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Meteorological Forcing Shapes Seasonal Surface Zooplankton Dynamics in Lake Karamurat, a Small Tectonic Lake in Türkiye

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Abstract

In temperate freshwater ecosystems, zooplankton play a crucial role in the pelagic food web and act as sensitive indicators of environmental change. They respond to shifts in water temperature, hydrodynamic mixing, and short-term meteorological events. This study investigated the epilimnetic zooplankton fauna of Lake Karamurat (Bolu, Türkiye), a small tectonic temperate lake, with a specific focus on the influence of rainfall events and wind speed on community structure. The samples were taken seasonally and horizontally using a plankton net (55 µm mesh size) and were analyzed alongside in situ physico-chemical measurements and meteorological data. In total, 74 zooplankton taxa were identified, comprising 54 rotifer species and 20 crustacean species (16 Cladocera and 4 Copepoda). *Testudinella greeni* was recorded for the first time in Türkiye, representing a new addition to the Turkish Rotifera fauna. Multivariate analyses revealed that electrical conductivity, water temperature, dissolved oxygen, precipitation, and wind speed were key drivers shaping community composition. The findings suggest that wind-driven surface mixing and episodic rainfall events enhanced vertical redistribution, leading to dominance of rotifers and small-bodied cladocerans in the epilimnion. These findings underscore the critical role of sampling strategy in shallow lakes under dynamic conditions and provide new faunistic insights into the zooplankton diversity of Anatolian lakes.

Keywords: zooplankton richness; seasonal community composition; wind-driven mixing; precipitation effects

Academic Editors: István Grigorszky, István Gyulai and Berta Csaba

Received: 11 December 2025
Revised: 14 January 2026
Accepted: 18 January 2026
Published: 21 January 2026

1. Introduction

Despite lakes only covering about 3.7% of terrestrial ecosystems [1], they have been characterized as sentinels for monitoring climate change, anthropogenic, and agricultural impacts [2]. Although approximately 90% of the world's lakes are small limnetic systems, they play a significant role in biodiversity, global biogeochemical cycles, nutrient deposition, etc. [3]. Moreover, species richness is inversely proportional to the lake area [4]. Most microscopic animals inhabit diverse environments, including lakes, ponds, rivers, and wetlands [5–7]. Because zooplanktonic organisms move passively with water currents, their community structure serves as an ideal indicator of water quality changes [8,9]. Some studies on the shallow lakes have shown that abiotic parameters (including light, water temperature, dissolved oxygen concentration, pH, electrical conductivity, salinity, nutrient levels, and turbidity) are more effective in the distribution of zooplanktonic organisms, while other studies have suggested that biotic factors (such as predation and interspecific or intraspecific competition) have a greater influence [10–13]. Furthermore, the distribution of zooplankton is significantly impacted by factors such as climate, land use, hydrological conditions, and macrophytes [14]. Unlike deep lakes, shallow lakes generally lack thermal stratification, making abiotic factors more effective in shaping zooplankton distribution [15,16]. While seasonal shifts in phyto- and zooplankton communities are well documented [17–19], surface zooplankton communities are likely to respond first to wind-driven mixing and rainfall-induced turbulence, and remain underrepresented in research on small lakes.

Small lakes are critical for freshwater biodiversity, because they serve as a refuge for many species and also provide ecosystem services such as carbon cycling and socio-economic benefits [20]. However, small and shallow lake systems are sensitive to anthropogenic activities [21]. Lake Karamurat is a small, shallow tectonic lake located in the western part of Bolu Province, Türkiye. The lake and its surroundings (coniferous forests and hilly terrain) are used for nature-based tourism and are located near a small village. Since 2021, it has been officially listed as a protected natural area under national conservation regulations. Although direct human impact is relatively low, the lake remains vulnerable to external pressure due to its small size and shallow morphology. Since zooplankton succession in dimictic and/or polymictic lakes is shaped by the nutrient availability in the lake, more diverse zooplankton groups are expected in polymictic lakes [22]. Weather conditions exert a strong influence in shallow lakes, where subsurface zooplankton communities may vary with wind-driven mixing and precipitation events. Such disturbances not only affect overall community composition but also disproportionately impact large-bodied crustaceans, particularly calanoid copepods, which are highly sensitive to turbulence, turbidity, conductivity, and trophic shifts in shallow lakes [23,24]. Previous limnological studies in Lake Karamurat have mainly focused on crustacean groups and rotifers, but detailed investigation of zooplanktonic organisms has been limited. By comparing current observations with previous records, this study also provides insights into long-term shifts in zooplankton composition. This study aims to characterize the seasonal distribution and community composition of subsurface zooplankton in Lake Karamurat. In addition, it aims to evaluate the influence of wind and precipitation on zooplankton patterns in a small tectonic temperate lake. We hypothesize that wind-driven mixing and episodic rainfall significantly alter the structure of small-bodied zooplankton taxon community.

