

Article

Sex Ratio Variation and Environmental Correlates in *Aphaniops* spp. Across the Wadi Systems of Northern Oman: A Preliminary Conservation Assessment

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Abstract

Sex ratio skew in wild fish populations may indicate environmental stress; however, this remains poorly understood in Omani wadi-endemic killifish. This study investigates sex ratio variation, environmental correlates, sexual dimorphism, and conservation implications in *Aphaniops* spp. across seven wadi sites in northern Oman. A total of 1417 individuals were collected in spring 2023, while 30 physicochemical variables were recorded over five seasons from spring 2022 to spring 2023. The pooled sex ratio was strongly female-biased (73.4% female; $\chi^2 = 310.21$, $p < 0.001$), with six sites deviating significantly from 1:1. Males were longer than females ($t = 3.94$, $p < 0.001$). Dissolved potassium was the strongest negative associate of the proportion of males ($\beta = -0.455$, OR = 0.635, $p < 0.001$), followed by turbidity ($\beta = +0.232$, $p = 0.005$) and depth ($\beta = +0.244$, $p = 0.006$); all associations are exploratory and do not establish causation. These findings suggest that dissolved potassium is associated with sex ratio variation in *Aphaniops* spp., and highlight Wadi Al Amirat as a priority site, five wadis as watch sites, and Wadi Surur as a baseline site (non-significant sex ratio only; not indicative of undisturbed reference conditions) for conservation.

Keywords: killifish; environmentally mediated sex ratio; dissolved potassium; hydrochemistry; conservation prioritization; Arabian Peninsula



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Key Contribution: This study documents a strong female-biased sex ratio in Omani wadi-endemic *Aphaniops* spp. and shows that dissolved potassium, turbidity, and depth are the strongest environmental correlates, though all associations are exploratory. It provides a preliminary conservation screening framework by identifying priority, watch, and baseline wadi sites.

1. Introduction

Sex ratio is an essential demographic parameter for population reproduction and recruitment [1] and although it ideally averages 1:1 at birth in the wild, most populations

differ from the baseline. Differences in sex-specific mortality, predation rates that exploit sex-specific traits, and the direct effects of environmental conditions that alter the developmental pathway can shift the observed sex ratio away from unity [2,3]. In freshwater systems, hydrological permanence, physical habitat structure, and chemical quality act as severe ecological filters that shift community composition and constrain available life histories [4,5]. Cyprinodontoids are characterized by their extreme tolerance to salt and heat, which, in turn, determines whether populations survive or perish when exposed to extreme chemical conditions [6,7].

Across a variety of Cyprinodontiformes, female biases have been reported among both non-annual and annual killifishes [8,9]. Skewed female-bias adults are not indicative of environmental degradation, but a natural result of high mortality among males [3,10]. As these are the dominant gender in a population, they dictate downstream population reproductive output and impact the food web of that particular ecosystem [11]. This sex ratio phenomenon is common in freshwater Aphaniidae across the arid landscapes of the Middle East, where studies of *Aphanius persicus* revealed female-biased cohorts in the Iranian River system, with sex ratios as low as 1:1.7 (males:females) [12]. Similarly, *Aphanius dispar dispar* was found to exhibit female-biased ratios in Iranian Rivers, with a 3:1 female:male dominance [13].

In intermittent river systems characterized by ephemeral flow regimes, non-perennial river networks, and intermittently occurring streams, extreme population isolation and bottlenecks occur. These events increase local mortality rates associated with reduced water quality and fragmentation of aquatic habitats [14,15]. Additionally, physical disturbances have been shown to induce varying levels of vulnerability by gender, increasing the likelihood of skewed population demographics [16]. Sex ratios among species within the Cyprinodontiformes are generally considered dynamic responses to changes in the environment; for example, the non-annual killifish, *Atlantirivulus riograndensis*, exhibits pronounced female biases within specific wetland habitats [8], while sex ratios in guppy populations exhibit fluctuations as a result of changes in environmental selective pressure [9].

These demographic fluctuations are further facilitated by the reproductive plasticity of teleost fishes, which possess sex-determination systems operating on a complex spectrum from strict Genotypic Sex Determination (GSD) to Environmental Sex Determination (ESD) [17–20]. Many fish possess “labile” genotypic systems; the effects of environmental parameters, such as high temperature and changes in dissolved ionic concentrations, can outweigh genetic effects during sensitive ontogenetic stages [21]. In Oman’s arid wadis, extreme summertime temperatures (often above 40 °C) promote rapid evaporation [22]. Water salinity consequently spikes downstream within the wadi bed [23], and these steep chemical gradients, together with labile sex determination, offer an environmental basis for shifting the sex ratio in wild fish populations.

Wadi networks in arid and semi-arid areas typically provide the only permanent source of freshwater for many aquatic species. These small bodies of water can harbor disproportionate amounts of biodiversity relative to their total water surface area [24]. As one of the driest places on earth, the Arabian Peninsula experiences growing environmental stress due to increased levels of extraction of groundwater, climate change, and saltwater intrusion into previously freshwater sources [25–30]. These compounding stressors directly threaten localized aquatic habitats, driving predicted contraction of ranges of native freshwater species [31–33]. Consequently, freshwater biodiversity in these hyper-arid zones faces several serious threats resulting from multiple interacting factors, and the wadi ecosystems of the Arabian Peninsula are among the highest-risk globally [24,28].

The Hajar Mountains in northern Oman are recognized as an important zone of localized endemism, within an arid-zone freshwater ecoregion [34]. These mountain ranges

contain endemic populations of fish and invertebrates whose distribution is shaped by geological variability, the frequency and duration of hydrologic events, and the specific ionic composition of spring-fed watercourses [23,35,36]. New systematic monitoring work, together with updated lists of fishes of the Arabian Peninsula, documents the complete native freshwater ichthyofauna of Oman, including local species of Aphaniidae [37,38]. The Hajar Mountains receive scant annual rainfall of 100–150 mm, making its wadi flow sensitive to even extreme climate variations [22]. Since the rocks composing specific catchment basins determine the inherent chemical characteristics of such streams, it is possible to recognize a given wadi in different locations by its unique background chemistry [23].

The family Aphaniidae is among the most important ecological elements of the Middle East's freshwater fish fauna [39,40]. Killifishes are characterized by flexible life-history strategies that enable them to adapt to variable physicochemical stressors, such as extreme high temperatures or hyper-salinity [39]. Moreover, due to their high degree of endemism and sensitivity to environmental changes, killifish serve as ideal indicators of diversity trends and conservation practices in fragmented habitats [32,39]. Freshwater systems of the Middle East are particularly susceptible to concurrent stressors; thus, it is imperative to develop baseline ecological studies of endemic killifish populations for future conservation efforts [24].

The genus *Aphaniops* recently revised [41] includes *Aphaniops kruppi*, which was originally identified as being part of the fauna of Oman's wadi systems [42], and *Aphaniops stoliczkanus*, whose variable phenotypes were demonstrated in northern Omani habitats by Bidaye et al. [43]. All species exhibit pronounced sexual dimorphism in coloration, fin shape, and body morphometrics [44,45]. Although the relationships between body size and weight parameters and their condition factors for populations of *Aphaniops* at all seven wadi sites in the present study are newly described [46], the patterns and determinants of sex ratios across spatial gradients remain completely unexplored in Omani freshwater fish species. This study represents the first comprehensive investigation of sex ratio ecology for any freshwater fish species in the region. Five formal hypotheses regarding how the sex ratio varies among locations relative to local habitat conditions are evaluated and outlined in the analytical framework (Table 1).

Table 1. Analytical framework: study hypotheses, objectives, and statistical methods for sex ratio variation in *Aphaniops* spp., across northern Omani wadi systems.

Hyp.	Hypothesis	Objective	Statistical Method
H1	Sex ratios will deviate significantly from the expected 1:1 ratio at one or more wadi sites, and the pooled sex ratio will show a significant female bias, suggesting a regional demographic pattern associated with localized habitat conditions [8,10].	Evaluate whether spatial variation in sex ratio reflects localized habitat conditions across wadi sites and assess the overall population-level sex ratio pattern.	Chi-square goodness-of-fit with Yates continuity correction per site; chi-square goodness-of-fit on pooled counts; Bonferroni correction ($\alpha/7 = 0.007$) for multiple comparisons.
H2	Specific water quality parameters will show statistically significant associations with the proportion of males, consistent with an environmentally mediated sex ratio response [17].	Identify environmental predictors of sex ratio variation and link site-level conditions to observed biases.	Binomial GLM (logit link; site-level proportions as response; $n = 7$ independent environmental units); Pearson correlation; biological variable selection + VIF screening.

Table 1. Cont.

Hyp.	Hypothesis	Objective	Statistical Method
H3	Significant sexual dimorphism in total length and body weight will be detectable between sexes [47,48].	Assess sexual dimorphism in body size traits and body condition across sites.	Shapiro–Wilk normality assessment (supplemented by visual inspection of size-frequency histograms [SF1] and Q-Q plots [SF3]); Wilcoxon rank-sum or Welch <i>t</i> -test; one-way ANOVA with Tukey HSD; Kruskal–Wallis with Dunn post-hoc; Cohen’s <i>d</i> effect size; Fulton’s condition factor (Kc) with two-way ANOVA and Wilcoxon within-site sex comparisons (Table S3 and Figure S5).
H4	Wadi sites will form distinct environmental clusters based on their hydrochemical profiles, which will correlate with specific fish population structures [43].	Characterize environmental gradients and group sites into ecologically coherent clusters.	PCA; hierarchical clustering (Ward’s D ² method); Kruskal–Wallis and ANOVA on all 30 variables (full results in Supplementary Table S1).
H5	Sites with the most extreme environmental conditions (e.g., highest salinity) will exhibit the most skewed sex ratios, identifying them as priority areas for conservation monitoring [21].	Identify priority wadis for conservation monitoring using a preliminary stress severity scoring framework.	Conservation cross-tabulation: significantly skewed sites × GLM-significant predictors × spring 2023 deviation from five-season site mean ± SD; composite stress score (high ≥ 1 SD: score 2; moderate: score 1); classes: priority ≥ 5, watch 3–4, baseline (sex ratio ns).

GLM = generalized linear model; PCA = principal component analysis; VIF = variance inflation factor; SD, standard deviation; Kc, Fulton’s condition factor; ns, not significant.

2. Materials and Methods

2.1. Study Site and Fish Sampling

Fish sampling occurred during spring 2023 at seven wadi systems in the Ad Dakhiliyah and Muscat governorates of northern Oman: Ain Wadhah (AW; 22.991 °N, 57.293 °E), Wadi Al Amirat (WAA; 23.540 °N, 58.514 °E), Wadi Aday (WA; 23.589 °N, 58.523 °E), Wadi Darsait (WD; 23.620 °N, 58.540 °E), Wadi Al Khoud (WAK; 23.576 °N, 58.118 °E), Wadi Fanja (WF; 23.458 °N, 58.107 °E), and Wadi Surur (WS; 23.378 °N, 58.105 °E). The geographic distribution of these sites is shown in Figure 1. These sites are part of the Oman Mountain freshwater ecoregion, a geographically isolated zone where endemic fish and invertebrate communities are shaped by high geological variability and localized hydrological intermittency [34–36]. Chemical properties of water in arid environments are controlled primarily by the geology of the drainage basin and by intermittent discharges of perched wadis aquifers whose chemical composition remains relatively constant throughout the year despite variable amounts of annual rainfall [23,49].

Fish were captured using foldable shrimp and crab fishing traps (3 × 3 mm mesh, four nets per site) left in the watercourse for a standardized soak time of approximately five hours [32,46]. All species were grouped together as *Aphaniops* spp. due to reported hybrids from *A. kruppi* and *A. stoliczkanus* haplotypes found at some locations in northern Oman [43,46,50]. Genetic evidence of ongoing hybridization at several sites makes species-level assignment unreliable [43,50]; any species-level differences in sex ratio response cannot be resolved with the current dataset and represent a priority for future investigation. The sex was determined by visual identification of the specimen based on the presence or

absence of the dimorphic patterns of coloration and fins that are typical of members of the family Aphaniidae [44,45]. Visual sexing is reliable in this family, owing to its pronounced and stable sexual dichromatism and dimorphism, as documented by Herbert Mainero et al. [45]. For each specimen, total length (TL, to 0.01 mm) and body weight (BW, to 0.01 g) were recorded using a digital caliper (INSIZE Caliper 300 MM, INSIZE, Suzhou, China), and a digital electronic balance (Precisa PB 320M Analytical Laboratory Balance, Precisa, Dietikon, Switzerland), respectively.

