BIOINDICATION OF WATER PROPERTIES BY ALGAL COMMUNITIES IN THE PAMIR HIGH MOUNTAIN MINERAL AND THERMAL SPRINGS

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DOI: 10.2478/trser-2018-0016

KEYWORDS: diatoms, thermal, mineral springs, Pamir, Tajikistan.

ABSTRACT
The bioindication methods have been implemented for the first time for the analyses of water properties in six mineral and thermal springs of Pamir. The studied environment was characterized as flow-alkaline, well oxygenated with low salinity, and low to middle organically polluted. Studied diatom communities preferred periphytonic and benthic habitats of temperate temperature waters. Bioindicator species preferred photosynthetic way of protein synthesis. In first time assessed the trophic level of each studied source show that all they have a state from oligotrophic to mesotrophic. Bioindication methods revealed the effectiveness of nature conservation system in Tajikistan and relevance of bioindication methods using in purpose of assessment and monitoring of water sources on the protected territories.

ZUSAMMENFASSUNG: Bioindikation von Wassereigenschaften durch Algengemeinschaften in den Pamir-Hochgebirgsmineral- und Thermalquellen.
Erstmals wurden für die Analyse der Gewässergüte in sechs Mineral- und Thermalquellen im Pamir Gebiet Bioindikationsmethoden eingesetzt. Die Umgebung der untersuchten Quellen wurde als schwach alkalisch, sauerstoffreich, salzarm und gering bis mittel-organisch eingestuft. Die untersuchten Kieselalgengemeinschaften bevorzugten periphytonische und benthische Habitate von Gewässern mit gemäßigter Temperatur. Die Bioindikator-Arten bevorzugten die photosynthetische Art der Proteinsynthese. Beim ersten Mal zeigte das trophische Niveau jeder untersuchten Quelle einen oligotrophen bis mesotrophen Zustand an. Die Bioindikationsmethoden verdeutlichen die Wirksamkeit des Naturschutzsystems in Tadschikistan sowie die Relevanz von Bioindikationsmethoden bei der Bewertung und Überwachung von Wasserquellen in den geschützten Gebieten.

REZUMAT: Bioindicarea proprietăților apei de către comunitățile de alge din izvoarele minerale și termale din munții Pamir.
Metoda bioindicatorilor a fost aplicată pentru prima dată pentru analiza proprietăților apei în șase izvoare minerale și termale din Pamir. Mediul surselor de apă studiate se caracterizează prin alcalinitate slabă, oxigenare bună, salinitate scăzută și poluare organică redusă până la moderată. Comunitățile de diatomee studiate preferă habitatele perifitice și bentonice ale apelor cu temperatură moderată. Speciile bioindicatoare sunt fotosintetizatoare. Pentru prima dată s-a evaluat nivelul trofic al fiecărei surse de apă studiate, constatându-se că acestea sunt de la oligotrofe până la mezotrofe. Metoda bioindicatorilor a evidențiat eficacitatea sistemului de conservare a naturii în Tadjikistan și relevanța folosirii acestei metode în scopul evaluării și monitorizării surselor de apă din ariile protejate.

INTRODUCTION

Mineral and thermal springs are widely distributed throughout the world but are most numerous in mountain areas in which there has been volcanic activity in late geologic time (Waring, 1965).

Mineral and thermal springs represent natural waters that are characteristic of the region. Biota in natural high mountain sources has been mostly studied from the middle period of 20th century (Winterbourn, 1969) when most attention was given to cyanobacteria, and only in last years to diatoms also (Fránková et al., 2009; Leira et al., 2017).

Algal species richness and occurrence up to now are studied not enough in mountain springs because their usually placed in hard-to-reach areas (Sisma-Ventura et al., 2010).

There are known many springs in Pamir with different water properties (Waring, 1965). The natural springs in Tajikistan are under protection (Bokhodjaev and Davlatmamadov, 1994) and can represent some natural environment as reference characteristics in the context of an increase in the anthropogenic load of the surrounding areas. But study of algal diversity in Pamir springs is in initial stage (Churshina, 1982; Barinova and Niyatbekov, 2017) although its algal species ecology can help to characterize the reference natural water properties in this important and interesting area of the world.

Freshwater algae are widely used in ecological assessment of water quality. It is very important to know about algal diversity in inland waters because most algal species can be used as environmental indicators. (Barinova et al., 2006; Sinitean and Kutaşi, 2012; Torrisi and Dell'uomo, 2012; Barinova and Niyatbekov, 2017)

Diversity of algae in Tajikistan has been studied sporadically during the last century. The uppermost part of Tajikistan territory is Pamir where large regional rivers as Panj and Gunt are started. This high mountain area is very rich in thermal and mineral waters. In these waters, for many centuries, a special community of algae with a specific species composition and degree of species resistance to peculiarly extreme environmental conditions was formed and developed. Therefore, Pamir is one of high altitude area in Eurasia with close relations to Hindu Cush, Altay, and Himalayas. Its territory has diverse aquatic habitats from clear freshwater large rivers, streams, lakes, to mineral and thermal springs which are occupied by diverse algal communities.

Our own study of diatoms in thermal and mineral springs was enriched by the regional diversity (Barinova and Niyatbekov, 2017) but we assume that the diversity study of this group of algae in Pamir is still far from complete. Nevertheless, it can help to characterize the high mountain aquatic habitats water quality by bio-indication methods.

Thus, the aim of our work was to reveal species-specific ecological preferences of diatom algae from studied mineral and thermal springs of Pamir to assess its water quality.

Pamir is very rich in thermal and mineral waters, which in a way are unique habitats characterized by a constantly and high temperature from 10°C to 86°C and various chemical compositions saturated with carbon dioxide and nitrogen gases such as hydrogen sulfide-siliceous, hydrocarbonate-sulphate-calcium-magnesium, chloride-sulfate-calcium-sodium, hydrocarbonate-sulfate-sodium and weak radon-chloride-sulfate (Churshina, 1982; Bokhodjaev and Davlatmamadov, 1994). In these waters, for many centuries, a special community of algae with a specific species composition was formed.

