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Posted Date: 24 January 2024

doi: 10.20944/preprints202401.1696.v1

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Article

Biodiversity and Environmental Factors Structuring Diatom Assemblages in the Protected High-Mountains Lakes of the Kaçkar Mountains National Park (Rize, Turkey)

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Abstract: The altitude of the habitat is one of the important regulators of species survival. Kaçkar Mountains National Park is located in the Eastern Black Sea region of Turkey. This is the first study on the benthic diatom flora of the high mountain lakes in Kaçkar Mountains National Park, which is situated between 2782 and 3075 m a.s.l. A total of 84 diatom species were identified from benthic communities of 15 habitats in summer (19 July, 28 August) and autumn (10 September) months of 2020. The genus Pinnularia (13 species) formed the basis of the taxonomic list followed by Eunotia (5 species), Navicula (5 species), and Frustulia (4 species) genera, respectively. The waters in all the studied lakes were fresh, low-saline, with low-alkaline or circumneutral pH and organically uncontaminated as evidenced by prevailed bioindicator groups. Statistical methods and comparative floristic results confirm the role of the lake altitude for the diatom species distribution. Species richness was higher in lakes with lower altitude, but a statistical approach also revealed a tendency for it to increase with altitude if species richness increased. Further studies will be needed to continue exploring this pattern. In the first round of analysis, diatom species groups were categorized according to IUCN categories, revealing one potentially threatened and one rare species. To protect studied high mountain lakes, their ecological conditions must be constantly monitored in the Kaçkar Mountains National Park.

Keywords: high mountain lakes; diatoms; benthic habitats; environmental factors; bioindicator; threatened and rare species; Kaçkar Mountains National Park; Turkey

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1. Introduction

Siliceous crystal mountain ranges are among the highest altitude regions in the world. This feature allows them to harbor pristine biodiversity, provide recreation areas, and maintain healthy water resources. Therefore, they hold a prominent position among natural areas that need protection [1]. The mountains in the Black Sea Region of Turkey rise from west to east, and their height reaches 3932 m in the Kaçkars. Kaçkar Mountains have rich flora and fauna as well as many water sources (lakes, streams, rivers, mineral and thermal springs). The area, which has remarkable geological and geomorphological formations, was taken under protection in 1994 [2].

High mountain lakes are habitats where a limited number of species live, as they generally have low nutrient and ion concentrations [3]. They are also sensitive to climate change, dissolved organic carbon and nitrogen inputs [4,5]. Increases in air temperature, changes in snow and ice cover on mountains in some regions have changed the functioning, diversity, and productivity of these lakes [6–8]. Despite these effects, high mountain lakes are still considered as undisturbed ecosystems [9].

Biodiversity, which bears the evidence of evolutionary processes, plays an important role in the maintenance of ecological functions and the stability of the ecosystem [10]. At the same time, biodiversity is also used to evaluate the environmental status of aquatic ecosystems [11]. Diatoms, which are found in almost all aquatic ecosystems, are an important group of algae used in evaluation of water quality [10]. Diatoms, which have very important ecological functions, contribute 20-25% to the world's global primary production, carbon fixation and oxygen release to the atmosphere, thanks to their photosynthetic activities [12,13]. In addition, the annual amount of carbon fixation by diatoms represents 40% of total primary production in seawater, an amount equivalent to the total amount fixed by all terrestrial tropical forests [14]. Therefore, examining the diatom communities in the sediments of high mountain lakes and using the obtained information in the creation of diatom-based biomonitoring programs will be the most effective way to understand the response of these lakes to climatic change [15].

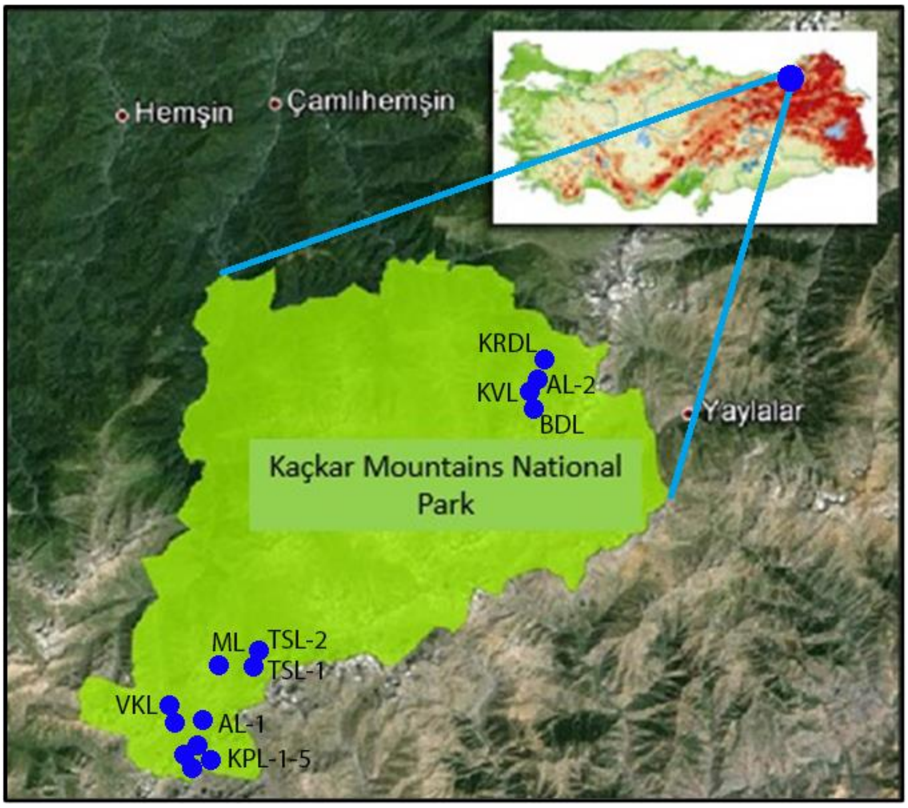
In the biomonitoring system of high mountain lake ecosystems of Eastern Black Sea region, the need to study the taxonomy and ecology of benthic diatoms increases with the accumulation of data on their species diversity in the different ecotopes. The studies have been carried out on the benthic diatom flora of high mountain lakes and the physico-chemical properties of their waters in the region since 1990 [16–19]. However, until now, no information has been obtained about the diatom flora of the high mountain lakes in the Kaçkar Mountains National Park.

Accordingly, the aim of this study is: (1) to determine the benthic diatom flora and physico-chemical environmental variables of 14 high mountain lakes and a pond in the Kaçkar Mountains National Park; and (2) to examine the relationship between their diversity and environmental factors and to determine the IUCN category of rarity and endemism.

2. Materials and Methods

2.1. Description of study site

Kaçkar Mountains National Park was declared as a national park in 1994 due to its interesting geological and geomorphological structure and richness of plants and wildlife. The park, which covers a total area of 51,550 hectares, is administratively located between Rize, Artvin, and Erzurum Provinces (40°57'49'' - 40°42'10'' north latitudes and 41°14'45''- 40°51'27'' east longitudes) (Figure 1) [2]. The Kaçkar Mountains, featuring interesting formations in terms of geology and geomorphology, rank as the 4th highest mountains in Turkey with an altitude of 3,932 meters.



 doi:10.20944/preprints202401.1696.v1

Figure 1. Geographical location of Kaçkar Mountains National Park (http//national parks of turkey.com) and the studied lakes as blue dots.

According to the climatic characteristics, the area of the park under study is typical for the Eastern Black Sea climate type. In the lower, northern part of the Kachkar Mountains National Park, for example around the Ayder Plateau, temperatures range from 0 °C to 4 °C in the winter months, while rising above 18 °C in summer. On the other hand, at an altitude of more than 3000 m in the mountains of the southern part of the park, temperatures in winter drop to -6 °C and in summer range from 6 to 9 °C. In the park, the annual average precipitation is over 2000 mm [2]. In high alpine areas, it is usually covered with snow from late September to mid-May, and many glacial lakes, large and small, are encountered in areas covered with glaciers. The richness of the current glaciation and other natural values in the Kaçkar Mountains attracts mountaineers, tourists, and scientific circles. Along with many glaciers in this area, there are glacial lakes, glacial valleys, circuses, and moraines [20]. The park area also has important flora and fauna features in terms of biodiversity. According to Davis, the floristic region where the research area is located is the Colchis (Colchis) part of the Euro-Siberian floristic region. In the forest belt, there are broad-leaved conifers and *Fagus orientalis*, *Castanea sativa*, *Carpinus* sp. In the alpine zone, there is a very rich vegetation with many endemic and relict species. This is the only place in Turkey where Rhododendrons reach 3000 m. It is one of the hotspot areas in Turkey and the surrounding floristic region due to the presence of natural old forests and other vegetation characteristics in the area. In the study area, which is one of the three important routes in terms of bird migration, the Northeast-South migration route is the most important route of the Western Palearctic in terms of daytime raptors [21].

Figure 2. View of the studied lakes in the Kaçkar Mountains National Park in 2020. North group a, Karadeniz Lake, b, Büyük Deniz Lake; Central group, c, Moçar Lake, d, Tatos Sulak Lakes 1-2; South group, e, Kapılı Lakes 1-4, f, Vercenik Kumlu Lake. Photo by Bülent Şahin.

2.2. Methods of Sampling and Laboratory Studies

In the Kaçkar Mountains Natural Park, there are 100 glacial in origin lakes [2]. In this study, it was visited only 14 of them (Table 1). In addition, algae samples were also taken from a pond.

Table 1. Geographic coordinates, altitude and surface area information of the lakes, algae samples were taken in Kaçkar Mountains National Park.

Lake with abbreviation	Geographic coordinates	Altitude (m)	Area (km²)
Kapılı Lake-1 (KPL-1)	40°42′56″.59 N; 40°54′51″.71 E	2980	0.71
Kapılı Lake-2 (KPL-2)	40°43′08″.70 N; 40°54′55″.30 E	2973	0.15
Kapılı Lake-3 (KPL-3)	40°42′34″.73 N; 40°54′49″.02 E	3074	0.36
Kapılı Lake-4 (KPL-4)	40°42′43″.97 N; 40°54′47″.24 E	3028	0.05
Kapılı Lake-5 (KPL-5)	40°42′59″.03 N; 40°54′20″.06 E	2926	0.07
Vercenik Kumlu Lake (VKL)	40°43′17″.91 N; 40°54′16″.58 E	2864	0.03
Karadeniz Lake (KRDL)	40°52′39″.19 N; 41°10′ 02″.06 E	2782	0.24
Kavron Lake (KVL)	40°52′24″.39 N; 41°09′45″.73 E	2911	0.09
Büyük Deniz Lake (BDL)	40°52′04″.60 N; 41°09′38″.54 E	2922	0.68
Adsız Lake-1 (AL-1)	40°42′39″.75 N; 40°54′57″.65 E	3075	1.62
Adsız Lake-2 (AL-2)	40°52′21″.18 N; 41°10′06″.94 E	2868	0.04
Moçar Lake (ML)	40°44′11″.63 N; 40°56′05″.36 E	2958	0.22
Tatos Sulak Lake-1 (TSL-1)	40°44′16″.11 N; 40°56′42″.25 E	2976	0.46
Tatos Sulak Lake-2 (TSL-2)	40°44′25″.50 N; 40°56′51″.18 E	2940	0.17

Located in the alpine zone (2782-3075 m a.s.l.), these lakes are covered with ice for at least 8 months of the year. Climatic conditions allow us to visit the lakes in summer and early autumn months. Epipelic, epilithic and epiphytic algae samples were taken on 19 July, 28 August, and 10 September 2020. Epipelic samples were taken with the help of a glass pipe, which is 1 m long and 0.8 cm diameter from the surface of the sediments of all lakes and a pond. Epilithic samples were obtained from only TSL-1, 2, BDL, and KVL, scraped from randomly chosen stones with the toothbrush, and washed into plastic bottles. Epiphytic algae samples were taken by squeezing out the macrophyte plants (*Potamogeton* sp. and *Juncus* sp.) from KVL and AP [22,23]. All samples were placed in 100 ml plastic bottles and fixed with 4% formaldehyde. Thermo Orion-4-Star pH (Hampton, NH, USA, Marshall Scientific) and YSI-55 (Letchworth, Hertfordshire, United Kingdom, Xylem Analytics) portable meters were used to measure water temperature, dissolved oxygen, conductivity, and pH. In the lab, the samples were treated with H_2SO_4 and HNO_3 and washed with distilled water [22]. And then, the cleaned diatom shells were placed in Naphrax®. Leica DM 2500 light microscope and Leica MC170 HD camera (Wetzlar, Germany, Leica Microsystems) were used to examine and photograph the diatoms. Other chemical analyzes of the waters were carried out in the DSI General Directorate Laboratories DSI 22nd Regional Directorate Quality Control and Laboratory Branch Office.