2. Materials and Methods

Lake Karamurat is a small and shallow lake in the western part of Bolu, Turkey. The lake's origin is Tectonic with an area of 0.05 km^2 [25] and a maximum depth of 9.25 m [26]. It lies at 705 m a.s.l. and is surrounded by coniferous forest and hills. The climate of the Lake Karamurat region is "Temperate oceanic climate" (Cfb), characterized by warm temperate, fully humid, warm summer according to the Köppen-Geiger Climate Classification [27].

We sampled the lake seasonally between May 2019 and February 2020. In addition to seasonal lake sampling, we also collected samples from two inflowing springs during the summer and winter periods except in March 2020 and April 2020, when the sampling procedure could not be implemented due to COVID-19 conditions. Sampling locations and the lake region are given in Figure 1. While four stations were selected from the littoral region to represent the entire surroundings of the lake, two stations were selected from the limnetic region of the lake. We collected several physico-chemical variables and zooplanktonic organisms. Water samples for dissolved oxygen (DO), electrical conductivity (EC), pH, water temperature (WT), total dissolved solids (TDSs), and salinity (Sal) were measured with a YSI Professional Plus-Multiprobe in situ. For measuring water transparency, a Secchi disk (20 cm) was used. Precipitation and wind speed data were obtained from the nearest stations of the Turkish State Meteorological Service and also wind speed measured in the field using a Kestrel anemometer (Boothwyn, PA, USA).

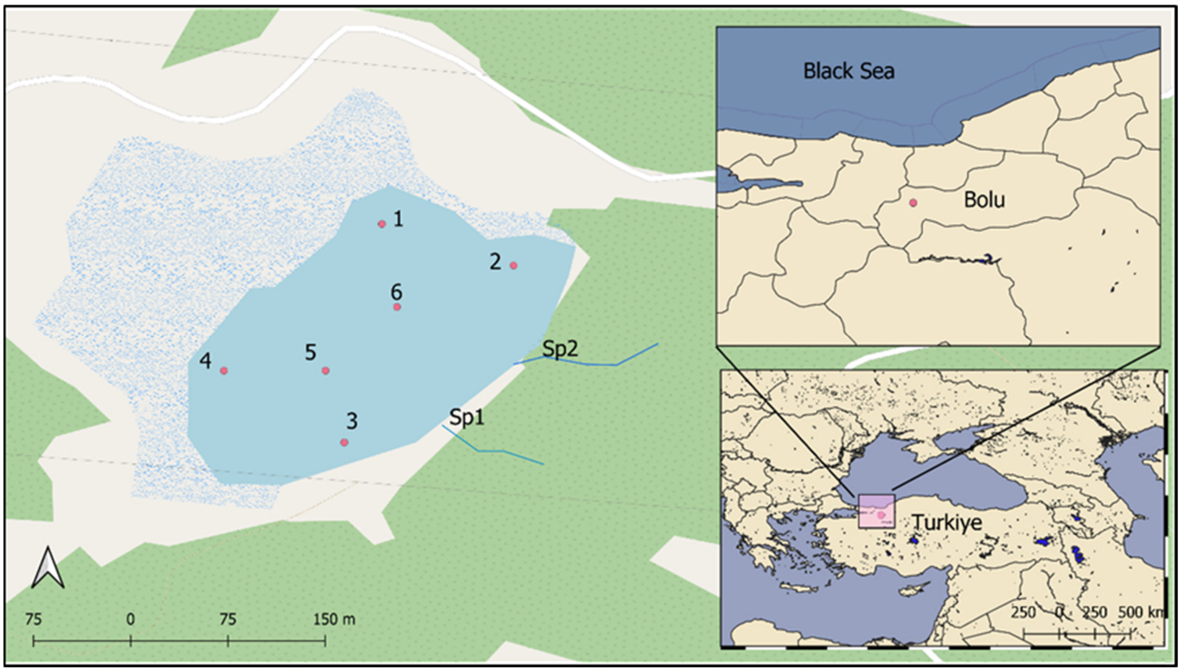

Figure 1. Map of the lake region and sampling points. Sp1 and Sp2 indicate seasonal inflowing streams active during the spring season.

Zooplankton samples were taken from the epilimnetic region of the lake. They were taken horizontally from a depth of 0.5 m below the lake surface using a Hydro-Bios Plankton Net (55 µm mesh size and 25 cm diameter) for approximately 5 min and fixed with formaldehyde solution to a final concentration of 4%. Zooplankton species were identified via inverted microscopy using a Leica DMLS microscope (Wetzlar, Germany) based on standard morphological and taxonomic characteristics. Specifically, rotifer taxa were identified following the standard taxonomic keys [28–31]; cladocerans were identified using the guides [32,33]; copepods, with particular emphasis on cylopoid taxa, were identified using taxonomic keys and reference works [25,33–39].