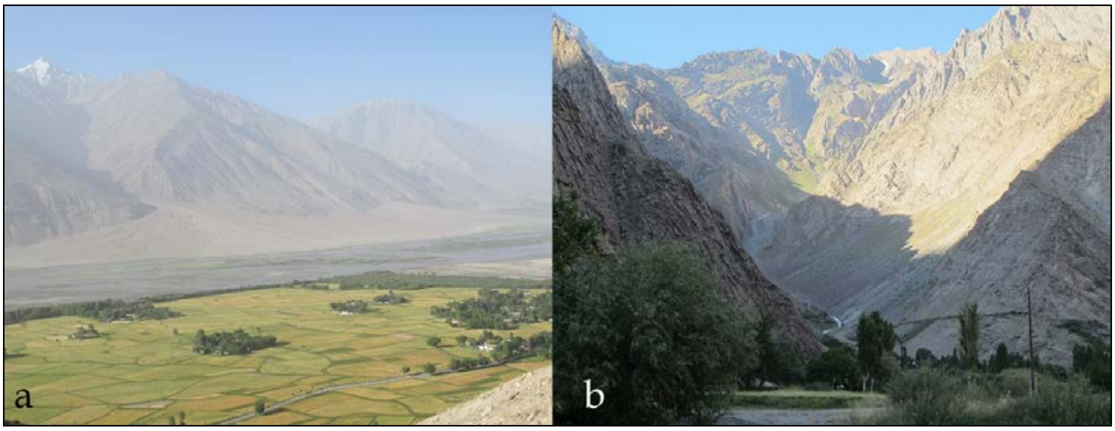

Figure 1: The Panj River, Ishkashim vicinity (a);
the Bartang Canyon (b).

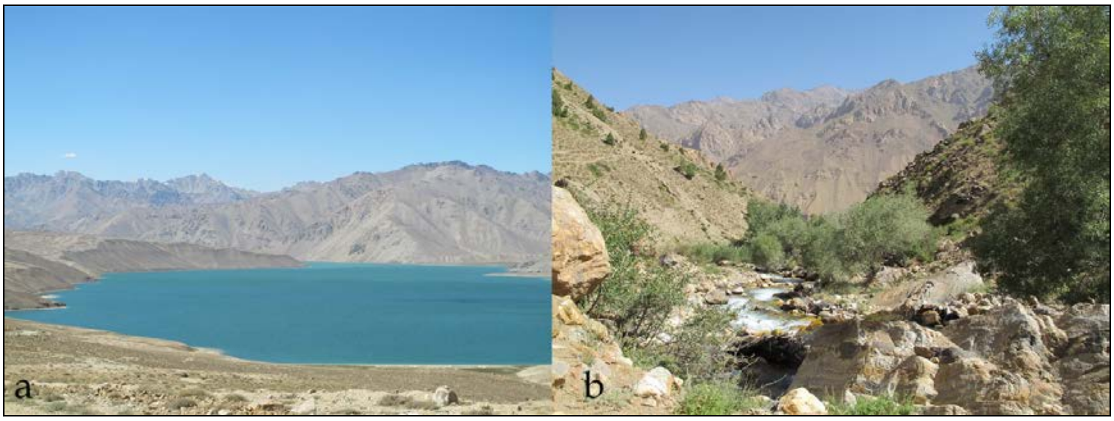

Figure 2: The Yashilkul Lake and its vicinity (a);
the Yazgulam Canyon (b).

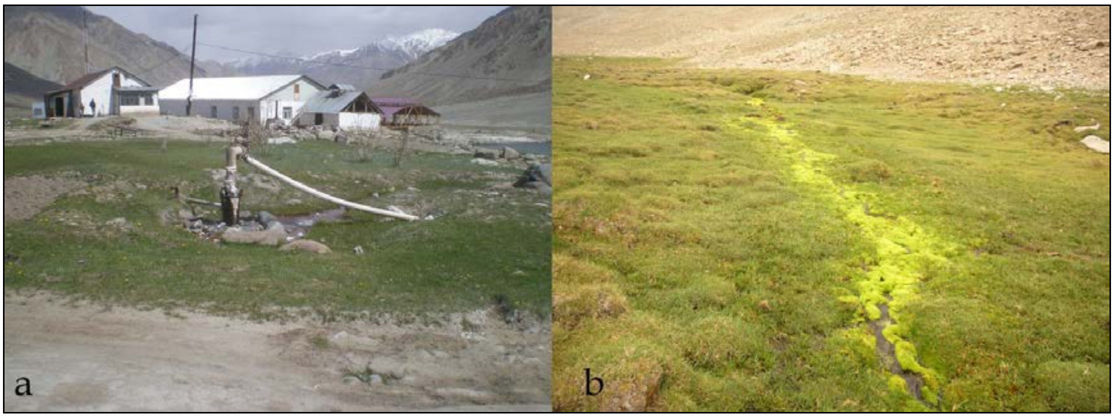

Figure 3: The Jelandy source near the Biological station (a);
the Jelandy source vicinity (b).

MATERIAL AND METHODS

The biological material for this study is represented by personal data (150 samples collected in the summer of 2000-2015 from Jelandy, Avadzh, Garm-Chashma, Sassykbulak, Sist and Barshor located at an altitude from 2,360 to 3,800 m a.s.l. (Figs. 1-3). Algal periphytonic samples were collected and processed from various places, springs, and griffins with a water temperature of 10°C to 86°C (Tab. 1).

Species ecology data come from database (Barinova et al., 2006) for nine ecological bioindication systems. A total list of revealed diatoms in Pamir mineral and hot springs was correlated with an ecological database in the Microsoft Access Program.

Table 1: Diatom indicator taxa and the major variables of habitats in the mineral water springs of Pamir with geographical coordinates.

Pamir region	East	West	West	East	West	West
Name of spring	Jelandy	Avadzh	Garm-Chashma	Sassykbulak	Sist	Barshor
No. of spring	1	2	3	4	5	6
No. of indicator taxa	92	48	18	14	9	18
Altitude, m a.s.l.	3,600	2,410	2,800	3,800	2,360	2,400
Temperature, °C	21-86	35	40-62	22	10-12	10-15
pH	7.8	7.1	7.1	7.4	5.8	6.4
North	37°34’ 30.84”	37°12’ 19.06”	37°12’ 11.06”	37°40’ 84.90”	37°10’ 18.26”	37°00’ 98.02”
East	72°34’ 41.93”	71°31’ 90.51”	71°32’ 11.18”	73°00’ 22.54”	71°30’ 19.87”	71°30’ 21.89”

RESULTS AND DISCUSSION

Data about studied communities from six sources are represented in table 1 with relation to the West or East Pamir regions. We calculated Pearson coefficients for species richness, water pH, temperature and altitude of source with wessa.net and find that only water pH and altitude have significant correlation 0.78 with $p < 0.03$.Alkaline sources are placed in highest altitude and acidic-water sources are in altitude about 2,400 m a.s.l. (Fig. 4). Water temperature in the studied sources is varied even in the same source, but uppermost localities have highest water temperature.

As a result of laboratory processing of 150 periphytonic samples from six thermal and mineral springs, the regional diversity was enriched by 134 diatom species (166 with infraspecific taxa) (Barinova and Niyatbekov, 2017). For the basic list of species, we revealed species-specific ecological properties that are represented in table 2. All found taxa were indicators of substrate preferences, oxygenation, water pH, chlorides concentration, organic pollution, nutrition type, and trophic level.