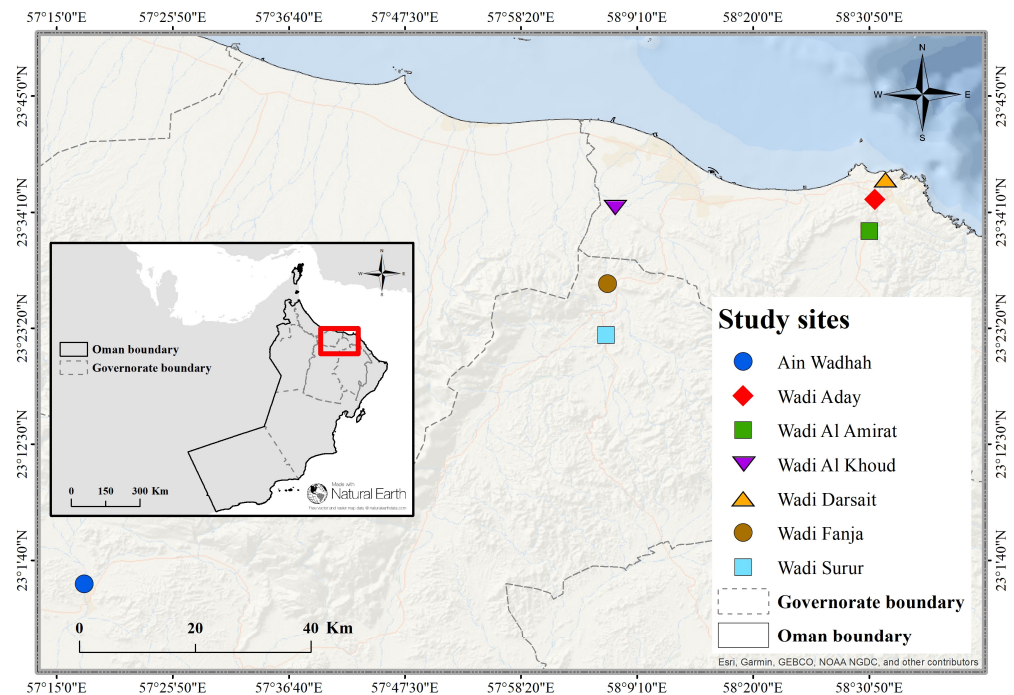


Figure 1. Spatial distribution of sampling locations across seven wadis in northern Oman. Here, the inset map shows the location of the study area (red outline) within Oman, situated across the Muscat and Ad Dakhiliyah governorates.

Foldable traps may introduce sex-specific capture bias if males and females differ in microhabitat use, activity level, or behavioral response to trap mesh; observed sex ratios should therefore be interpreted as relative rather than absolute estimates of population sex composition. The spring time was selected for sampling to ensure consistent thermal conditions (mean $\pm$ SD = 28.0 ± 1.5 °C) and low turbidity (mean $\pm$ SD = 1.9 ± 0.9 NTU), thus avoiding the unsuspected influences of the region's extreme summer heat and cyclone-induced rainfall events [22,51]. By sampling during a period of stable flow and thermal conditions, this study provides a representative 'snapshot' of these population structures under chronic regimes [52]. The total sample size offers high statistical power, comparable to other peer-reviewed demographic studies with 100–1000 fish in their respective samples [53–57].

2.2. Environmental Variable Selection

Thirty physicochemical parameters spanning five categories: physical hydrology (depth, width, velocity); thermal and chemical conditions (water temperature, pH, DO, electrical conductivity, TDS, salinity, and turbidity); organic load indicators (BOD, COD, TOC, TSS, and total solids); macronutrients and major ions (sulfate, magnesium, calcium, sodium, potassium, and total hardness); and trace metals and nutrient cycling parameters (nitrite, nitrate, ammonia, phosphate, iron, boron, manganese, copper, and aluminum) were analyzed quarterly at each site for five seasons (from spring 2022 to spring 2023).

Measurements were taken from replicated field readings at each site in each season (water depth: $n = 10$, channel width: $n = 5$, water quality parameters: $n = 3$). Measurements were made using established protocols [58]. Spring 2023 values were complete for all 30 variables and were used exclusively for GLM and multivariate analyses. Because of issues managing site sampling schedules and the associated distances between sampling locations, Wadi Al Khoud was always sampled at the same times between 12:00 and 14:30 over the five seasons during which it was sampled; thus, temperatures reported for this site could potentially represent afternoon solar heating conditions more than the mean daytime temperature, and comparisons between Wadi Al Khoud temperatures and those from the remaining six sampling regions should reflect this fact. On the other hand, Wadi Surur was sampled between 09:30 a.m. and 10:50 a.m. across all five seasons, confirming that measurements at this site reflect pre-noon ambient conditions.

2.3. Sex Ratio Analysis

Sex ratios were quantified as the proportion of males at each sampling site and across the pooled dataset (H1). Departures from the expected 1:1 ratio were evaluated per site using a Yates-corrected chi-squared goodness-of-fit test ($n \geq 20$, both sexes ≥ 5) or an exact binomial test. Full summary statistics were calculated for each site, for each sex, and for each site-by-sex combination.

2.4. Sexual Dimorphism

To address H3, length and weight differences between sexes were analyzed using a normality-guided adaptive framework [59]: normality was assessed visually using size-frequency histograms (Supplementary Figure S1) and Q-Q plots (Supplementary Figure S3); non-parametric tests were applied throughout regardless of formal Shapiro–Wilk outcomes given the sensitivity of the test at large sample sizes. A Welch t -test or Wilcoxon rank-sum test was used as appropriate, followed by one-way ANOVA with Tukey HSD post-hoc comparisons was used for site-level body size differences; Kruskal–Wallis tests with Dunn’s post-hoc (Bonferroni correction) were applied as non-parametric complements. Length–weight relationship (LWR) parameters by sex and site are presented in Supplementary Table S2, and body condition (Fulton’s K_c) is summarized in Supplementary Table S3 and Figure S5.

2.5. Variable Standardization and Multicollinearity Screening

All 30 spring 2023 variables screened at three separate levels to determine a parsimonious, non-collinear predictor set for the GLM (H2). Full details of the variable selection procedure, including biological grouping rationale, cross-correlation screening results, and VIF values for all 30 variables, are available from the corresponding author upon request. (i) Biological grouping into six clear groups, with one representative within each group was retained per correlated pair ($|r| > 0.70$); (ii) removal of cross-group pairwise collinear pairs ($|r| > 0.70$); (iii) applying an iterative variance inflation factor (VIF) method for filtering the predictors using `usdm::vifstep()`, ([60]; VIF threshold = 5) to retain only those with low multicollinearity. The final five predictors selected through this process were: electrical conductivity (EC), calcium (Ca), potassium (K), turbidity, and depth (all VIF ranged from 1.18 to 1.50).

2.6. Binomial Generalized Linear Model

To address H2, a generalized linear model (GLM) with a binomial distribution and a logit link function [61] was used. Site-level proportions of males were modelled as the response variable, with $n = 7$ sites constituting the independent environmental replicates. The individual fish count does not increase the number of independent environmental units, as fish within the same wadi share identical environmental conditions. Five standardized

predictors were fitted, resulting in one residual degree of freedom; the model is therefore near-saturated, and all results should be interpreted as exploratory associations rather than definitive causal relationships. Predictors were standardized to a mean of 0 and a variance of 1 prior to fitting. Dispersion was checked and confirmed acceptable. Using the broom package [62], the model fit estimates were obtained, including the standardized regression coefficient, the odds ratio ($OR = \exp(b)$), the 95% Wald confidence intervals, and the associated p -value. Associations identified in this model, including the link between potassium and sex ratio, are statistical in nature and should be interpreted as speculative until confirmed by experimental validation; no causal mechanism is established from this analysis alone.

2.7. Multivariate Environmental Analysis

To address H4, principal component analysis (PCA; [63]), as well as hierarchical clustering analysis (Euclidean distance, Ward's D2 linkage; [64,65]), were applied to the standardized data for the 5 spring 2023 VIF selected variables. The optimal number of clusters from the k-means elbow plot were used to determine cluster number. Kruskal–Wallis tests with Dunn's post-hoc (Bonferroni corrected) were applied to all 30 variables across site and season grouping factors, with each observation representing the mean of replicated field measurements per site per season.

2.8. Conservation Cross-Tabulation

To address H5, sites with significantly skewed sex ratios were compared to the three GLM-significant predictors (potassium, turbidity, depth) by expressing each site's spring 2023 value as a deviation from its five-season mean $\pm$ SD. Then the predictors of high (>1 SD) and moderate (within range) classification were used to develop a composite stress severity score ($(2 \times \text{high}) + (1 \times \text{moderate})$), which was then used to assign the sites to conservation prioritization classes; baseline = (0), watch site = (3–4), priority site (≥ 5). This constitutes a preliminary conservation screening framework intended to generate hypotheses for targeted monitoring; thresholds are operationally defined within this study and require independent validation before formal management application. We acknowledge that the predictors used in this scoring are the same variables identified as GLM-significant correlates, introducing a degree of circularity; scores should be interpreted as indicative only. The 'Baseline' designation for Wadi Surur refers to the non-significant sex ratio deviation only and does not imply undisturbed reference conditions.

2.9. Statistical Software

All analyses were conducted in R version 4.4.3 [66] using the tidyverse, car, rstatix, usdm, FactoMineR, factoextra, broom, dunn.test, and openxlsx packages. Figures were produced with ggplot2 version 4.0.1 [67]. Statistical significance was set at $\alpha = 0.05$.

3. Results

3.1. Sex Ratios by Site and Overall (H1)

A total of 1417 individuals of *Aphaniops* spp. were collected: 377 males (26.6%) and 1040 females (73.4%). The pooled ratio was skewed toward females ($\chi^2 = 310.21$, $p < 0.001$, proportion male = 0.266, M:F = 0.363). All sites except Wadi Surur showed skewed sex ratios (all $p < 0.001$, Table 2 and Supplementary Figure S2). The largest skew occurred at Wadi Darsait (proportion male = 0.211, M:F = 0.268); the strongest statistical signal was at Wadi Al Amirat ($\chi^2 = 112.02$, $p < 0.001$), which also had the largest sample size ($n = 405$). The corrected Wadi Aday values ($n = 192$, M = 39, F = 153, proportion male = 0.203, $\chi^2 = 67.69$) reflect a data entry error identified during revision in which Wadi Aday measurements had

been duplicated; all downstream analyses use the corrected dataset. Wadi Surur was the only site where the sex ratio was not statistically different from 1:1 (proportion male = 0.427; $\chi^2 = 3.23$, $p = 0.072$). All six significantly skewed sites retained $p < 0.001$ after Bonferroni correction ($\alpha/7 = 0.007$; Table 2). Adult sex ratios are determined through the accumulation of various factors—for instance, history of recruitment, variation of mortality between sexes, seasonal movement, and gear catch selectivity—and should not be used as direct evidence of sex determination but should be interpreted with caution.

Table 2. Sex ratio results for *Aphaniops* spp. at seven wadi sites in northern Oman (spring 2023) and pooled across all sites.

Site	Males	Females	Total	Prop. Male	M:F Ratio	χ^2 (Yates)	p -Value	Bonferroni p
Ain Wadhah	45	107	152	0.296	0.421	25.29	<0.001 ***	<0.001 ***
Wadi Al Amirat	96	309	405	0.237	0.311	112.02	<0.001 ***	<0.001 ***
Wadi Aday	39	153	192	0.203	0.255	67.69	<0.001 ***	<0.001 ***
Wadi Darsait	42	157	199	0.211	0.268	66.46	<0.001 ***	<0.001 ***
Wadi Al Khoud	60	124	184	0.326	0.484	22.26	<0.001 ***	<0.001 ***
Wadi Fanja	31	104	135	0.230	0.298	39.47	<0.001 ***	<0.001 ***
Wadi Surur	64	86	150	0.427	0.744	3.23	0.0724 (ns)	0.507 (ns)
All sites (pooled)	377	1040	1417	0.266	0.363	310.21	<0.001 ***	—

Here, Test: Yates-corrected chi-square (all sites $n \geq 20$). Bonferroni-corrected p -values ($\alpha/7 = 0.007$). *** $p < 0.001$; ns, not significant. All significant deviations are female-biased (proportion male < 0.50). Pooled row represents a single test; Bonferroni correction is not applied.

3.2. Fish Morphometrics and Sexual Dimorphism (H3)

Both body weight and total length were non-normally distributed; normality was assessed visually using size-frequency histograms (Supplementary Figure S1) and Q-Q plots (Supplementary Figure S3). Total length of males was greater than females pooled across all sampling sites (males 4.07 ± 0.72 cm; females 3.91 ± 0.80 cm; mean difference 0.158 cm, 95% CI 0.069–0.252 cm; $t = 3.44$, $df = 1415$, $p < 0.001$; Wilcoxon $W = 179,687$, $p = 0.016$). The Cohen's d effect size was $d = 0.21$ (small effect), indicating that while the difference is statistically significant, the biological magnitude is modest. No significant difference was observed in the mean body weight of males and females across all sites ($t = 1.610$, $p = 0.108$; Figure 2). Body condition (Fulton's K_c) varied significantly among sites (Kruskal–Wallis $H_6 = 326.74$, $p < 0.001$), with Wadi Al Amirat showing the highest mean condition (K_c = females: 1.905 ± 0.313 , males: 1.853 ± 0.244) and Wadi Al Khoud the lowest (K_c = females: 1.539 ± 0.188 , males: 1.564 ± 0.169); sex-specific differences in K_c were detected only at Wadi Fanja (females > males, Wilcoxon $p = 0.008$) and Wadi Darsait (males > females, $p = 0.019$), with no significant sex difference at the remaining five sites (full statistics in Supplementary Table S3 and Figure S5).

