



Determinant factors of diatom assemblage's distribution along the Coastal Central Constantine (Northeastern Algeria)

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Abstract The present study is based on the identification of benthic diatoms sampled along the Coastal Central Constantine in northeastern of Algeria. Our work aims to address relationships between environmental variables and characterize the spatial and temporal distribution of the diatom flora. Diatoms and samples for physicochemical analysis were collected from 26 sampling sites between May 2017 and August 2018. The number of species accounted for was 109 species in the Safsaf watershed, 117 taxa in the Kebir and 129 species in the watershed of Guebli which was the most diversified catchment. The great majority of diatom taxa were cosmopolitan species. Naviculaceae were the most abundant (47.87%). Our results demonstrated the main environmental

variables controlling the diatom distribution in all the watersheds, including conductivity, and pollution gradients highlighted in Canonical Correspondence Analyses (CCA). The results of the Shannon diversity index (H') showed that the species diversity observed in the sampled sites during summer is higher than that observed in spring and winter. During this season, mean Shannon diversity values were around $H' = 4.49, 3.98, \text{ and } 4.17$, respectively, while species richness varied between 13 and 34 across the three watersheds.

Keywords Benthic diatoms · Canonical correspondence analysis · Diversity indices · Environmental gradients

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Introduction

Diatoms are unicellular microalgae belonging to the phylum Bacillariophyta. They proliferate in rivers, colonizing nearly all suitable habitats, and have been widely used in studies related to water quality monitoring (Round 1991). They are the most common and diverse group of organisms found in many rivers and streams, making them vital components of these ecological systems. River benthic communities are influenced by a variety of factors, particularly ionic content, pH, dissolved organic matter, and nutrients, with populations responding differently depending on their particular environmental tolerances (Potapova and Charles 2003, 2005; Blanco and Bécares 2010).

Benthic diatom communities respond quickly to water disturbances, such as changing physicochemical conditions or pollution-related stressors. Due to their ability to respond to environmental changes, benthic diatoms have been used in aquatic bio-assessment over the years (Round 1991; Szczepocka and Szulc 2009; Solak and Acs 2011; Taş et al. 2019), and for example they are widely used as indicators of water quality in lotic ecosystems (Pandey et al. 2017; Tan et al. 2017; Ozer et al. 2018). In various regions, numerous diatom indices have been developed as a tool to assess the ecological status of rivers (Prygiel and Coste 1996; Prygiel et al. 2002; Lavoie et al. 2006; Tison et al. 2008).

Most research on benthic diatoms and their relationships with ecological factors has been conducted in Europe and the United States (Potapova and Charles 2003; Rimet 2009; Blanco et al. 2013; Oğuz et al. 2020). To our knowledge studies on benthic diatoms in Algeria are limited. To date Baudrimont (1974) made significant contributions to the diatom flora from fresh and brackish waters of Algeria.

Further, to our knowledge, Algerian hydrosystems have been very little studied to date, particularly with regard to their ecological aspects using benthic diatoms. Studies by Chaïb et al. (2011), Chaïb and Tison-Rosebery (2012), and Nehar et al. (2015) who mainly focused on taxonomy and/or water quality assessment of rivers from northern Algeria, constitute a significant contribution to the diatom database of Algeria.

Chaïb et al (2011) described numerous diatom taxa in El Kebir-east watershed in the eastern coastal area of Constantine (northeast Algeria), reaching 322

identified species sampled over a span of 3 years at 23 sampling stations, where a marked longitudinal gradient was the key determinant of the distribution of these diatom communities. In addition, two more factors that affected the shape of diatom assemblages were related to water conductivity and also the man-made impact. In comparison, Nehar et al. (2015) reported 56 taxa collected from El-hammam stream at Mascara and estuary of Cheliff River at Mostaganem (northwest Algeria), most of them cosmopolitan species but with 10 taxa being recorded for the first time in the country. In their papers, those authors suggest a revision of autecological values for taxa because of the peculiar water quality context of the Algerian hydrosystems.

Recent works conducted on diatoms of some Algerian wetlands have recorded few numbers of diatom taxa compared to other studies, e.g., El Haouati et al. (2015) recorded 24 species in Reghaïa lake in northern Algeria, and Chabaca et al (2020) reported 18 genera in Oubeira lake (northeast Algeria). The diatom flora of Chott-Chergui and Ain Dalia dam (northwest and northeast Algeria) was composed of 36 and 72 species, respectively (Heramza et al. 2021; Negadi et al. 2021), while the study of Draredja et al. (2019), carried out in Mellah lagoon (northeast of Algeria), reported 160 diatom taxa including 52 centric species and 108 pennate species. All of those authors focused their studies on monitoring the spatiotemporal evolution of diatom communities and on defining the main abiotic factors contributing to these dynamics.

The present study is a contribution to complete the Algerian database of diatoms inventoried, set up to date by the aforementioned works and the determinant factors of their distribution. Our investigation is the first of its kind to be carried out with a large sample size in space and time in the watershed of the Coastal Central Constantine, divided into three main watersheds (Safsaf, Kebir, and Guebli) which belongs to the Mediterranean region, characterized by a humid to sub-humid (subtropical) climate (Titi Benrabah et al. 2013).

The present paper aims to: (a) Evaluate the contribution of the environmental variables in the distribution of diatom species, and (b) Set up a checklist of the diatom species identified in all sampling sites of the Coastal Central of Constantine.

Table 1 Geographical location and characteristics of the studied sites

Watershed	Sites number	Sites name	Sites codes	Latitude	Longitude	Altitude	Width	Depth
Saf Saf	1	Safsaf upstream	SSU	36° 42' 9.6588" N	6° 51' 45.5076" E	35	10	31
	2	Safsaf downstream	SSD	36° 50' 45.9420" N	6° 56' 9.5388" E	21	10	32
	3	Zeramna upstream	SZU	36° 50' 24.8496" N	6° 53' 26.7720" E	22	4	24
	4	Zeramna downstream	SZD	36° 52' 7.1400" N	6° 55' 21.6408" E	14	9	32
	5	Aghbel upstream	SAU	36° 41' 54.3876" N	6° 47' 49.5888" E	89	3	17
	6	Aghbel downstream	SAD	36° 42' 10.4580" N	6° 48' 0.0900" E	87	4	15
Kebir	7	El kebir upstream	KKU	36° 45' 41.7060" N	7° 17' 50.5968" E	31	5	32
	8	El kebir downstream	KKD	36° 51' 39.7116" N	7° 17' 53.0880" E	14	7	43
	9	Mougger upstream	KMU	36° 42' 4.2696" N	7° 18' 35.4240" E	43	7	34
	10	Mougger downstream	KMD	36° 42' 6.4116" N	7° 18' 34.7220" E	47	6	32
	11	Emchekel upstream	KEU	36° 44' 38.4576" N	7° 14' 22.2720" E	39	6	50
	12	Emchekel downstream	KED	36° 44' 36.8340" N	7° 14' 25.8936" E	38	6	38
	13	Fendek upstream	KFU	36° 43' 38.2080" N	7° 05' 1.9644" E	97	8	36
	14	Fendek downstream	KFD	36° 43' 42.6036" N	7° 05' 2.5260" E	104	6	32
	15	Adjoul upstream	KAU	36° 44' 33.7380" N	7° 08' 55.9320" E	72	3	18
Guebli	16	Adjoul downstream	KAD	36° 44' 37.7376" N	7° 08' 59.4600" E	73	3	20
	17	Guebli upstream	GGU	36° 45' 46.0116" N	6° 39' 27.9468" E	85	5	31
	18	Guebli downstream	GGD	36° 49' 34.9176" N	6° 38' 57.6708" E	46	4	28
	19	Fessa upstream	GFU	36° 40' 8.3388" N	6° 36' 14.2488" E	183	3	22
	20	Fessa downstream	GFD	36° 40' 22.2096" N	6° 36' 17.4528" E	201	3	19
	21	Bir recade upstream	GBU	36° 50' 5.0388" N	6° 39' 39.1248" E	80	3	23
	22	Bir recade downstream	GBD	36° 49' 57.1584" N	6° 38' 19.9896" E	54	4	25
	23	Meraba upstream	GMU	36° 37' 38.5356" N	6° 38' 4.0200" E	264	3	14
	24	Meraba downstream	GMD	36° 38' 11.5656" N	6° 38' 28.4568" E	238	3	12
	25	Bin oidene upstream	GOU	36° 48' 5.8464" N	6° 33' 54.8640" E	84	3	18
	26	Bin oidene downstream	GOD	36° 48' 35.0568" N	6° 34' 6.3948" E	72	3	18