Species richness of diatoms in the studied source communities is varied in the broad range from 92 in Jelandy to 9 in Sist. Table 1 and figure 4 shows that highest diversity was found in the studied sources with alkaline water with highest temperature. Remarkably, the Jelandy source, where water is 7.8 pH and temperature varied in the range 21-86°C, it was revealed that maximal species richness was – 92 taxa.

Table 2: Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Achnanthes exigua Grunow in Cleve and Grunow	1	–	–	–	–	–	B	eterm	st-str	alf	i	sp	2.0	o-e	ate
Achnanthes gibberula Grunow	1	–	1	1	–	–	B	eterm	st-str	ind	mh	sx	0.3	o-m	–
Achnanthes Gibberula var. *interrupta* Poretzky and Anisimova	1	–	–	–	–	–	B	eterm	st-str	ind	mh	sx	0.3	o-m	–
Achnanthidium minutissimum (Kützing) Czarnecki	1	–	–	–	–	–	P-B	eterm	st-str	ind	i	es	0.95	o-e	ate
Achnanthidium thermal Rabenhorst	1	–	–	–	–	–	B	eterm	st-str	ind	mh	sx	0.3	o-m	–
Actinella punctata Lewis F. W.	1	–	–	–	–	–	B	–	–	acf	hb	–	1.0	ot	–
Amphora ovalis (Kützing) Kützing	1	–	1	–	–	–	B	temp	st-str	alf	i	sx	1.5	me	ate
Amphora ovalis var. *ediculus* (Kützing) Van Heurck	–	1	–	–	–	–	B	temp	st	alf	i	es	1.7	o-m	ate

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Amphora ovalis var. *lybica* (Ehrenberg) Cleve	–	1	–	–	–	–	B	temp	st	alf	i	es	1.5	o-m	–
Aneumastus minor Lange-Bertalot	1	–	–	–	–	–	P-B	–	–	alf	i	–	1.2	o-m	–
Aneumastus rostratus (Hustedt) Lange-Bertalot	–	–	–	1	–	–	P-B	–	–	alf	i	–	2.0	–	–
Aneumastus tuscula f. *intermedia* Kisselev	1	–	–	–	–	–	P-B	–	–	alf	i	–	0.9	o-e	–
Aulacoseira italica (Ehrenberg) Simonsen	1	1	–	–	–	–	P-B	cool	st-str	ind	i	es	1.45	me	–
Brachysira serians (Brébisson) Round and Mann D. G.	1	–	–	–	–	–	B	–	st-str	acf	hb	–	0.2	ot	ats
Caloneis bacillum (Grunow) Cleve	1	–	–	–	–	1	B	temp	st-str	ind	i	es	1.3	me	ats
Caloneis silicula (Ehrenberg) Cleve	1	–	–	–	–	–	B	–	st	ind	i	sp	1.3	o-m	ats
Caloneis silicula var. *kjellmaniana* Cleve	1	–	–	–	–	–	B	–	–	alb	i	–	–	–	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Cavinula lacustris (Gregory W.) Mann D. G. and Stickle in Round, Crawford and Mann	1	–	–	–	–	–	B	–	–	ind	i	–	1.0	o-m	ats
Cocconeis pediculus Ehrenberg	–	1	–	–	–	–	B	–	st-str	alf	i	sx	1.8	me	ate
Cocconeis placentula Ehrenberg	1	1	–	–	–	–	P-B	temp	st-str	alf	i	es	1.35	me	ate
Cocconeis placentula var. *rouxii* (Héribaud-Joseph and Brun) Cleve	1	–	–	–	–	–	B	–	–	alf	i	–	1.4	–	–
Cocconeis scutellum Ehrenberg	–	1	–	–	–	–	B	–	–	–	hl	–	–	–	–
Craticula cuspidata (Kützing) Mann	1	–	–	–	–	–	B	temp	st-str	alf	i	es	2.45	me	–
Craticula halophila (Grunow) Mann D. G. in Round, Crawford and Mann	–	1	–	–	–	–	B	–	st-str	alf	mh	es	3.0	e	ate

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Cymbella affinis Kützing	1	–	–	1	–	–	B	temp	st-str	alf	i	sx	1.1	ot	ats
Cymbella aspera (Ehrenberg) Cleve	1	–	–	–	–	–	B	–	st-str	neu	i	es	0.3	o-e	ats
Cymbella cistula (Ehrenberg) Kirchner O.	–	1	–	–	–	–	B	–	st-str	alf	i	sx	1.2	e	ats
Cymbella compacta Østrup	1	–	1	1	–	–	B	–	–	–	–	–	0.7	–	–
Cymbella cymbiformis Agardh C.	1	–	–	–	–	1	B	temp	str	ind	i	sx	2.0	o-m	ats
Cymbella falaisensis (Grunow) Krammer and Lange-Bertalot	–	–	–	–	1	–	B	–	str	–	hb	es	1.0	o-m	ats
Cymbella helvetica Kützing	–	1	–	–	–	–	B	–	str	ind	i	–	0.6	o-m	–
Cymbella helvetica var. *curta* Cleve	–	1	–	–	–	–	B	–	–	alf	i	–	–	–	–
Cymbella hustedtii Krasske	1	–	–	–	–	–	B	–	str	neu	i	–	1.0	o-m	ats

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Cymbella lanceolata (Agardh C.) Agardh C.	1	–	–	–	–	1	B	–	str	alf	i	sx	1.5	me	ats
Cymbella stuxbergii (Cleve) Cleve	1	–	–	–	–	–	B	–	–	neu	i	–	1.0	ot	–
Cymbella tartuensis Molder	–	1	–	–	1	–	B	–	–	ind	i	–	–	–	–
Cymbella tumida (Brébisson) van Heurck	–	1	–	1	–	–	B	temp	str	alf	i	sx	2.2	me	ats
Cymbella ventricosa Kützing	1	–	–	–	–	–	B	–	–	ind	i	es	1.4	–	–
Cymbella laevis Nägeli in Rabenhorst	1	–	–	1	–	–	B	cool	–	ind	i	sx	–	–	–
Cymbopleura naviculiformis (Auerswald ex Heiberg) Krammer	1	–	–	1	–	–	B	–	st-str	ind	i	es	1.2	o-m	ate
Cymbopleura reinhardtii (Grunow) Krammer K.	1	–	–	–	–	–	B	–	str	ind	i	sx	1.0	m	ats