To identify the diatom species, relevant books were used [24–35]. The current names of the species were checked in AlgaeBase [36].

Frequencies of algal taxa were determined based on the number of lakes in the Kaçkar Mountains Natural Park where species were found, according to the following scale. Very rare (VR): taxa recorded in 1-20% of investigated lakes; rare (R) - in 21-40%; common (C) - in 41-60%; frequent (F) - in 61-80%; very frequent (VF) - in 81-100% [37].

The ecological preferences of the identified communities in lakes were determined by bioindication methods [38]. For each species, its indicator properties for one or more environmental variables were identified [39,40]. Then, data on the abundance of species in a particular lake were summarized for each indicator group. The distribution of the number of species with the same indicator properties was plotted by ecological groups for each environmental variable. The class of water quality indicators was grouped by the range of the species-specific index of saprobity S: class 1, S = 0.0–0.5; class 2, S = 0.5–1.5; class 3, S = 1.5–2.5; class 4, S = 2.5–3.5 [38]. In total, groups of indicators for nine environmental variables were used for analysis. The arrangement of groups of indicators for each environmental variable on the histogram was in increasing order of indicated variable.

Bray-Curtis's analysis was performed using BioDiversity Pro 9.0 and a similarity tree was constructed. Pearson correlation coefficients were calculated using [41]. Correlation analysis of species data in each lake was performed as a network graph in JASP (Jeffrey's Amazing Statistics Program 0.16.4) statistics botnet package with R [42]. Three-dimensional surface plots of the number of species versus individual parameters were constructed in Statistica 12.0 using the distance-weighted least squares method. For comparison, for each graph, one main parameter and two others are selected, within which the program calculates probable changes in the main parameter. Thus, the resulting graph shows the trends in each of the related parameters. From here, extreme values may appear that are not real, but only reflect trends for a given distribution. The graph can be interpreted as a trend of changes (increases or decreases) in the values of the main parameter (z-axis) when the other two parameters (x and y-axis) change. Redundancy discriminant analysis (RDA) to calculate the relationship between biological dominant variables and environmental variables was performed using the CANOCO program [43].

Rare and endangered species are noted based on the distribution of well-studied diatoms in Central Europe [44] in comparison with IUCN (International Union for Conservation of Nature) criteria [45] (Table 2).

Table 2. Threat categories for diatom species and number of taxa in 14 high mountain lakes in the Kaçkar Mountains National Park, 2020.

IUCN Category	IUCN Code	No of Red List Category	Red List Category	Number of taxa
EXTINCT	EX	1	Extinct or Lost	0
CRITICALLY ENDANGERED	CR	2, 3	Threatened with Extinction, Highly Threatened	1
ENDANGERED	EN	4, 5	Threatened, Threat of Unknown Extent	13
VULNERABLE	VU	6	Extremely Rare	0
NEAR THREATENED	NT	7	Near Threatened	19
LEAST CONCERN	LC	9	Not Threatened	34
DATA DEFICIENT	DD	8	Data Deficient	6
NOT EVALUATED	NE	0, 10	Not established	2

3. Results

3.1. Physical and chemical properties of waters

The water temperatures of the studied lakes fluctuated between 7.1-22.5 °C. While the pH values of the waters were determined between 6.10-8.21, the dissolved oxygen values were measured between 8.02-9.17 mg L^{-1}. Total dissolved solids were 9.92-44.27 mg L^{-1} and electrical conductivity values were found as 14.1-71.4 µSm cm^{-1}. Total hardness was measured in the range of 17.59-38.84 mg L^{-1} in the KPL-1,2,3,4,5, BDL and ML. The amount of nitrate that could not be detected in the waters of KPL-1, VKL and KVL was detected in the range of 0.207-0.575 mg L^{-1} in other lakes. Nitrite was detected as 0.020 mg L^{-1} in ML and TSL-1, while phosphate was detected as 0.113 mg L^{-1} only in KPL-5. Potassium, calcium, magnesium, ammonium, and chlorine values of the waters were also determined (Table 3).

Table 3. Averaged physical and chemical data of the 14 high mountain lakes in the Kaçkar Mountains National Park, 2020.

Parameters	KPL-1	KPL-2	KPL-3	KPL-4	KPL-5	VKL	KRDL	KVL	BDL	AL-1	AL-2	ML	TSL-1	TSL-2
Temperature (°C)	14.2	14.0	14.5	14.0	14.8	22.5	12.5	14.7	11.2	17.6	7.1	12.2	13	13
DO (mg L^{-1})	8.03	8.33	8.14	8.02	8.20	8.18	8.89	8.55	8.69	7.98	8.97	9.03	9.17	8.90
pH	6.30	6.30	6.55	6.32	8.21	7.88	6.33	7.18	6.10	7.30	6.54	7.13	6.9	6.9
Conductivity (µSm cm^{-1})	23.4	23.2	27.1	26.0	29.30	22.9	36.8	19.9	71.4	14.1	38.9	46	40	40
TDS (mg L^{-1})	17.73	15.93	18.72	18.23	20.46	17.86	22.82	12.34	44.27	9.92	27.34	21.89	20.34	19.84
Potassium (mg L^{-1})	0.37	0.37	0.50	0.40	0.47	-	-	0.38	0.44	0.35	-	-	-	-
Total hardness $CaCO_3$ (mg L^{-1})	17.96	17.64	19.94	19.70	23.60	-	-	-	38.84	-	-	17.59	-	-
Calcium (mg L^{-1})	5.13	5.00	5.92	5.82	7.17	-	-	4.02	12.69	-	7.25	4.52	5.30	5.33
Magnesium (mg L^{-1})	-	-	-	-	1.38	-	-	-	1.73	-	-	1.53	-	-
Ammonium (mg L^{-1})	0.31	0.28	0.34	0.23	0.40	0.35	0.17	0.76	0.82	0.31	0.13	0.11	0.08	0.12
Chlorine (mg L^{-1})	2.11	1.77	2.20	2.70	1.98	1.51	7.51	2.44	1.70	2.02	7.48	7.26	7.03	7.74
Nitrate (mg L^{-1})	-	0.214	0.207	0.232	0.330	-	0.575	-	0.233	0.225	0.515	0.361	0.279	0.218
Nitrite (mg L^{-1})	-	-	-	-	-	-	-	-	-	-	-	0.020	0.020	-
Phosphate (P_2O_5) (mg L^{-1})	-	-	-	-	0.113	-	-	-	-	-	-	-	-	-

Note: (-): Could not be detected as below the determination level. Variables in AP pond was not tested because water sample was lost.

3.2. Floristic composition and diversity of diatoms

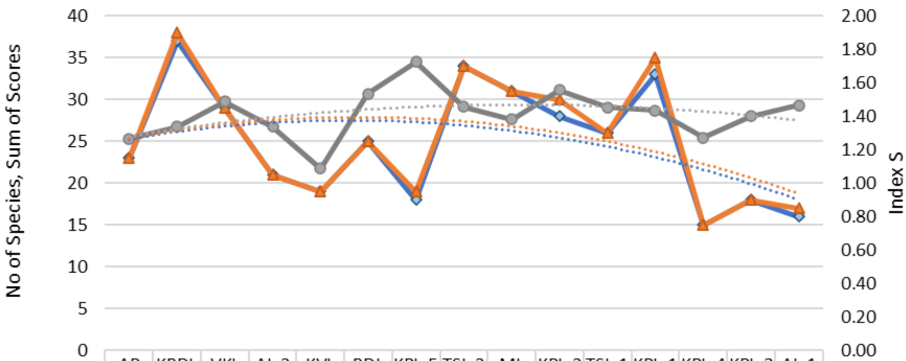
As a result of the research, a total of 84 species and intraspecific taxa of Bacillariophyta, belonging to three classes, 15 orders, 25 families, and 42 genera were identified (Appendix A Figures A1–A4). While the two classes (Mediophyceae, Coscinodiscophyceae, 4 species in each class and 4.76%) represent a very small part of the benthic diatom flora (9.52%), class Bacillarophyceae formed the basis of the species richness of the flora (76 species, 90.47%). The top two orders of the flora composition of benthic diatoms included Naviculales (35 species) and Cymbellales (10 species). Among the dominant families were Pinnulariaceae (13 species), Naviculaceae (8 species), Surirellaceae (7 species), Cymbellaceae (5 species) and Eunotiaceae (5 species). The main part of the benthic diatom flora was formed by genera *Pinnularia* (13 species), *Eunotia* (5 species), *Navicula* (5 species), and *Frustulia* (4 species) (Appendix A Table A1). One diatom species was identified as new records for freshwater algal flora of Turkey. It is marked with an asterisk (*) in Appendix A Table A1. Information on taxonomic and ecological characteristics of the new record species was given in a separate publication [46].

About 8.33% of the diatom species have been found in more than 80% of investigated lakes (Very Frequent, VF), whereas 72.61% have been found in less than 40% of the investigated lakes (Very Rare, VR, Rare R). The representation ratios of the species in the frequent (F) and common (C) groups are the same (8 species in each group, 9.52%). Some diatom species were identified only in one lake. The number of them is 30, and they represented 35.71% of all the flora. On the other hand, *Iconella capronii* is the only species identified in all studied lakes and a pond. Likewise, *Didymosphenia geminata* and *Encyonema minutum* were observed in 14 habitats. The others main species (*Caloneis silicula*, *Navicula cryptocephala*, *Pinnularia interrupta*, and *P. major*) were found in 13 lakes (Appendix A Table A1; Appendix A Figures A1–A4).

When the benthic diatom flora of the studied lakes was compared, it was observed that the species diversity and relative abundances were different. Especially, the composition of epilithic diatoms (81 species) identified to be more diverse than that of epipelic and epiphytic diatoms. In general, a significant part of the flora consisting of cosmopolitan species is of alpine and subalpine origin. The flora also includes northern alpine and alpine diatom species.

3.3. Bioindicators

Distribution of indicator properties of diatom species in studied lakes is represented in Appendix A Table A2 and summarized in Appendix A Table A3. It can be seen that the total number of diatom species in each lake strongly correlated with the abundance scores, R= 0.995, $p<0.0001$ (Figure 3). The dashed trend lines show a decrease in both variables with increasing altitude of the lake. The organic pollution evidence is crucial for the protected lakes, and in the Kaçkar Mountains National Park, we can observe that the calculated Index of Saprobity (S) reflects clear waters in the studied lakes, falling within Class 2 or 3 of water quality (Figure 3) with a tendency to slightly decrease with increasing altitude.



	AP	KRDL	VKL	AL-2	KVL	BDL	KPL-5	TSL-2	ML	KPL-2	TSL-1	KPL-1	KPL-4	KPL-3	AL-1
No Species	23	37	29	21	19	25	18	34	31	28	26	33	15	18	16
Sum Scores	23	38	29	21	19	25	19	34	31	30	26	35	15	18	17
Index S	1.26	1.34	1.49	1.34	1.09	1.53	1.72	1.45	1.38	1.55	1.45	1.43	1.27	1.40	1.46

Figure 3. Distribution of diatom species richness, abundance sum of scores, and Index saprobity S value over studied lakes in the Kaçkar Mountains National Park, 2022. The order of studied lakes is in increasing of the lake altitude. Trend lines are as dashed lines.

The distribution of each group of indicators is represented in Figures 4 and 5. While it was determined that benthic species dominated the habitats of the examined lakes, plankto-benthic species were also observed in their existence (Figure 4a). It can be seen that the percentage of benthic inhabitants slightly increased with altitude (Figure 4a). While it was determined that water temperature indicators were collected in four groups, temperate species-indicators strongly prevailed in the examined lakes (Figure 4b). In the studied lakes, bioindication groups were related to standing water. Three groups were found related to oxygenation, water moving and oxygen saturation (Figure 4c). The low-streaming water indicators prevailed in all studied waters. The results of the pH bioindication show that indifferent species (45.45%) are common in the Kaçkar Mountains Natural Park. It was followed by alkaliphiles (35.06%) and acidophiles species (15.58%), respectively. Additionally, alkalibiontes species were also seen in VKL and KPL-3 lakes (Appendix A Table A3). As a whole, indicator groups consisting of indifferent, alkaliphiles and acidophiles comprised 96.09% of the indicator species in each lake community (Figure 4d).