We tested the zooplankton communities' responses to environmental factors in different seasons with multivariate analysis models using CANOCO software version 4.5 [40]. Before the analysis, all the data (except pH and precipitation) were first $\log_{10}(x+1)$ transformed for approximate a normal distribution, and for the selection of the model, detrended correspondence analysis (DCA) was applied to species parameters. As a result of the DCA analysis, the longest gradient was found to be 5.423 and the data showed unimodal responses. Therefore, we chose canonical correspondence analysis (CCA) for the species distribution model. To evaluate statistical differences between seasons and stations, a random Monte Carlo permutation (n = 999) test was used. Additionally, the Shannon–Weaver species diversity index [41], Margalef species richness index [42] calculations, and visualizations of seasonal species presence-absence data were performed using R software (version 4.4.0) with the "vegan" package [43].

3. Results

Environmental characteristics of the lake as measured in the field are given in Table 1. The lake has two inflows and one outflow. The maximum water temperature of the lake during summer was 25.1 °C; therefore, it was classified as a temperate lake [44]. The dissolved oxygen concentration was highest during the winter period (18.99 mg L^{-1}) and lowest in fall (1.34 mg L^{-1}), but the lowest seasonal mean was generally observed during summer. Electrical conductivity and total dissolved solids reached their highest value in the fall season (218.3 µS cm^{-1} and 224.15 mg L^{-1}, respectively), while both parameters decreased in spring. Salinity remained low during the study period and showed minimal seasonal variability. The pH value of the lake revealed an alkaline profile throughout the year.

Table 1. Minimum, maximum, and mean values of environmental parameters and index results of the studied lake.

		T	DO	EC	TDS	SAL	pH	S	H′(log_2)	d
W	Mean	7.21	12.15	148.16	144.95	0.11	7.41	47	5.55	11.95
	Std. Dev.	2.31	2.28	20.87	17.79	0.02	0.91			
	Max	4.6	9.6	122.8	125.45	0.09	5.71			
	Min	11.2	18.99	208.1	183.95	0.14	8.51			
F	Mean	13.73	7.88	160.68	136.44	0.10	8.22	26	4.70	7.67
	Std. Dev.	3.66	2.79	20.98	23.99	0.01	0.22			
	Max	9.6	1.34	138.2	116.35	0.09	7.75			
	Min	20.6	12.26	218.3	224.15	0.11	8.7			
SP	Mean	17.44	7.79	115.52	88.01	0.06	8.40	20	4.32	6.34
	Std. Dev.	3.29	1.34	7.65	4.02	0.01	0.07			
	Max	11.6	6.4	105.9	83.85	0.06	8.28			
	Min	19.5	9.98	127	92.3	0.07	8.46			
SM	Mean	22.04	6.76	147.15	101.83	0.07	8.44	58	5.86	14.04
	Std. Dev.	4.67	2.24	27.23	17.94	0.01	0.14			
	Max	11.9	3.42	107	87.1	0.06	8.14			
	Min	25.1	12.98	198.4	139.1	0.1	8.69			

The units of environmental parameters are water temperature (°C), dissolved oxygen (mg L^{-1}), electrical conductivity (mS cm^{-1}), total dissolved solids (mg L^{-1}), and salinity (ppt). Abbreviations: S—total number of species; H′—Shannon−Weaver index of diversity with log_2; d—Margalef richness.

The daily precipitation and wind speed value graphs obtained by the Turkish State Meteorological Service are shown in Figure 2. According to the precipitation data of both meteorological stations, the month with the highest rainfall was February and the months with the highest rainfall per unit of time were June and late July. Both stations showed a marked decrease in precipitation during the fall, followed by an increase in January and February. Wind speed data were also measured during the field study, and the region was observed to be generally breezy, particularly in late May and August. The maximum wind speed recorded was 16.8 m sn^{-1} (6–7 Bofour) on 21 May, and August was identified as the windiest month of the year. The wind speed data revealed notable daily fluctuations, with higher intensities observed in early summer and mid-winter and calmer conditions in late autumn.

In the studied region, a total of 74 taxa were identified, included 54 rotifer species and 20 crustacean species. The crustaceans included 16 species of Cladocera and 4 species of Copepoda. All specimens are given in Table 2 A total of 26 families belonging to six orders were identified within the zooplankton community. Rotifers were represented by 20 families, whereas cladocerans and copepods were represented by four and two families, respectively. Across all seasons, the family Chydoridae was most diverse, with 12 taxa. Among the rotifers, the families Lepadellidae, Lecanidae, and Trichocercidae each contributed seven taxa to the community.