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Denticula elegans Kützing	–	1	–	–	–	–	P-B, aer	–	–	alf	i	–	0.4	ot	–
Denticula thermalis Kützing	1	–	–	–	1	–	B	warm	–	alf	–	–	2.0	me	–
Diatoma anceps (Ehrenberg) Kirchner	1	–	–	1	–	–	P-B	cool	st-str	neu	hb	sx	0.6	ot	–
Diatoma mesodon Kützing	1	–	1	–	–	–	B	cool	st-str	neu	hb	sx	0.4	ot	ats
Diatoma vulgaris Bory	1	–	–	–	–	–	P-B	–	st-str	ind	i	sx	2.2	me	ate
Diatoma vulgaris var. *linearis* Grunow in van Heurck	1	–	–	–	–	–	B	–	str	alf	i	es	2.2	me	ate
Diatoma vulgaris var. *brevis* Grunow	1	–	–	–	–	–	P-B	–	st-str	alb	i	sx	2.2	me	ate
Didymosphenia geminata (Lyngbye) Schmidt M.	1	–	1	–	–	–	B	–	st-str	ind	i	sx	0.7	ot	–
Diploneis ovalis (Hilse) Cleve	1	–	–	–	–	–	B	–	str	alf	i	sp	0.9	o-m	ats

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Diploneis ovalis var. *oblongella* (Nägeli) Cleve	1	–	1	–	–	–	B	–	str	ind	i	sx	0.9	ot	ats
Ellerbeckia arenaria (Moore ex Ralfs) Crawford	–	1	–	–	–	–	P-B	cool	st-str	alf	i	–	0.6	ot	ats
Encyonema alpinum (Grunow) Mann D. G. in Round, Crawford R. M. and Mann D. G.	–	1	–	–	–	–	B	–	str	ind	hb	es	0.5	ot	ats
Encyonema elginense (Krammer) Mann D. G. in Round, Crawford and Mann	–	1	1	–	–	–	B	temp	st	acf	hb	sx	1.5	–	–
Encyonema pergracile Krammer	–	1	1	–	–	1	B	–	–	–	–	–	–	–	–
Encyonema prostratum (Berkeley) Kützing	–	1	–	–	–	–	P-B	–	str	alb	i	es	1.3	e	ats
Epithemia adnata (Kützing) Brébisson	1	1	–	–	–	–	B	temp	st	alb	i	sx	1.2	me	ats

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Epithemia adnata var. *porcellus* (Kützing) Ross R.	1	–	–	–	–	–	B	–	–	alf	i	–	2.0	me	–
Epithemia adnata var. *saxonica* (Kützing) Patrick R. M. in Patrick and Reimer	–	–	1	–	–	–	B	temp	–	alf	i	–	1.2	me	–
Epithemia argus (Ehrenberg) Kützing	1	–	–	–	–	–	P-B	–	st-str	ind	i	es	0.7	m	–
Epithemia argus var. *angusta* Tarnavschi	–	–	1	–	–	–	B	–	–	ind	i	–	–	–	–
Epithemia argus var. *longicornis* (Ehrenberg) Grunow	1	–	–	–	–	–	P-B	–	–	ind	i	–	–	–	–
Epithemia sorex Kützing	–	1	–	–	–	1	B	temp	st-str	alf	i	sx	1.1	me	ats
Epithemia turgida (Ehrenberg) Kützing	–	–	1	–	–	–	B	temp	st	alf	i	sx	0.9	me	ats
Epithemia turgida var. *capitata* Fricke	1	–	–	–	–	–	B	–	–	alf	i	–	–	–	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Epithemia turgida var. *granulata* (Ehrenberg) Brun	–	–	–	–	–	1	B	–	st	alf	i	–	0.9	o-m	ats
Eucocconeis flexella (Kützing) Meister	1	–	–	–	–	–	B	–	str	ind	mh	sx	0.2	ot	ats
Eunotia diodon Ehrenberg	1	–	–	–	–	–	B	cool	st	acf	i	–	0.2	ot	ats
Eunotia faba Ehrenberg	–	–	–	1	–	–	B	temp	st-str	acf	i	sx	1.1	o-m	ats
Fragilaria capucina var. *vaucheriae* (Kützing) Lange-Bertalot	–	1	–	–	–	–	P-B, Ep	–	st-str	alf	i	sx	1.95	e	ate
Fragilaria tenera (Smith W.) Lange-Bertalot	1	–	–	–	–	–	P-B	–	str	acf	hb	sx	2.3	o-m	ats
Fragilariforma virescens (Ralfs) Williams D. M. and Round	1	–	–	–	–	–	P-B	–	st	ind	i	es	0.4	o-m	ats
Gomphoneis olivaceum (Hornemann) Dawson ex Ross and Sims	1	–	–	–	–	–	B	–	st-str	alf	i	es	1.45	e	ate

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Gomphonema angustatum (Kützing) Rabenhorst	–	1	–	–	–	–	B	–	st-str	ind	i	es	1.3	o-m	–
Gomphonema longiceps Ehrenberg	–	1	–	–	1	–	B	–	str	ind	i	es	0.4	–	–
Gomphonema longiceps var. *subclavatum* Grunow in Schneider	–	1	–	–	–	–	B	–	str	ind	i	es	1.4	–	–
Gomphonema productum (Grunow) Lange-Bertalot and Reichardt in Lange-Bertalot	1	–	–	–	–	–	B	–	str	ind	i	es	1.3	o-m	ate
Gomphonema ventricosum Gregory	–	1	–	–	–	–	B	cool	str	ind	i	–	0.3	ot	ats
Gomphonema gracile Ehrenberg	1	–	–	–	–	1	B	temp	st	alf	i	es	0.8	m	ats
Halamphora acutiuscula (Kützing) Levkov	-	1	–	–	–	–	P-B	warm	–	alf	mh	sp	2.0	–	–
Halamphora coffeaeformis (Agardh) Levkov	–	–	–	–	1	–	B	–	st-str	alf	mh	–	3.0	e	ate

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Halamphora subcapitata (Kisselew) Levkov	–	–	1	–	–	–	B	–	–	–	hl	–	1.0	–	–
Halamphora veneta (Kützing) Levkov	1	–	–	–	–	–	B	–	st-str	alf	i	es	2.6	e	ate
Hannaea arcus (Ehrenberg) Patrick R. M. in Patrick R. M. and Freese L. R.	1	1	1	–	–	–	B	temp	str	alf	i	es	0.3	o-m	ats
Humidophila perpusilla (Grunow) Lowe at al.	1	–	–	–	–	–	B	warm	str	ind	i	sp	0.7	o-m	ats
Kurtkrammeria aequalis (Smith W.) Bahls L.	1	–	–	–	–	–	P-B	–	–	ind	i	–	1.0	ot	–
Mastogloia smithii Thwaites	1	–	–	–	–	–	B	–	–	alf	mh	sx	1.3	me	–
Meridion circulare (Greville) Agardh	1	–	–	–	–	–	B	–	str	ind	i	es	1.1	o-m	ate
Meridion circulare var. *constrictum* (Ralfs) Brun	1	–	–	–	–	–	P-B	–	st-str	ind	hb	sx	1.1	o-e	ate