Materials and methods

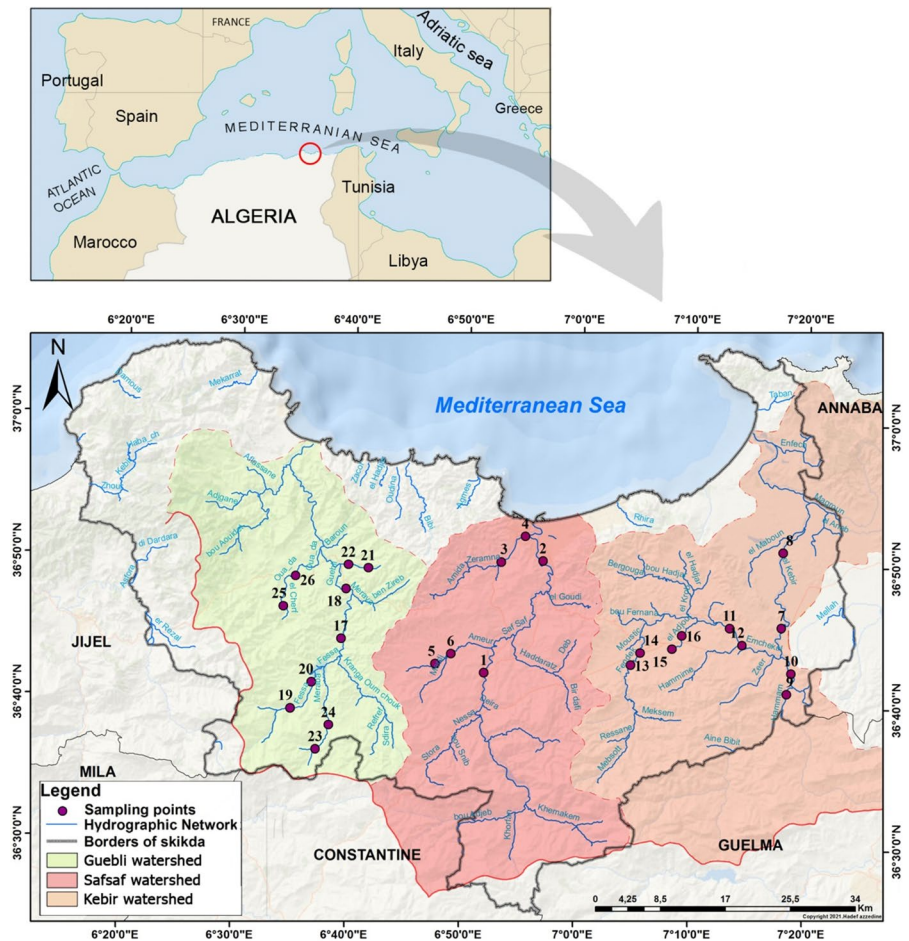
Study area

As aforementioned our study was conducted throughout the Coastal Central Constantine, divided into three main watersheds (Safsaf, Kebir, and Guebli). In each watershed, samples were taken upstream and downstream of the main watercourse and its tributaries (Table 1).

The Coastal Central Constantine watershed is situated in the northern part of Algeria and encompasses the entire city of Skikda. The cities of Constantine and Guelma border the south, Annaba city borders the east, and Jijel and Mila cities border the west. The watershed belongs to the Mediterranean region, which is defined by a humid to sub-humid climate

(Titi Benrabah et al. 2013), with rainfall varying from 650 to 1800 mm. The riverbed substratum includes pebbles, stones, silt, sand, gravel, and blocks. All three watersheds are characterized by various anthropogenic pressures: the Safsaf watershed receives the discharges of the industrial zone of Skikda city (location of a petrochemical complex), and urban domestic water inflows (Khelfaoui and Zouini 2010). The Kebir watershed is subject to significant anthropogenic activities, including deforestation, misuse of agricultural fertilizers, population growth, untreated discharges of industrial activities, and urban wastewaters (Bouleknafet and Derradji 2017). In the Guebli watershed, the pressures from agglomerations and urban sewage threaten also its water quality (Mecibah et al. 2019).

Fig. 1 Map of the study area indicating the location of the sampling sites from the Coastal Central Constantine. See Table 1 for sampling sites codes



Diatom sampling

The sampling sites were selected according to their accessibility, the presence of suitable substrata, and the shade. The samples were collected across the three seasons: winter, spring, summer which encompasses the fall. A total of 26 sampling sites were monitored upstream and downstream of thirteen tributaries between May 2017 and August 2018 (Fig. 1).

Diatoms were collected together with water samples for physicochemical analyses. The samples were collected and treated according to the standardized (Frensh) method NF T90-354 (AFNOR 2007) by scraping a total area of 100 cm² of the upper substrate surface (rocks, pebbles, and stones) using a small brush. At least 5 stones or small blocks were scrapped, then the diatom suspensions were poured and preserved in bottles containing 5% formaldehyde. In the laboratory, samples were digested by heating

in a sandbox using a few drops of hydrogen peroxide (H₂O₂ 30%) to remove any existing organic matter, in addition to hydrochloric acid to eliminate carbonate matter. For samples with high organic content, few ml of nitric and/or sulfuric acids are added to improve the mineralization of our samples. This step is followed by a series of centrifugations and rinsing until a neutral pH was obtained. Permanent slides were prepared from cleaned diatom frustules, mounted, and conserved using Canada Balsam (IR = 1.55). Diatoms were identified under light microscopy (Optika® BX60, ×1000, Ponteranica - BG, Italy). From each permanent slide, a minimum of 400 valves were identified and counted. Taxa identification was accomplished at the species-level in accordance with the works of Hofmann et al. (2011), Blanco et al. (2010), and Krammer and Lange-Bertalot (1988–1991).

Physicochemical and environmental parameters

Water samples were collected at mid-depth, against the stream, and well away from the river bank. Three samples were collected for each sampling site to obtain a representative sample of water quality. Water temperature, flow velocity, and water depth were measured in situ, together with dissolved oxygen (DO, HI 9146 oxymeter, HANNA, Rhode Island, USA), and water conductivity (ORION 3-STAR conductimeter Thermo Scientific, Waltham, Massachusetts, USA). Total nitrogen (Nt) and phosphates (Pt) were subsequently determined in the laboratory using a photometer (UV-1700 pharmaSpec, SHIMADZU, Tokyo, Japan), biochemical oxygen demand (BOD₅, Oxi Top Box® BOD-meter type, Xylem Inc., Washington, D.C., USA), whereas chlorides and chemical oxygen demand (COD) were measured using volumetric dosage methods according to the American Society for Testing Materials (ASTM).