Significant variation was found in both total length and body weight between sampling sites (ANOVA: $F = 74.8$ and $F = 69.1$, $p < 0.001$ for both; KW: $\chi^2 = 297.4$ and 244.3 , $p < 0.001$ for both). Wadi Fanja had the largest individuals among all the samples collected (mean length 4.95 ± 0.62 cm, mean weight 2.26 ± 0.83 g), differing from all other sites in both traits (Tukey HSD, all $p < 0.001$). Wadi Darsait had the lowest mean length (3.56 ± 1.07 cm) and the greatest size variability ($CV = 30\%$). These differences in size across sites support their distinct environmental cluster membership (Section 3.3). Figure 2 presents dodged side-by-side boxplots representing the distribution of total length for females (salmon) and

males (steel blue) in each of the surveyed Wadis, with Tukey HSD group designations (letters) plotted on top of the site data. Wadi Fanja (group d) is larger than all others ($p < 0.001$ for all), while Wadi Darsait (group a) is the smallest. Within-site comparisons of length frequencies for males and females are illustrated in overlapping histograms using a seven-panel facet grid in Supplementary Figure S1.

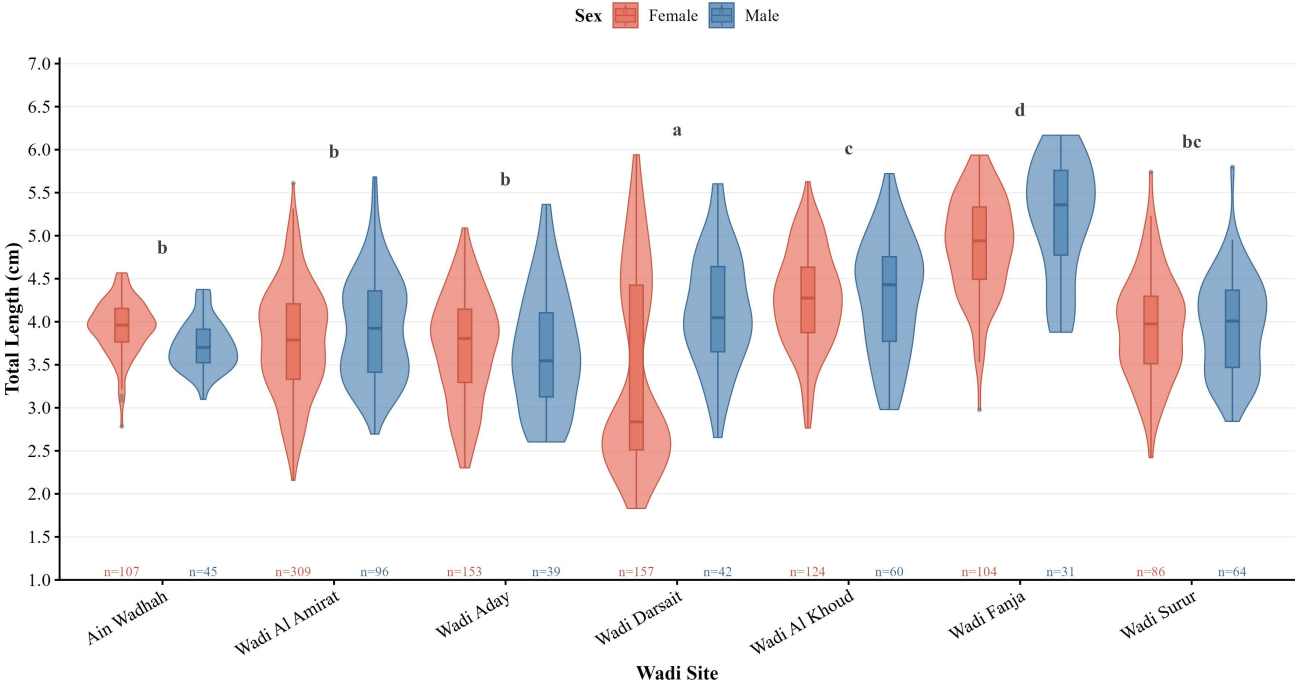


Figure 2. Sexual size dimorphism (total length) at seven sites in northern Oman (spring 2023). Here, Violins show the kernel density distribution of total length (cm) for females (salmon) and males (steel blue) at each site; violin width reflects the relative frequency of observations. Inner boxes show median and interquartile range (IQR); whiskers extend to $1.5 \times \text{IQR}$. Sample sizes (n) are shown below each violin pair. Compact letter display (CLD) above each site summarizes Tukey HSD pairwise comparisons of site-level total length (sexes pooled; $\alpha = 0.05$). CLD groups: a = Wadi Darsait (smallest); b = Wadi Al Amirat, Wadi Aday, Ain Wadhah; bc = Wadi Surur; c = Wadi Al Khoud; d = Wadi Fanja (significantly larger than all other sites, all $p < 0.001$). Site-level means and standard deviations are given in Table 3.

Table 3. Five-season summary statistics (mean $\pm$ SD) for the five VIF-selected environmental predictors at seven wadi sites in northern Oman, with environmental cluster assignments.

Site	Ca (mg/L)	Depth (cm)	EC ($\mu\text{S}/\text{cm}$)	K (mg/L)	Turbidity (NTU)	Cluster
Ain Wadhah	35.4 $\pm$ 21.1	63.6 $\pm$ 12.4	692.4 $\pm$ 191.9	11.8 $\pm$ 7.2	4.5 $\pm$ 2.9	1
Wadi Al Amirat	94.3 $\pm$ 40.1	57.2 $\pm$ 9.03	2132.5 $\pm$ 56.8	21.8 $\pm$ 1.9	1.9 $\pm$ 0.7	2
Wadi Aday	58.3 $\pm$ 23.3	47.8 $\pm$ 13.6	2176.1 $\pm$ 155.4	24.3 $\pm$ 9.1	4.4 $\pm$ 2.5	3
Wadi Darsait	37.1 $\pm$ 22.8	38.9 $\pm$ 9.8	1628.7 $\pm$ 68.2	16.4 $\pm$ 3.2	6.5 $\pm$ 5.1	1
Wadi Al Khoud	23.9 $\pm$ 5.3	80.0 $\pm$ 17.6	2505.5 $\pm$ 153.1	12.8 $\pm$ 3.0	3.7 $\pm$ 3.6	2
Wadi Fanja	32.1 $\pm$ 7.7	27.7 $\pm$ 7.3	2173.6 $\pm$ 125.7	12.4 $\pm$ 2.3	140.0 $\pm$ 275.8	1
Wadi Surur	47.7 $\pm$ 26.1	24.7 $\pm$ 4.5	1770.3 $\pm$ 401.7	11.1 $\pm$ 2.8	20.0 $\pm$ 31.8	1
KW p -value	*	***	***	**	ns	

Here, Cluster assignments from hierarchical cluster analysis ($k = 3$). KW p -value row shows Kruskal–Wallis significance for between-site differences. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns = not significant.

3.3. Environmental Characterization (H4)

The five-season sample shows strong and spatially distinct environmental gradients in most sampled predictor variables (Table 3). Electrical conductivity at Ain Wadhah was minimal, at only 692 $\mu\text{S}/\text{cm}$ compared to the highest of 2506 $\mu\text{S}/\text{cm}$ at Wadi Al Khoud (KW $\chi^2 = 29.9$, $p < 0.001$). In addition, Wadi Al Khoud had the greatest depth (80.0 ± 17.6 cm; KW $\chi^2 = 26.4$, $p < 0.001$). Significant variations in potassium were reported among sites (KW $p = 0.003$), with the highest concentrations at Wadi Aday (24.3 mg/L) and Wadi Al Amirat (21.8 mg/L). Turbidity varied significantly by season (KW $p = 0.0003$) but not significantly among sites (KW $p = 0.477$); Wadi Fanja showed the greatest seasonal variability (140.0 ± 275.8 NTU), while all sites recorded low turbidity in spring 2023 (range 0.9–3.3 NTU). Of the 30 recorded environmental variables, 18 differed between sites (KW, $p < 0.05$), whereas 8 differed by season (Kruskal–Wallis $p < 0.05$; full results in Supplementary Table S1). Seasonally varying variables included primarily temperature, turbidity, nitrate, ammonia, phosphate, iron, and aluminum; most ionic variables remained stable across seasons, reflecting the geochemical consistency of the perched wadi aquifers. The boxplots showing all 30 parameters across sites and seasons are in Supplementary Figures S6 and S7. Figure 3 directly contrasts these two variables: Figure 3A shows that each site's potassium trace is nearly flat across all five seasons (ionic stability), while Figure 3B shows a distinct seasonal temperature arch peaking in summer 2022 (Wadi Surur = 40.0 °C) before recovering by spring 2023.

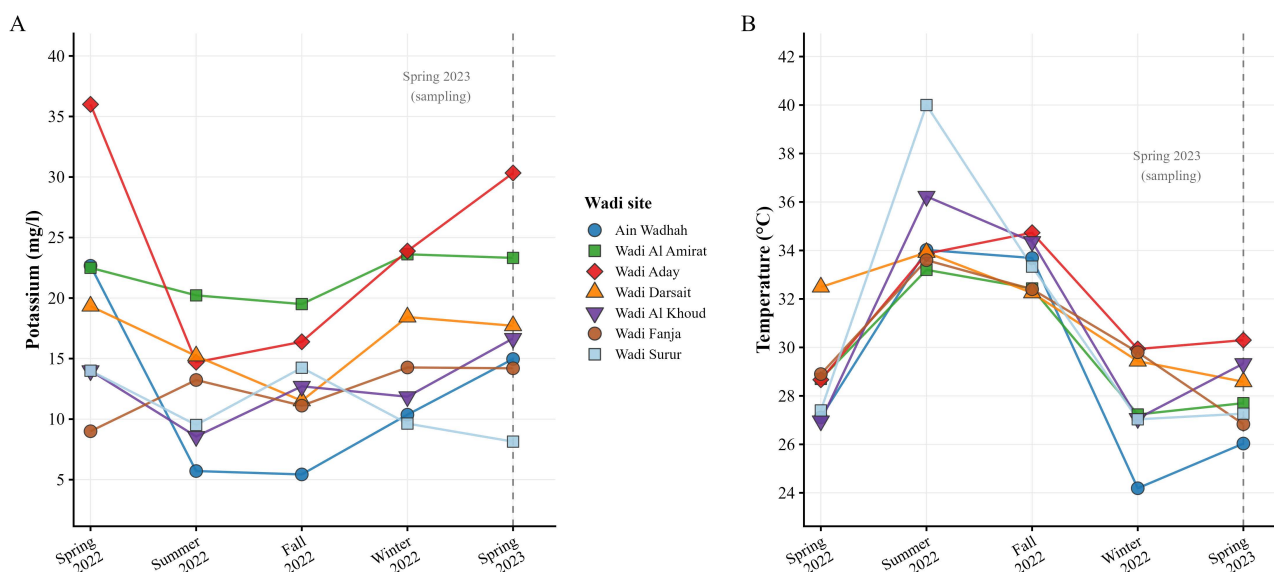


Figure 3. Seasonal stability of dissolved K^+ vs. variability of water temperature across five seasons (spring 2022–spring 2023). Here, Panel (A): K^+ nearly flat across seasons (KW $p = 0.336$). Panel (B): temperature shows strong seasonal cycle (KW $p < 0.001$). Vertical dashed line = spring 2023 (fish sampling).

Principal component analysis (PCA) of the five spring 2023 selected variables indicates that PC1 accounted for 36.1% of the total variance (eigenvalue = 1.81), while PC2 accounted for 28.2% of the total variance (eigenvalue = 1.41). In total, the first three components accounted for 81.2% of the total variance. PC1 represented ionic strength and habitat permanence, electrical conductivity ($\lambda = 0.583$) and depth ($\lambda = 0.506$) had positive scores, while turbidity ($\lambda = -0.417$) had a negative score. PC2 represented ionic composition gradient: potassium had a strongly negative loading ($\lambda = -0.611$) and calcium had a positive score ($\lambda = 0.461$). Three different environmental site clusters were created by hierarchical clustering with Ward's D2 method ($k = 3$): Cluster 1 (Ain Wadhah, Wadi

Darsait, Wadi Surur, Wadi Fanja), Cluster 2 (Wadi Al Amirat, Wadi Al Khoud) and Cluster 3 (Wadi Aday). A PCA biplot with the clusters indicated is displayed in Figure 4 and the dendrogram generated from this clustering is in Figure 5. As clearly observed in Figure 4, Wadi Aday stands apart from all of the other locations in PC2 because of its highest potassium score, while Ain Wadhah is distinguished from the remaining sites along PC1 by its markedly lower electrical conductivity.