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Meridion lineare Williams	1	1	–	1	–	–	B	–	str	ind	i	es	1.1	o-m	ate
Navicula brasiliensis Grunow	–	1	–	–	–	–	B	–	–	–	–	–	–	–	–
Navicula cincta (Ehrenberg) Ralfs	1	–	–	–	–	–	B	warm	st-str	alf	hl	es	0.5	me	ate
Navicula cryptocephala Kützing	1	–	–	–	–	–	P-B	temp	st-str	ind	i	es	2.1	o-e	ate
Navicula cryptocephala var. *lata* Poretzky and Anisimova	1	–	–	–	–	–	B	–	–	–	i	–	–	–	–
Navicula dicephala Ehrenberg	1	–	–	–	–	–	B	–	–	ind	i	–	1.4	–	–
Navicula digitoradiata (Gregory) Ralfs in Prichard	–	–	–	1	–	–	B	–	–	alf	I	es	2.0	me	–
Navicula gothlandica Grunow	1	–	–	–	–	–	P-B	–	–	alf	hl	es	2.0	o-m	–
Navicula lacustris var. *paulseniana* (Petersen J. B.) Zabelina	–	–	–	–	–	1	B	–	–	–	i	–	–	–	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Navicula lanceolata (Agardh) Ehrenberg	–	1	–	–	–	–	B	–	st-str	alf	i	es	2.5	e	ate
Navicula lucidula Grunow	–	–	–	–	–	1	B	–	–	–	i	–	–	–	–
Navicula peregrina (Ehrenberg) Kützing	–	–	–	1	–	–	P-B	–	–	alf	mh	es	1.5	o-m	–
Navicula radiosa var. *tenella* (Brébisson) Cleve and Möller	–	–	–	1	–	–	P-B	–	–	ind	i	sx	1.3	o-m	–
Navicula rhynchoce-phala Ehrenberg	–	1	–	–	–	–	B	–	–	alf	hl	–	1.95	o-m	ate
Navicula rostellata Kützing	–	–	–	–	–	1	B	–	st-str	alf	i	es	2.2	e	ate
Navicula rotaeana (Rabenhorst) Grunow	–	1	–	–	–	–	P-B	–	st	ind	i	–	0.7	ot	–
Navicula scutum Schumann	–	–	–	–	1	–	B	–	–	–	–	–	–	–	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Navicula tripunctata (Müller O. F.) Bory in Bory de Saint-Vincent	–	1	–	–	–	–	P-B	–	st-str	ind	i	es	1.7	e	ate
Navicula tuscula f. *obtusa* (Hustedt) Proschkina-Lavrenko	–	–	–	–	–	1	P-B	–	–	alf	i	–	1.2	o-m	–
Navicula viridula (Kützing) Ehrenberg	–	–	1	–	–	–	B	–	st-str	alf	hl	es	2.2	me	ate
Neidiomorpha binodis (Ehrenberg) Cantonati M., Lange-Bertalot and Angeli N.	1	–	–	–	–	–	B	–	str	alf	i	–	1.0	me	ate
Neidium Affine (Ehrenberg) Pfizer	–	1	–	–	–	–	B	–	str	ind	i	–	0.7	ot	ats
Neidium affine var. *undulatum* (Grunow) Cleve	–	1	–	–	–	–	B	–	str	ind	i	–	0.7	ot	ats
Neidium productum (Smith W.) Cleve	–	1	–	–	–	–	P-B	temp	–	ind	i	sx	0.9	ot	ats
Nitzschia amphibian Grunow	1	–	–	–	–	–	P-B, S	temp	st-str	alf	i	sp	2.1	e	hne

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Nitzschia amphibia var. *thermalis* Grunow	1	–	–	–	–	–	B	–	–	–	–	–	–	–	–
Nitzschia dissipata (Kützing) Rabenhorst	1	–	–	–	–	–	B	–	st-str	alf	i	sx	1.7	me	ate
Nitzschia dubia Smith W.	1	–	–	–	–	–	P-B	–	st-str	alf	i	–	2.7	e	hne
Nitzschia fasciculate (Grunow) Grunow in Van Heurck	–	–	–	1	–	–	B	–	st	alf	hl	sx	1.1	–	–
Nitzschia gracilis Hantzsch	1	–	–	–	–	–	P-B	temp	st-str	ind	i	sp	1.8	m	–
Nitzschia gradifera Hustedt	–	–	–	–	1	–	B	–	–	–	hl	–	–	–	–
Nitzschia linearis (Agardh) Smith W.	1	–	–	–	–	–	B	temp	st-str	alf	i	es	1.7	me	ate
Nitzschia linearis var. *tenuis* (Smith W.) Grunow in Cleve and Grunow	–	–	–	–	–	1	B	–	str	alf	i	es	1.7	me	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Nitzschia sublinearis Hustedt	–	1	–	–	–	–	P-B	–	–	alf	i	es	3.0	me	–
Nitzschia subtilis (Kützing) Grunow in Cleve and Grunow	–	1	–	–	–	–	B	–	–	alf	i	es	1.7	o-m	–
Nitzschia thermalis (Ehrenberg) Auerswald in Rabenhorst	1	–	–	–	–	–	P	–	–	ind	i	es	2.8	–	–
Nitzschia thermalis var. *minor* Hilse	1	–	–	–	–	–	B	–	st-str	acf	–	–	1.0	–	–
Nitzschia vermicularis (Kützing) Hantzsch in Rabenhorst	–	–	1	–	–	–	P-B	–	str	alf	i	–	2.2	m	–
Parlibellus crucicula (Smith W.) Witkowski, Lange-Bertalot and Metzeltin	1	–	–	–	–	–	B	–	–	ind	mh	-	2.0	–	–
Pinnularia appendiculata (Agardh C.) Schaarschmidt	1	–	–	–	–	–	B	–	str	ind	i	es	0.3	o-m	ats
Pinnularia elegans (Smith W.) Krammer K.	1	–	–	–	–	–	B	–	–	alf	hl	–	2.0	m	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Pinnularia fonticola Hustedt	1	–	–	–	–	–	B	–	–	ind	i	–	–	–	–
Pinnularia gibbiformis Krammer K.	1	–	–	–	–	–	B	–	–	–	–	–	0.3	–	–
Pinnularia lata (Brébisson) Smith W.	1	–	–	–	–	–	P-B	–	str	acf	i	–	1.0	ot	–
Pinnularia microstauron (Ehrenberg) Cleve	–	1	–	–	–	–	P-B	temp	st-str	ind	i	sp	0.7	ot	ate
Pinnularia viridis Ehrenberg (Nitzsch)	–	–	–	–	–	1	P-B	temp	st-str	ind	i	es	0.3	o-e	ate
Placoneis amphibola (Cleve) Cox E. J.	–	–	–	–	–	1	B	cool	str	ind	i	–	1.0	o-m	ats
Placoneis exigua (Gregory) Mereschko-vsky	1	–	–	–	–	–	B	–	–	ind	i	es	1.4	o-m	–
Placoneis placentula (Ehrenberg) Mereschko-wsky	1	–	–	–	–	–	B	temp	st-str	alf	i	sx	1.5	e	ate