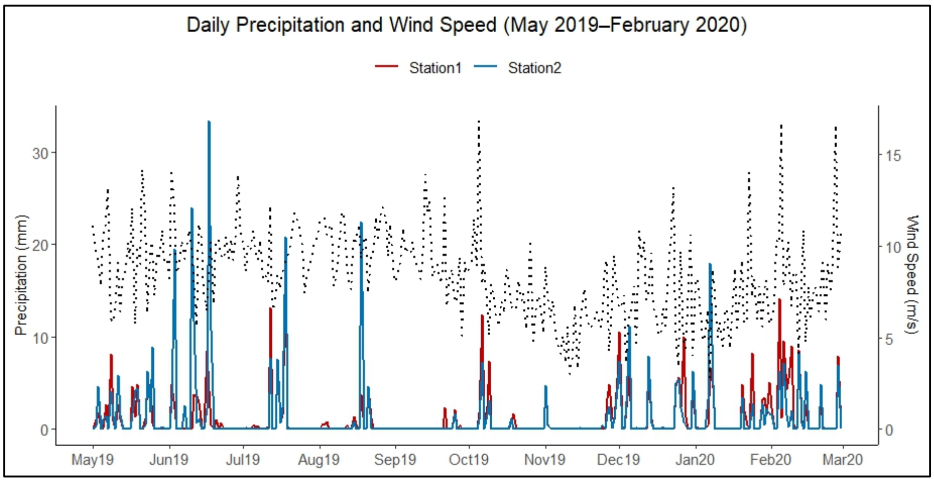

Figure 2. Time series of daily precipitation (red and blue lines represent station 1 and station 2, respectively) from two meteorological stations and daily wind speed (dashed lines) from May 2019 to February 2020 around the lake stations.

Table 2. List of zooplankton taxa found in Lake Karamurat.

	Abbr.	**SP**	**SM**	**F**	**W**		**Abbr.**	**SP**	**SM**	**F**	**W**
Rotifera											
Anureopsis fissa (Gosse, 1851)	af		X			*Lecane lunaris* (Ehrenberg, 1832)	llu	X	X		X
Ascomorpha ecaudis Perty, 1850	ae		X	X	X	*Lepadella acuminata* (Ehrenberg, 1834)	la	X	X		
Asplanchna priodonta Gosse, 1850	ap			X	X	*Lepadella ovalis* (Müller, 1786)	lo		X		
Brachionus angularis Gosse, 1851	ba				X	*Lepadella patella* (Müller, 1773)	lp	X	X	X	X
Cephalodella catellina (Müller, 1786)	cc		X		X	*Lepadella triptera* (Ehrenberg, 1830)	lt		X		X
Cephalodella gibba (Ehrenberg, 1830)	cg		X		X	*Lophocharis salpina* (Ehrenberg, 1834)	ls		X		
Cephalodella hoodii (Gosse, 1886)	ch		X		X	*Mytilina ventralis* (Ehrenberg, 1830)	mv		X		
Collotheca pelagica (Rousselet, 1893)	cp		X	X	X	*Notholca acuminata* (Ehrenberg, 1832)	na	X			
Collotheca mutabilis (Hudson, 1885)	cm		X		X	*Notholca squamula* (Müller, 1786)	ns	X			
Colurella adriatica Ehrenberg, 1831	ca		X	X	X	*Philodina megalotrocha* Ehrenberg, 1832	pm		X	X	X
Colurella colurus (Ehrenberg, 1830)	cco		X	X		*Platyias quadricornis* (Ehrenberg, 1832)	pq		X		
Encentrum mustela (Milne, 1885)	em		X		X	*Polyarthra dolichoptera* Idelson, 1925	pd	X		X	
Euchlanis deflexa Gosse, 1851	ed				X	*Polyarthra vulgaris* Carlin, 1943	pv	X	X	X	X
Euchlanis dilatata Ehrenberg, 1830	edi	X	X		X	*Pompholyx sulcata* Hudson, 1885	ps		X		X
Filinia longiseta (Ehrenberg, 1834)	fl			X		*Rotaria rotatoria* (Pallas, 1766)	rr		X		
Filinia opoliensis (Zacharias, 1898)	fo		X	X		*Synchaeta oblonga* Ehrenberg, 1832	so				X
Dicranophorus epicharis Harring & Myers, 1928	de		X			*Synchaeta pectinata* Ehrenberg, 1832	sp		X	X	X