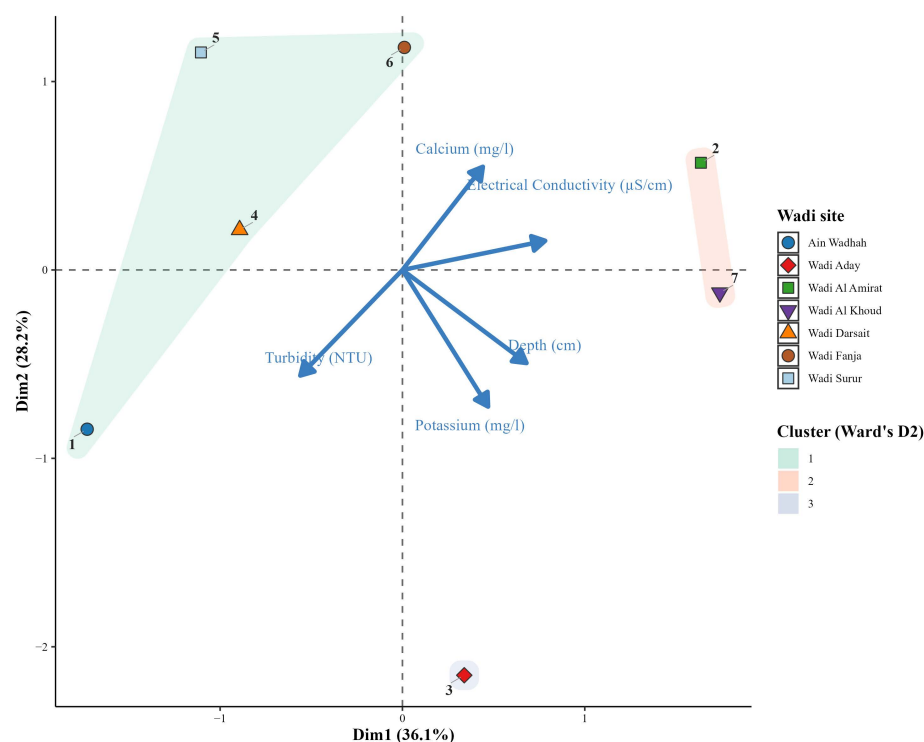


Figure 4. Environmental gradients among seven wadi sites in northern Oman: PCA biplot of five VIF-selected physicochemical predictors (spring 2023) with hierarchical cluster overlay (Ward's D2, $k = 3$). Here, numbered points (1–7) correspond to sites identified in the legend; arrows show predictor loadings, with direction and length indicating association strength with each axis. Shaded regions denote the three clusters. Dim1 and Dim2 explain 36.1% and 28.2% of variance, respectively (64.3% cumulative).

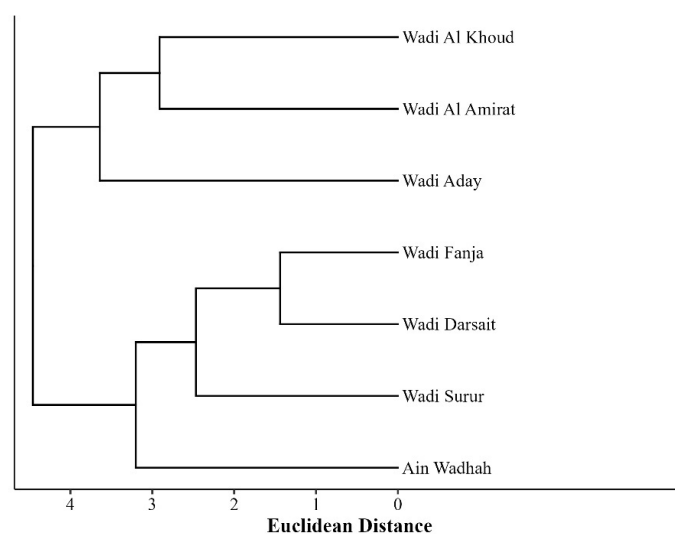


Figure 5. Hierarchical clustering (Ward's D2, Euclidean distance) of seven sites in northern Oman based on five physicochemical variables (spring 2023).

3.4. Environmental Predictors of Sex Ratio (H1 and H2)

In the bivariate analysis, potassium showed the strongest association with the proportion of males ($r = -0.736$; $n = 7$ sites, $p = 0.059$; Figure 6); This bivariate p -value reflects the limited statistical power inherent in a sample size of 7 and does not contradict the GLM outcome, since the two tests are applied at distinct analytical scales. Turbidity showed a weaker positive association ($r = 0.174$). We found a near-zero correlation coefficient ($r = -0.032$) for depth despite the variable's significance in the multivariate GLM ($p = 0.006$); whether this divergence represents a genuine suppressor effect or a statistical artefact of the near-saturated model structure cannot be resolved with the present data and should be treated with caution [68]. The binomial GLM showed no overdispersion (residual deviance = 0.134, $df = 1$). With $n = 7$ sites and five predictors, the model has only one residual degree of freedom; results are exploratory. Given the model's near-saturated structure (1 residual df), all coefficient estimates should be treated as indicative only. Potassium was the dominant negative associate ($\beta = -0.455$ OR = 0.635, $p < 0.001$, Δ odds = -36.5%). Turbidity was the strongest positive associate ($\beta = +0.232$, OR = 1.261, $p = 0.005$), and depth also showed a significant positive association ($\beta = +0.244$, OR = 1.276, $p = 0.006$). Electrical conductivity (EC) and calcium did not influence male sex ratio, and our *Aphaniops* spp. Indicator is specific to wadi environments. We present standardized GLM estimates with 95% confidence intervals in Figure 7. The bivariate relationship is shown in Figure 6 (Pearson $r = -0.736$, $p = 0.059$, descriptive only; inferential test for the potassium effect is the Wald z -test in Table 4 ($p < 0.001$)).

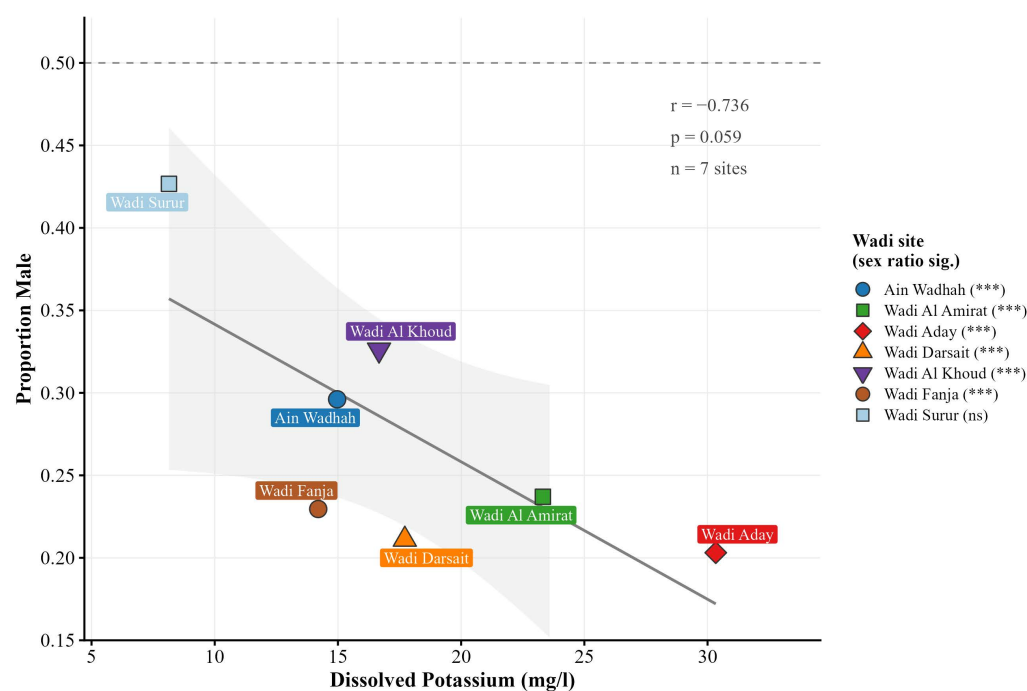


Figure 6. Bivariate relationship between dissolved potassium and the proportion of males in *Aphaniops* spp. across seven wadi sites in northern Oman. Here, the solid line shows the ordinary least-squares regression fit; the shaded band is the 95% confidence interval. The dashed horizontal line marks the balanced sex ratio (0.50). Site labels indicate the significance of sex ratio deviation from 1:1 (***) $p < 0.001$; ns = not significant). Pearson $r = -0.736$ ($n = 7$ sites, $p = 0.059$) is shown for descriptive purposes only; the inferential test for the potassium association is the GLM Wald z -test (Table 4, $p < 0.001$). A non-linear fit may be equally or better supported and should be evaluated in future work with larger sample sizes.

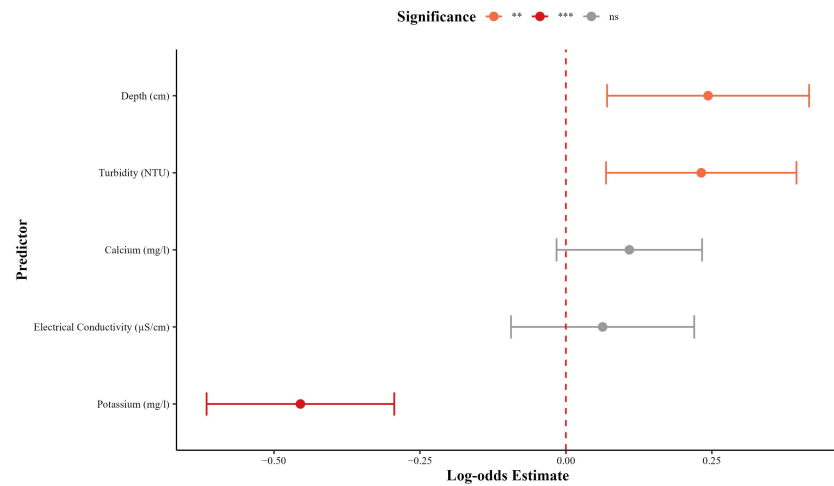


Figure 7. Environmental predictors of *Aphaniops* spp. sex ratio: standardized log-odds estimates (β) and 95% Wald confidence intervals for five environmental predictors of sex ratio variation across sites. Filled symbols indicate significance (** $p < 0.01$; *** $p < 0.001$; ns = non-significant). The vertical reference line marks $\beta = 0$. All predictors standardized to zero mean, unit SD. $n = 7$ sites.

Table 4. Binomial generalized linear model results: environmental predictors of *Aphaniops* spp. sex ratio across seven wadi sites in northern Oman (spring 2023).

Predictor	β (SE)	z	p-Value	OR	95% CI	Δ Odds (%)	VIF
(Intercept)	−0.991 (0.064)	−15.55	<0.001 ***	0.371	0.328–0.421	—	—
Potassium (K, mg/L)	−0.455 (0.082)	−5.54	<0.001 ***	0.635	0.540–0.745	−36.53	1.47
Turbidity (NTU)	0.232 (0.083)	2.79	0.005 **	1.261	1.071–1.484	+26.09	1.38
Depth (cm)	0.244 (0.088)	2.76	0.006 **	1.276	1.073–1.517	+27.57	1.50
Electrical conductivity (EC, μ S/cm)	0.063 (0.080)	0.786	0.432 (ns)	1.065	0.910–1.246	+6.49	1.35
Calcium (mg/L)	0.109 (0.064)	1.709	0.088 (ns)	1.115	0.984–1.263	+11.48	1.18
Model diagnostics:	n sites = 7		n predictors = 5		Residual df = 1 (near-saturated; interpret with caution)		
	Null deviance = 32.009 (df = 6)		Residual deviance = 0.134 (df = 1)		Dispersion ratio = 0.134 (binomial model valid; not over dispersed)		

Here, β = standardized log-odds estimate; SE = standard error; z = Wald z-statistic; OR = odds ratio; Δ odds = percentage change in male odds per 1 SD increase in the predictor $((OR - 1) \times 100)$; VIF = variance inflation factor (all < 5, confirming acceptable multicollinearity). All predictors standardized to zero mean; unit SD. Model diagnostics shown within table. With $n = 7$ sites and 5 predictors, the model has 1 residual degree of freedom; results should be interpreted as exploratory statistical associations rather than definitive causal relationships. ** $p < 0.01$; *** $p < 0.001$; ns, not significant.

3.5. Conservation Assessment (H6)

Six sites with skewed sex ratios scored ≥ 3 . Wadi Al Amirat was classified as a ‘priority site’ and had a stress severity score of 5 because of anomalously low turbidity (1.12 vs. mean 1.94 NTU, >1 SD below) and a high depth (70.2 vs. mean 57.2 cm, 1.4 SD above). Wadi Aday and Wadi Al Khoud were ‘watch sites’ (score = 4). Wadi Aday’s mean depth was 1.4 SD above the seasonal mean and potassium was 1.3 SD above the seasonal mean at Wadi Al Khoud. Moreover, Ain Wadhah, Wadi Darsait, and Wadi Fanja received ‘watch site’ statuses (score = 3) and fell within the expected range for their stress predictors. Wadi Surur was classified as ‘baseline’ (score = 0, see Table 5). Figure 8 maps the conservation flags geographically: Wadi Al Amirat (score 5) as a ‘priority site’, five ‘watch sites’ (Wadi Aday score 4; Wadi Al Khoud score 4; Ain Wadhah, Wadi Darsait, and Wadi Fanja each score 3) as amber triangles, and Wadi Surur (score 0) as a ‘baseline site’.