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Planothidium lanceolatum (Brébisson ex Kützing) Lange-Bertalot 1999	–	–	–	–	1	–	P-B	warm	st-str	alf	i	sx	1.6	e	ate
Rhopalodia gibba (Ehrenberg) Otto Müller	1	–	–	–	–	–	B	temp	–	alf	i	es	1.4	o-m	–
Rhopalodia gibba var. *mongolica* (Østrup) Proschkina-Lavrenko	–	1	–	–	–	–	B	temp	–	alf	i	es	1.4	–	–
Rhopalodia gibba var. *ventricosa* (Kützing) Mayer	1	–	–	–	–	–	B	temp	–	alf	i	es	1.4	–	–
Rhopalodia gibberula (Ehrenberg) Müller O.	1	–	–	–	–	–	B	temp	str	alf	mh	es	2.0	me	–
Rhopalodia gibberula var. *producta* (Grunow) Müller O.	–	1	–	–	–	–	B	–	str	alf	hl	–	–	–	–
Rhopalodia musculus (Kützing) Müller O.	1	–	–	–	–	–	P-B,S	–	str	alb	mh	–	1.0	–	–
Rhopalodia musculus var. *mirabilis* Fricke	1	–	–	–	–	–	B	–	–	alf	hl	–	2.0	me	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Rossithidium anastasiae (Kaczm.) Potapova	–	–	–	–	1	–	B	–	–	–	–	es	0.4	–	–
Sellaphora pupula (Kützing) Mereschko-wsky	–	1	–	–	–	–	B	eterm	st	ind	hl	sx	1.9	me	ate
Stauroneis acuta Smith W.	–	–	1	–	–	–	B	–	st-str	alf	i	–	1.0	o-m	–
Stauroneis anceps Ehrenberg	–	–	1	–	–	1	P-B	–	st-str	ind	i	sx	1.3	o-m	ate
Staurosira construens Ehrenberg	–	1	–	–	–	1	P-B	temp	st-str	alf	i	sx	1.3	me	ats
Stephanodiscus astraea (Ehrenberg) Grunow in Cleve and Grunow	–	–	1	–	–	1	P	temp	st	alb	i	es	1.5	me	–
Surirella angusta Kützing	–	1	–	–	–	1	P-B	–	st-str	alf	i	es	1.7	e	ate
Surirella angusta var. *constricta* Hustedt	1	–	–	–	–	–	B	–	–	–	i	–	–	–	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Surirella brebissonii Krammer and Lange-Bertalot	1	–	–	–	–	–	B	–	st-str	alf	i	–	1.7	–	–
Surirella linearis Smith W.	1	–	–	–	–	–	P-B	–	–	ind	i	es	0.5	o-m	–
Surirella linearis var. *helvetica* (Brun) Meister	–	1	–	–	–	–	B	–	–	neu	i	es	0.5	ot	–
Surirella minuta Brébisson ex Kützing	1	–	–	–	–	–	B	–	st-str	ind	i	es	1.8	me	–
Synedra montana Krasske ex Hustedt	–	1	–	–	–	–	B	–	–	–	–	–	–	–	–
Synedra rumpens Kützing	–	1	–	–	–	–	B	–	–	alf	i	es	1.55	–	–
Synedra goulardii Brébisson ex Cleve and Grunow	–	1	–	–	–	–	B	–	–	–	–	–	–	–	–
Tabularia fasciculata (Agardh C.) Williams D. M. and Round	1	–	–	–	–	–	P-B	–	st	ind	mh	es	2.5	e	ate
Tetracyclus rupestris (Kützing) Grunow in Van Heurck	1	–	–	–	–	–	P-B	cool	ae	acf	i	–	0.8	ot	–

Table 2 (continued): Diversity and ecology of diatom algae in the thermal and mineral water sources of Pamir with species autecology. Number of springs 1-6 as in table 1.

Taxa	1	2	3	4	5	6	Hab	T	Oxy	pH	Hal	D	Sap	Tro	Aut-Het
Ulnaria oxyrhynchus (Kützing) Aboal in Aboal, Alvarez Cobelas, Cambra and Ector	1	–	–	–	–	–	P-B	–	–	alf	i	es	2.4	o-m	–
Total:	92	48	18	14	9	18									

Note. Substrate preferences (Hab): P – planktonic, P-B – plankto-benthic, B – benthic, S – soil, Ep – epiphyte. Temperature preferences (T): temp – temperate temperature, eterm – eurythermic, warm – warm-water, cool – could water inhabitants. Oxygenation and streaming (Oxy): st – standing water, str – streaming water, st-str – low streaming water, ae – aerophiles. Halobity degree (Hal): i – oligohalobes-indifferent, hl – halophiles, hb – halophobes, mh – mesohalobes. Acidity degree (pH): alf – alkaliphiles, ind – indifferents; acf – acidophiles, alb – alkalibiontes. Organic pollution indicators according to Watanabe (D): sx – saproxenes, es – eurysaprobes, sp – saprophiles. Species-specific index of saprobity S (Sap). Nitrogen uptake metabolism (Aut-Het): 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 (Tro): ot – oligotraphentic; o-m – oligo-mesotraphentic; m – mesotraphentic; me – meso-eutraphentic; e – eutraphentic; o-e – oligo-eutraphentic.

We analyzed bioindicator species representation in each studied source as well as distribution of specific groups over source communities and between them. The bioindication histograms are organized in order of water pH decreasing. Table 2 and figure 4 shows that benthic species prevail in all studied sources but Garm-Chashma and Barshor were slightly enriched by planktonic inhabitants because only two of these sources have some water mass (Barinova and Niyatbekov, 2017). Temperature species-indicators were represented as whole small taxa, but it also shows prevalence of temperate temperature water inhabitants, a number of which are increased with decreasing of water alkalinity. In figure 4, we have demonstrated that in the Sist community, the presence of warm-water species was high but it is not true because this community contains only nine taxa and we found only one temperature indicator which is related to warm-water group.