Data analyses

Statistical analyses

A Corrplot analysis was carried out in OriginPro2021 (Seifert 2014) to identify highly significant Pearson correlations ($p < 0.001$) between environmental variables including temperature, velocity, altitude, dissolved oxygen (DO), water conductivity, total nitrogen (Nt), phosphates (Pt), biochemical oxygen demand (BOD₅), chlorides (Cl), and chemical oxygen demand (COD).

Agglomerative Hierarchical Clustering was carried out using the R package pvclust (Suzuki and Shimodaira 2006) version i386 4.1.1 (R Development Core Team 2020) with the Ward method (Ward.D2, Murtagh and Legendre 2014, 2011). This method shows groups of sampling sites, each resulting in a cluster including a group of sites based on their indicator species.

This is a method of arranging factors into homogeneous groups which share the same information and are strongly related to each other (Chavent et al. 2012). By summing up the clusters at various levels, and looking for similarities and differences, each object or data point is treated as a single individual cluster at the very beginning (Vijaya et al. 2019). The algorithm uses comparison metrics (for

example, distance metrics) to compare the clusters and determine their similarities and differences, and the two most similar clusters or data points are merged together (Vijaya et al. 2019). P values were calculated using the IndVal Analysis (Monte Carlo permutation tests McCune and Grace 2002) under R using the package Indicspecies (De Cáceres and Legendre 2009) to obtain diatom indicator species for each group of sampling sites resulting from the cluster analysis.

A preliminary CA showed that gradient length is > 2 and thus an unimodal response of species is assumed and that is why we chose the unimodal CCA method. Canonical correspondence analysis (CCA) is a multivariate method of determining the relationships between biotic assemblages and abiotic variables. The method is intended for the extraction of ecological gradients from environmental data. The gradients serve as the foundation for describing and visualizing differential habitat preferences among taxa using an ordination diagram (ter Braak and Verdonschot 1995). CCA was performed on the environmental parameters cited above using PAST v. 4.03 (Hammer et al. 2001). Variables were log-transformed ($\log(1+x)$) for species abundances to avoid $\log(0)$ values. Two environmental variables were considered for CCA analysis as independent factors: ‘seasons’ and ‘pollution’ are expressed as multistate variables. ‘Seasons’ were converted into numeric values in R using combined functions `as.character/as.numeric` (spring = 1, summer = 2, winter = 3). The factor ‘Pollution’ was first calculated as an average value of the variables Nt, Pt, BOD₅, and COD, then classified as a numeric value ranging from heavily impacted sites (100) to reference sites (10), with higher values meaning higher degree of pollution. Five (5) classes were defined (heavily impacted = 100, bad quality = 80, moderately impacted = 50, slightly impacted = 30, no impact = 10). Rare species (less than five individuals per site or in less than 3 sites) were eliminated for multivariate analyses.

Diatom indices and BDI

Diversity indices were computed also for each sampling site (Shannon’s diversity index (H'), Evenness (E), species richness), besides the diatom-based water quality index BDI calculated using Omnidia v. 5.3 (Lecointe et al. 1993). Shannon Weaver Diversity

Index (H') is the most commonly and widely used method to compute the biotic diversity of a given assemblage, determined by the following Eq. (1) (Shannon and Weaver 1949).

$$H' = -\sum p_i \log_2 p_i \quad (1)$$

where p_i (the relative abundance of species i) = (n_i/N) .

Species evenness (E) is the ratio of observed (H') to maximum diversity (H_{\max}) given its specific richness following Eq. (2):

$$E = H' / H_{\max} \quad (2)$$

where $H_{\max} = \log_2 S$ (Ramade 2009).

The Biological Diatom Index (BDI) (Lenoir and Coste 1996) is a standardized method developed and used in France for monitoring the quality of watercourses. Prygiel and Coste (2000) provide detailed descriptions of field sampling, laboratory processes, taxonomic determinations, and calculation methods in their manual (Coste et al. 2009). The BDI has values ranging from 0 to 20 with 5 classes: poor, low, moderate, good and very good. The higher the value of the index, the better the ecological status of the water (Szulc and Szulc 2013). For a given site, BDI score is the average of pollution sensitivity values of the diatom species present, multiplied by their relative abundances, and weighted by the ecological amplitude of each taxon following Eq. (3):

$$BDI = \sum A_i S_i V_i / \sum A_i V_i \quad (3)$$

where A_i , S_i and V_i denote, respectively, the abundance, pollution sensitivity and ecological amplitude of the i th taxon in the diatom assemblage.

The identified taxa with their abundance are listed in Appendix 1.

Results

Diatoms identification and ecology

The diatom species identified belong to seven families. Naviculaceae and Nitzschiaceae have shown the highest species abundance (47.87 and 31.86%, respectively). The total number of species taken into account for all multivariate analyses was 109 species in Safsaf watershed, and 117 species in Kebir watershed. Guebli watershed was the most diversified

catchment with 129 species. The three watersheds share 61 common taxa (see Appendix 1).

During spring, the taxa *Achnantheidium minutissimum* (3.80%), *Nitzschia umbonata* (3.41%), and *Navicula phyllepta* (2.88%) were the most dominant among all the species, respectively, in Guebli, Kebir and safsaf watersheds. During summer, the most dominant taxa were *Mayamaea permitis* (2.44%) at Kebir watershed, and *Nitzschia palea* (9.91%) in Guebli and Safsaf watersheds, being dominant during winter at the three watersheds.