Gastropus stylifer Imhof, 1891	gs			X	X	*Testudinella greeni* Koste, 1981 *	tg		X		X
Habrotrocha tripus (Murray, 1907)	ht				X	*Testudinella patina* (Hermann, 1783)	tp				X
Itura aurita (Ehrenberg, 1830)	ia		X			*Trichocerca capucina* (Wierzejski & Zacharias, 1893)	tc		X	X	X
Keratella cochlearis (Gosse, 1851)	kc	X	X	X	X	*Trichocerca cylindrica* (Imhof, 1891)	tc		X		X
Lecane bulla (Gosse, 1851)	lb		X			*Trichocerca porcellus* (Gosse, 1851)	tpo	X		X	
Lecane closterocerca (Schmarda, 1859)	lc		X		X	*Trichocerca pusilla* (Jennings, 1903)	tpu		X		
Lecane flexilis (Gosse, 1886)	lf		X			*Trichocerca rattus* (Müller, 1776)	tr		X		
Lecane hamata (Stokes, 1896)	lh		X	X	X	*Trichocerca similis* (Wierzejski, 1893)	ts		X		
Lecane inermis (Bryce, 1892)	li				X	*Trichocerca tenuior* (Gosse, 1886)	ttn		X	X	X
Lecane luna (Müller, 1776)	ll		X			*Trichotria tetractis* (Ehrenberg, 1830)	tt	X			X
Cladocera											
	Abbr.	**SP**	**SM**	**F**	**W**		**Abbr.**	**SP**	**SM**	**F**	**W**
Acroperus harpae (Baird, 1834)	ah	X	X	X	X	*Bosmina longirostris* (O.F. Müller, 1785)	bl		X		
Alona affinis (Leydig, 1860)	af		X		X	*Chydorus ovalis* Kurz, 1875	co	X	X		X
Alona costata G.O. Sars, 1862	ac	X	X	X		*Chydorus sphaericus* (O.F. Müller, 1776)	cs		X	X	X
Alona guttata G.O. Sars, 1862	ag		X	X	X	*Macrothrix laticornis* (Jurine, 1820)	ml	X	X		X
Coronatella rectangula (G.O. Sars, 1862)	cr		X		X	*Pleuroxus aduncus* (Jurine, 1820)	pa		X	X	X
Alonella excisa (Fischer, 1854)	aex		X		X	*Peracantha truncata* (O.F. Müller, 1785)	pt				X
Alonella exigua (Lilljeborg, 1853)	aexi		X			*Scapholeberis mucronata* (O.F. Müller, 1776)	sm	X	X	X	
Alonella nana (Baird, 1843)	an	X	X	X	X	*Simocephalus vetulus* (O.F. Müller, 1776)	sv	X	X		
Copepoda											
	Abbr.	**SP**	**SM**	**F**	**W**		**Abbr.**	**SP**	**SM**	**F**	**W**
Canthocamptus staphylinus Jurine, 1820	ct	X	X		X	*Paracyclops fimbriatus* (Fischer, 1853)	pf				X
Thermocyclops dybowskii (Landé, 1890)	td		X	X	X	*Megacyclops viridis* (Jurine, 1820)	mvr	X	X		X