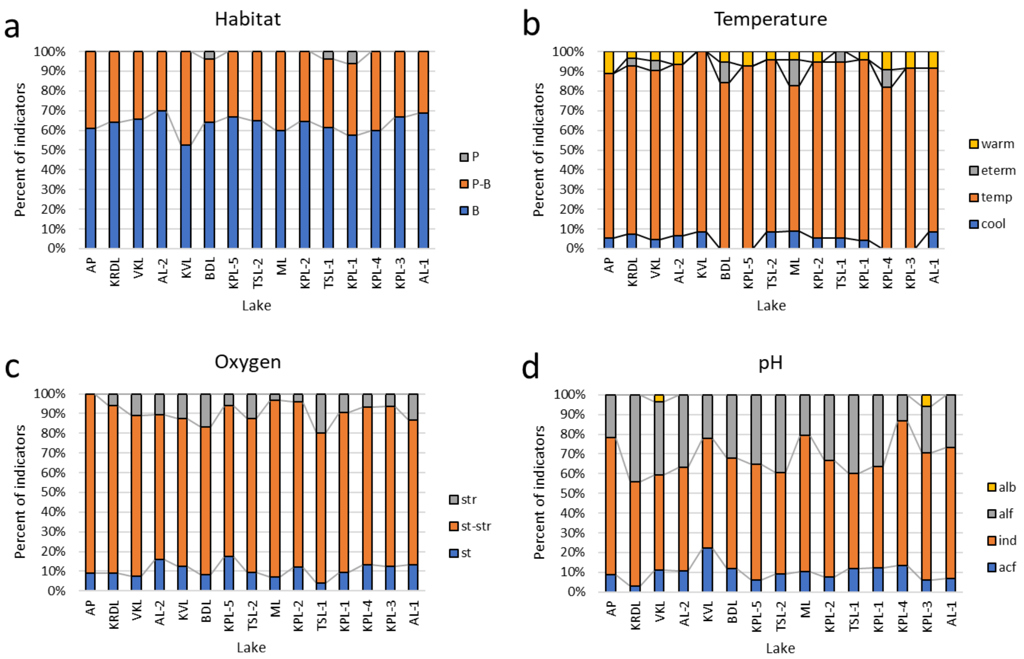


Figure 4. Distribution of indicators of organic pollution according to Watanabe, class of water quality, trophic state, and nutrition type for phytoplankton communities in the Kaçkar Mountains National Park. Habitat (a): P-B – plankto-benthic, B – benthic; Temperature preferences (b): cool – cool-water, temp – temperate, eterm – eurythermic, warm – warm-water; Oxygenation and water moving (c): str – streaming water, st-str – low streaming water; pH preferences groups (d): alb – alkalibiontes; alf – alkaliphiles, ind – indifferent; acf – acidophiles. The lakes order is in increasing of altitude. The indicator groups order is in increasing of the indicated variable value.

Salinity is a crucial component of the total ion content in water, influencing the algal community. Bioindication based on water salinity reveals that indifferent species dominate in all studied lakes. The other groups were oligohalobes-halophobes, halophiles and mesohalobes (Figure 5a). Light and temperature are the basic climatic variables affecting photosynthesis, so, these global climatic factors define life and evolution also [5]. Photosynthetic diatoms prevail in communities of all studied lakes (Figure 5b) and strongly prevail with increasing altitude.

The bioindication results of organic pollution obtained from the Sládeček's systems are shown in Figure 5c. According to these results, it can be stated that all examined lake ecosystems have all indicator groups of Watanabe's method that is not presented on the histogram but can be seen in Appendix A Table A3 and Appendix A Table A4. While the indicators of Class 2 in the Sládeček system contained a significant portion of the diatom community in all the studied waters, Class 3 was second. While Class 1 was represented in the KVL and KPL-1 lakes, Class 4 were also represented in the AP, KRDL, VKL, BDL, KPL-5, TSL-2, ML, KPL-2 and KPL-1. KPL-1 was the only lake where all classes indicators were found. The indicators for water pollution in Class 5 were not identified. Figure 5c illustrates a decrease in Class 4 indicators with an increase in altitude, accompanied by a rising percentage of indicators corresponding to Class 3 water quality.

The trophic state of the lake usually correlates to organic matter saturation. Oligotrophic diatom species, constituting 15.47% of all diatom species, dominate the diatom communities of the studied lakes. They are followed by oligo-mesotrophic (13.09%) and eutrophic (11.90%) diatom species, respectively. In total, they comprised 40.46% of all diatom species. Additionally, mesotrophic, meso-eutrophic, and oligo-eutrophic diatoms were recorded, representing a smaller share in the diatom community (5.95%) (Figure 5d).

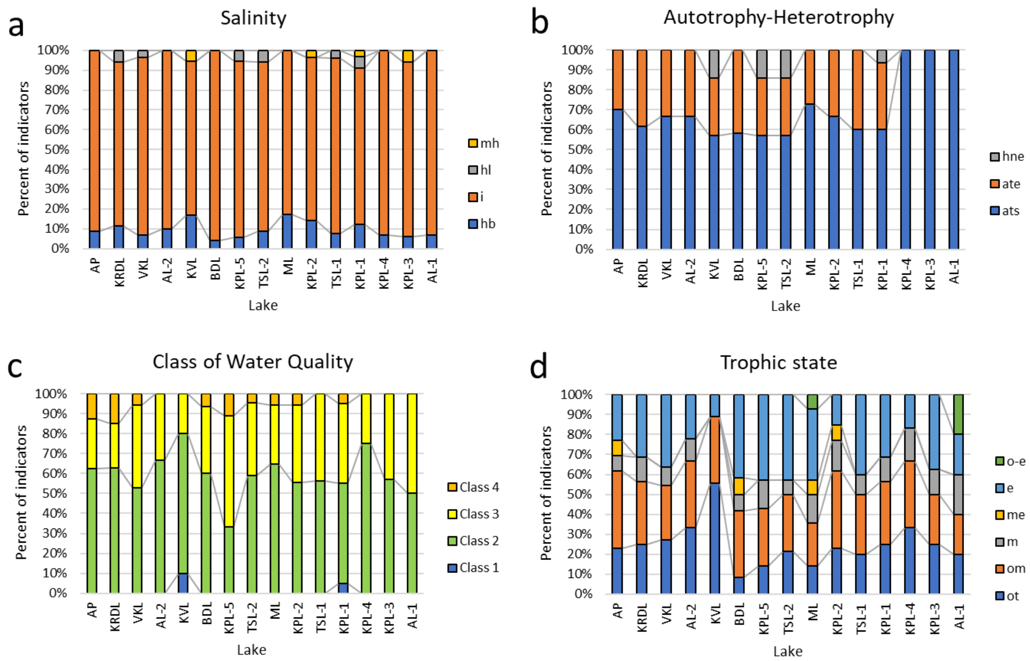


Figure 5. Distribution of indicators of organic pollution according to Watanabe, class of water quality, trophic state, and nutrition type for phytoplankton communities in the Kaçkar Mountains National Park. Abbreviations of ecological groups are given in Appendix Table A2. Salinity ecological groups (a): hb – oligohalobes-halophobes, i – oligohalobes-indifferent, hl – halophiles; mh – mesohalobes, oh – oligohalobes of wide spectrum with optimum as indifferent. Nitrogen uptake metabolism (Autotrophy-Heterotrophy) (b): ats – nitrogen-autotrophic taxa, tolerating very small concentrations of organically bound nitrogen; ate – nitrogen-autotrophic taxa, tolerating elevated concentrations of organically bound nitrogen. The water quality class is determined as the sum of indicators whose species-specific index saprobity S from Appendix A Table A2 is within the range of each class. Classes of water quality colored in EU color code (c). Trophic state indicators (d): ot – oligotraphentic; om – oligomesotraphentic; m – mesotraphentic; me – mesoeutraphentic; e – eutraphentic; o-e – hypereutraphentic. The lakes are ordered in increasing altitude, and the indicator groups are arranged in increasing order of the indicated variable value.

3.4. Statistical Analysis

A JASP Network plot of bioindicators correlation of studied lakes in the Kaçkar Mountains National Park was constructed based on Appendix A Table A3. Figure 6 shows two different clusters. Cluster 1 combines the AL-1,2, KVL, and KPL-3,4 lakes, where the diversity structure is similar, and the species content has a positive correlation, as outlined by the black dashed line in diatom floras. All other lakes' indicators are grouped in cluster 2, outlined with a red dashed line. As seen in Appendix A Table A3, cluster 2 datasets exhibit greater species richness and sum of abundance scores but are not strongly dependent on altitude.

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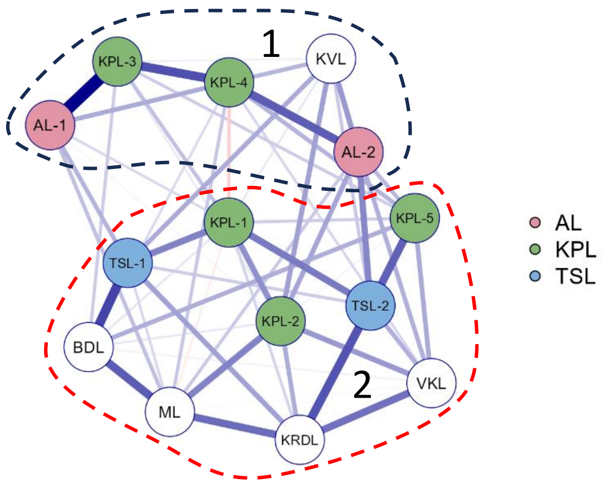

Figure 6. JASP Network plot of diatom bioindicators correlation in the communities of the lakes of the Kaçkar Mountains National Park, p< 0.5, calculated based on Appendix A Table A3. Major groups of the lakes abbreviated and colored in the legend. Blue lines are positive correlations, while red lines are negative correlations. The line thickness reflects the value of correlation. Dashed line outlined different clusters.

The comparison of the species richness and the abundance scores data from Appendix A Table A1 by Bray-Curtis's calculation of similarity for diatom species composition shows two groups of lakes (Figure 7), outlined by dashed line and toned by different color. It can be observed that the smaller group of lakes includes only KPL lakes 3,4,5, and AL 1 and 2. All other diatom communities are outlined by the largest cluster. Both type analysis (JASP and Bray-Curtis) shows similar results because the smallest group also included the lakes with low species richness and abundance of diatoms, but the lake KVL was replaced by AL-2 with similar data.

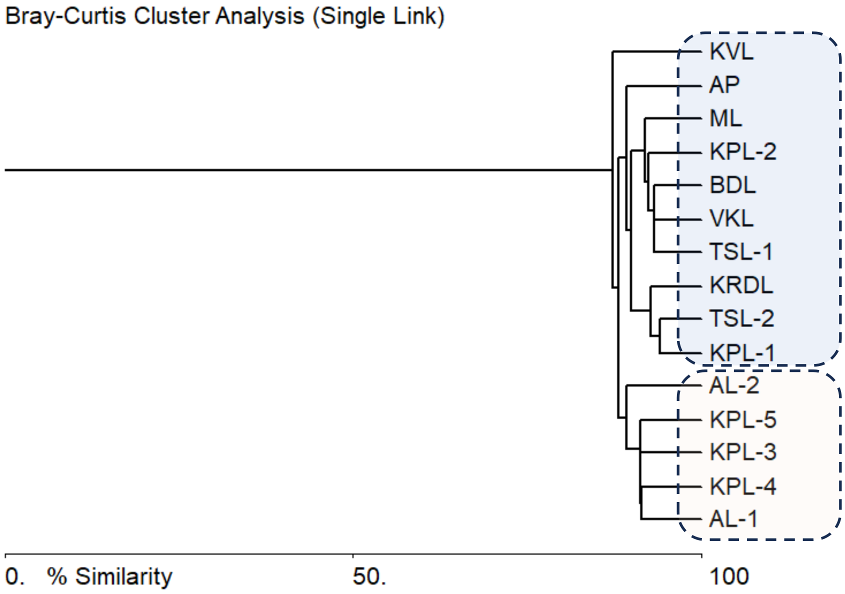

Figure 7. Tree of Bray-Curtis's similarity analysis of diatom species composition in communities of the Kaçkar Mountains National Park, 2020. Clusters are outlined by dashed lines and toned by different colors.

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3.5. Species-environment relationships

RDA plot of the relationships analysis of dominated ecological groups and environmental variables is represented on Figure 8a. Data from eleven lakes were used for this analysis, as the environmental data for some variables were partially missing. Figure 8a shows that the majority of indicators are combined into one set related to the increase in dissolved ions and oxygen concentration. The other set of environmental variables represents a negative influence on most indicator groups and includes ammonia, pH, temperature, and the lake area variables. It is remarkable that one of the most species-rich indicator groups of oligotrophic waters stays in opposition to the Index Saprobity S value. An increase in the Index Saprobity S value is typically associated with eutrophication.