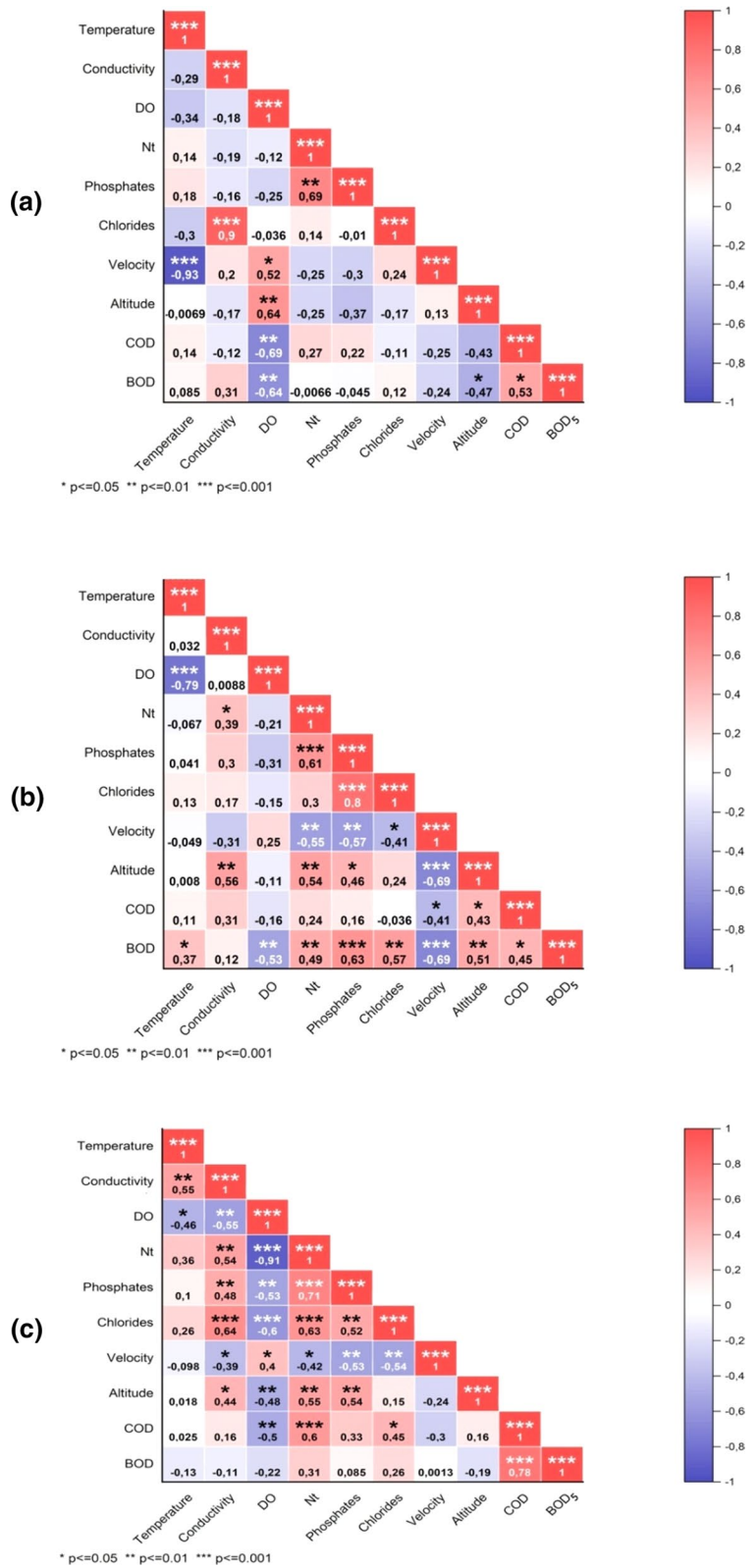
Nitzschia capitellata and *Achnantheidium minutissimum* were frequent in Guebli and Kebir watersheds during the spring, while *Navicula phyllepta* and *Gomphonema parvulum* were frequent in Kebir and Safsaf watersheds. *Navicula* species were also common in the spring including *Navicula phyllepta* in Safsaf and Kebir watersheds and *Navicula veneta* in Guebli. While *Mayamaea permitis* was frequent in Kebir and Guebli watersheds during the summer period.

The mean values of the environmental variables calculated for the 3 seasons are summarized in Appendix 2. Temperature maximum values have been recorded in summer and ranged between 26.35 and 31.5 °C, conductivity varied from 300 to 2646 $\mu\text{S cm}^{-1}$, and maximum value of total nitrogen (Nt) was recorded in summer at Guebli watershed estimated at 943.27 mg.L^{-1} while in phosphates, at Kebir watershed it was recorded as 37.26 mg.L^{-1} . Maximum velocity and dissolved oxygen values have been recorded in winter; velocity varied between 0.04 and 4.25 cm.s^{-1} whereas dissolved oxygen ranged from 0.88 to 16.97 mg.L^{-1} . Concerning pollution, the sampling sites ranged from slightly to heavily impacted, which are the most downstream sampling points. In general, samples sampled in summer were characterized by high values of temperature, conductivity, and nutrients compared to those sampled in spring, while samples sampled in winter presented high current velocity and dissolved oxygen (see Appendix 2).

Correlations between environmental variables

A global correlation analysis was performed on 10 environmental parameters. In the Safsaf watershed (Fig. 2a), chlorides are correlated strongly and positively to water conductivity (Pearson coefficient (r)=0.9; $p < 0.001$). BOD_5 and COD are associated negatively to DO (r =0.64 and 0.69, respectively;

Fig. 2 Environmental variables corrplot of Safsaf, Kebir and Guebli watersheds. The letters indicate the watersheds: **(a)** for Safsaf, **(b)** for Kebir and **(c)** for Guebli. The color of the squares is proportional to the Pearson coefficient (red for positive correlation, blue for negative correlation, * $p < 0.05$ shows significant correlation, ** $p < 0.01$ shows good correlation, *** $p < 0.001$ for excellent correlation). The numbers inside the squares reflect the precise Pearson value



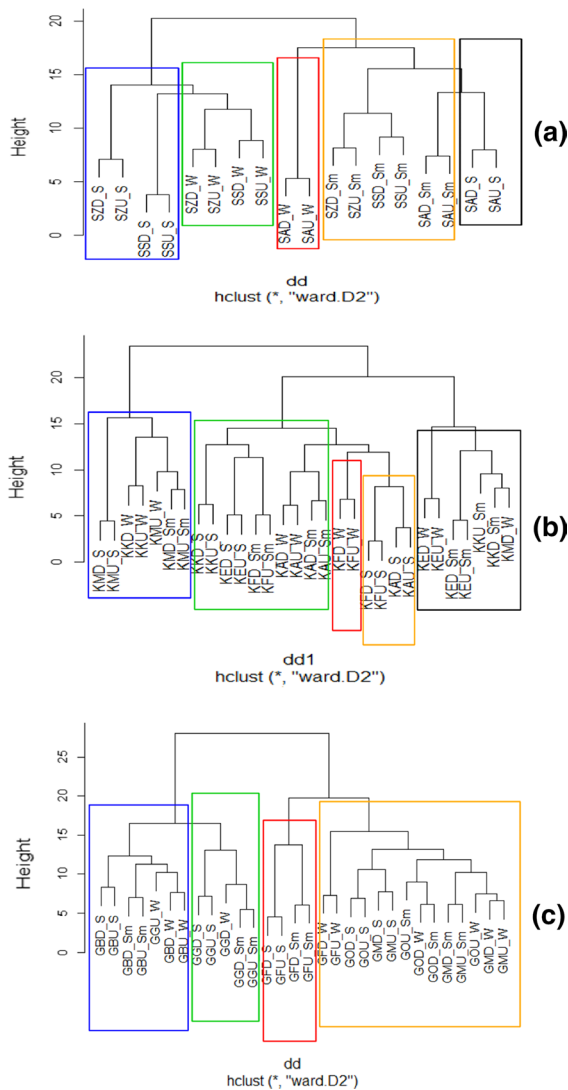


Fig. 3 Hierarchical clustering dendrogram of diatom species of Safsaf, Kebir, and Guebli watersheds. The letters indicate the watersheds: (a) for Safsaf, (b) for Kebir and (c) for Guebli. Capital letters indicate the seasons: W for winter, Sm for summer, and S for spring. The colored frames represent the groups: blue = group1, green = group2, red = group3, orange = group4, black = group5

$p < 0.01$). For Kebir watershed (Fig. 2b), phosphates showed a positive correlation with total nitrogen (Nt) ($r = 0.61$; $p < 0.001$). DO demonstrated a negative correlation with temperature ($r = 0.79$; $p < 0.001$). In the Guebli watershed (Fig. 2c), conductivity showed a significant positive correlation with chloride concentrations ($r = 0.64$; $p < 0.001$). DO is associated negatively to total nitrogen (Nt) ($r = 0.91$; $p < 0.001$).

Indicator species

The dendrograms in Fig. 3 show the results of the Agglomerative Hierarchical Cluster Analysis, grouping of sampling sites. Each cluster includes a group of sites based on their indicator species.