Table 5. Conservation stress severity scores and priority classification for *Aphaniops* spp. wadi sites in northern Oman based on GLM-significant environmental predictors.

Site	Predictor	Spring 2023 Value	5-Season Mean $\pm$ SD	Deviation (SD Units) and Flag	Stress Flag	Score Contribution
Wadi Al Amirat						
Female-biased Prop. male = 0.237 *** Priority site (composite score = 5)	Potassium (mg/L)	23.32	21.83 $\pm$ 1.86	Within range (+0.80 SD)	Moderate	1
	Turbidity (NTU)	1.115	1.94 $\pm$ 0.66	Exceeds +1 SD (−1.24 SD)	High	2
	Depth (cm)	70.15	57.18 $\pm$ 9.03	Exceeds +1 SD (+1.44 SD)	High	2
Wadi Aday						
Female-biased Prop. male = 0.203 *** Watch site (composite score = 4)	Potassium (mg/L)	30.33	24.26 $\pm$ 9.06	Within range (+0.67 SD)	Moderate	1
	Turbidity (NTU)	3.28	4.38 $\pm$ 2.49	Within range (−0.44 SD)	Moderate	1
	Depth (cm)	66.85	47.81 $\pm$ 13.63	Exceeds +1 SD (+1.40 SD)	High	2
Wadi Al Khoud						
Female-biased Prop. male = 0.484 *** Watch site (composite score = 4)	Potassium (mg/L)	16.67	12.76 $\pm$ 2.97	Exceeds +1 SD (+1.32 SD)	High	2
	Turbidity (NTU)	0.93	3.74 $\pm$ 3.65	Within range (−0.77 SD)	Moderate	1
	Depth (cm)	95.5	80.04 $\pm$ 17.61	Within range (+0.88 SD)	Moderate	1
Ain Wadhah						
Female-biased Prop. male = 0.296 *** Watch site (composite score = 3)	Potassium (mg/L)	14.97	11.83 $\pm$ 7.21	Within range (+0.44 SD)	Moderate	1
	Turbidity (NTU)	2.43	4.51 $\pm$ 2.92	Within range (−0.71 SD)	Moderate	1
	Depth (cm)	60.57	63.64 $\pm$ 12.37	Within range (−0.25 SD)	Moderate	1
Wadi Darsait						
Female-biased Prop. male = 0.211 *** Watch site (composite score = 3)	Potassium (mg/L)	17.71	16.44 $\pm$ 3.15	Within range (+0.40 SD)	Moderate	1
	Turbidity (NTU)	1.69	6.51 $\pm$ 5.07	Within range (−0.95 SD)	Moderate	1
	Depth (cm)	30.03	38.92 $\pm$ 9.89	Within range (−0.90 SD)	Moderate	1
Wadi Fanja						
Female-biased Prop. male = 0.268 *** Watch site (composite score = 3)	Potassium (mg/L)	14.20	12.36 $\pm$ 2.27	Within range (+0.81 SD)	Moderate	1
	Turbidity (NTU)	1.07	140.05 $\pm$ 275.78	Within range (−0.50 SD)	Moderate	1
	Depth (cm)	30.8	27.68 $\pm$ 7.28	Within range (+0.43 SD)	Moderate	1
Wadi Surur						
Not significantly skewed Prop. male = 0.744 ns Baseline (sex ratio not significant)	Potassium (mg/L)	8.14	11.11 $\pm$ 2.82	—	Baseline	0
	Turbidity (NTU)	2.79	20 $\pm$ 31.8	—	Baseline	0
	Depth (cm)	29.6	24.7 $\pm$ 4.52	—	Baseline	0

Here, scoring: high flag (predictor value exceeds 5-season mean by >1 SD) contributes 2 points; moderate (within seasonal range) contributes 1 point. Composite score = sum of contributions across three predictors. Conservation classes: ≥ 5 = priority site; 3–4 = watch site; sex ratio not significant = baseline. This constitutes a preliminary conservation screening framework intended to guide monitoring priorities; thresholds are operationally defined and require independent validation before formal management application. ‘Baseline’ designation for Wadi Surur refers only to the non-significant sex ratio deviation, not to undisturbed reference conditions. *** $p < 0.001$; ns, not significant.

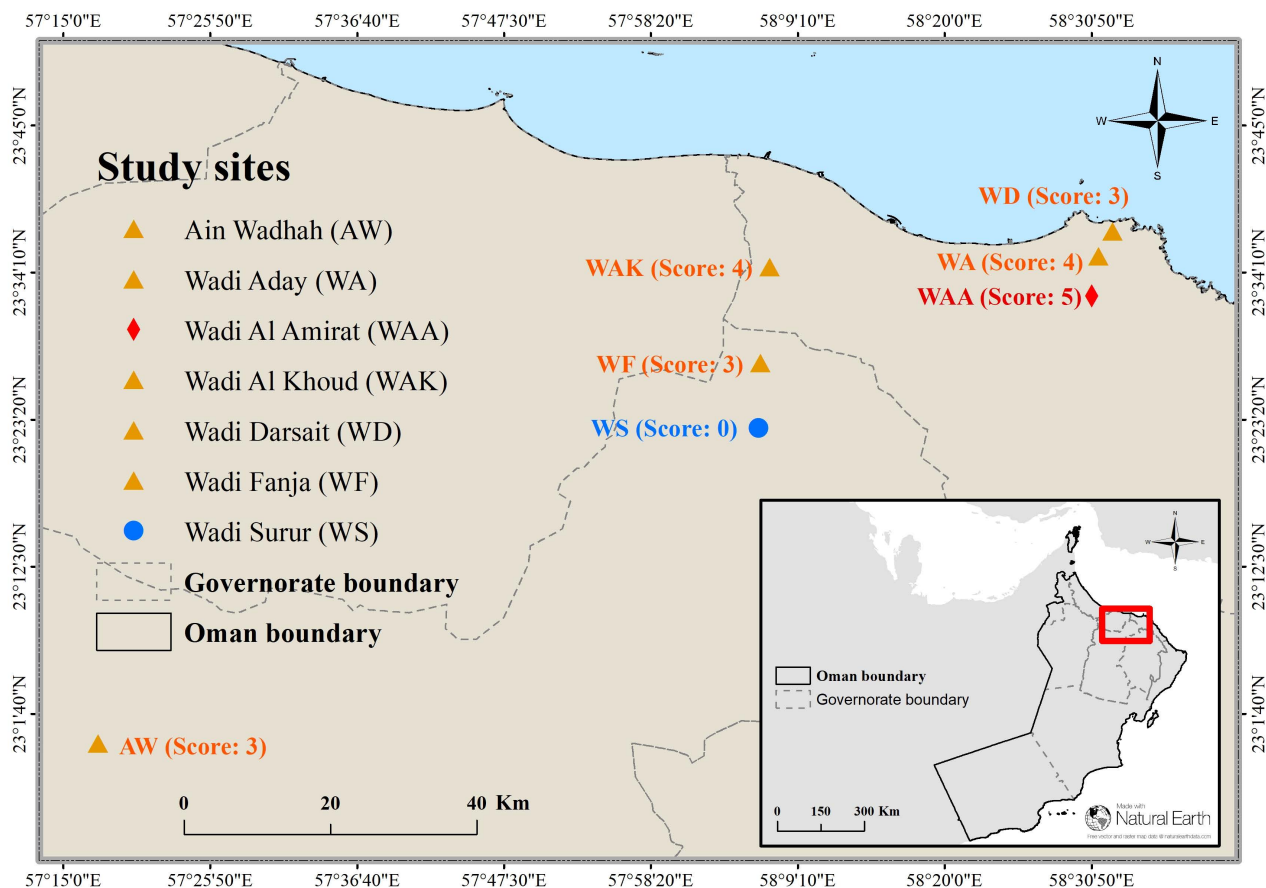


Figure 8. Geographic distribution and conservation priority of sites in northern Oman. Here, Symbols: red diamond = priority, amber triangle = watch, blue circle = baseline. Stress severity score = $(2 \times \text{high}) + (1 \times \text{moderate})$ for three GLM-significant predictors (K^+ , turbidity, depth). The inset map shows the location of the study area (red outline) within Oman, situated across the Muscat and Ad Dakhiliyah governorates.

4. Discussion

4.1. Female-Biased Sex Ratios and the Exception of Wadi Surur

The overall sex ratio for the wild population of *Aphaniops* was strongly female-biased, with six of seven sites deviating from 1:1 (Table 2). This female bias at the regional level in adult fishes is consistent with results reported in cyprinodontiform killifishes in isolated freshwater systems [8] and in fish populations in physically constrained or chemically challenged habitats more broadly [53]. After Bonferroni correction for seven simultaneous tests ($\alpha/7 = 0.007$), all six significantly skewed sites retained *** significance ($p < 0.001$), confirming that the female bias is not an artefact of multiple comparisons.

Wadi Surur stands out as a critical demographic exception, with a non-significant deviation in the sex ratio. It recorded the lowest potassium level found across these study sites. The unique designation of this population as *Aphaniops* spp. is supported by genetic evidence of historical or ongoing hybridization, a trait highly characteristic of stable, well-connected aquatic habitats [50]. Hybridization in itself could reflect higher connectivity, with stronger inter-population genes at this site, which could buffer sex-determination mechanisms from local chemical stressors, as evidenced by mixed mitochondrial haplotypes of both *Aphaniops kruppi* and *Aphaniops stoliczkanus* within the drainage overlap area between Wadi Surur and Wadi Fanja [42,50]. Parallely, abiotic factors could be interlaid with biotic pressures, such as parasite infections by *Clinostomum* sp., to affect adult demographics. Al Sheriyani [69] reported a higher prevalence of females among the infected

population than males across all three overlapping wadis, with females carrying considerably higher infection intensities per infected individual. Interestingly, unlike the standard trend in vertebrates, where sex-biased occurrence of higher incidence in males is attributed to testosterone-induced immunosuppression [70], the pronounced female bias observed here may suggest a reversal of this conventional paradigm, consistent with sex-specific exposure patterns or host physiology in *Aphaniops*.

4.2. Sexual Dimorphism: Pooled Patterns and Site-Level Heterogeneity

In the pooled analysis, total length was greater in males than in females. Sexual dimorphism is a well-established trait across the family Aphaniidae, where all recognized species are sexually dimorphic in color, fin structure, or body morphometrics [45]. Moreover, within *Aphaniops stoliczkanus*, Herbert Mainero et al. [45] documented phenotypic dimorphism in anal- and dorsal-fin length, providing the first quantitative evidence for sexually selected traits in this family of fishes, used during courtship displays and intrasexual male-male competition, showing condition-dependent expression; males from high-quality habitats form more pronounced dimorphic structures [47]. In addition, specialized sexually dimorphic contact organs have been documented on the scales and fin rays of Aphaniidae, further suggesting a complex evolutionary history of sexual selection in the family [44].

This pooled pattern, however, obscures interesting site-level differences. At six of seven sites, the mean total length of males exceeded that of females, but at Ain Wadhah, females were larger (3.94 vs. 3.72 cm). The direction of dimorphism is therefore broadly consistent throughout the wadi network, but the magnitude is not, varying from negligible (Wadi Surur, 0.02 cm) to strong (Wadi Darsait, 0.74 cm), indicating modulation by local site conditions rather than solely by wadi-level factors. Horppila et al. [48] similarly showed that water quality and conspecific density affect male and female feeding rates differently, potentially leading to sex-specific trajectories depending on habitat quality.

Sex-specific LWR parameters (Supplementary Table S2 and Figure S4) show that at Ain Wadhah both sexes fall within the isometric range ($b = 3.106$ males, 2.993 females), with males showing a modestly higher slope despite being the shorter sex (3.72 vs. 3.94 cm), as predicted by condition-dependent dimorphism theory [47].

Site-level differences in body condition (Fulton's Kc; Section 3.2, Supplementary Table S3 and Figure S5) broadly paralleled the LWR patterns described above, with the sex-specific reversals at Wadi Fanja and Wadi Darsait suggesting that local resource or habitat conditions, rather than a uniform sex effect, may underlie site-level variation in condition.