Enrichments of water with oxygen is a very important characteristic of aquatic ecosystem because without it cannot exist as a biotic part of the ecosystem. Bioindication groups were mostly related to slow moving or standing water that is in small water sources that we study. In the second place we studied, there were indicators of streaming waters that reflect output of water from the sources with small streams. Standing water indicators are slightly increased with decreasing water alkalinity but it can be more related to the water volume of the source. In the Sist we found only two groups related to water moving and oxygenation but it is difficult to assess because the species richness of diatom indicators is represented by nine taxa only.

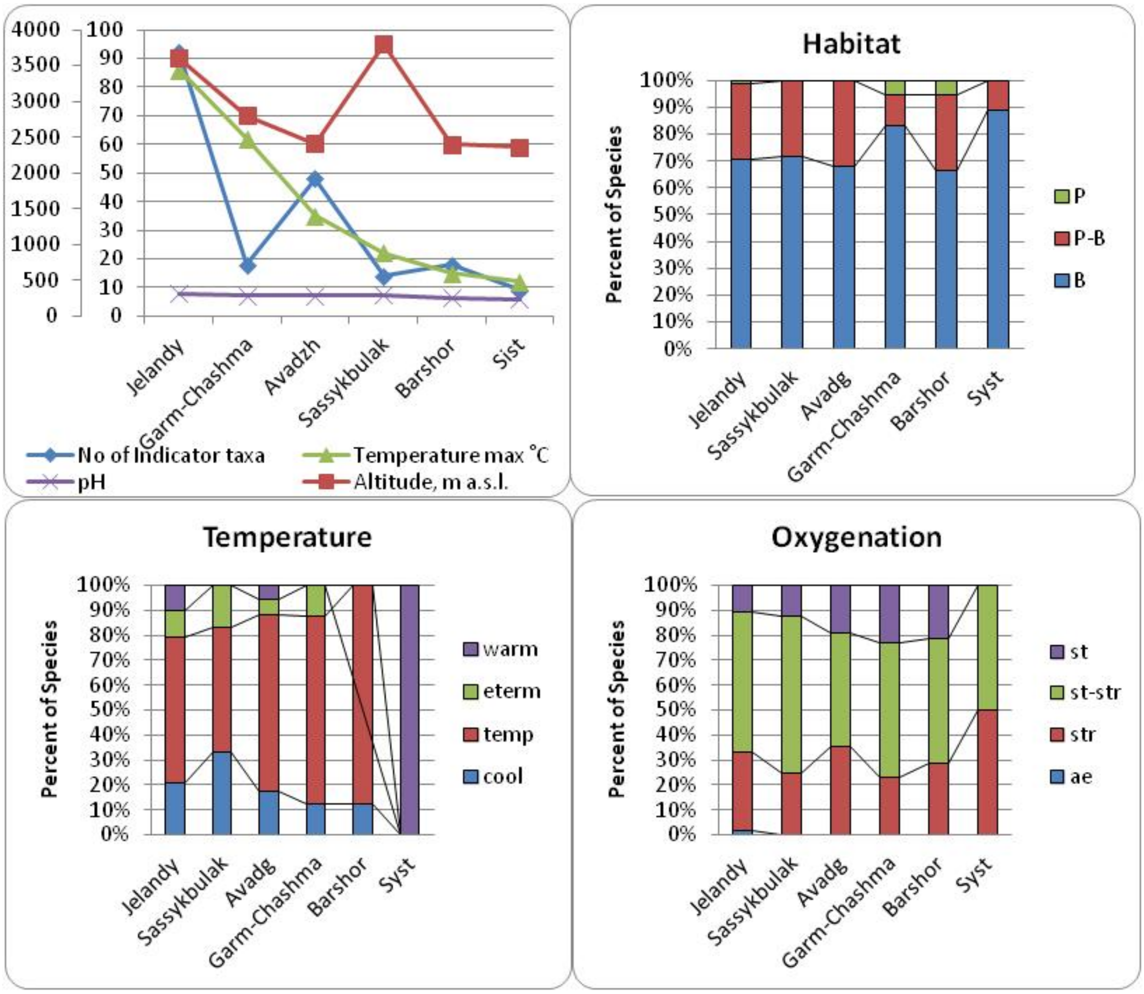

Figure 4: Water variables and indicator species of substrate preferences, temperature, and oxygenation distribution in the studied sources of Pamir.

Water pH bioindication shows (Fig. 5) prevailing alkalic waters over the studied sources although water pH is slightly decreased from 7.8 in Jelandy to 5.4 in Sist. As a whole, indicator groups of alkaliphiles and indifference take about 90% of indicator species in each source community. We assume that the community of each source has some buffered property for stabilizing source environment, and give the possibility to survive for species with broad ecological amplitude. The same situation can be seen in bioindication of water salinity. Figure 5 shows the prevalence of indifferent group and insufficient numbers of the low- and high-salinity indicator number.