Figure 8b reflects the lakes related to the groups of variables described above. So, ammonia is an important factor for lakes KVL and AL-2, favoring oligotrophic species domination. The increasing water pH influenced diversity mostly in KPL-5, while a decrease in pH is important for diatom species abundance in KRDL lake.

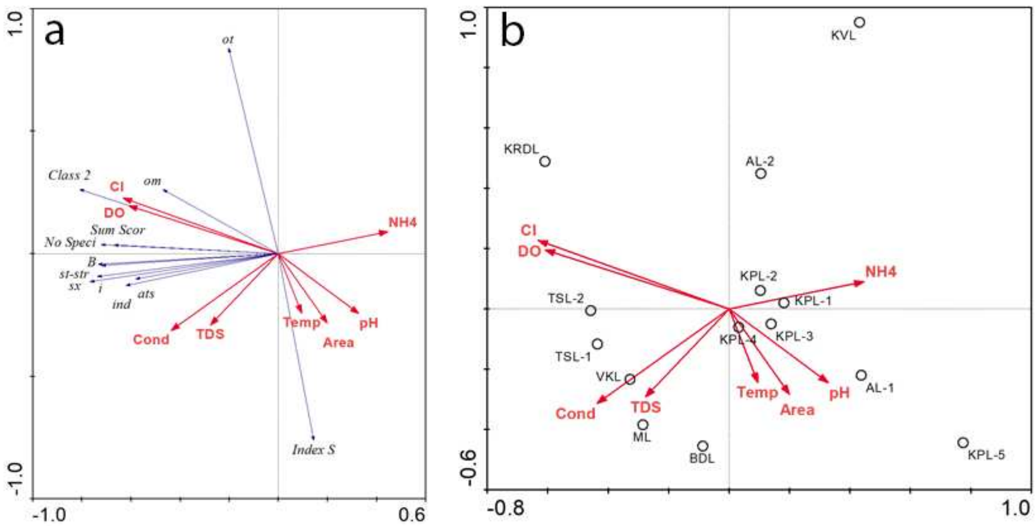

Figure 8. RDA plots for dominated groups of species-indicators and environmental variables in 11 studied lakes based on data from Tables 1, 3, and Appendix Tables A1 and A4 in the Kaçkar Mountains National Park. RDA for species richness, sum of scores and environmental variables (a). RDA plot for studied lakes and environmental variables (b).

The relationships between species richness in diatom community of the protected lakes in the Kaçkar Mountains National Park and the major climatic and water property variables were studied with the 3D plots in Statistica program. Figures 9–12 show the surface plots in which independent variable was Number of diatom species in 14 lakes community and dependent variable for each plot was the lake altitude, but third variable for each plot was different. Figure 9a shows an increase in the number of diatom species in the community when water conductivity and lake altitude are low. The same tendency can be seen in relation to dissolved oxygen (Figure 9b).

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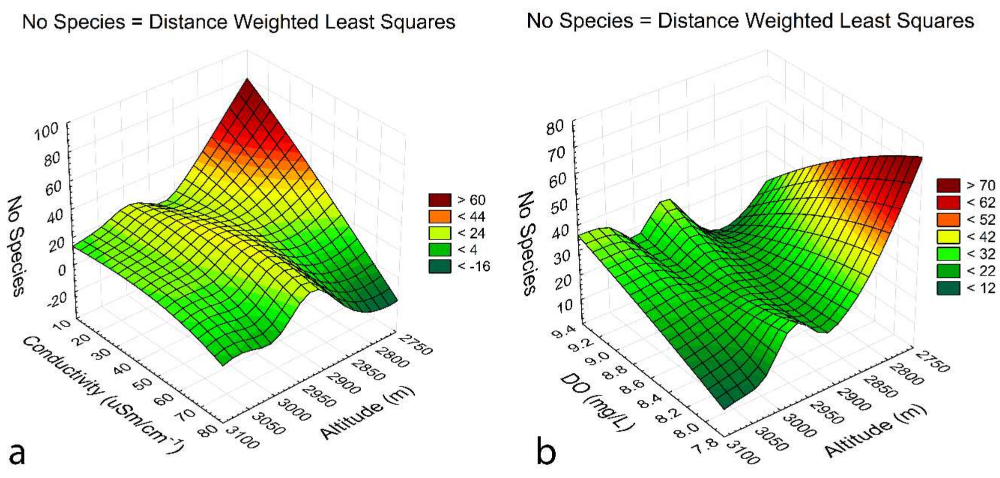

Figure 9. 3D surface plots of species richness in diatom community, lake altitude, and water Conductivity (a) and Dissolved oxygen (b) in the protected lakes in the Kaçkar Mountains National Park, 2020.

Figure 10a demonstrated the relationships of water pH that fluctuated between 6.0 and 8.4 in which at the low altitude lakes the species number increased. In contrast, the temperature surface has a two-wave shape that reflects the complex relation of species richness with this environmental factor. In any case, it increased with the highest temperature in the low altitude lakes (Figure 10b).

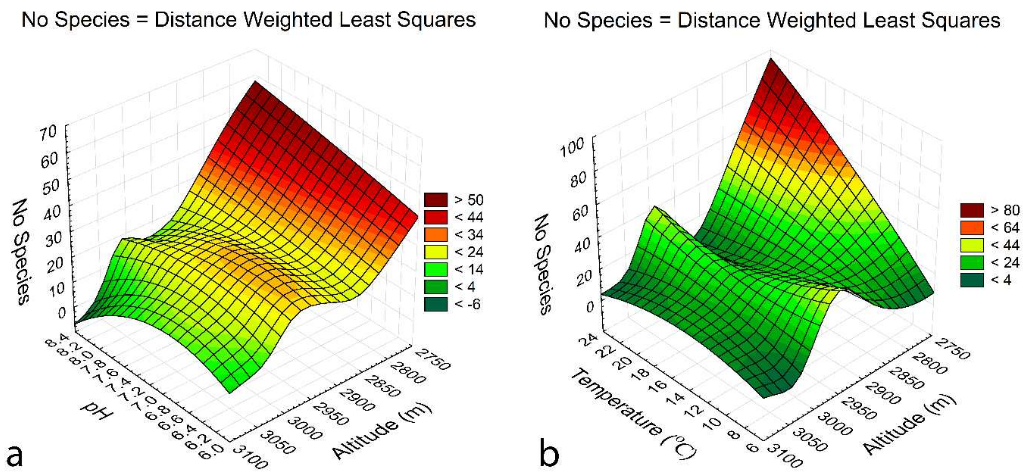

Figure 10. 3D surface plots of species richness in diatom community, lake altitude, and water pH (a) and Temperature (b) in the protected lakes in the Kaçkar Mountains National Park, 2020.

Index saprobity S is evidence of organic pollution that is an important factor for the protected lakes diversity. Figure 11a demonstrates that the relationships between species richness in the diatom community and organic pollution are complex, showing a two-wave pattern. But overall, the richness be seen increasing in species richness in the lowermost lakes when organic pollution increased. Ammonium impact is reflected in the surface of Figure 11b when increasing of which stimulate the species richness in both high altitude and low altitude lakes.

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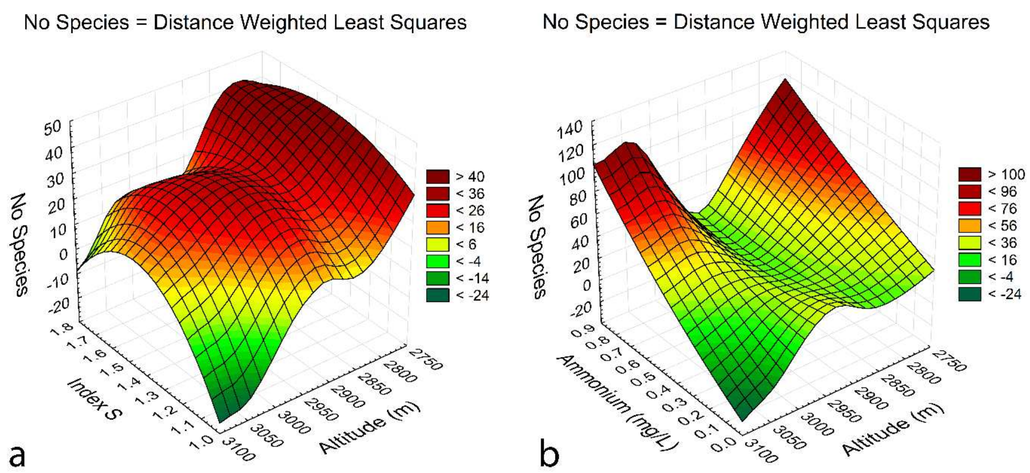

Figure 11. 3D surface plots of species richness in diatom community, lake altitude, and Index saprobity S (a) and Ammonia (b) in the protected lakes in the Kaçkar Mountains National Park, 2020.

It was a special part of the 3D analysis in which we tried to reveal the relationships of species richness with the calculated index of species number per lake area, and the lake area as an environmental factor for the Kaçkar Mountains National Park lakes. So, Figure 12a shows that the number of diatom species is decreased in the lakes on the low altitude and that have a large surface area. This may be the result of insufficient research but in any case, pointed to the future navigation of the diatom studies in the protected areas. At the same time, Figure 12b shows an increase in the number of species per lake surface area in 'lowland' lakes if the Sp/Area index has low values. However, the left side of Figure 12b shows a trend of increasing both the number of species per lake area and increasing species richness in high altitude lakes if efforts are made to deplete diatom diversity in the Kaçkar Mountains National Park in future studies.

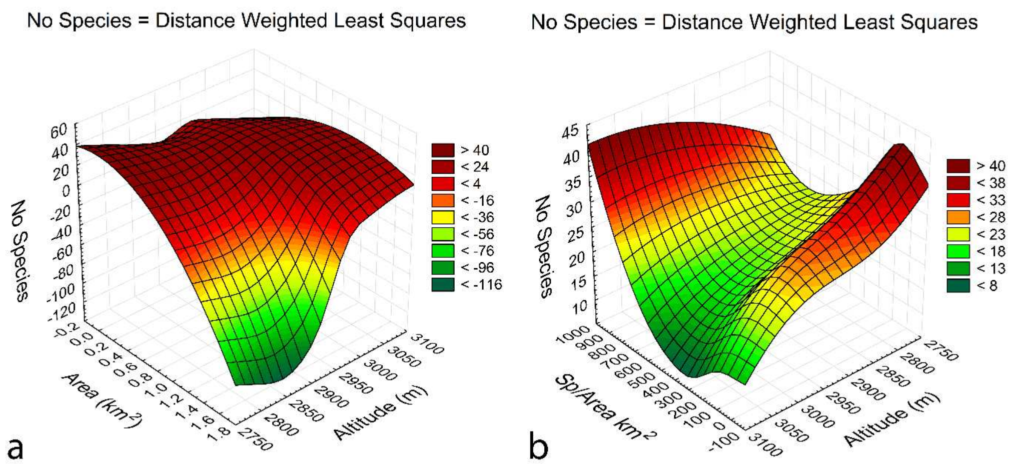

Figure 12. 3D surface plots of species richness in diatom community, lake altitude, and water area (a) and Index of Species per Area (b) in the protected lakes in the Kaçkar Mountains National Park, 2020.

3.6. Species in Threat Categories

Appendix A Tables A1 and A3 show the number of diatom species in the lakes of the entire Kaçkar Mountains National Park is not yet high but forces us to analyze the degree of their endemism and rarity, as well as the threat of extinction. We used Germany's most developed red data book diatom species resource [44] as a basis for identifying potentially threatened species in the Kaçkar Mountains National Park (Table 2).

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Analysis of the revealed species composition of diatoms showed that 75 of 84 species can be classified in relation to categories. Distribution of the species found in the lakes of the Kaçkar Mountains National Park over threat categories can be seen in Table 2 and Figure 13.