4.3. Environmental Associates of Sex Ratio Variation

Water quality gradients are increasingly recognized as primary structuring forces for fish assemblage composition and population demography across freshwater systems [71], and the GLM results identify statistical associations between site chemistry, physical characteristics, and sex ratio variation across *Aphaniops* populations within Oman. Potassium emerged as the strongest associate of sex ratio variation ($r = -0.736$; $\beta = -0.455$ OR = 0.635 , $p < 0.001$). While Wadi Aday has the highest mean potassium concentration of any site (24.3 mg/L), it was selected independently as a suitable *Aphaniops* spp. habitat (HSI = 0.945 ; [32]). The consistency between the bivariate correlation and GLM direction may suggest that female-biased sex ratios are associated with enduring site conditions rather than transient disturbances, though the small number of sites ($n = 7$) precludes firm conclusions. A lack of seasonal variation in potassium levels (Kruskal–Wallis, $p = 0.336$) is consistent with the interpretation that site-level differences reflect enduring hydrochemical conditions rather than transient fluctuations. Chronic exposure to dissolved ions has been shown in other taxa to influence gonadal differentiation towards female phenotypes during critical early developmental

windows [17,18,72,73]; however, the specific mechanism by which potassium may influence sex ratio variation in *Aphaniops* remains speculative and requires experimental validation. Other co-occurring stressors documented in these hydrological networks include boron, which induces developmental toxicities when concentrations are elevated [74,75], and seasonally variable ammonia, which causes sub-lethal stress to osmoregulatory organs and the central nervous system [76–78], highlighting a multi-stressor chemical environment. Wild *Aphaniops* cohorts also face microplastic and heavy metal exposure, as highlighted by Al-Mandhari [79], who documented microplastic and heavy metal bioaccumulation in *Cyprinion muscatense* within the same hydrological network.

LWR metrics (Supplementary Table S2) provide indirect evidence of this physiological pressure: site- and sex-level cohorts exhibit positive allometric growth ($b > 3$), while isometric growth ($b \approx 3$) was restricted to the male cohorts at Wadi Al Khoud and Wadi Fanja, and to the pooled Wadi Fanja sample; the pooled Wadi Al Khoud sample instead showed marginal positive allometry, driven by females. For the male cohort at Wadi Al Khoud, this isometric shift exactly parallels a severe potassium event that exceeded the five-season site mean by more than 1.32 standard deviations (Table 5). Wadi Fanja also showed isometric growth, though its spring 2023 potassium remained within the seasonal range (0.81 SD), suggesting that co-occurring stressors may additionally contribute to the growth pattern at that site. Isometry often flags a sub-optimal energetic state [80], suggesting that potassium elevation may be associated with broader physiological strain.

Conversely, turbidity showed a positive association with the proportion of males ($\beta = 0.232$, $p < 0.005$). It has been proposed to reduce the foraging efficiency of visually oriented predators, which could, in turn, decrease selective predation on conspicuously colored males and consequently affect sex-specific survival rates [81]. However, this mechanism remains purely speculative for *Aphaniops* and has not been directly tested within the current study system. The high turbidity levels observed at Wadi Fanja, with spikes reaching 631 NTU in the winter of 2022, illustrate the significant sediment movement characteristic of flash floods in arid regions [82]. Lastly, the multivariate analysis revealed a significant positive relationship between water depth and male proportion ($\beta = 0.244$, $p = 0.006$), despite a near-zero bivariate correlation ($r = -0.010$). Whether this divergence represents a genuine ecological suppressor effect or a statistical artefact of the near-saturated model structure (1 residual df) cannot be resolved with the present data and should be treated with caution [68]. Deeper water offers greater thermal consistency and more stable living conditions, which serve as primary environmental controls that influence fish life histories and shape population structure in desert waterways [4].

4.4. Environmental Clustering, Habitat Quality, and Body Size

The three distinct environmental clusters largely correspond to specific ionic and hydrological gradients, which are shaped by the unique geological makeup of the Hajar Mountain wadi system [83]. One notable feature of this environment is its remarkable geochemical consistency throughout the year; while 18 of 30 measured physical–chemical variables differed markedly between locations, only 8 showed significant seasonal variation. This consistent state suggests that each wadi channel retains its own enduring geochemical signature, determined more by the underlying rock types in the catchment area and the chemistry of the perched aquifers than by temporary seasonal rainfall [23,25]. Across all studied sites, water consistently shows alkaline conditions, with pH values ranging from 7.74 to 8.76, which aligns with the carbonate-rich sedimentary rocks that characterize the Hajar Mountains [35]. The Aphaniidae family, known for its wide range of physiological tolerance and adaptability, can flourish even amid these marked shifts in water chem-

istry [39]. This makes *Aphaniops* species a useful bioindicator taxon, helping to assess the quality of desert wadi habitats.

Specimens gathered from Wadi Fanja consistently yielded the largest individuals, despite comparatively isometric growth (Supplementary Table S2), suggesting body size here reflects sustained favorable conditions rather than a shift in growth allometry. The co-occurrence of maximum adult body sizes with a severely skewed, female-biased sex ratio (proportion male = 0.230) suggests that demographic imbalances at this site are not a consequence of resource limitation or nutritional stress. Instead, these biases are consistent with persistent local conditions related to conductivity and turbidity. This is true even though the habitat's productivity allows for excellent individual growth.

4.5. Conservation Implications and the Wadi Al Amirat Paradox

Wadi Al Amirat stood out as a 'priority site', designated as such based on anomalous spring 2023 values for depth and turbidity relative to the five-season site baseline. The present study's condition-factor analysis found the highest Fulton's condition factor (K_c = females: 1.905 ± 0.313 , males: 1.853 ± 0.244) of any *Aphaniops* population at this site (Supplementary Table S3), indicating the physically fittest fish across all samples. This pattern is consistent with established teleost life-history frameworks, showing that crucial environmental sex-determination pathways operating during narrow early ontogenetic windows are established independently of later conditions affecting adult nutrition or overall physical health [84]. The robustness observed in adult fish likely reflects their dynamic response to immediate seasonal food availability in the wadi [80]. Nonetheless, early embryonic differentiation may have been influenced by the site's persistently high potassium concentrations (five-season mean $K = 21.8$ mg/L, the second highest of all sites), though this remains speculative and untested. Prolonged exposure to elevated dissolved ions can trigger sustained cellular stress responses. This alters baseline osmoregulatory allocations, activating corticosteroid pathways that can override genetic blueprints by altering aromatase-mediated steroidogenesis during larval development [17,73], though this proposed link remains speculative for *Aphaniops* and requires targeted experimental testing.

The five 'watch sites' and one 'priority site' identified collectively encompass six of the seven wadi systems studied, indicating female-biased sex ratios are a widespread issue throughout the entire region. Critically, a spatial analysis of Oman's 31 nature reserves shows that only 2.6% of wadi networks with high suitability for *Aphaniops* species are located within protected areas. Consequently, nearly 97% of crucial corridors for freshwater connectivity remain completely unprotected [32]. This is a notable conservation concern for Wadi Al Amirat, which also bears the highest burden of *Clinostomum* (Digenea) parasites across the entire study network [69]. A coordinated program integrating sex ratio surveys, condition indices, parasite levels, and tissue composition would create a robust early-warning system for conserving endemic freshwater communities. The preliminary conservation scoring framework developed here (Table 5) is intended to guide monitoring priorities, not as a validated management tool; thresholds require independent validation before formal application.

Furthermore, anticipated macroclimatic warming and more severe droughts across the Arabian Peninsula are expected to increase dissolved concentrations in ephemeral streams [27,85], making chronic ionic stress a more pressing issue. Employing native fish populations as indicator proxies to inform wadi protection strategies amidst climate shifts is a proven method, as highlighted by existing studies [86]. This approach also aligns well with species distribution models for other endemic species inhabiting the same environments, including *Garra shamal* [31] and *Cyprinion muscatense* [33,87].

4.6. Study Limitations and Future Directions

The following limitations should be considered when interpreting these findings. First, the GLM is based on only seven independent environmental units (wadi sites); with five predictors, only one residual degree of freedom remains, making the model near-saturated and all coefficient estimates inherently unstable. Second, the individual fish count ($n = 1417$) does not increase the number of independent environmental replicates, as fish within the same wadi share identical environmental conditions. Third, foldable traps may introduce sex-specific capture bias if males and females differ in microhabitat use, activity level, or body-size response to mesh; observed sex ratios should be interpreted as relative rather than absolute population estimates. Fourth, the unified *Aphaniops* spp. treatment, while justified by hybridization evidence [43,50], prevents resolution of any species-level differences in sex ratio response to environmental variables. Fifth, fish were sampled only in spring 2023; adult sex ratios integrate recruitment history, differential mortality, and seasonal movement from earlier periods, and cannot be attributed solely to current environmental conditions. Critically, experimental studies are needed to establish whether potassium directly affects sex determination pathways in *Aphaniops* or whether the observed associations are driven by correlated environmental factors or other unmeasured variables. The MaxEnt species distribution models and habitat suitability assessment previously conducted for this wadi network [32] offer a spatial and climatic modeling framework, within which species-level sex ratio comparisons could be positioned.

Multi-season sex ratio data would enhance our ability to infer causality. Condition factor analysis is now demonstrated as directly achievable from the standard length-weight data collected in this study (Supplementary Table S3 and Figure S5); Kc varied significantly among sites, confirming that body condition monitoring should accompany future sex ratio surveys, with extended monitoring allowing tracking of directional shifts over time [88]. Additionally, this study focused only on abiotic predictors; parasite burden was not assessed during sampling. *Clinostomum* (Digenea) infections have been documented in Omani *Aphaniops* sp. with varying intensities [69]. Sex-differential parasite susceptibility thus represents an unmeasured biotic mechanism that may contribute independently to the observed female-biased ratios.

Future research should include analyses of pollutant levels at the tissue level to differentiate ionic stress from anthropogenic chemical impacts on sex determination. Controlled thermal exposure experiments could clarify whether the marked seasonal temperature fluctuations observed across sites influence sex ratio patterns during spring breeding [89].

5. Conclusions

Sex ratios in wild *Aphaniops* spp. from seven wadi sites in northern Oman were strongly and consistently female-biased: six of seven sites deviated significantly from 1:1 (H1, confirmed), and all six retained significances after Bonferroni correction. Wadi Surur retained a non-significant sex ratio and was assigned a provisional 'baseline' status, noting that this designation reflects only the absence of a statistically significant deviation and does not imply undisturbed environmental conditions. Dissolved potassium emerged as the strongest negative environmental associate of the proportion of males ($\beta = -0.455$, OR = 0.635, $p < 0.001$; H2, supported), with turbidity and depth also showing significant associations; all associations are exploratory and do not establish causation. Males were significantly longer than females overall (H3, supported). Three distinct hydrochemical site clusters were identified (H4, supported). Wadi Al Amirat was classified as a 'priority site' and five sites as 'watch sites' under the preliminary conservation scoring framework (H5, partially supported; thresholds require independent validation).

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fishes11080452/s1>, Figure S1. Size frequency distributions (total length, cm) by sex across seven sites in northern Oman (Spring 2023). Overlapping histograms: females (salmon), males (blue). $n = 1417$. Figure S2. Sex ratio (proportion male) of *Aphaniops* spp. at seven sites in northern Oman (Spring 2023). Dashed line = balanced ratio (0.50). Significance: *** $p < 0.001$ (female-biased); ns = not significant (χ^2 with Yates correction). Total $n = 1417$. Figure S3. Normal Q-Q plots for total length (cm) by sex and site (Spring 2023). Points on the diagonal indicate approximate normality. Non-parametric tests were used throughout regardless of formal normality outcomes. Figure S4. Length-weight power curves ($W = a \times L^b$) for *Aphaniops* spp. by sex across seven wadi sites (Spring 2023). Raw data points shown with fitted curves on arithmetic axes. Figure S5. Body condition (Fulton's Kc) of *Aphaniops* spp. by sex across seven wadi sites in northern Oman (Spring 2023). Violin bodies show the kernel density distribution of Kc values for females (salmon) and males (steel blue); width reflects the relative frequency of observations. Inner boxes show median and interquartile range (IQR); whiskers extend to $1.5 \times \text{IQR}$. Sample sizes (n) are shown below each violin pair. Significance of sex difference within each site (Wilcoxon rank-sum, Bonferroni-adjusted): ** $p < 0.01$; * $p < 0.05$; ns, not significant. Compact letter display (CLD) above each site summarizes Dunn post-hoc pairwise comparisons of site-level Kc (sexes pooled, Bonferroni-adjusted α). Full descriptive statistics and test results are in Table S3. Figure S6. Distribution of 30 physicochemical variables across seven sites in northern Oman (all seasons pooled per site). Variables are grouped by biological category: physical hydrology (depth, width, velocity), thermal and chemical conditions (temperature, pH, DO, EC, TDS, salinity, turbidity), organic load (BOD, COD, TOC, TSS, total solids), macronutrients and major ions (sulfate, Mg, Ca, Na, K, total hardness), and trace metals (nitrite, nitrate, ammonia, phosphate, Fe, B, Mn, Cu, Al). Kruskal-Wallis significance annotated: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns = not significant. 18 of 30 variables differed significantly among sites. n per box = 7 seasonal means (field replicates: depth $n = 10$, width $n = 5$, water quality $n = 3$ per site per season). Figure S7. Seasonal variation of 30 variables across five seasons in northern Oman (seven sites pooled per season). Eight variables differed significantly by season ($p < 0.05$): temperature, turbidity, Al, Fe, TSS, nitrate, phosphate, ammonia. Ionic variables (EC, K^+ , Ca^{2+} , Mg^{2+} , Na^+ , salinity, TDS, total hardness) were seasonally stable (ns). n per box = 5 seasonal means (field replicates: depth $n = 10$, width $n = 5$, water quality $n = 3$ per site per season). Table S1. Kruskal-Wallis H-test results for all 30 measured physicochemical variables tested for significant differences across seven wadi sites and across five seasons (Spring 2022–Spring 2023). Table S2. Length-weight relationship (LWR) parameters for *Aphaniops* spp. by site and sex group (Spring 2023). Table S3. Condition factor analysis for *Aphaniops* spp. across seven wadi sites in northern Oman (Spring 2023). Three indices are reported: Fulton's condition factor ($\text{Kc} = 100 \times W/L^3$); allometric condition factor ($\text{Ka} = 100 \times W/L^b$, using site $\times$ sex-specific slope b from Table S2); and relative condition factor ($\text{Kn} = 100 \times W/\hat{y}$, Le Cren 1951 [90], where $\hat{y} = a \times L^b$ is the predicted weight). $\text{Kn} \approx 100$ by definition when LWR parameters are well-fitted; its non-significance in Panel B confirms model adequacy rather than absence of biological variation. Ka sex differences are a mathematical consequence of sex-specific b values and should not be interpreted as independent evidence of body condition dimorphism. Kc is therefore the primary index reported for ecological interpretation.