Abbreviations: W—winter; F—fall; SP—spring; SM—summer; *—new record for the Turkish Rotifera fauna and the Palearctic region. Abbreviations of the species are provided for use in CCA triplots.

In terms of species diversity and richness, the surface zooplankton diversity was found to be quite high in the summer and winter seasons (as shown in Table 1 and Figure 3). Fifty-eight individuals were identified in the summer period, while forty-seven were observed in the winter, and twenty-six and twenty individuals were observed in the fall and spring, respectively. Both fall and spring had comparatively lower richness for all groups. Shannon−Weaver diversity (H′) values were consistently high across seasons, ranging from 4.32 to 5.86, and have compatible results with the species richness. Margalef richness followed a similar seasonal pattern with the diversity, reflecting reduced taxonomic richness in transitional seasons. A total of 40 rotifer species were recorded during summer, followed by 32 in winter. Cladoceran richness peaked in summer, while copepods show low diversity across all seasons. The following species have been observed throughout the year: *Keratella cochlearis*, *Lepadella patella*, and *Polyarthra vulgaris* from the rotifer group, and *Acroperus harpae* and *Alonella nana* from the cladocerans. Interestingly, no calanoid copepods were observed or recorded during any season.

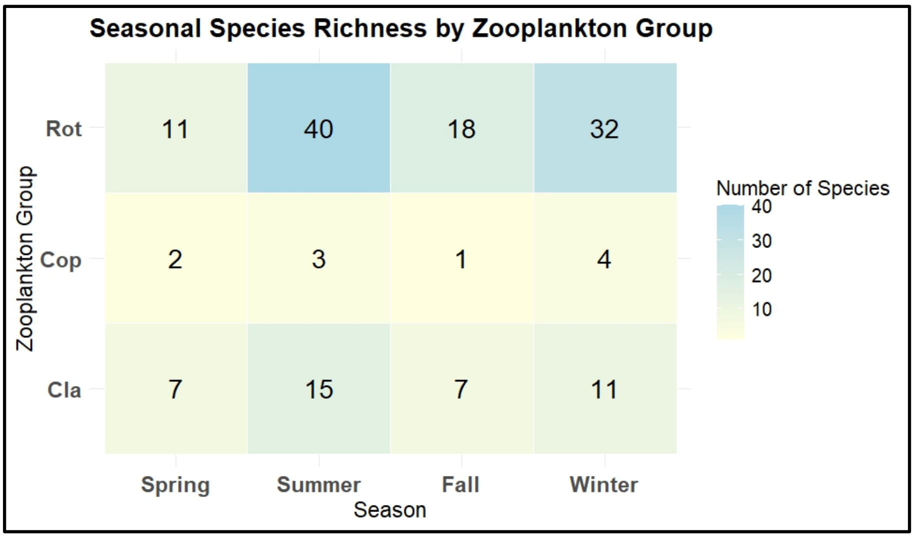

Figure 3. Seasonal species richness of zooplankton groups in the studied lake. The heatmap represents the number of taxa observed in each group during sampling seasons.

The physico-chemical parameters (given in Table 1) were used as explanatory variables in CCA to evaluate the relationship between environmental characteristics and seasonal zooplankton distribution. The CCA triplots explain 42.7% (Axis 1: 22.9%, Axis 2: 19.8%) of the variation in species distribution based on environmental variables. In the micro-crustacean CCA triplot (Figure 4), summer samples were clustered along the gradients of higher EC and water temperature, and were associated with the cladoceran species such as *C. ovalis* and *B. longisrostris*. In contrast, winter samples were positioned near the DO and precipitation, and were positively correlated with species such as *P. truncata* and *P. fimbriatus*. In the rotifer CCA triplot (Figure 5), rotifer taxa were positively correlated with DO, precipitation, and wind speed, with most of these species associated with the winter and spring samples. Each season grouped distinct clusters in the triplots based on taxonomic composition. Spring and summer samples were located in the same region of the triplot, close to the temperature eigenvector, whereas winter and fall samples grouped in areas associated with lower temperature and higher DO values.

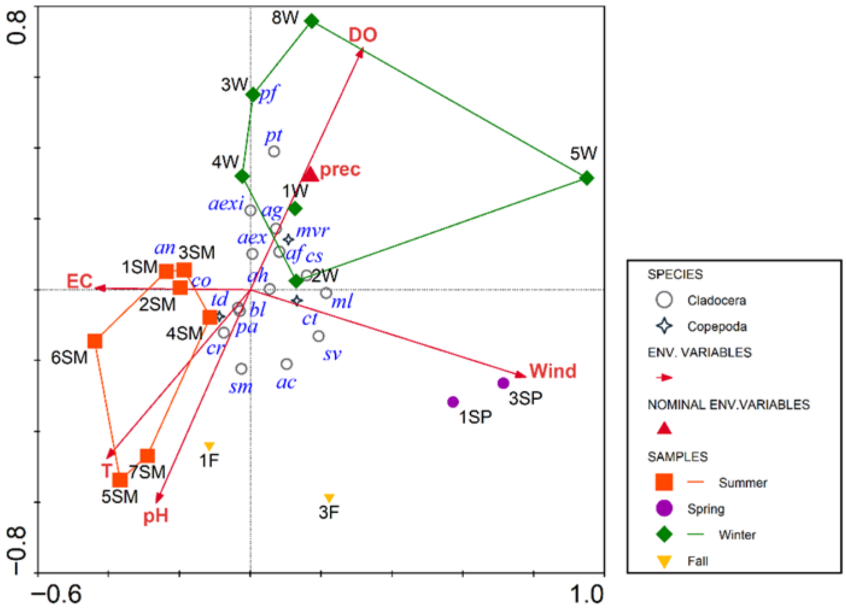

Figure 4. Microcrustacean CCA triplot diagram showing the seasonal distribution of Cladocera and Copepoda taxa in relation to environmental variables. Summer samples are associated with higher EC and temperature, while winter samples are related to DO and precipitation. The abbreviations of taxa are given in Table 2.