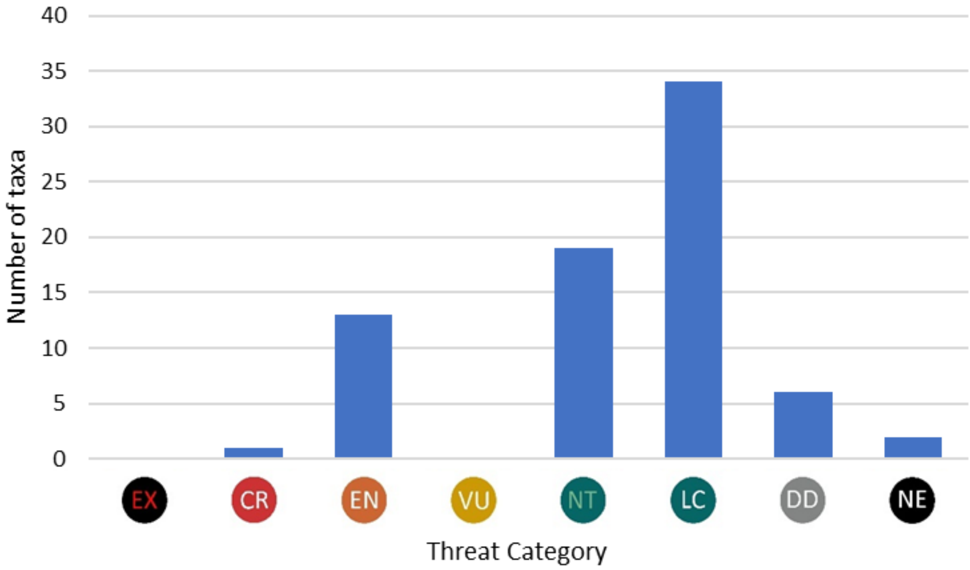

Figure 13. Distribution of the number of diatom species in the flora of the studied lakes of the Kachkar Mountains National Park, 2020, according to IUCN threat categories. The order of the IUCN categories corresponds to threat reduction.

Only one species *Neidium iridis* was concerned to category CRITICALLY ENDANGERED (CR) found in the lakes KRDL and ML. The most of species were related to categories ENDANGERED (EN), 13, and NEAR THREATENED (NT), 19 species. EN-species *Iconella capronii* was revealed in each lake, *Eunotia mucophila* in 8 lakes but other EN-species were found in 1-5 lakes. A similar distribution in species percent in categories was found in the Lena Delta Narure Reserve [47] but with large number in LEAST CONCERN (LC) and NOT EVALUATED (LE) categories. It may be related to insufficient research on diatoms in our lakes on the one hand and the low degree of their endemism and rarity on the other, as *Neidium iridis* is a widely distributed species in Turkey and *Eunotia cristagalli* is rare in turkey but distributed wide in continental waters of the World.

4. Discussion

In this study, the detection of diatom communities of 14 high mountain lakes and one pond in Kaçkar Mountains National Park and their relationship with environmental factors were examined. During the study period, 84 taxa of epipelic, epilithic and epiphytic diatoms were identified. The families (Pinnulariaceae, Naviculaceae, Surirellaceae, Cymbellaceae and Eunotiaceae) and genera (*Pinnularia*, *Eunotia*, *Navicula* and *Frustulia*) that stand out in the flora are also characteristic members of other high mountain lakes studied in the region. The flora, which generally consists of common species, is also similar to the diatom communities of the alpine and subalpine lakes in the region [16–19]. It is thought that the macro-climatic conditions, the similarity of the land structure and the lake characteristics are the factors in the formation of this situation.

The common species were *Caloneis silicula*, *Encyonema minutum*, *Iconella capronii*, *Navicula cryptocephala*, and *Pinnularia interrupta* (Appendix A Table A1). These species are found in almost every lake and thus can be indicators of the state of the environment of the entire park as a whole (Appendix A Table A2). The most abundant and common species were benthic autotrophes, indicated temperate well oxygenated waters with circumneutral and low alkaline pH and low saturated with organic matter of Class 2 of water quality.

Among the diatom flora of the park, attention was drawn to representatives of *Pinnularia*, which are usually found in fresh, slightly acidic waters with low electrical conductivity [47–49], which is confirmed by our chemical analyzes (Table 3). Thus, the ecological conditions of the waters created a suitable environment for the development of representatives of *Pinnularia*. In addition, species of the genus *Pinnularia* are also known to inhabit extreme habitats, including highlands and arctic [49], indicators of hotspot biodiversity in the Ecotones, which are a border area of different landscapes [50]. *Pinnularia interrupta* and *P. maior*, which were found in 13 of the investigated lakes, were recorded very frequent (VF) (86.66%) and were among the remarkable species in the diatom flora of the park (Appendix A Table A1). *Pinnularia interrupta* occurs in low mineral content, circumneutral, oligosaprobic, and oligo-mesotrophic waters, while *P. maior* prefers low mineral content, circumneutral, β-mesosaprobic and meso-eutrophic waters [34,48]. In addition, *Pinnularia borealis* and *P. viridis* species were also recorded as common (C).

Caloneis silicula is usually found in alkaliphilic, oligosaprobic, and meso-eutrophic waters, and in littoral areas of freshwater habitats with moderate electrolyte content [31,48]. Whereas Patrick and Reimer (1966) [34] state that the species has a wide ecological tolerance. *Didymosphenia geminata* prefers cool, low conductivity and with circumneutral pH waters [35,48]. *Encyonema minutum*, which has a wide geographical distribution, prefers oligo-mesotrophic freshwater habitats with medium electrolyte content, and circumneutral pH waters [31,34,48]. According to Krammer and Lange-Bertalot [28], *Iconella capronii* is a cosmopolitan benthic form common throughout Europe and generally prefers meso-eutrophic waters with moderate to high electrolyte levels. In addition, Van Dam et al. [48] states that the species has alkaliphilic and oligosaprobic ecological properties. *Navicula cryptocephala*, which has a wide ecological tolerance, is found in oligo-eutrophic and eutrophic-polytrophic freshwater habitats with poor electrolyte content, and circumneutral pH and alkaline waters. At the same time, this species also tolerates saprobic levels exceeding beta-alpha-mesosaprobic [31,34,48]. The detected physico-chemical properties in the studied lakes support the above-mentioned references.

A comparison of the influence of individual environmental parameters on the diatom communities of 14 lakes showed that the flora consists of diatom taxa that are influenced by the ionic composition of water and habitat altitude.

Eutrophication and acidification are among the important problems of high mountain lakes [51,52]. Obtained at the end of the research, bioindication and chemical data showed us that these problems do not exist in the studied lakes. In addition, the low diversity of the identified diatoms and the absence of a pronounced domination in the communities are among the notable features of the detected flora, and these features are inherent in the intact ecosystems of high mountain lakes [53–55].

Thus, bioindicator analysis allows us to conclude that the lakes of the park were clean, mesotrophic, and class 2 water quality. The aquatic inhabitants of the lakes developed in well-oxygenated waters of moderate temperature, and the number of benthic species increased slightly with altitude.

The increasing of autotrophic species percent in communities was detected with increasing of the lake altitude whereas alkaliphilic species slightly decreased within altitude. The low degree of studied lakes diatoms endemism and rarity [18,19,47] were revealed for this first study that demonstrated insufficient study in the park on the one hand and stimulate its research in future from the other.

5. Conclusions

The species composition, dominant species, prominent Families and Genera determined in this study are characteristic of benthic diatom composition of high mountain lakes. Very frequent (VF) species comprised only 8.33% of the species composition, while very rare (VR) species comprised 57.14%. The composition of very frequent (VF) species is not rich (7 species).

The data we obtained from the research show that the physico-chemical properties of the waters, environmental conditions, and the lake altitude are effective in shaping the benthic diatom flora and

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in the distribution of diatoms. Future research in the Kaçkar Mountains National Park should include a greater number of high mountain lakes, so that deeper information about the distribution of diatoms within the park should be obtained. Continued research is all the more important as our analysis reveals a trend for diatom diversity to increase in high mountain lakes if research is expanded. This study is the first on the benthic diatom flora of the high mountain lakes in Kaçkar Mountains National Park and therefore constitutes a starting point for the creation of diatom-based biomonitoring programs for further investigation on diatom-environment relationships and implementation of sustainable management plans.

High mountain lakes (especially oligotrophic lakes), which are a very fragile ecosystem type, are under the influence of local (road construction) and global (climatic warming) threats. They will be among the ecosystems that will be strongly affected by species loss, especially when it comes to climatic warming [6]. In order to protect these high mountain lakes, where rare and endangered diatom species by IUCN criteria have been detected, from the above-mentioned threats, their ecological conditions must be constantly monitored in the Kaçkar Mountains National Park.

Author Contributions: Conceptualization, B.Ş. and S.B.; methodology, B.Ş. and S.B.; software, S.B.; validation, B.Ş. and S.B.; formal analysis, B.Ş. and S.B.; investigation, B.Ş.; resources, B.Ş.; data curation, B.Ş.; writing—original draft preparation, B.Ş. and S.B.; writing—review and editing, B.Ş. and S.B.; visualization, B.Ş. and S.B.; supervision, B.Ş.; project administration, B.Ş.; funding acquisition, B.Ş. All authors have read and agreed to the published version of the manuscript.

Funding: This research received financially supported by Trabzon University Scientific Research Projects Coordination Unit (Project No: 20TAP00102).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the authors.

Acknowledgments: This work was supported by Trabzon University Scientific Research Projects Coordination Unit (Project No: 20TAP00102) and partly by the Israeli Ministry of Aliya and Integration.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Appendix A

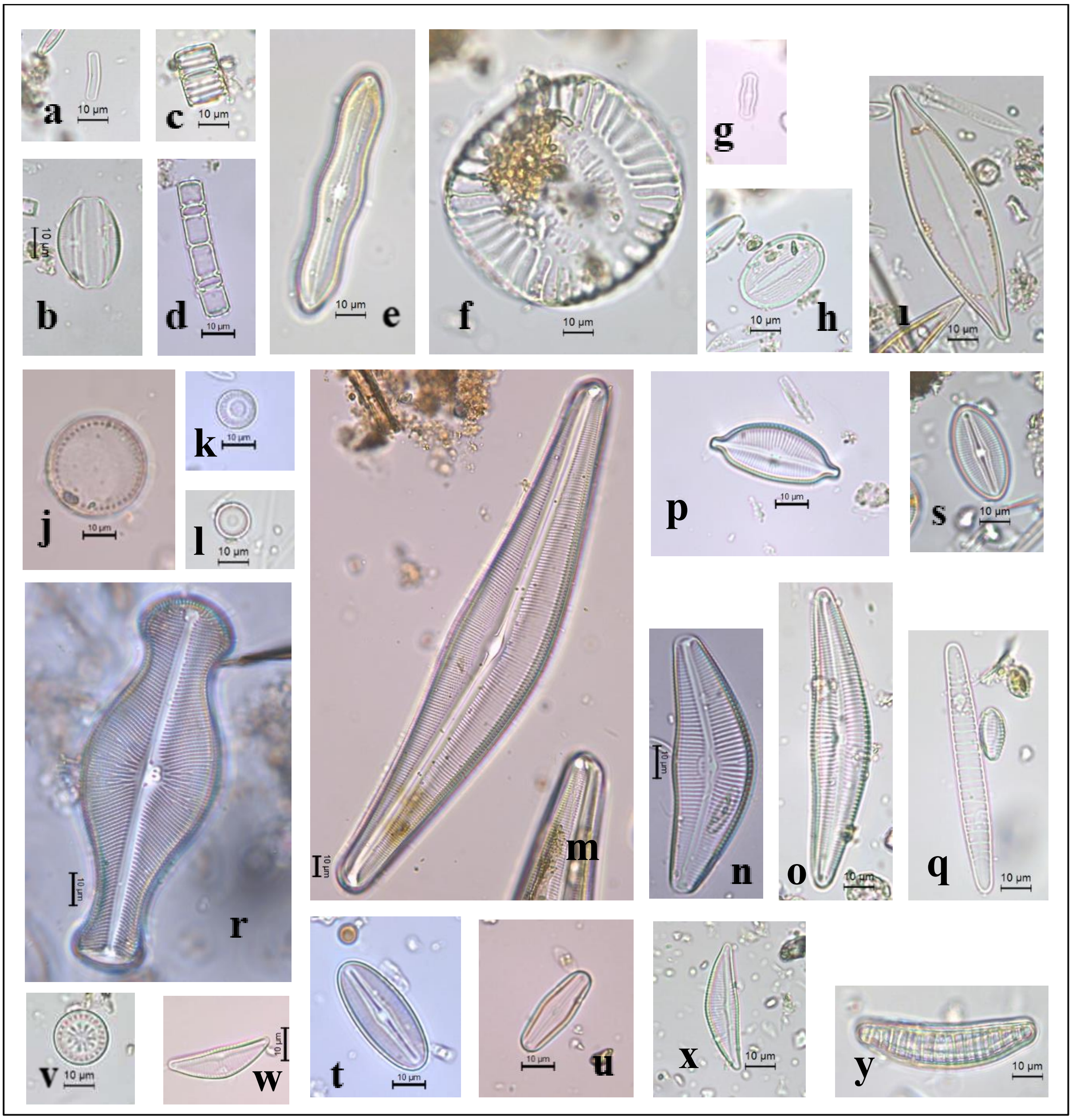

Figure A1. (**a**) Achnanthidium minutissimum, (**b**) Amphora ovalis, (**c**) Aulacoseira ambigua, (**d**) A. valida, (**e**) Caloneis silicula, (**f**) Campylodiscus bicostatus, (**g**) Chamaepinnularia hassiaca, (**h**) Cocconeis lineata, (**ı**) Craticula cuspidata, (**j**) Cyclotella bodanica var. lemanica, (**k**) C. distinguenda, (**l**) C. meneghiniana, (**m**) Cymbella aspera, (**n**) C. cistula, (**o**) C. cymbiformis, (**p**) Cymbopleura naviculiformis, (**q**) Diatoma vulgaris, (**r**) Didymosphenia geminata, (**s**) Diploneis elliptica, (**t**) D. oblongella, (**u**) D. petersenii, (**v**) Discostella stelligera, (**w**) Encyonema minutum, (**x**) E. silesiacum, (**y**) Epithemia adnata. Scale bar: 10 µm.