Indicator species of each group of sites were obtained by IndVal analysis using Monte Carlo permutation tests, and resulting P values are shown in Table 2. We have obtained 16 common indicator species that are considered good indicators in European diatom indices included in Omnidia (<https://hydrobiodec.irstea.fr/wp-content/uploads/2014/05/OMNIDIAFILE.xls>) with Indexed Parameter Value (IPV) = 3.

The cluster sites were classified based on the indicator species present, and the sampling sites in each cluster shared the same environmental conditions. Five clusters were determined for Safsaf and Kebir watersheds (Figs. 3a, b), while four groups appeared in the Guebli watershed dendrogram (Fig. 3c). For Safsaf watershed, the first cluster grouping sites of the streams Safsaf and Zeramna sampled in spring, is characterized by high Nt concentrations ranging from 73.01 to 747.74 mg.L⁻¹, and COD (99.55 to 163.97 mg.L⁻¹) including two species of the genus *Nitzschia*. The second cluster is less diversified with only *Craticula subminuscula*. While the third group is the most diversified among all the clusters with five species. The sampling sites regrouped into these two clusters are sampled in winter, and showed maximal values of current velocity (4.25 cm.s⁻¹), dissolved oxygen (13.44 cm.s⁻¹), and chlorides (414.90 mg.L⁻¹). The 4th Cluster, comprised all sites sampled in summer characterized by high temperature ranging between 24.1 and 29.99 °C, and low current velocity (0.52 cm.s⁻¹). The last cluster includes the two remaining sites SAD-S and SAU-S with high altitude (85 and 89 m, respectively) and grouped three species.

The first cluster of Kebir watershed included sites almost slightly impacted with low water conductivity (300 to 1140.5 μS.cm⁻¹) and comprised three taxa. The second group which comprised sites with slightly high conductivity surpassing 1650 μS.cm⁻¹ was the most diversified with six species. The third cluster comprising the two impacted sites of Fendek stream showed the highest conductivity values with two taxa *Craticula accomoda* and *Nitzschia umbonata* followed by the fourth group which included

nutrient-rich sites with high BOD and COD loads and maximal values on chlorides (521.85 mg.L^{-1}), which incorporated five taxa. Coming later the last group comprising sites slightly to moderately impacted showing the highest dissolved oxygen values (16.97 mg.L^{-1}) while current velocity ranged from 0.16 to 0.29 cm.s^{-1} with four diatoms.

In Guebli watershed, the first cluster included sites with low water conductivity (from 463 to $873.5 \text{ }\mu\text{S.cm}^{-1}$) and high current velocity (maximum 0.33 cm.s^{-1}) with three taxa. The second group comprised sites with high dissolved oxygen concentrations showing the lowest diversity with only one specie of the family Surirellaceae. The third cluster included sites with strong water conductivity compared to the stations previously cited, with high altitude with three diatom species. The last cluster was composed of the most impacted sites with high concentrations of BOD, COD, chlorides, and nutrients (Nt and phosphates) and showed the highest diversity with five taxa.

Environmental variables affecting diatom's distribution

CCA analysis triplots highlighted the main drivers among abiotic variables explaining the distribution of the sampling sites for each watershed (Fig. 4). Species names are given in Appendix 1.

For the Safsaf watershed, the first two axes explained 44.51% of the total variance (Fig. 4a). Along the first axis, the sampling sites were arranged according to a seasonal gradient, sites sampled in spring being plotted on the right positive part of the axis, as opposed to samples taken in summer and winter that are plotted on the left side of axis 1 (Fig. 4a).

The sampling sites in summer and winter were plotted along the second axis. The sites sampled in winter and associated with high conductivity, current velocity, and dissolved oxygen values, were characterized by the presence of *Nitzschia frustulum* ($p=0.013$), *Amphora copulata* ($p=0.024$), *Nitzschia clausii* ($p=0.034$), *Hantzschia abundans* ($p=0.047$), and *Nitzschia tryblionella* ($p=0.039$) on the positive part of the axis, whereas *Craticula subminuscula* ($p=0.031$) was plotted on the negative part of the axis. Sites sampled in summer, characterized by the lowest current velocity, hosted *Navicula erifuga* ($p=0.004$), *Navicula cryptocephala* ($p=0.044$), and

Nitzschia umbonata ($p=0.048$). In the upper quadrant appear diatoms such as *Cymatopleura elliptica* ($p=0.001$), *Navicula tripunctata* ($p=0.006$), and *Navicula cryptotenella* ($p=0.029$). The pollution vector was observable in the second quarter on the right of CCA1. Species associated with this parameter included *Nitzschia fonticola* ($p=0.033$), and *Nitzschia soratensis* ($p=0.016$).

The first two axes in the CCA carried out on Kebir watershed explained 25.95 and 20.03% , respectively, of the total inertia. The first axis segregated sites with low water conductivity from polluted sites, characterized by the presence of species such as *Nitzschia frustulum* ($p=0.007$), *Cocconeis euglypta* ($p=0.016$), and *Craticula subminuscula* ($p=0.006$). The sampling sites sampled in the winter and summer seasons were plotted on the upper quadrant while those sampled in spring were clustered on the lower quadrant. Stations with high current velocity and dissolved oxygen values were plotted in the upper quadrant, characterized by the presence of *Diademsis confervacea* ($p=0.003$), *Sellaphora pupula* ($p=0.001$), *Fallacia arvensis* ($p=0.001$), and *Sellaphora difficilima* ($p=0.013$). On the opposite side, sampling sites showing strong water conductivity were plotted and characterized by the presence of *Cocconeis pediculus* ($p=0.001$), *Cymbella excisa* ($p=0.006$), *Encyonopsis microcephala* (0.015), *Bacillaria paxillifera* ($p=0.031$), *Gyrosigma acuminatum* ($p=0.030$), and *Rhoicosphenia abbreviata* ($p=0.034$). The contaminated sites were clustered around the pollution vector: diatoms taxa showing affinity to this type of habitat were *Craticula accomoda* ($p=0.016$) and *Nitzschia umbonata* ($p=0.001$), while *Navicula gregaria* ($p=0.047$), *Planothidium frequentissimum* ($p=0.002$), *Achnantheidium minutissimum* ($p=0.008$), *Tryblionella constricta* ($p=0.032$), and *Navicula rostellata* ($p=0.008$) were plotted on the right part of the CCA plot (Fig. 4b, Table 2).

Finally, in the Guebli watershed (Fig. 4c), the first CCA axis accounted for 20.76% and the second for 19.62% of the total inertia. A seasonal gradient was visible along the first axis separating sites sampled in spring from those sampled in summer and winter periods. The pollution gradient appeared along the second axis which distinguished the stations with high altitude and chlorides, and was characterized by the presence of *Cymatopleura solea* ($p=0.001$), *Cymatopleura elliptica* ($p=0.001$), *Caloneis amphisbaena*

◀**Fig. 4** Canonical correspondence analysis (CCA) triplots showing ordination of diatom species, sites and environmental variables studied in Safsaf, Kebir and Guebli watersheds. The letters indicate the watersheds: (a) for Safsaf, (b) for Kebir and (c) for Guebli. Environmental variables are represented by arrows in green. Sites names are written in black with capital letters indicating the seasons: W for winter, Sm for summer, and S for spring. Species codes are shown in blue. Some taxa codes are hidden. See Table 1 for sites codes and Appendix 1 for species codes

($p=0.001$), *Tryblionella levidensis* ($p=0.001$) and *Caloneis amphibia* f. *subsalina* ($p=0.003$), from the stations with high velocity and oxygen values and lower conductivity levels. The most indicative species were *Navicula radiosa* ($p=0.001$), *Geissleria decussis* ($p=0.002$), *Achnanthes exigua* ($p=0.048$), and *Surirella angusta* ($p=0.001$), whereas *Nitzschia capitellata* ($p=0.001$), *Navicula phyllepta* ($p=0.031$), and *Gomphonema tergestinum* ($p=0.006$) were the most representative species recorded in Fessa wadi sampling sites.