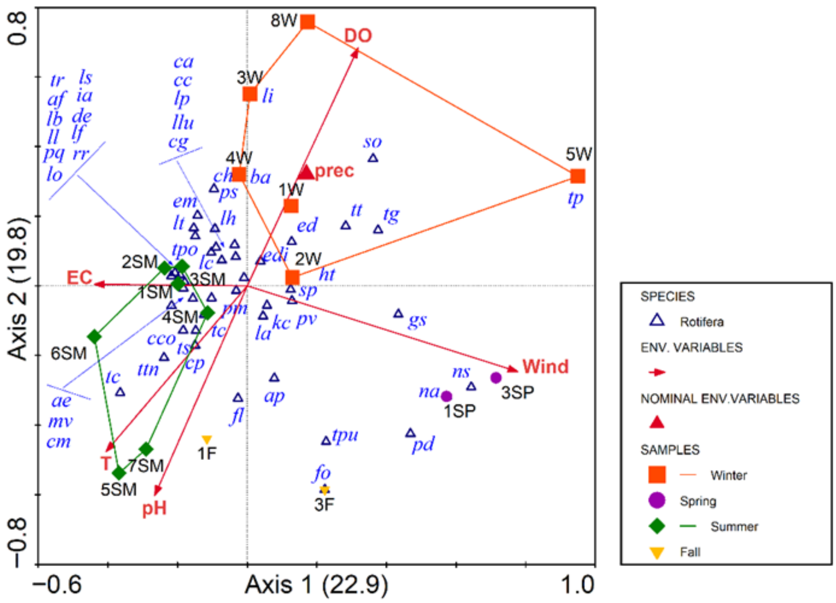

Figure 5. Rotifer CCA triplot diagram showing the distribution of rotifer taxa by season and environmental gradients. Rotifer communities are positively correlated with DO, precipitation, and wind, especially during winter and spring. The abbreviations of taxa are given in Table 2.

4. Discussion

This study focuses on the zooplankton community patterns of a small lake, Lake Karamurat, and the environmental parameters that may be effective in influencing species diversity, richness, distribution, etc. Our findings strongly support the hypothesis that wind-driven mixing and episodic rainfall selectively favor small-bodied zooplankton taxa in the epilimnion. These microscopic animals have diversities that depend on some abiotic and biotic parameters as well as lake area, meteorological conditions, pray and predator interactions, water temperature, etc. Although the lake covers a small area, observed zooplankton diversity was quite high. Species richness of microcrustaceans is positively influenced by lake area [45]; however, our study revealed that, despite the small surface area of the lake, it exhibited high richness in both microcrustaceans and rotifers. In a study conducted by Özdemir Mis et al. (2017) in the Western Black Sea region, including Lake Karamurat, 13 to 41 taxa were identified in lakes with surface areas ranging from 0.05 to 15.62 km^2 across 13 different lakes [25]. In the same region, Lake Poyrazlar has 57 zooplankton taxa with a surface area of 0.6 km^2 [18]. In our study, 74 taxa were identified, which is quite high compared to the rates in the region. Rotifera dominated the zooplankton community, comprising 72.97% of the identified taxa, followed by Cladocera (21.62%) and Copepoda (5.40%). The majority of the identified rotifer species belonged to the cosmopolitan genera Trichocerca, Lecane, Lepadella, and Cephalodella, which are commonly associated with lentic systems characterized by submerged aquatic plants.

In the Lake Rotifera community, *Testudinella greeni* is the new record for the Turkish Rotifera fauna. *T. greeni* has been recorded by researchers from Nigeria, Australia, Malaysia, Thailand, Argentina, and India [46–52]. In Segers' 2007 publication, it was reported that this species is found in Afrotropical, Australian, Neotropical, and Oriental regions [52]. It is understood that this species is a new record not only for the Turkiye but also for the Palearctic region.

Previously, studies were focused on cladoceran fauna in 1997, on both physico-chemical and zooplankton fauna in 2017, and finally on the limoecological characteristics of the Lake Karamurat and Ostracoda fauna in 2023 [25,26,53]. In 1997, *Daphnia longispina* was reported from the lake [53], and *D. longispina* and *D. cucullata* species from *Daphnia longispina* complex were identified in 2017 [25]. However, we did not find any Daphnia species in the lake during our study, unlike the study conducted ten years ago. Although the species belonging to the *D. longispina* complex are pelagic, this may be due to diurnal vertical migration (avoiding predation or tracking food) and their preference for the hypolimnion zone. We think that the same situation may also be possible for *D. brachyurum*, a large-bodied Cladocera previously reported in 1997. However, even though we conducted our study in the subsurface area of the lake, we found quite high numbers of Cladocera species. Only 1 of the 16 species, *S. vetulus*, has the structure of a large-bodied Cladocera. Perhaps, with wind and rainfall events, rotifers and small-bodied Cladocera tend to be more abundant in the epilimnion.

During seasonal sampling in the lake, nauplii and copepodites were detected in the coastal region (sampling points 1, 2, 3, and 4 in Figure 1). However, neither large nor small-bodied calanoid species were observed, and *Acanthodiaptomus denticornis*, previously reported in the lake, was not found in our study. It is known that *A. denticornis* shows shore avoidance behavior and populates open water [54], but their absence from pelagic samples suggests that habitat selection alone cannot explain their disappearance.