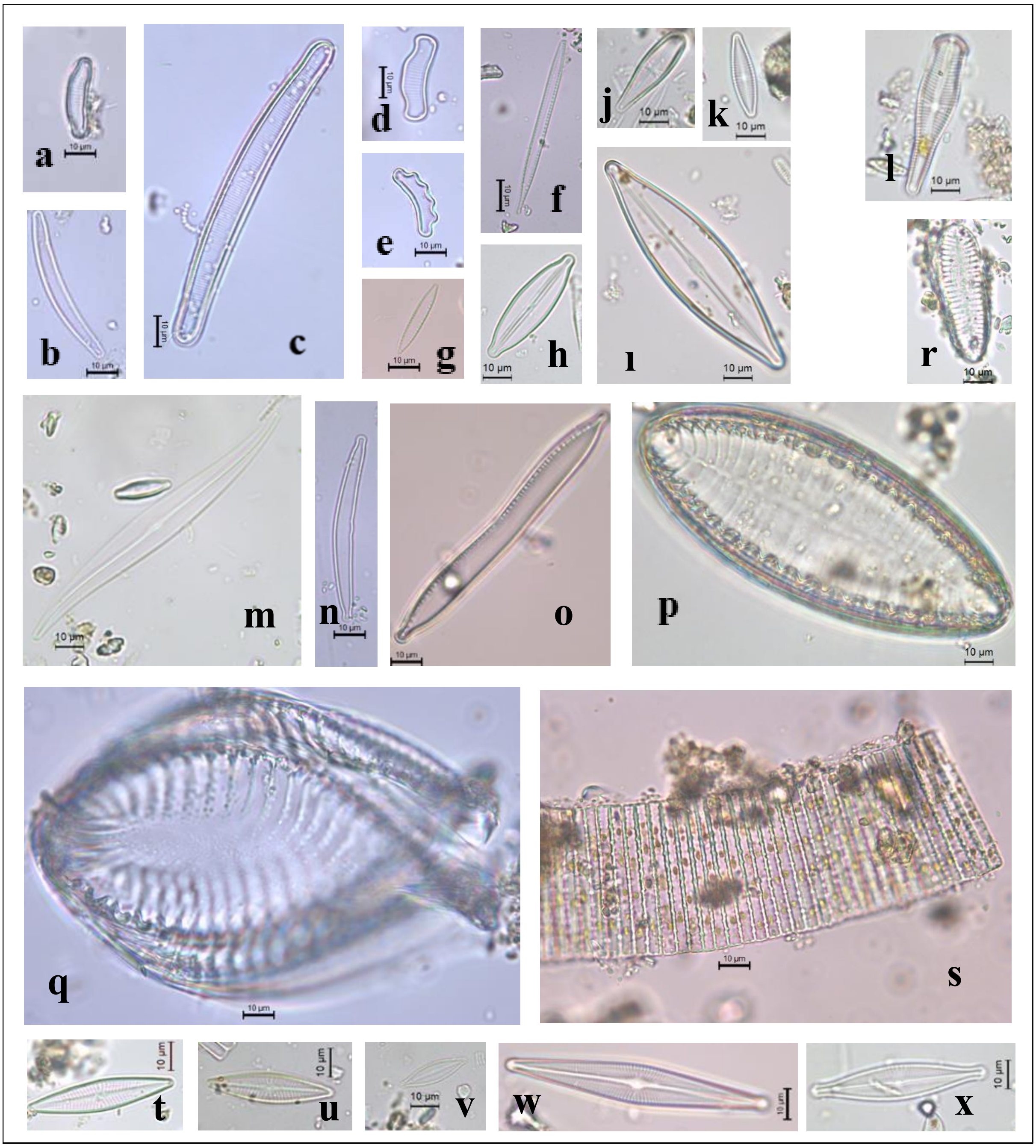

Figure A2. (**a**) Eunotia arcus, (**b**) E. mucophila, (**c**) E. paludosa, (**d**) E. praerupta, (**e**) E. cristagalli, (**f**) Fragilaria gracilis, (**g**) F. rumpens, (**h**) Frustulia crassinervia, (**ı**) F. saxonica, (**j**) Gomphonella olivacea, (**k**) Gomphonema parvulum, (**l**) G. truncatum, (**m**) Gyrosigma acuminatum, (**n**) Hannaea arcus, (**o**) Hantzschia amphioxys, (**p**) Iconella capronii, (**q**) I. spiralis, (**r**) I. tenera, (**s**) Meridion circulare, (**t**) Navicula cryptocephala, (**u**) N. cryptotenella, (**v**) N. phyllepta, (**w**) N. radiosa, (**x**) N. rhynchocephala. Scale bar: 10 µm.

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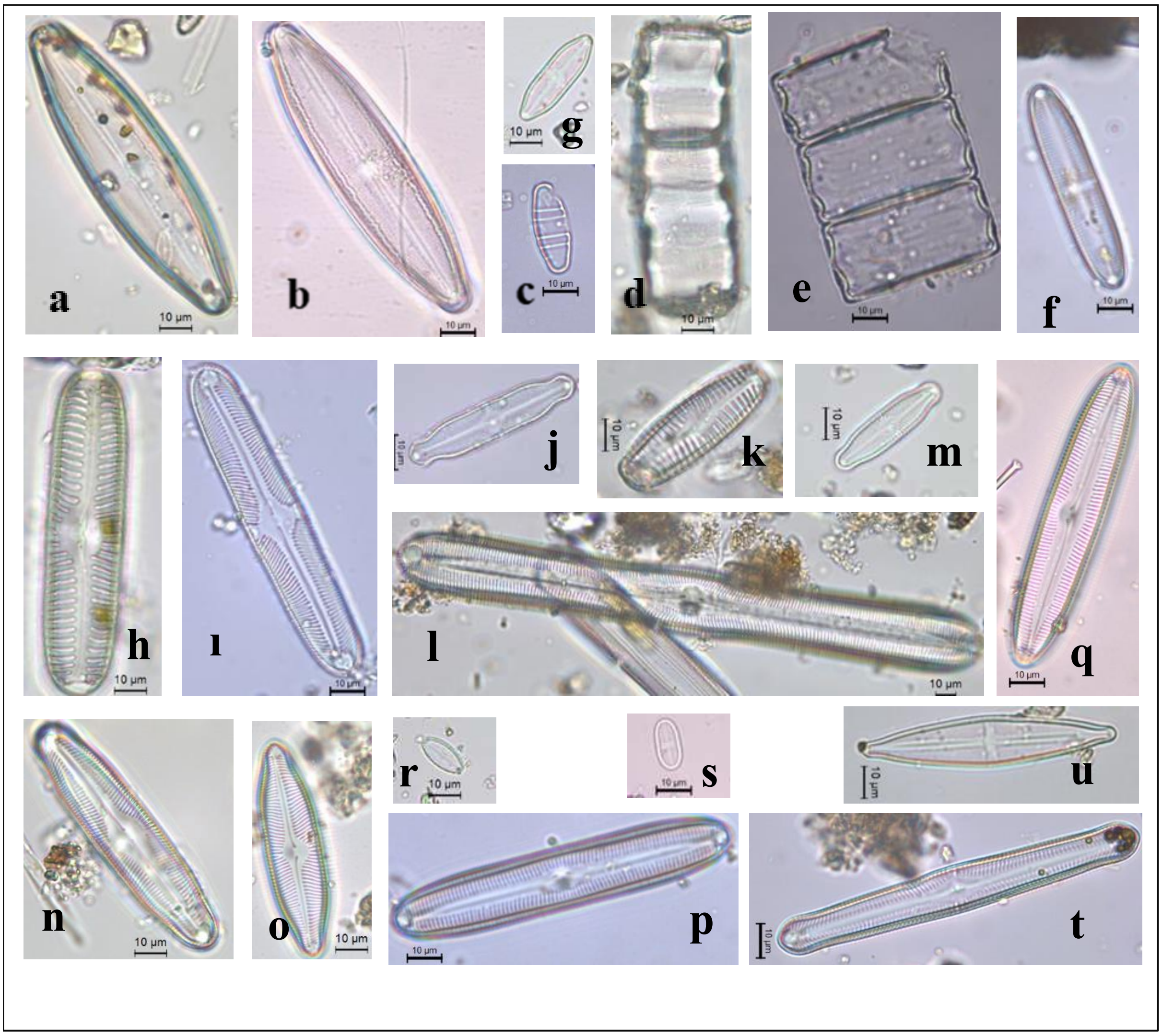

Figure A3. (**a**) Neidium ampliatum, (**b**) N. iridis, (**c**) Odontidium mesodon, (**d**) Orthoseira dendroteres, (**e**) O. roeseana, (**f**) Pinnularia aestuarii, (**g**) P. balatoni (**h**) P. borealis, (**ı**) P. brebissonii, (**j**) P. interrupta, (**k**) P. lata, (**l**) P. major, (**m**) P. mesogongyla, (**n**) P. microstauron, (**o**) P. microstauron var. nonfasciata, (**p**) P. rupestris, (**q**) P. viridis, (**r**) Planothidium distinctum, (**s**) Psammothidium helveticum, (**t**) Rhopalodia gibba, (**u**) Stauroneis anceps. Scale bar: 10 µm.

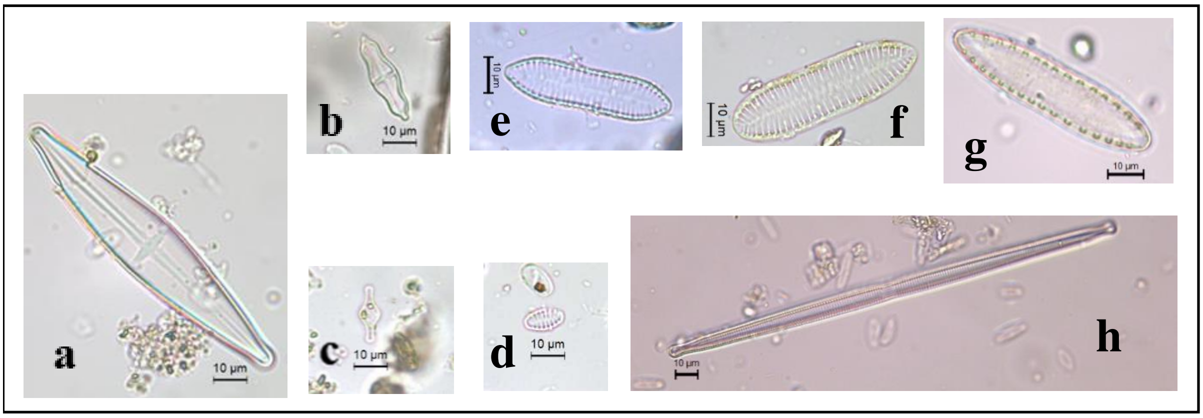

Figure A4. (**a**) Stauroneis phoenicenteron, (**b**) S. smithii, (**c**) Staurosira construens, (**d**) Staurosirella pinnata, (**e**) Surirella angusta, (**f**) S. minuta, (**g**) S. roba, (**h**) Ulnaria ulna. Scale bar: 10 µm.

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Table A1. Distribution of diatom species over the lakes in the Kaçkar Mountains National Park, in summer and autumun of 2020 with H: Substrate, F: Frequency, and Abundance scores: in Table.