Diatom indices and BDI

Shannon index values showed that the specific diversity observed in the sampled sites across the three watersheds during summer season is higher than in spring and winter. Mean values of Shannon diversity during summer were around $H' = 4.49$, 3.98 , and 4.17 , respectively, at the three watersheds Safsaf, Kebir, and Guebli, while species richness varied between 13 and 34 across the three watersheds (Table 3).

The average diversity (H') and evenness (E) values for Kebir watershed in winter and spring were similar, recording $H' = 3.86$ and $E = 0.88$, respectively, in winter and 3.64 and 0.85 , respectively, in spring, while in summer the values were $H' = 3.98$ and $E = 0.91$, respectively. In Guebli watershed, the mean values of diversity (H') and evenness (E) during spring were $H' = 4.02$ and $E = 0.90$, respectively, which are very close to those recorded in the summer ($H' = 4.17$ and $E = 0.91$). At the three watersheds, mean values of diversity and evenness in summer were greater than those obtained in winter and spring.

BDI scores ranged from 1 to 16.5. At Safsaf watershed the highest BDI score (11.05) was obtained in station 5 sampled in spring, while in Guebli watershed the highest value was at station 20 sampled in spring. In Kebir watershed, four stations situated

upstream and downstream of the Mougger watercourse sampled in spring and summer recorded the highest BDI scores (16.5, 14.53, 16.5, and 13.63, respectively). The lowest diversity, evenness, and BDI values that were observed at station 13 sampled in spring in Kebir watershed recorded 2.35, 0.62, and 1, respectively (Table 3).

Discussion

Diatom communities

Spatial and temporal relationships between environmental variables and diatom communities were investigated throughout the present study, and illustrated by the hierarchical clusters, corrplots, and CCA analyses for each watershed separately. Our species diversity findings are coherent with those of Baudrimont (1974), who studied taxa from Algerian fresh and brackish waters in arid and semi-arid regions; which has demonstrated also that these species are comparable to those in European freshwaters with noticeable saline and alkaline composition. Most of our identified taxa have been already illustrated in the book by Lange-Bertalot et al. (2017), and are known to be cosmopolitan, indicating high conductivity and nutrient-rich waters. The diatom taxa identified in our sampling sites are common and typically found in the Kebir East, El Hammam, and Cheliff Rivers (northeastern and northwest of Algeria) as reported in the papers of Chaïb et al. (2011), Chaïb and Tison-Rosebery (2012) and Nehar et al. (2015).

Most of these species were identified recently also in the study of El Haouati et al. (2015) who recorded 24 taxa in Reghaïa Lake. Chabaca et al. (2020) recorded over 18 genera in the Oubeira lake, and the study by Hermaza et al. (2021) identified 72 species in Ain Dalia dam.

The current study is the first attempt to determine the species composition of the Coastal Central Constantine, Northeastern Algeria, where no research has been conducted before. It contributes to the completion of the Algerian database of diatoms inventoried thus far by the aforementioned works, as well as the determinants of their distribution. Furthermore, our study demonstrates that the key drivers can differ between geographically close watersheds.

Dominant taxa and diversity

Over the three watersheds, our floristic results revealed the dominance of Naviculaceae, which showed the highest abundance (47.87%). Similar results were demonstrated at El Kebir-East River (Chaïb et al. 2011), and at the streams of Chott Chergui wetland with a percentage of 25.71% (Negadi et al. 2021).

Among the identified diatoms, the taxa *Gomphonema parvulum*, *Achnanthydium minutissimum*, *Navicula gregaria*, *Nitzschia frustulum*, *Craticula subminuscula*, *Amphora pediculus* and *Nitzschia palea* are common in studies conducted in running waters in northern Algeria (Chaïb and Tison-Rosebery 2012; Nehar et al. 2015; Negadi et al. 2021).

Diatoms and water quality

Nitzschia umbonata was most abundant in site 13 (KFU_S) sampled in spring, with an abundance of 70.41%, which decreased largely diversity and evenness values ($H' = 1.62$, $E = 0.54$) thus reflecting the poor water quality of this station ($BDI = 1$). The presence of this species is related to pollution (Duong et al. 2007). Chaïb et al. (2011) observed the proliferation of this diatom at sites associated to pollution in Kebir East, commonly associated with *Nitzschia palea* and *Navicula veneta*. In Turkey, Çetin et al. (2021) recorded also a high abundance of this species (15.6%) in a polluted river in the Kızılırmak basin. In terms of water quality, as inferred from diatom-based indices, Chaïb and Tison-Rosebery (2012) have already tested the Biological Diatom Index (BDI) in the Kebir-East River, despite the dominance of the indifferent *Achnanthydium minutissimum* (75%) at Ain Assel station (that becomes a temporary pool during the dry periods) with nutrient (PO_4^{3-} and NH_4^+) levels attaining 0.5 and 1 $mg.L^{-1}$ respectively, this station recorded the highest BDI score (18/20), which did not reflect the actual poor water quality of the site.

Effect of environmental variables on diatoms distribution

The results of the CCA triplots demonstrated three environmental gradients controlling the diatom distribution in all the watersheds including conductivity,

temperature, and pollution. Some studies have revealed the links between the environmental variables and the diatom community throughout Co-Inertia Analysis (CIA) and Canonical Correlation Analysis (CCorA), e.g., the diatom communities of the Kebir-East River are controlled by environmental conditions, including a high seasonal gradient between floods and drought, acidic to neutral waters, high conductivities and pollution (Chaïb et al. 2011; Chaïb and Tison-Rosebery 2012) while the distribution of diatom assemblages of rivers from Chott Chergui wetland are mainly influenced by temperature and conductivity (Negadi et al. 2021). Kivrak and Uygun (2012) reported that the distribution and the composition of the diatom flora in the Turkish stream Akarçay are affected by the physic-chemistry of water including conductivity, PO_4^{3-} , and BOD.

According to Nehar et al. (2015), the diatom species composition and distribution are linked to anthropogenic pressures and driven by various environmental factors such as chlorides, pH, and temperature. In the same way, Hermaza et al. (2021) studied the spatial and temporal distribution of diatoms of the Aïn Dalia dam and emphasized the impact of nutrients (NO_2^- and PO_4^{3-}), suspended matter, temperature, and dissolved oxygen on the diatom distribution. Furthermore, El Haouati et al. (2015) highlighted the relationship between the environmental characteristics of Reghaia Lake and the diatoms, reporting the direct impact of nutrients (PO_4^{3-} and NH_4^+), temperature, conductivity, and oxygen on the occurrence of different diatom taxa.

The waters of the three watersheds were characterized by high conductivities ($> 1000 \mu S.cm^{-1}$), and high chloride contents, as confirmed by correlation analyses which revealed a strong correlation between the concentration of chlorides and water conductivity. In particular, conductivity is one of the main environmental factors influencing the structure and the distribution of diatom communities (Rimet 2009).