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References

1. Fisher, R.A. *The Genetical Theory of Natural Selection*; Clarendon Press: Oxford, UK, 1930.
2. Nikolskii, G.V. *The Ecology of Fishes*; Academic Press: Cambridge, MA, USA, 1963.
3. Wootton, R.; Smith, C. Reproductive Biology of Teleost Fishes. In *Reproductive Biology of Teleost Fishes*; John Wiley & Sons: Hoboken, NJ, USA, 2014; pp. 1–472. [\[CrossRef\]](#)
4. Baruch, E.M.; Ruhi, A.; Harms, T.K.; Sabo, J.L. Flow Variation at Multiple Scales Filters Fish Life Histories and Constrains Community Diversity in Desert Streams. *Ecosphere* **2022**, *13*, e4086. [\[CrossRef\]](#)
5. Tesfay Gebrekiros, S. Factors Affecting Stream Fish Community Composition and Habitat Suitability. *J. Aquac. Mar. Biol.* **2016**, *4*, 76. [\[CrossRef\]](#)
6. Lowe, C.H.; Heath, W.G. Behavioral and Physiological Responses to Temperature in the Desert Pupfish *Cyprinodon Macularius*. *Physiol. Zool.* **1969**, *42*, 53–59. [\[CrossRef\]](#)
7. Nordlie, F.G. Physicochemical Environments and Tolerances of Cyprinodontoid Fishes Found in Estuaries and Salt Marshes of Eastern North America. *Rev. Fish Biol. Fish.* **2006**, *16*, 51–106. [\[CrossRef\]](#)
8. Lanés, L.E.K.; Keppeler, F.W.; Maltchik, L. Abundance, Sex-Ratio, Length & Weight Relation, and Condition Factor of Non-Annual Killifish *Atlantirivulus riograndensis* (Actinopterygii: Cyprinodontiformes: Rivulidae) in Lagoa Do Peixe National Park, a Ramsar Site of Southern Brazil. *Acta Ichthyol. Piscat.* **2012**, *42*, 247–252. [\[CrossRef\]](#)
9. Pettersson, L.B.; Ramnarine, I.W.; Becher, S.A.; Mahabir, R.; Magurran, A.E. Sex Ratio Dynamics and Fluctuating Selection Pressures in Natural Populations of the Trinidadian Guppy, *Poecilia Reticulata*. *Behav. Ecol. Sociobiol.* **2004**, *55*, 461–468. [\[CrossRef\]](#)
10. Reichard, M.; Polačik, M.; Blažek, R.; Vrtílek, M. Female Bias in the Adult Sex Ratio of African Annual Fishes: Interspecific Differences, Seasonal Trends and Environmental Predictors. *Evol. Ecol.* **2014**, *28*, 1105–1120. [\[CrossRef\]](#)
11. Fryxell, D.C.; Arnett, H.A.; Apgar, T.M.; Kinnison, M.T.; Palkovacs, E.P. Sex Ratio Variation Shapes the Ecological Effects of a Globally Introduced Freshwater Fish. *Proc. R. Soc. B Biol. Sci.* **2015**, *282*, 20151970. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Esmaeili, H.R.; Shiva, A.H. Reproductive Biology of the Persian Tooth-Carp, *Aphanius Persicus* (Jenkins, 1910) (Cyprinodontidae), in Southern Iran. *Zool. Middle East* **2006**, *37*, 39–46. [\[CrossRef\]](#)
13. Bibak, M.; Rakhshani, M.; Hosseini, S.; Koochani, M.; Moien, M. Reproduction of *Aphanius Dispar Dispar* (Rüppell, 1829) in Bushehr Dalaki River, South of Iran. *World J. Fish Mar. Sci.* **2012**, *4*, 597–601.
14. Datry, T.; Larned, S.T.; Tockner, K. Intermittent Rivers: A Challenge for Freshwater Ecology. *BioScience* **2014**, *64*, 229–235. [\[CrossRef\]](#)
15. Skoulikidis, N.T.; Sabater, S.; Datry, T.; Morais, M.M.; Buffagni, A.; Dörflinger, G.; Zogaris, S.; del Mar Sánchez-Montoya, M.; Bonada, N.; Kalogianni, E.; et al. Non-Perennial Mediterranean Rivers in Europe: Status, Pressures, and Challenges for Research and Management. *Sci. Total Environ.* **2017**, *577*, 1–18. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Shalloof, K.; El-ganainy, A.; Aly, W. Sex-Specific Vulnerability of Fish to Dredging in the Mediterranean Coastal Lagoon (Lake Manzala, Egypt). *Aquat. Sci. Eng.* **2025**, *40*, 153–162. [\[CrossRef\]](#)
17. Baroiller, J.F.; D’Cotta, H.; Saillant, E. Environmental Effects on Fish Sex Determination and Differentiation. *Sex. Dev.* **2009**, *3*, 118–135. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Baroiller, J.F.; D’Cotta, H. Environment and Sex Determination in Farmed Fish. *Comp. Biochem. Physiol. Part C Toxicol. Pharmacol.* **2001**, *130*, 399–409. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Valenzuela, N.; Adams, D.C.; Janzen, F.J. Pattern Does Not Equal Process: Exactly When Is Sex Environmentally Determined? *Am. Nat.* **2003**, *161*, 676–683. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Valenzuela, N.; Lance, V. (Eds.) *Temperature-Dependent Sex Determination in Vertebrates*; Smithsonian Institution Scholarly Press: Washington, DC, USA, 2004.

21. Geffroy, B.; Wedekind, C. Effects of Global Warming on Sex Ratios in Fishes. *J. Fish Biol.* **2020**, *97*, 596–606. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Kwarteng, A.Y.; Dorvlo, A.S.; Vijaya Kumar, G.T. Analysis of a 27-Year Rainfall Data (1977–2003) in the Sultanate of Oman. *Int. J. Climatol.* **2009**, *29*, 605. [\[CrossRef\]](#)
23. Al-Shukaili, A.; Obnosov, Y.; Al-Maktoumi, A.; Rashid Al-Abri, R.; Kacimov, A. Salinity Variations along the Beds of Ephemeral Streams Caused by Perched Wadi Aquifers in Arid Regions. *Am. Geophys. Union Fall Meet.* **2020**, *2020*, 90.
24. López-López, E. Editorial: Freshwater Ecosystems in Arid and Semiarid Zones Facing Multiple Stressors: Human Disturbances, Climate Change, and Dryland River Conservation. *Front. Environ. Sci.* **2021**, *9*, 814225. [\[CrossRef\]](#)
25. Al Barwani, A.; Helmi, T. Sea Water Intrusion in a Coastal Aquifer: A Case Study for the Area between Seeb and Suwaiq, Sultanate of Oman. *J. Agric. Mar. Sci. JAMS* **2006**, *11*, 55–69. [\[CrossRef\]](#)
26. Alfarrakh, N.; Walraevens, K. Groundwater Overexploitation and Seawater Intrusion in Coastal Areas of Arid and Semi-Arid Regions. *Water* **2018**, *10*, 143. [\[CrossRef\]](#)
27. Almazroui, M.; Islam, M.N.; Saeed, S.; Saeed, F.; Ismail, M. Future Changes in Climate over the Arabian Peninsula Based on CMIP6 Multimodel Simulations. *Earth Syst. Environ.* **2020**, *4*, 611–630. [\[CrossRef\]](#)
28. Odhiambo, G.O. Water Scarcity in the Arabian Peninsula and Socio-Economic Implications. *Appl. Water Sci.* **2017**, *7*, 2479–2492. [\[CrossRef\]](#)
29. Saharwardi, M.S.; Dasari, H.P.; Gandham, H.; Ashok, K.; Hoteit, I. Spatiotemporal Variability of Hydro-Meteorological Droughts over the Arabian Peninsula and Associated Mechanisms. *Sci. Rep.* **2024**, *14*, 20296. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Sherif, M.; Liaqat, M.U.; Baig, F.; Al-Rashed, M. Water Resources Availability, Sustainability and Challenges in the GCC Countries: An Overview. *Heliyon* **2023**, *9*, e20543. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Al Adhoobi, A.S.; Al Jufaili, S.M.; Al Ruheili, A. Predicting Habitat Distributions for the Endemic Fish Garra Shamal (Teleostei: Cyprinidae) in the Omani Hajar Mountain under Present and Future Climate Change Scenarios Using MaxEnt. *J. Surv. Fish. Sci.* **2023**, *10*, 3591–3600. [\[CrossRef\]](#)
32. Al Adhoobi, A.S.; Al Ruheili, A.; Al Jufaili, S.M.; Gallardo, W. Integrated Approach to Model Distribution and Assess Habitat Suitability of Killifish Species in Oman's Local Streams (Wadis) under Current and Future Climate Conditions. *PLoS ONE* **2026**, *21*, e0346581. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Masoumi, A.H.; Esmaeili, H.R.; Khosravi, R.; Gholamhosseini, A.; Korkmaz, M.; Jeppesen, E. Species on the Move: Impacts of Climate Change on the Spatial Range of Endemic Fishes of the Eco-Sensitive Semi-Arid Area of the Arabian Peninsula. *Sci. Total Environ.* **2024**, *947*, 174095. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Abell, R.; Thieme, M.L.; Revenga, C.; Bryer, M.; Kottelat, M.; Bogutskaya, N.; Coad, B.; Mandrak, N.; Balderas, S.C.; Bussing, W. Freshwater Ecoregions of the World: A New Map of Biogeographic Units for Freshwater Biodiversity Conservation. *BioScience* **2008**, *58*, 403–414. [\[CrossRef\]](#)
35. Al-Kalbani, M.S.; Price, M.F.; O'Higgins, T.; Ahmed, M.; Abahussain, A. Integrated Environmental Assessment to Explore Water Resources Management in Al Jabal Al Akhdar, Sultanate of Oman. *Reg. Environ. Change* **2016**, *16*, 1345–1361. [\[CrossRef\]](#)
36. Esmaeili, H.R.; Jufaili, S.A.; Masoumi, A.H.; Zarei, F. Ichthyodiversity in Southeastern Arabian Peninsula: Annotated Checklist, Taxonomy, Short Description and Distribution of Inland Fishes of Oman. *Zootaxa* **2022**, *5134*, 451–503. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Esmaeili, H.R.; Hamidan, N. Inland Fishes of the Arabian Peninsula: Review and a Revised Checklist. *Zootaxa* **2023**, *5330*, 201–226. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Freyhof, J.; Els, J.; Feulner, G.R.; Hamidan, N.A.; Krupp, F. *Freshwater Fishes of the Arabian Peninsula*; Motivate Media Group: Dubai, United Arab Emirates, 2020; Volume 20309.
39. Bitetto, F.G.; Ruocco, N.; Murano, C.; Manfellotto, F.; D'Ambrosio, P.; Mutalipassi, M.; Terlizzi, A. Aphaniidae as Ecological Models: An Analysis of Biodiversity and Environmental Resilience. *Biodivers. Conserv.* **2026**, *35*, 23. [\[CrossRef\]](#)
40. Pörtner, H.O.; Schulte, P.M.; Wood, C.M.; Schiemer, F. Niche Dimensions in Fishes: An Integrative View. *Physiol. Biochem. Zool.* **2010**, *83*, 808–826. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Freyhof, J.; Yoğurtçuoğlu, B. A Proposal for a New Generic Structure of the Killifish Family Aphaniidae, with the Description of *Aphaniops teimorii* (Teleostei: Cyprinodontiformes). *Zootaxa* **2020**, *4810*, zootaxa-4810. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Freyhof, J.; Weissenbacher, A.; Geiger, M. *Aphaniops Kruppi*, a New Killifish from Oman with Comments on the A. Dispar Species Group (Cyprinodontiformes: Aphaniidae). *Zootaxa* **2017**, *4338*, 557–573. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Bidaye, R.G.; Al-Jufaili, S.M.; Charmpila, E.A.; Jawad, L.; Vukić, J.; Reichenbacher, B. Possible Links between Phenotypic Variability, Habitats and Connectivity in the Killifish *Aphaniops stoliczkanus* in Northeast Oman. *Acta Zool.* **2022**, *104*, 262–278. [\[CrossRef\]](#)
44. Esmaeili, H.R.; Echreshavi, S.; Masoumi, A.H.; Nejad, A.M. On a Remarkable Sexual Dimorphic Trait on Scales and Fins of the Old World Cyprinodontiformes (Actinopterygii: Aphaniidae). *Acta Zool.* **2023**, *105*, 302–316. [\[CrossRef\]](#)
45. Herbert Mainero, A.; Al-Jufaili, S.M.; Jawad, L.; Reichenbacher, B. Sex Dimorphism and Evidence of Sexually Selected Traits: A Case Study on the Killifish *Aphaniops stoliczkanus* (Day, 1872). *Acta Zool.* **2022**, *104*, 473–487. [\[CrossRef\]](#)

