renewal). Conversely, reservoirs with managed inflow (Tudakul, Uchkizil) may function as refugia where stable hydrology maintains favorable conditions.

Three applied recommendations emerge. First, embed LWR and condition indices in a standardized seasonal monitoring program. Sampling pre-spawn, post-spawn, and late summer will disentangle reproductive from trophic drivers of K and Kn. Second, pair fish condition metrics with environmental data (temperature profiles, conductivity / salinity, chlorophyll-a, zooplankton composition) and fishery effort to enable causal inference. Third, where salinity is increasing (Aydarkul, Tuzkan), prioritize freshwater inputs where feasible, manage water levels to maintain littoral habitat, and consider mesh-size regulation to reduce overharvest of 3–4-year cohorts. Because roach is short-cycled and resilient, adaptive management can quickly improve condition and size structure.

Strengths of this study include broad spatial coverage, consistent field methods, and convergent evidence from SL–TL and LWR models. Several limitations merit note: (i) gear selectivity and the absence of truly random sampling can bias size spectra and hence b estimates; incorporating multi-gear approaches (seines, electrofishing in littoral zones) would better represent small size classes; (ii) seasonal restriction to March–April may overrepresent pre-spawn condition; multi-season panels are recommended; (iii) confidence limits were provided for parameters, but their interpretation depends on data scale – future tables should ensure unit consistency and avoid formatting ambiguities; (iv) the lack of diet, age, and sex data limits mechanistic inference–otolith aging, gonadosomatic index (GSI), and gut-content/stable-isotope work would clarify drivers of among-site differences. These caveats do not undermine the main conclusions but outline priorities for follow-up.

Nationally, roach has shifted from incidental to a principal commercial component in several Uzbek water bodies since the 2000s. Reliable length-based conversions allow biomass estimation from length-frequency data, improving catch advice where weighing every fish is infeasible. Condition indices function as cost-effective sentinels of habitat change. Given that annual catches can reach 2–6 thousand tons in favorable years, maintaining quality (not just quantity) depends on environmental conditions that sustain $b \approx 3$ and $K \geq 1.2$. Where indices deteriorate, managers can adjust: reduce mesh size during vulnerable periods, safeguard inflows, restore littoral habitats, and coordinate water management across irrigation and fisheries sectors.

Taken together, the results indicate that roach populations in the lentic waters of Uzbekistan are generally in good condition and adapted to anthropogenically transformed ecosystems: isometric growth predominates, and K and Kn values support a stable energy balance. Deviations in particular water bodies align with salinity gradients and hydrological regime features, identifying actionable levers for sustaining productivity. Integrating the simple, informative tools used here–SL–TL regressions, LWRs, and the K and Kn indices–into an ecologically oriented monitoring system will enable early detection of unfavorable shifts and provide a practical basis for adaptive fishery regulation. When interpreting patterns, it is important to consider that interannual hydrology shapes cohort strength and can temporarily depress mean K via density-dependent competition; within-waterbody spatial heterogeneity (windward/leeward contrasts) reorganizes foraging fields and thus condition; and sustained selective harvest of deep-bodied morphs can trigger eco-evolutionary feedbacks that shift morphotype distributions over time. To elucidate habitat-use mechanisms, spatially explicit sampling (pelagic–littoral transects) should be combined with hydroacoustic surveys, and time series of b and K should be modeled as functions of conductivity and temperature to quantify thresholds beyond which deterioration becomes likely. Methodologically, regression diagnostics (residual analysis, tests for heteroscedasticity) should be standard; where variance increases with length, generalized least squares or variance-stabilizing transformations are appropriate. Comparisons of b among populations should be accompanied by confidence intervals and t-tests against the isometric expectation $b = 3$ (Froese, 2006). Finally, meta-analytic approaches pooling years and sites improve precision and sensitivity to subtle trends, which is critical for management decisions in large multipurpose basins.

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