Indicator species and their ecological preferences

The clustering and Indval analysis revealed the presence of the genus *Navicula* such as *N. erifuga* and *N. cryptocephala* (Table 2) showing their preference for high temperatures in Safsaf watershed during summer (group 4) (Fig. 3a); the mean value of temperature being around 29.14 °C. According to Hermaza et al.

Table 2 Diatom indicator species of the three watersheds

Watersheds	Species name	Species code	p values	Groups	
Safsaf	<i>Nitzschia fonticola</i>	NFON	0.033*	1	
	<i>Nitzschia soratensis</i>	NSTS	0.016*	1	
	<i>Craticula (Eolimna) subminuscula</i>	ESBM	0.031*	2	
	<i>Nitzschia frustulum</i>	NIFR	0.013*	3	
	<i>Amphora copulata</i>	ACOP	0.024*	3	
	<i>Nitzschia clausii</i>	NCLA	0.034*	3	
	<i>Nitzschia tryblionella</i>	NTRY	0.039*	3	
	<i>Hantzschia abundans</i>	HABU	0.047*	3	
	<i>Navicula erifuga</i>	NERI	0.004**	4	
	<i>Navicula cryptocephala</i>	NCRY	0.044*	4	
	<i>Nitzschia umbonata</i>	NUMB	0.048*	4	
	<i>Cymatopleura elliptica</i>	CELL	0.001***	5	
	<i>Navicula tripunctata</i>	NTPT	0.006***	5	
	<i>Navicula cryptotenella</i>	NCTE	0.029*	5	
	Kebir	<i>Nitzschia frustulum</i>	NIFR	0.007***	1
		<i>Cocconeis euglypta</i>	CEUG	0.016*	1
		<i>Craticula (Eolimna) subminuscula</i>	ESBM	0.006**	1
		<i>Cocconeis pediculus</i>	CPED	0.001***	2
		<i>Cymbella excisa</i>	CAEX	0.006**	2
		<i>Encyonopsis microcephala</i>	ENCM	0.015*	2
<i>Gyrosigma acuminatum</i>		GYAC	0.030*	2	
<i>Rhoicosphenia abbreviata</i>		RABB	0.034*	2	
<i>Bacillaria paradoxa</i>		BPAR	0.031*	2	
<i>Craticula accomoda</i>		CRAC	0.016*	3	
<i>Nitzschia umbonata</i>		NUMB	0.001***	3	
<i>Planothidium frequentissimum</i>		PLFR	0.002**	4	
<i>Achnantheidium minutissimum</i>		ADMI	0.008**	4	
<i>Tryblionella constricta</i>		TRCO	0.032*	4	
<i>Navicula gregaria</i>		NGRE	0.047*	4	
<i>Navicula rostellata</i>		NROS	0.008**	4	
<i>Diadesmis confervacea</i>		DCOF	0.003**	5	
<i>Sellaphora pupula</i>		SPUP	0.001***	5	
<i>Navicula (Fallacia) arvensis</i>		NARV	0.001***	5	
<i>Navicula (Sellaphora) difficillima</i>		NDIF	0.013*	5	
Guebli	<i>Navicula radiosa</i>	NRAD	0.001***	1	
	<i>Geissleria decussis</i>	GDEC	0.002**	1	
	<i>Achnanthes exigua</i>	AEXG	0.048*	1	
	<i>Surirella angusta</i>	SANG	0.001***	2	
	<i>Nitzschia capitellata</i>	NCPL	0.001***	3	
	<i>Navicula phyllepta</i>	NPHY	0.031**	3	
	<i>Gomphonema tergestinum</i>	GTER	0.006**	3	
	<i>Cymatopleura solea</i>	CSOL	0.001***	4	
	<i>Cymatopleura elliptica</i>	CELL	0.001***	4	
	<i>Caloneis amphisbaena</i>	CAMP	0.001***	4	
<i>Tryblionella levidensis</i>	TLEV	0.001***	4		
<i>Caloneis amphisbaena fo. subsalina</i>	CASS	0.003**	4		

The italics represent the full name of the indicator species, the bolds represent species codes

*Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Indicator

species codes are underlined on the CCA triplots. For the complete names and explanation of the species codes see Appendix 1. Species in green are commonly considered good indicators of European streams water quality (see indexed parameter value (IPV = 3) column values in <https://hydrobio-dce.irstea.fr/wp-content/uploads/2014/05/OMNIDIAFILE.xls>)

Table 3 Diversity indices calculated for each season for the 26 sampling sites along the watersheds Safsaf, Kebir, and Guebli

Watersheds	Sites codes	Richness	BDI 2014	Diversity	Evenness
Safsaf	SSU_W	28	7.6	4.69	0.98
	SSU_S	18	6.2	3.67	0.89
	SSU_Sm	24	7.9	4.27	0.94
	SSD_W	23	6.1	4.22	0.93
	SSD_S	16	7.1	3.42	0.86
	SSD_Sm	25	10.25	4.26	0.92
	SZU_W	33	8.9	4.60	0.91
	SZU_S	22	9.5	4.18	0.94
	SZU_Sm	33	9.9	4.83	0.97
	SZD_W	14	6.1	2.35	0.62
	SZD_S	17	6.5	3.45	0.86
	SZD_Sm	26	8.2	4.21	0.89
	SAU_W	31	8.8	4.70	0.95
	SAU_S	29	11.05	4.48	0.93
	SAU_Sm	34	10.5	4.79	0.94
	SAD_W	35	8.7	4.97	0.97
	SAD_S	31	10.75	4.6	0.95
	SAD_Sm	30	10.25	4.59	0.94
Kebir	KKU-W	29	10.7	4.50	0.93
	KKU-S	31	7.0	4.61	0.93
	KKU-Sm	22	7.73	4.08	0.91
	KKD-W	30	7.5	4.43	0.90
	KKD-S	30	7.1	4.18	0.85
	KKD-Sm	26	9.33	4.39	0.93
	KMU-W	28	13.8	4.56	0.95
	KMU-S	23	16.5	4.12	0.91
	KMU-Sm	29	14.53	4.52	0.94
	KMD-W	26	9.3	4.48	0.95
	KMD-S	24	16.5	4.03	0.88
	KMD-Sm	29	13.63	4.48	0.92
	KEU-W	19	7.1	3.98	0.94
	KEU-S	24	6.4	4.32	0.94
	KEU-Sm	26	7.5	4.36	0.93
	KED-W	24	9.1	4.40	0.96
	KED-S	30	6.4	4.50	0.92
	KED-Sm	24	7.4	4.37	0.95
	KFU-W	11	2.2	3.13	0.90
	KFU-S	8	1	1.62	0.54
	KFU-Sm	14	4.7	3.18	0.84
	KFD-W	13	3.1	3.02	0.82
	KFD-S	9	1	2.28	0.72
	KFD-Sm	16	4.33	3.46	0.88
KAU-W	18	6.2	3.00	0.72	
KAU-S	14	4.0	3.40	0.89	
KAU-Sm	18	6.6	3.76	0.91	
KAD-W	18	5.3	3.11	0.75	
KAD-S	14	3.2	3.38	0.89	
KAD-Sm	13	4.3	3.17	0.88	

Table 3 (continued)