Taxa	H	F	Red List Category	IUCN Category	KPL-1	KPL-2	KPL-3	KPL-4	KPL-5	VKL	KRDL	KVL	BDL	AL-1	AL-2	ML	TSL-1	TSL-2	AP
Achnanthes sp.	1	VR	-	-	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Achnanthidium minutissimum (Kützing) Czarnecki	1,2,3	R	9	LC	0	0	0	0	0	0	1	0	1	0	0	1	1	0	0
Amphora ovalis (Kützing) Kützing	1,2,3	C	9	LC	2	0	0	0	1	1	2	0	1	0	1	1	0	1	1
Aulacoseira ambigua (Grunow) Simonsen	1	VR	9	LC	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aulacoseira valida (Grunow) Krammer	1,2,3	VR	5	EN	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0
Caloneis silicula (Ehrenberg) Cleve	1	VF	9	LC	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1
Campylodiscus bicostatus W.Smith ex Roper	1	VR	7	NT	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Chamaepinnularia hassiaca (Krasske) Cantonati & Lange-Bertalot	1	VR	-	EN	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Cocconeis lineata Ehrenberg	1	VR	9	LC	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Craticula cuspidata (Kutzing) D.G.Mann	1	VR	7	NT	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Cyclotella bodanica var. *lemanica* (O.Müller ex Schroter) Bachmann	1,2,3	VR	-	-	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Cyclotella distinguenda Hustedt	1	VR	9	LC	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Cyclotella meneghiniana Kützing	1	VR	7	NT	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0
Cymbella aspera (Ehrenberg) Cleve	1,3	VR	-	EN	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Cymbella cistula (Ehrenberg) O.Kirchner	1,2,3	C	-	-	1	1	1	0	0	1	1	0	1	0	0	1	1	1	0
Cymbella cymbiformis C.Agardh	1	VR	4	EN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cymbopleura naviculiformis (Auerswald ex Heiberg) Krammer	1,2,3	F	9	LC	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1
Diatoma vulgaris Bory	1,2	C	9	LC	0	2	0	0	1	1	1	0	0	1	0	1	1	1	0
Didymosphenia geminata (Lyngbye) Mart.Schmidt	1,2,3	VF	9	LC	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
Diploneis elliptica (Kützing) Cleve	1,2,3	F	7	NT	0	0	1	1	1	1	1	0	1	1	1	0	1	1	0
Diploneis oblongella (Nägeli ex Kützing) A.Cleve	1	VR	8	DD	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Diploneis petersenii Hustedt	1	VR	-	EN	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Discostella stelligera (Cleve & Grunow) Houk & Klee	1	R	9	LC	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0
Encyonema minutum (Hilse) D.G.Mann	1,2,3	VF	9	LC	2	2	1	1	2	1	1	0	1	2	1	1	1	1	1
Encyonema silesiacum (Bleisch) D.G.Mann	1	R	9	LC	1	0	0	0	0	0	0	1	0	0	1	1	1	0	0
Epithemia adnata (Kützing) Brébisson	1	VR	9	LC	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Eunotia arcus Ehrenberg	1	VR	7	NT	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
**Eunotia cristagalli* Cleve	1	VR	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Eunotia mucophila (Lange-Bertalot, Nörpel-Schempp & Alles) Lange-Bertalot	1,3	C	5	EN	1	1	1	1	1	0	0	1	0	0	0	0	0	1	1
Eunotia paludosa Grunow	2	VR	-	EN	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Eunotia praerupta Ehrenberg	1,2,3	F	0	NE	1	0	0	0	0	1	1	1	0	1	1	1	1	1	1
Fragilaria gracilis Østrup	1	VR	7	NT	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
Fragilaria rumpens (Kützing) G.W.F.Carlson	1	VR	9	LC	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Frustulia crassinervia (Brébisson ex W.Smith) Lange-Bertalot & Krammer	1	R	7	NT	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0
Frustulia saxonica Rabenhorst	1	VR	7	NT	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Frustulia vulgaris (Thwaites) De Toni	3	VR	9	LC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Frustulia sp.	1	VR	-	-	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Gomphonella olivacea (Hornemann) Rabenhorst	1	F	9	LC	1	1	0	0	1	1	1	0	1	0	1	0	1	1	1

Gomphonema parvulum (Kützing) Kützing	1,2,3	R	9	LC	1	0	0	0	0	0	1	0	0	1	0	0	1	1	1
Gomphonema truncatum Ehrenberg	1,2,3	R	9	LC	1	1	0	0	0	1	0	0	1	0	0	0	1	1	0
Gyrosigma acuminatum (Kützing) Rabenhorst	1,3	F	9	LC	1	0	1	1	1	1	1	1	1	1	0	0	0	1	0
Hannaea arcus (Ehrenberg) R.M.Patrick	1,2,3	C	7	NT	0	1	0	0	0	1	1	0	1	1	1	0	1	1	0
Hantzschia amphioxys (Ehrenberg) Grunow	1	R	9	LC	0	1	0	0	0	0	0	0	1	0	0	1	0	0	1
Iconella capronii (Brébisson & Kitton) Ruck & Nakov	1,2	VF	-	EN	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Iconella spiralis (Kützing) E.C.Ruck & T.Nakov	1	VR	7	NT	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Iconella tenera (W.Gregory) Ruck & Nakov	1	VR	7	NT	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Meridion circulare (Greville) C.Agardh	1	VR	9	LC	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Navicula cryptocephala Kützing	1	VF	9	LC	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0
Navicula cryptotenella Lange-Bertalot	1	VR	9	LC	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
Navicula phyllepta Kützing	1	VR	9	LC	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Navicula radiosa Kützing	1,2	F	9	LC	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1
Navicula rhynchocephala Kützing	1	VR	9	LC	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
Neidium ampliatum (Ehrenberg) Krammer	1	R	7	NT	1	0	0	0	1	0	1	1	0	0	0	0	0	1	0
Neidium bisulcatum (Lagerstedt) Cleve	1	VR	4	EN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neidium iridis (Ehrenberg) Cleve	1	VR	3	CR	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Odontidium mesodon (Kützing) Kützing	1,2	R	9	LC	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0
Orthoseira dendroteres (Ehrenberg) Genkal & Kulikovskiy	1	C	-	DD	0	1	0	0	1	1	1	0	0	0	1	0	1	1	0
Orthoseira roeseana (Rabenhorst) Pfitzer	1	VR	-	DD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Pinnularia aestuarii Cleve	1	VR	-	-	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
Pinnularia appendiculata (C.Agardh) Schaarschmidt	1	VR	7	NT	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Pinnularia balatonis (Pantocsek) F.W.Mills	1	VR	-	-	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Pinnularia borealis Ehrenberg	1	C	7	NT	0	1	0	1	0	1	1	1	0	0	0	0	0	1	1
Pinnularia brebissonii (Kützing) Rabenhorst	1	VR	9	LC	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1
Pinnularia interrupta W.Smith	1	VF	-	-	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1
Pinnularia lata (Brébisson) W.Smith	1	VR	4	EN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinnularia major (Kützing) Rabenhorst	1,2,3	VF	-	-	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1
Pinnularia mesogongyla Ehrenberg	1	VR	8	DD	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinnularia microstauron (Ehrenberg) Cleve	1	VR	7	NT	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pinnularia microstauron var. *nonfasciata* Krammer	1	VR	-	EN	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0
Pinnularia rupestris Hantzsch	2	VR	5	EN	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Pinnularia viridis (Nitzsch) Ehrenberg	1,3	C	8	DD	1	0	1	1	1	1	1	1	0	0	0	1	0	0	1
Planothidium distinctum (Messikommer) Lange-Bertalot	1	VR	-	EN	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Psammothidium helveticum (Hustedt) Bukhtiyarova & Round	1	R	9	LC	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0
Rhopalodia gibba (Ehrenberg) O.Müller	1,2	R	9	LC	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1
Stauroneis anceps Ehrenberg	1,2,3	F	7	NT	0	1	1	1	0	1	1	1	1	0	0	1	0	1	1
Stauroneis phoenicenteron (Nitzsch) Ehrenberg	1	VR	7	NT	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stauroneis smithii Grunow	1	VR	9	LC	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0
Staurosira construens Ehrenberg	1	VR	7	NT	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0

Staurosirella pinnata (Ehrenberg) D.M.Williams	1	VR	0	NE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Surirella angusta Kützing	1	F	9	LC	1	1	1	0	0	1	1	0	0	0	1	1	1	1	1
Surirella minuta Brébisson ex Kützing	1	VR	9	LC	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Surirella roba Leclercq	1	VR	5	EN	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Tabellaria flocculosa (Roth) Kützing	1,3	R	9	LC	0	0	0	1	0	1	0	0	1	0	0	1	0	0	0
Ulnaria ulna (Nitzsch) Compère	1,2,3	R	8	DD	1	0	0	0	0	1	0	0	1	0	0	0	1	1	0

Note: Frequencies of algal taxa were determined according to the following scale based on the number of lakes studied in the Kaçkar Mountains Natural Park. Very rare (VR): taxa recorded in 1-20% of investigated lakes; rare (R): taxa recorded in 21-40% of investigated lakes; common (C): taxa recorded in 41-60% of investigated lakes; frequent (F): taxa recorded in 61-80% of investigated lakes; very frequent (VF): taxa recorded in 81-100% of investigated lakes [37]. Abbreviation of the IUCN categories: EXTINCT (EX); CRITICALLY ENDANGERED (CR); ENDANGERED (EN); VULNERABLE (VU); NEAR THREATENED (NT); LEAST CONCERN (LC); DATA DEFICIENT (DD); NOT EVALUATED (NE).

Table A2. Indicator properties of diatom species in the lakes of the Kaçkar Mountains National Park, in summer and autumn of 2020.

Taxa	Hab	T	Oxy	Sal	pH	D	S	Aut-Het	Tro
Achnanthes sp.	-	-	-	-	-	-	-	-	-
Achnanthidium minutissimum (Kützing) Czarnecki	P-B	eterm	st-str	i	ind	es	0.95	ate	e
Amphora ovalis (Kützing) Kützing	B	temp	st-str	i	alf	sx	1.50	ate	e
Aulacoseira ambigua (Grunow) Simonsen	P	temp	st-str	i	alf	sp	1.70	ate	om
Aulacoseira valida (Grunow) Krammer	P-B	-	-	i	alf	es	1.30	ate	om
Caloneis silicula (Ehrenberg) Cleve	B	warm	st	i	ind	sp	1.30	ats	om
Campylodiscus bicostatus W.Smith ex Roper	B	-	-	mh	alb	-	-	ats	e
Chamaepinnularia hassiaca (Krasske) Cantonati & Lange-Bertalot	B	temp	st-str	hb	acf	es	1.00	ats	ot
Cocconeis lineata Ehrenberg	P-B	temp	st-str	i	alf	sx	1.20	ate	e
Craticula cuspidata (Kutzing) D.G.Mann	B	temp	st-str	i	alf	es	2.45	-	me
Cyclotella bodanica var. *lemanica* (O.Müller ex Schroter) Bachmann	P	-	-	i	ind	-	-	-	-
Cyclotella distinguenda Hustedt	P	-	str	hl	alf	-	1.30	-	om
Cyclotella meneghiniana Kützing	P-B	temp	st-str	hl	alf	sp	2.80	hne	e
Cymbella aspera (Ehrenberg) Cleve	B	-	st-str	i	neu	es	0.30	ats	e
Cymbella cistula (Ehrenberg) O.Kirchner	B	-	st-str	i	alf	sx	1.20	ats	e
Cymbella cymbiformis C.Agardh	B	temp	st-str	i	alf	sx	2.00	ats	om
Cymbopleura naviculiformis (Auerswald ex Heiberg) Krammer	B	temp	st-str	i	ind	-	-	-	-
Diatoma vulgaris Bory	P-B	temp	st-str	i	alf	-	2.40	-	-
Didymosphenia geminata (Lyngbye) Mart.Schmidt	B	-	st-str	i	ind	-	2.00	-	-
Diploneis elliptica (Kützing) Cleve	B	temp	str	i	alf	es	-	-	-
Diploneis oblongella (Nägeli ex Kützing) A.Cleve	B	-	st-str	i	ind	-	-	-	-
Diploneis petersenii Hustedt	B	-	str	i	ind	-	-	-	-
Discostella stelligera (Cleve & Grunow) Houk & Klee	P-B	temp	st-str	i	ind	-	-	-	-
Encyonema minutum (Hilse) D.G.Mann	B	temp	st-str	i	ind	sx	1.50	ats	-
Encyonema silesiacum (Bleisch) D.G.Mann	B	temp	st-str	i	ind	-	-	-	-
Epithemia adnata (Kützing) Brébisson	B	temp	st-str	i	alb	-	1.20	-	-
Eunotia arcus Ehrenberg	B	temp	st-str	i	acf	sx	0.40	ats	ot
**Eunotia cristagalli* Cleve	P-B	-	st-str	i	acf	-	1.00	-	ot
Eunotia mucophila (Lange-Bertalot, Nörpel-Schempp & Alles) Lange-Bertalot	P-B	temp	st-str	hb	acf	-	-	-	-
Eunotia paludosa Grunow	B	-	str	hb	acf	sx	0.50	ats	ot
Eunotia praerupta Ehrenberg	P-B	cool	st-str	hb	acf	-	0.30	-	-
Fragilaria gracilis Østrup	P-B	temp	str	i	ind	es	1.55	hne	-
Fragilaria rumpens (Kützing) G.W.F.Carlson	P-B	eterm	st-str	i	ind	-	2.00	ats	e
Frustulia crassinervia (Brébisson ex W.Smith) Lange-Bertalot & Krammer	B	-	str	hb	acf	sx	0.50	ats	ot
Frustulia saxonica Rabenhorst	B	temp	st-str	hb	acf	-	-	ate	-
Frustulia vulgaris (Thwaites) De Toni	P-B	temp	st-str	i	alf	-	1.00	-	-
Frustulia sp.	-	-	-	-	-	-	-	-	-
Gomphonella olivacea (Hornemann) Rabenhorst	B	temp	st-str	i	alf	-	2.30	ate	om
Gomphonema parvulum (Kützing) Kützing	B	temp	st-str	i	ind	-	0.70	ats	ot
Gomphonema truncatum Ehrenberg	B	temp	st-str	i	ind	-	2.00	-	-
Gyrosigma acuminatum (Kützing) Rabenhorst	B	temp	st-str	i	alf	-	-	-	-
Hannaea arcus (Ehrenberg) R.M.Patrick	B	temp	str	i	alf	-	-	-	-
Hantzschia amphioxys (Ehrenberg) Grunow	B,aer	temp	st-str	i	ind	-	3.00	-	me