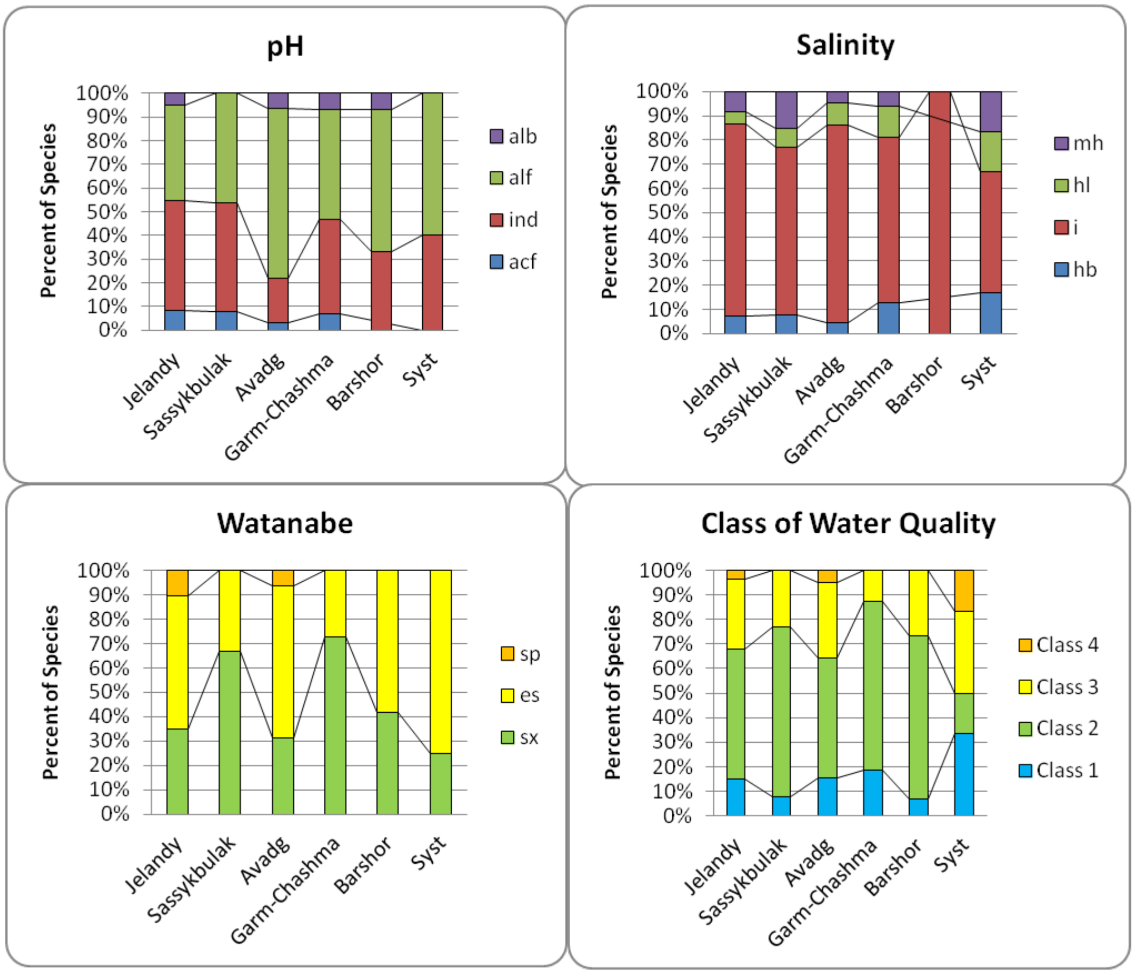

Figure 5: Indicator species of water pH, salinity, and organic pollution with Water Quality Classes distribution in the studied sources of Pamir.

Studied thermal and mineral springs are represented by natural protected areas, therefore, most important to reveal anthropogenic influence on its communities as criteria of protection effectiveness. Figure 5 represents bioindication results of organic pollution with the Watanabe system as well as with the Sládeček's system. The source communities are represented by all indicator groups of Watanabe's method but number of taxa of clear (sx) and middle polluted (es) indicators are prevalent. The colours of groups are the same as are used in the EU system. Classes 1 and 2 indicators in Sládeček system contain most parts of the community in each studied source. That means that water sources are organically clear. Even indicators of middle pollution Class 3 were not as large in number as Class 2. Only few species of Class 4 were found but indicators of polluted water Class 5 were not revealed at all. All this led us to conclude that studied sources are represented by natural unpolluted waters with natural undisturbed aquatic ecosystems.

The effectiveness of photosynthesis was determined in each of the sources with help of the nutrition type indicator species distribution. The photosynthetic diatoms are prevail (97%) in communities of all studied sources (Fig. 6). Organic pollution of sources is related to trophic level of its ecosystem and shows (Fig. 6) that communities of each source are represented by different groups of indicators of trophic state. In the trend of increasing trophic level from oligotrophic indicators (ot) to eutrophic (e and o-e) can be seen that most part of indicators was related to oligo- and mesotrophic groups in each source. Eutrophic groups were represented by about 20% of indicators in Jelandy, Avadg, and Barshor sources. We can see eutrophic groups as half of indicators in the Sist only, but can be keeping in mind that all species in Sist are represented by nine taxa. Therefore, ecosystems of studied sources can be characterized as the oligo-mesotrophic level that usually is in the unpolluted protected areas.

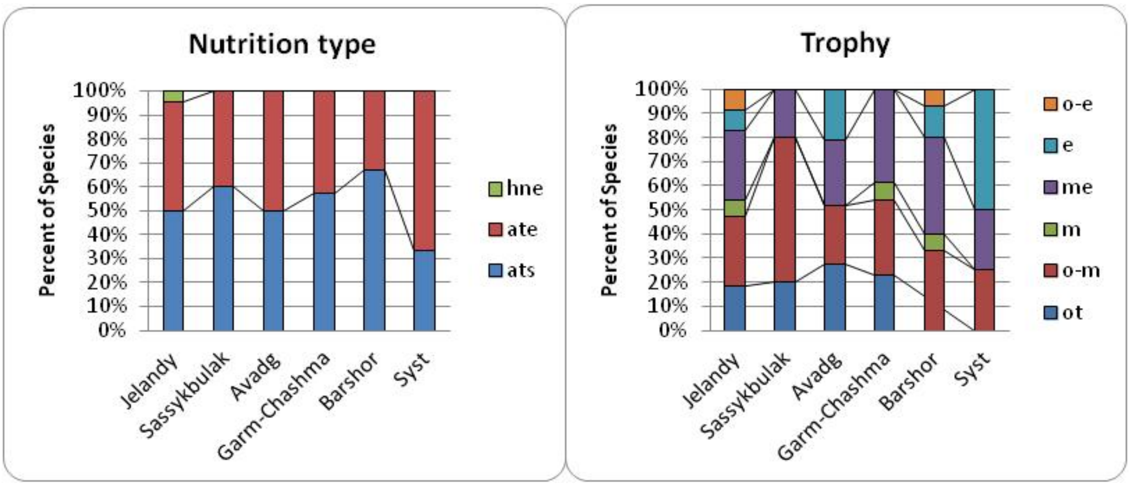

Figure 6: Distribution of indicator species of algal nutrition type and trophic level of aquatic ecosystem in the studied thermal and mineral sources of Pamir.

CONCLUSIONS

Algae diversity study in the sources of the Pamir Mountains is far from complete, but it is very important because thermal and mineral springs in Pamir are represented by diversity in the natural protected areas. Bioindication of diverse variables in six studied sources help us to characterize the environmental variables that have not yet been measured on these hard-to-reach sources. We implemented bioindication approach for the first time for Pamir sources ecosystem assessment. The results can confirm or disprove the applicability of bioindication methods for such different source waters. This first experience can help to characterize the effectiveness of natural conservation and protection mechanisms for Pamir protected areas.

Bioindication on the base of 166 revealed taxa of diatom algae characterize six studied sources environment as low-alkaline, well oxygenated waters with low salinity, and low to middle organically polluted in which diatom community preferred to survive as periphytonic and benthic occupants that preferred temperate temperature waters and photosynthetic way of protein synthesis. The trophic level of each studied source was assessed for the first time, and the data revealed that all of them have a state from oligotrophic to mesotrophic. These results can confirm the effectiveness of a nature conservation system in Tajikistan as well as the relevance of bioindication methods used to assess and monitor water sources on the protected territories.

ACKNOWLEDGEMENTS
The work was partly supported by the Israeli Ministry of Absorption.

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