46. Al Jufaili, S.M.; Adhoobi, A.; Saud, A.; Al Mamari, H.D.; Al Hinai, S.Y. Length-Weight Relationship and Condition Factors of Native Freshwater Fishes in the Hajar Mountain, Oman. *Fish. Aquat. Sci.* **2025**, *28*, 439–450. [\[CrossRef\]](#)
47. Bonduriansky, R. The Evolution of Condition-Dependent Sexual Dimorphism. *Am. Nat.* **2007**, *169*, 9–19. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Horppila, J.; Estlander, S.; Olin, M.; Pihlajamäki, J.; Vinni, M.; Nurminen, L. Gender-Dependent Effects of Water Quality and Conspecific Density on the Feeding Rate of Fish—Factors behind Sexual Growth Dimorphism. *Oikos* **2011**, *120*, 855–861. [\[CrossRef\]](#)
49. Alshehri, F.; Abdelrahman, K. Integrated Approach for the Investigation of Groundwater Quality Using Hydrochemical and Geostatistical Analyses in Wadi Fatimah, Western Saudi Arabia. *Front. Earth Sci.* **2023**, *11*, 1166153. [\[CrossRef\]](#)
50. Zarei, F.; Masoumi, A.H.; Al Jufaili, S.M.; Esmaili, H.R. Contribution to the Diversity and Distribution of *Aphaniops* (Teleostei: Aphaniidae) in Oman Freshwater Ecoregions: Units for Taxonomy and Conservation. *Biologia* **2022**, *78*, 851–863. [\[CrossRef\]](#)
51. Gunawardhana, L.N.; Al-Rawas, G.A.; Al-Hadhrami, G. Quantification of the Changes in Intensity and Frequency of Hourly Extreme Rainfall Attributed Climate Change in Oman. *Nat. Hazards* **2018**, *92*, 1649–1664. [\[CrossRef\]](#)
52. Rajesh, L.; Al-Farsi, A.; Victor, R. The Diversity and Distribution of Freshwater Macrophytes in the Wedian of the Mountainous Northern Oman. *Int. J. Environ. Stud.* **2017**, *74*, 979–990. [\[CrossRef\]](#)
53. Ashrafi, R.; Westermarck, A.; Leppänen, M.T.; Vehniäinen, E.-R. Female-Biased Sex Ratios and Delayed Puberty in Two Fish Species with Different Ecologies in an Anthropogenically Affected Urban Lake. *Environ. Res.* **2024**, *262*, 119844. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Dumont, S.C.; Schlechte, W. Use of Resampling to Evaluate a Simple Random Sampling Design for General Monitoring of Fishes in Texas Reservoirs. *N. Am. J. Fish. Manag.* **2004**, *24*, 408–416. [\[CrossRef\]](#)
55. Kritzer, J.; Davies, C.; Mapstone, B. Characterizing Fish Populations: Effects of Sample Size and Population Structure on the Precision of Demographic Parameter Estimates. *Can. J. Fish. Aquat. Sci.* **2001**, *58*, 1557–1568. [\[CrossRef\]](#)
56. Miranda, L.E. Approximate Sample Sizes Required to Estimate Length Distributions. *Trans. Am. Fish. Soc.* **2007**, *136*, 409–415. [\[CrossRef\]](#)
57. Wyatt, R.J. Estimating Riverine Fish Population Size from Single- and Multiple-Pass Removal Sampling Using a Hierarchical Model. *Can. J. Fish. Aquat. Sci.* **2002**, *59*, 695–706. [\[CrossRef\]](#)
58. Bridgewater, L.L.; Baird, R.B.; Eaton, A.D.; Rice, E.W.; American Public Health Association; American Water Works Association; Water Environment Federation (Eds.) *Standard Methods for the Examination of Water and Wastewater*, 23rd ed.; American Public Health Association: Washington, DC, USA, 2017.
59. Dorgham, A.; Candolin, U.; Ivanova, T.; Ivanov, M.; Nadtochii, E.; Yurtseva, A.; Lajus, D. Sexual Dimorphism Patterns of the White Sea Threespine Stickleback (*Gasterosteus aculeatus*). *Biol. Commun.* **2021**, *66*, 256–267. [\[CrossRef\]](#)
60. Correia, H.E. Semiparametric Model Selection for Identification of Environmental Covariates Related to Adult Groundfish Catches and Weights. *Sci. Rep.* **2021**, *11*, 9949. [\[CrossRef\]](#) [\[PubMed\]](#)
61. McCullagh, P.; Nelder, J.A. Binary Data. In *Generalized Linear Models*; Springer: Berlin/Heidelberg, Germany, 1989; pp. 98–148.
62. Robinson, D.; Hayes, A.; Couch, S. *Broom: Convert Statistical Objects into Tidy Tibbles*; R Foundation for Statistical Computing: Vienna, Austria, 2025.
63. Legendre, P.; Legendre, L. Numerical Ecology. In *Developments in Environmental Modelling*; Third English Ed.; Elsevier: Amsterdam, The Netherlands, 2012; p. 1006.
64. Quinn, G.P.; Keough, M.J. *Experimental Design and Data Analysis for Biologists*; Cambridge University Press: Cambridge, UK, 2002.
65. Singh, W.; Hjorleifsson, E.; Stefansson, G. Robustness of Fish Assemblages Derived from Three Hierarchical Agglomerative Clustering Algorithms Performed on Icelandic Groundfish Survey Data. *ICES J. Mar. Sci.* **2011**, *68*, 189–200. [\[CrossRef\]](#)
66. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2024.
67. Wickham, H. *Ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2009.
68. Cohen, J.; Cohen, P.; West, S.G.; Aiken, L.S. *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences*; Routledge: Abingdon, UK, 2003.
69. Al Sheriyani, M.R. Unraveling *Clinostomum* (Digenea) Infections in an Omani Population of the Killifish *Aphaniops* sp. Morpho-Molecular Traits, Population Dynamics, and Parasite Host Interface. Master's Thesis, Sultan Qaboos University (Oman), Seeb, Oman, 2024.
70. Zuk, M.; McKean, K.A. Sex Differences in Parasite Infections: Patterns and Processes. *Int. J. Parasitol.* **1996**, *26*, 1009–1024. [\[CrossRef\]](#)
71. Jargal, N.; Mamun, M.; Choi, C.-Y.; An, K.-G. Combining Functional Diversity of Lotic Fish Communities with River Health Assessment Based on Multi-Metric Chemical Pollution and Biological Integrity Index Models. *Front. Environ. Sci.* **2022**, *10*, 1012420. [\[CrossRef\]](#)
72. Abdelrahim, T.M.M.; Hanbal, M.M.; Salem, M.F.; Elnakeeb, M.A. Effect of Some Heavy Metals (Pb, Hg, Cd and Cu) on Physiological and Immunological Parameters in the Nile Tilapia (*Oreochromis niloticus*). *Egypt. J. Aquat. Biol. Fish.* **2025**, *29*, 849–866. [\[CrossRef\]](#)

73. Kültz, D. Physiological Mechanisms Used by Fish to Cope with Salinity Stress. *J. Exp. Biol.* **2015**, *218*, 1907–1914. [[CrossRef](#)] [[PubMed](#)]
74. Schoderboeck, L.; Mühlegger, S.; Losert, A.; Gausterer, C.; Hornek, R. Effects Assessment: Boron Compounds in the Aquatic Environment. *Chemosphere* **2011**, *82*, 483–487. [[CrossRef](#)] [[PubMed](#)]
75. Soucek, D.J.; Dickinson, A.; Koch, B.T. Acute and Chronic Toxicity of Boron to a Variety of Freshwater Organisms. *Environ. Toxicol. Chem.* **2011**, *30*, 1906–1914. [[CrossRef](#)] [[PubMed](#)]
76. Edwards, T.M.; Puglis, H.J.; Kent, D.B.; Durán, J.L.; Bradshaw, L.M.; Farag, A.M. Ammonia and Aquatic Ecosystems—A Review of Global Sources, Biogeochemical Cycling, and Effects on Fish. *Sci. Total Environ.* **2024**, *907*, 167911. [[CrossRef](#)] [[PubMed](#)]
77. Randall, D.J.; Tsui, T.K.N. Ammonia Toxicity in Fish. *Mar. Pollut. Bull.* **2002**, *45*, 17–23. [[CrossRef](#)] [[PubMed](#)]
78. Soler, P.; Faria, M.; Barata, C.; García-Galea, E.; Lorente, B.; Vinyoles, D. Improving Water Quality Does Not Guarantee Fish Health: Effects of Ammonia Pollution on the Behaviour of Wild-Caught Pre-Exposed Fish. *PLoS ONE* **2021**, *16*, e0243404. [[CrossRef](#)] [[PubMed](#)]
79. Al-Mandhari, N.H.M. The Occurrence of Microplastic and Heavy Metals in Omani Freshwater Fishes: The Case of Muscat Cyprinion, *Cyprinion muscatense* (Boulenger, 1888). Master's Thesis, Sultan Qaboos University (Oman), Seeb, Oman, 2023.
80. Froese, R. Cube Law, Condition Factor and Weight-Length Relationships: History, Meta-Analysis and Recommendations. *J. Appl. Ichthyol.* **2006**, *22*, 241–253. [[CrossRef](#)]
81. Cano-Rocabayera, O.; Vargas-Amengual, S.; Aranda, C.; de Sostoa, A.; Maceda-Veiga, A. Mosquito Larvae Consumption in Turbid Waters: The Role of the Type of Turbidity and the Larval Stage in Native and Invasive Fish. *Hydrobiologia* **2020**, *847*, 1371–1381. [[CrossRef](#)]
82. Hooke, J.M. Extreme Sediment Fluxes in a Dryland Flash Flood. *Sci. Rep.* **2019**, *9*, 1686. [[CrossRef](#)] [[PubMed](#)]
83. Burt, J.A. Aquatic Macroinvertebrates of an Intermittent Stream in the Arid Hajar Mountains, Oman. *Tribulus* **2003**, *13*, 14–22.
84. Devlin, R.H.; Nagahama, Y. Sex Determination and Sex Differentiation in Fish: An Overview of Genetic, Physiological, and Environmental Influences. *Aquaculture* **2002**, *208*, 191–364. [[CrossRef](#)]
85. Saharwardi, M.S.; Dasari, H.P.; Hassan, W.U.; Gandham, H.; Pathak, R.; Zampieri, M.; Ashok, K.; Hoteit, I. Projected Increase in Droughts over the Arabian Peninsula and Associated Uncertainties. *Sci. Rep.* **2025**, *15*, 1711. [[CrossRef](#)] [[PubMed](#)]
86. Yousefi, M.; Jouladeh-Roudbar, A.; Kafash, A. Using Endemic Freshwater Fishes as Proxies of Their Ecosystems to Identify High Priority Rivers for Conservation under Climate Change. *Ecol. Indic.* **2020**, *112*, 106137. [[CrossRef](#)]
87. Gholamhosseini, A.; Yousefi, M.; Esmaili, H.R. Predicting Climate Change Impacts on the Distribution of Endemic Fish *Cyprinion muscatense* in the Arabian Peninsula. *Ecol. Evol.* **2024**, *14*, e11720. [[CrossRef](#)] [[PubMed](#)]
88. Fisher, D.N.; Kilgour, R.J.; Siracusa, E.R.; Foote, J.R.; Hobson, E.A.; Montiglio, P.-O.; Saltz, J.B.; Wey, T.W.; Wice, E.W. Anticipated Effects of Abiotic Environmental Change on Intraspecific Social Interactions. *Biol. Rev.* **2021**, *96*, 2661–2693. [[CrossRef](#)] [[PubMed](#)]
89. Podrabsky, J.E.; Clelen, D.; Crawshaw, L.I. Temperature Preference and Reproductive Fitness of the Annual Killifish *Austrofundulus limnaeus* Exposed to Constant and Fluctuating Temperatures. *J. Comp. Physiol. A* **2008**, *194*, 385–393. [[CrossRef](#)] [[PubMed](#)]
90. Le Cren, E.D. The Length-Weight Relationship and Seasonal Cycle in Gonad Weight and Condition in the Perch (*Perca fluviatilis*). *J. Anim. Ecol.* **1951**, 201–219.

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