Iconella capronii (Brébisson & Kitton) Ruck & Nakov	P-B,S	-	st	i	ind	sx	1.00	ats	e
Iconella spiralis (Kützing) E.C.Ruck & T.Nakov	B	-	str	i	alf	-	1.10	-	-
Iconella tenera (W.Gregory) Ruck & Nakov	P-B	temp	st	i	alf	-	0.20	ats	ot
Meridion circulare (Greville) C.Agardh	P-B	temp	st-str	i	ind	-	-	-	-
Navicula cryptocephala Kützing	P-B	temp	st-str	i	ind	-	2.40	-	-
Navicula cryptotenella Lange-Bertalot	P-B	temp	st-str	i	ind	-	-	-	-
Navicula phyllepta Kützing	B	-	-	hl	-	-	-	-	-
Navicula radiosa Kützing	B	temp	st-str	i	ind	sx	-	-	-
Navicula rhynchocephala Kützing	B	temp	st-str	hl	alf	-	1.30	-	-
Neidium ampliatum (Ehrenberg) Krammer	B	temp	st	i	ind	-	-	-	-
Neidium bisulcatum (Lagerstedt) Cleve	B	-	st-str	i	ind	-	1.00	-	-
Neidium iridis (Ehrenberg) Cleve	B	temp	st-str	hb	ind	-	-	-	-
Odontidium mesodon (Kützing) Kützing	B	cool	st-str	hb	ind	-	0.90	-	-
Orthoseira dendroteres (Ehrenberg) Genkal & Kulikovskiy	B,aer	-	-	i	-	es	1.80	-	-
Orthoseira roeseana (Rabenhorst) Pfitzer	P-B	warm	-	i	ind	-	-	-	om
Pinnularia aestuarii Cleve	B	-	-	mh	alf	-	-	-	-
Pinnularia appendiculata (C.Agardh) Schaarschmidt	B	-	st-str	i	ind	-	1.00	-	ot
Pinnularia balatonis (Pantocsek) F.W.Mills	-	-	-	-	-	-	0.80	-	-
Pinnularia borealis Ehrenberg	B,aer	-	st-str,aer	i	ind	-	1.00	-	ot
Pinnularia brebissonii (Kützing) Rabenhorst	B	temp	st-str	i	ind	-	1.00	-	-
Pinnularia interrupta W.Smith	B	-	st-str	i	ind	-	-	-	-
Pinnularia lata (Brébisson) W.Smith	P-B	-	str	i	acf	-	0.30	-	-
Pinnularia major (Kützing) Rabenhorst	B	temp	st-str	i	ind	-	1.00	ats	m
Pinnularia mesogongyla Ehrenberg	B	-	st	i	ind	sx	0.20	ats	ot
Pinnularia microstauron (Ehrenberg) Cleve	P-B	temp	st-str	i	ind	-	0.30	ats	ot
Pinnularia microstauron var. *nonfasciata* Krammer	B	-	-	-	-	-	-	-	ot
Pinnularia rupestris Hantzsch	B	temp	str	i	acf	-	-	-	-
Pinnularia viridis (Nitzsch) Ehrenberg	P-B	temp	st-str	i	ind	-	0.90	-	ot
Planothidium distinctum (Messikommer) Lange-Bertalot	B	-	-	-	-	-	2.00	-	o-e
Psammothidium helveticum (Hustedt) Bukhtiyarova & Round	B	temp	st-str	hb	alf	es	2.40	ate	m
Rhopalodia gibba (Ehrenberg) O.Müller	P-B	temp	st-str	i	alf	es	1.40	ate	om
Stauroneis anceps Ehrenberg	P-B	temp	st-str	i	ind	sx	1.30	ats	om
Stauroneis phoenicenteron (Nitzsch) Ehrenberg	P-B	temp	st-str	i	ind	-	-	-	-
Stauroneis smithii Grunow	P-B	-	st-str	i	alf	-	1.00	-	om
Staurosira construens Ehrenberg	P-B	temp	st-str	i	alf	-	1.00	-	-
Staurosirella pinnata (Ehrenberg) D.M.Williams	P-B	temp	st-str	hl	alf	es	1.10	ats	om
Surirella angusta Kützing	P-B	temp	st-str	i	alf	-	-	-	-
Surirella minuta Brébisson ex Kützing	B	temp	st-str	i	alf	-	-	-	-
Surirella roba Leclercq	B	-	str	i	acf	-	-	-	-
Tabellaria flocculosa (Roth) Kützing	P-B	eterm	st-str	i	acf	-	0.30	-	-
Ulnaria ulna (Nitzsch) Compère	P-B	temp	st-str	i	alf	es	2.40	ate	e

Note: “0“, not found. Abbreviations: Habitat (Hab) (P-B – plankto-benthic, B – benthic); temperature (T) preferences (cool – cool-water, temp – temperate, eterm – eurythermic, warm – warm-water); oxygenation and streaming (Oxy) (str – streaming water, st-str – low streaming water); pH preferences groups (pH) according to Hustedt (1957) [56] (alb – alkalibiontes; alf – alkaliphiles, ind – indifferent; neu – neutrophiles as a part of indifferent group; acf – acidophiles; salinity ecological groups (Sal) according to Hustedt (1938–1939) [57] (hb – oligohalobes-halophobes, i – oligohalobes-indifferent, hl – halophiles; mh – mesohalobes, oh – oligohalobes of wide spectrum with optimum as indifferent); Index S, species-specific index saprobity according to Sládeček, 1986 [58]; organic pollution indicators according to Watanabe et al. (1986) [59] (D): sx – saproxenes; es – eurysaprobes; sp – saprophiles; nitrogen uptake metabolism (Aut-Het) (Van Dam et al., 1994) [48]: ats – nitrogen-autotrophic taxa, tolerating very small concentrations of organically bound nitrogen; ate – nitrogen-autotrophic taxa, tolerating elevated concentrations of organically bound nitrogen; Trophic state indicators (Tro) (Van Dam et al., 1994) [48]: (ot – oligotraphentic; om – oligomesotraphentic; m – mesotraphentic; me – mesoeutraphentic; e – eutraphentic; he – hypereutraphentic).

Table A3. Bioindicators in the diatom communities of the lakes in the Kaçkar Mountains National Park, in summer and autumun of 2020.

Indicator group	AL-1	KPL-3	KPL-4	KPL-1	TSL-1	KPL-2	ML	TSL-2	KPL-5	BDL	KVL	AL-2	VKL	KRDL	AP
Habitat															
B	11	12	9	19	16	18	18	22	12	16	10	14	19	23	14
P-B	5	6	6	12	9	10	12	12	6	8	9	6	10	13	9
P	0	0	0	2	1	0	0	0	0	1	0	0	0	0	0
Temperature															
cool	1	0	0	1	1	1	2	2	0	0	1	1	1	2	1
temp	10	11	9	22	17	16	17	21	13	16	11	13	18	24	15
eterm	0	0	1	0	1	0	3	0	0	2	0	0	1	1	0
warm	1	1	1	1	0	1	1	1	1	1	0	1	1	1	2
Oxygen															
st	2	2	2	3	1	3	2	3	3	2	2	3	2	3	2
st-str	11	13	12	26	19	21	26	25	13	18	12	14	22	29	20
str	2	1	1	3	5	1	1	4	1	4	2	2	3	2	0
Salinity															
hb	1	1	1	4	2	4	5	3	1	1	3	2	2	4	2
i	14	15	14	26	23	23	24	29	16	24	14	18	26	29	21
hl	0	0	0	2	1	0	0	2	1	0	0	0	1	2	0
mh	0	1	0	1	0	1	0	0	0	0	1	0	0	0	0
pH-groups															
acf	1	1	2	4	3	2	3	3	1	3	4	2	3	1	2
ind	10	11	11	17	12	16	20	17	10	14	10	10	13	18	16
alf	4	4	2	12	10	9	6	13	6	8	4	7	10	15	5
alb	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
Watanabe															
sx	3	5	3	6	5	5	6	6	3	7	4	4	7	7	5
es	1	1	1	2	5	3	3	6	2	4	3	4	4	5	2
sp	1	1	1	3	0	1	1	2	2	1	0	1	1	1	1
Autotrophy-Heterotrophy															
ats	5	7	5	9	6	8	8	8	4	7	4	6	6	8	7
ate	0	0	0	5	4	4	3	4	2	5	2	3	3	5	3
hne	0	0	0	1	0	0	0	2	1	0	1	0	0	0	0
Trophic state															
ot	1	2	2	4	2	3	2	3	1	1	5	3	3	4	3
om	1	2	2	5	3	5	3	4	2	4	3	3	3	5	5
m	1	1	1	2	1	2	2	1	1	1	0	1	1	2	1
me	0	0	0	0	0	1	1	0	0	1	0	0	0	0	1
e	1	3	1	5	4	2	5	6	3	5	1	2	4	5	3
o-e	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Class of Water Quality															
Class 1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Class 2	4	4	6	10	9	10	11	13	3	9	7	8	9	17	5
Class 3	4	3	2	8	7	7	5	8	5	5	2	4	7	6	2
Class 4	0	0	0	1	0	1	1	1	1	1	0	0	1	4	1
No of Species	16	18	15	33	26	28	31	34	18	25	19	21	29	37	23
Sum of Scores	17	18	15	35	26	30	31	34	19	25	19	21	29	38	23
Index S	1.46	1.40	1.27	1.43	1.45	1.55	1.38	1.45	1.72	1.53	1.09	1.34	1.49	1.34	1.26

Note: "0", not found. Abbreviations: Habitat (P-B – plankto-benthic, B – benthic); temperature preferences (cool – cool-water, temp – temperate, eterm – eurythermic, warm – warm-water); oxygenation and streaming (str – streaming water, st-str – low streaming water, st – standing water); pH preferences groups according to Hustedt (1957) [56] (alb – alkalibiontes; alf – alkaliphiles, ind – indifferent; acf – acidophiles; salinity ecological groups according to Hustedt (1938–1939) [57] (hb – oligohalobes-halophobes, i – oligohalobes-indifferent, hl – halophiles; mh – mesohalobes); Index S, species-specific index saprobity according to Sládeček, 1986 [58]; organic pollution indicators according to Watanabe et al. (1986) [59]: sx – saproxenes; es – eu - rysaprobes; sp –

saprophiles; nitrogen uptake metabolism (Aut-Het) (Van Dam et al., 1994) [48]: ats – nitrogen-autotrophic taxa, tolerating very small concentrations of organically bound nitrogen; ate – nitrogen-autotrophic taxa, tolerating elevated concentrations of organically bound nitrogen, hne – facultatively nitrogen–heterotrophic taxa, needing periodically elevated concentrations of organically bound nitrogen; trophic state indicators (Van Dam et al., 1994) [48]: (ot – oligotraphentic; om – oligomesotraphentic; m – mesotraphentic; me – mesoeutraphentic; e – eutraphentic; o-e – oligo- to eutraphentic). The water quality class is determined as the sum of indicators whose species-specific index saprobity S from Appendix A Table A2 is within the range of each class.

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