In shallow lakes, large-bodied calanoids are particularly sensitive to wind-driven mixing, increased turbidity, and trophic alteration [23]. *A. denticornis* has been more vulnerable to fish predation, and due to competition with cyclopoids, it has declined over the years. The absence of calanoids in shallow, alkaline lakes (pH > 6) is an indicator of trophic status [55]. Therefore, the disappearance of these organisms over the years may be affected by the lake's trophic structure. Thus, the most plausible explanation for the loss of calanoid copepods in Lake Karamurat is a combination of disturbance-driven habitat instability and long-term trophic alteration, rather than short-term behavioral avoidance. At the family level, the zooplankton community of Lake Karamurat was largely composed of small-bodied taxa. The members of the families Lecanidae, Lepadellidae, and Trichocercidae accounted for the highest taxonomic richness among rotifers. These families were represented across seasons with increased richness during summer and winter periods. These periods showed higher wind activity and precipitation (Figure 2 and

Table 2). In turbid environments, rotifers may be indirectly affected (reduced competition and predation pressure), and their short development time and rapid population rates may help them dominate in such environments [23,24]. Larger zooplankton such as calanoid copepods and large-bodied Cladocera are more negatively affected under turbid conditions [56]. Therefore, the dominance of these small bodied rotifer families in Lake Karamurat appears consistent with a disturbance driven community structure shaped by meteorological events.

According to the 2019 report of the General Directorate of Meteorology (GDM), there is a temperature anomaly of 1.1 to 2 °C in the region where Lake Karamurat is located, and the precipitation regime is within seasonal norms [57]. Numerous studies have demonstrated that increasing temperature can reduce zooplankton body size, lead to the loss of cold stenothermic species and indirectly affect community structure through changes in salinity and mixing dynamics [10,58–60]. In addition, warmer winters are expected to affect the mixing regime of small lakes [60], and it may influence the benthic zone zooplanktonic organisms during the stagnation period. Therefore, other organisms in the lake will be impacted by this change.

The meteorological data suggest that the summer months, especially June and July, were dominated by rainfall events, which are characterized by short duration and high intensity. The simultaneous occurrence of precipitation peaks and wind speed maxima, particularly in late spring and winter, could indicate surface mixing patterns. Zooplankton composition and species richness closely tracked these meteorological patterns, rather than reflecting seasonal temperature variation alone. The seasonal trend in species richness reflects ecological responses to shifting environmental conditions throughout the year (Figure 3). Periods of increased zooplankton richness (summer and winter) coincided with higher wind activity and precipitation events, particularly in June and January–February. CCA (Figures 4 and 5) further revealed that rotifer taxa were positively associated with wind speed and precipitation, whereas cladocerans and copepods (Table 2) showed weaker or no association with these drivers. These meteorological conditions may have enhanced water column mixing, favoring small-bodied zooplankton such as rotifers. The advantages of rotifers, rapid reproduction times, and reduced predation in turbid environments may explain how quickly they become dominant in the environment. In contrast, calmer and drier periods in spring and fall corresponded to reduced richness, supporting the role of meteorological dynamics in structuring seasonal zooplankton communities.

Despite its small surface area (~0.05 km^2), Lake Karamurat exhibited notably high zooplankton diversity, reflected in consistently elevated Shannon–Weaver (from 4.32 to 5.86) and Margalef indices. While species richness is commonly linked to lake area, habitat heterogeneity, and macrophyte coverage [61–64], the high diversity observed in this study underscores the importance of sampling strategy in small, dynamically mixed lakes. Surface-focused horizontal sampling likely captured a substantial proportion of taxa that may be underestimated by conventional approaches [65], particularly under conditions of frequent wind-driven mixing and episodic disturbance. These findings highlights that the variation in zooplankton diversity in shallow lakes is shaped not only by size but also by physical stressors and methodological approaches.

This study demonstrates that short-term meteorological forcing, particularly wind-driven mixing and episodic precipitation, plays a key role in structuring surface zooplankton communities in small shallow tectonic lakes. Despite its small surface area, Lake Karamurat exhibited high zooplankton diversity, largely driven by rotifers and small-bodied cladocerans that thrive under mixed conditions. In contrast, calanoid copepods and large bodied cladoceran (*Daphnia* sp.), previously reported in the lake, were absent, likely reflecting long-term trophic alteration and disturbance-driven habitat instability. These

https://doi.org/10.3390/d18010055

results highlight that surface-focused horizontal sampling can reveal higher zooplankton diversity in small shallow lakes than expected from lake size alone. In the context of ongoing climate change, with projected warmer winters and increased rainfall-driven mixing, the restructuring of zooplankton communities caused by such shifts may become more apparent. Finally, the detection of *Testudinalla greeni* represents not only a new record for Türkiye but also the first record for the Palaeoarctic region, underlining the faunistic and biogeographical significance of detailed zooplankton surveys in small, understudied lake ecosystems.

Author Contributions: P.G. conceptualized the paper, conducted data analysis and wrote the paper. A.A. participated in field data collection, identified species and revised the paper. O.K. was involved in the field study and conducted data analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We thank Çağdas Güleç, Filiz Batmaz, Çağatay Çapraz, Ahmet Özdilek, and Alper Ataman for their help during the field works.

Conflicts of Interest: The authors declare no conflicts of interest.

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