Watersheds	Sites codes	Richness	BDI 2014	Diversity	Evenness
Guebli	GGU-W	32	12.6	4.71	0.94
	GGU-S	32	11.25	4.71	0.95
	GGU-Sm	34	10.05	4.95	0.98
	GGD-W	33	11.2	4.86	0.96
	GGD-S	31	10.8	4.75	0.96
	GGD-Sm	32	10.75	4.72	0.95
	GFU-W	26	10.5	4.35	0.93
	GFU-S	19	14.05	3.58	0.85
	GFD-Sm	23	13.05	4.08	0.9
	GFD-W	21	9.4	3.62	0.82
	GFD-S	20	15.7	3.77	0.89
	GFD-Sm	23	13.05	4.08	0.9
	GBU-W	37	11.2	5.04	0.97
	GBU-S	24	14.65	4.22	0.93
	GBU-Sm	30	12.1	4.76	0.97
	GBD-W	33	11.9	4.99	0.99
	GBD-S	29	10.3	4.54	0.94
	GBD-Sm	31	10.15	4.86	0.98
	GMU-W	25	7.2	3.53	0.76
	GMU-S	12	3.7	2.78	0.83
	GMU-Sm	17	6.75	3.47	0.86
	GMD-W	15	6.0	2.60	0.67
	GMD-S	21	6.25	3.92	0.9
	GMD-Sm	19	4.95	3.32	0.78
	GOU-W	13	5.6	2.55	0.69
	GOU-S	21	8.9	3.81	0.87
	GOU-Sm	19	9.05	3.66	0.87
	GOD-W	13	6.4	2.95	0.80
	GOD-S	24	10.45	4.07	0.9
	GOD-Sm	21	7.5	3.75	0.86

For the explanation of sites codes see Table 1. *W* Winter, *Sm* Summer, and *S* Spring

(2021), this genus prefers high temperatures in the summer and slightly polluted environments.

According to Indval analysis (Table 2), the presence of the indicator species *Nitzschia fonticola* in group 1 (Fig. 3a, Table 2) was related to high Nt concentrations and COD. This diatom was recorded also in polluted rivers in north-eastern France (Rimet 2009).

The species *Navicula gregaria* (Fig. 3b, Table 2) showed its preference to nutrient-rich sites in Kebir watershed, which indicates the trophic status of these locations. This species has been already noted in Noga et al. (2014) as tolerant to eutrophic waters. Blanco and Bécares (2010) confirmed that pollution and the trophic state of water affect the structure and the distribution of such diatom communities.

The taxa *Navicula cryptotenella* in Safsaf watershed, *Navicula rostellata* and *Achnantheidium minutissimum* from Kebir watershed, as well as *Cymatopleura solea* from the watershed of Guebli are related to high loads on Nt and phosphates, which explained their presence in the sampling sites located close to agricultural lands exposed to soil drainage. These taxa colonized nutrient-rich rivers with high N and P loads, as demonstrated in the works of Chaïb et al. (2011), Chaïb and Tison-Rosebery (2012), El Haouati et al. (2015), and Negadi et al. (2021).

Craticula subminuscula was recorded in stations showing the greatest water conductivity in Kebir watershed, this species is known by its tolerance to high conductivity levels, which confirms the results and conclusions of Chaïb and Tison-Rosebery (2012) and Nehar et al. (2015).

Seasonal variation, diversity, and diatom assemblages

The specific diversity observed in the sampled sites across the three watersheds during summer is above that observed in spring and winter.

This can be explained by the high level recorded in summer of the main variables controlling the distribution of diatoms including temperature, conductivity, and pollution (availability of nutrients). According to Bussard (2015), temperature, light, nutrient concentration, movement of water masses, and even salinity would all influence algae growth and distribution.

Similar findings have been noted in other studies, at Mellah lagoon ($H' = 4.56$ in Draredja et al. (2019)), and in Aïn Dalia dam ($H' = 3$ in Hermaza et al. (2021)). In contrast to these results, diatom assemblages at Oubeïra Lake (Chabaca et al. 2020) were less diversified compared to those found in our studied basins, with a diversity score of $H' = 2.35$. On the other hand, the wet season was the most diverse at Chott Chergui wetland (Negadi et al. 2021), while in Reghaïa lake, diatom assemblages were more diversified during spring and fall (El Haouati et al. 2015).

Achnantheidium minutissimum (ADMI) was abundant in the Kebir watershed during the spring and summer seasons exceeding 17% in station 10 sampled in spring, whereas in Guebli watershed this species was the most dominant during the spring period reaching 17.91% in relative abundance. Other studies reported also the dominance of this diatom reaching abundances of up to 75% at Kebir East River (Chaïb

and Tison-Rosebery 2012), and 55% at El Hammam stream (Nehar et al. 2015) in summer, with a mean diversity and evenness scores of $H' = 2.5$, $E = 0.8$ and $H' = 1.9$, $E = 0.6$, respectively, also subdominant (21.26%) in spring at Mina watershed (Negadi et al. 2018) with an average of 2.5 and 0.8, respectively, in diversity and evenness. In Chabaca et al. (2020), the mean diversity values were 2.34, and 2.22 respectively at two stations in Oubeïra Lake, northeastern Algeria.

Diatom populations in relation to pollution

Populations exposed to impaired waters harbor species tolerant to organic pollution (Castillejo et al. 2018; Karaouzas et al. 2018). In our case, high levels of organic and chemical pollution (related to sewage and industrial effluents) explained the presence of the tolerant taxa *Craticula accomoda* and *Nitzschia umbonata* in stations 13 and 14 sampled in winter. Çetin et al. (2021) reported that those species were also predominant in winter with rates of 12.5% for *C. accomoda*, and 15.6% for *N. umbonata*.

Other pollution-tolerant species were also identified from impacted sampling sites (mostly all downstream locations in all the watersheds) such as *Nitzschia palea*, *Nitzschia capitellata*, *Navicula veneta*, *Gomphonema parvulum*, and *Mayamaea permittis*. These species, considered pollution indicators, have been already found at polluted sampling sites in a number of studies such as (Cochero et al. 2017; Kheiri et al. 2018; Rybak et al. 2019; Bezzeghoud and Bouhameur 2021) besides the monograph by Lange-Bertalot (2017). The significant dominance of *Craticula subminuscula*, *Gomphonema parvulum*, *Nitzschia palea*, and the species complex formed by *Nitzschia inconspicua* and *Nitzschia frustulum* indicate the polluted status of these waters, as shown in a study conducted on Hassar stream in Morocco by Fawzi et al. (2011).

Conclusion

The current study is the first attempt to characterize the benthic diatom communities of Coastal Central Constantine, including three watersheds (Safsaf, Kebir and Guebli) in Northeastern Algeria. Data analyses allowed us to highlight the relationships

between the environmental variables and the diatom community composition and distribution. The examined sampling sites in Safsaf, Kebir, and Guebli watersheds are driven by fluctuations in water quality, characterized by high conductivity and pollution levels. A seasonal gradient was also evident, segregating clearly species dominant in spring from those most common in summer or winter. The main variables controlling the distribution of diatom communities across the three watersheds were temperature, conductivity, and pollution. There was a seasonal variation across the three watersheds; summer was the most diversified; the specific diversity observed in the sampled sites during summer is above that observed in spring and winter.

Our results are congruent with all studies carried out on benthic diatoms in Algerian streams and highlight the distribution particularities of our species, compared to the ecological profiles elaborated during surveys in France, notably for the development of the BDI.

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Faïza Noune and Sabrina Dzizi. Hadjer Kaddeche and Nadjla Chaïb collected data, analyzed the results and wrote the first draft of the manuscript. Nadjla Chaïb and Zine Eddine Boudjellab are thanked for realization and conceptualization of the graphs. Saúl Blanco-Lanza identified species, supervised the project and reviewed the results. The final manuscript was read and approved by all authors.

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Data Availability Not applicable.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval This study did not involve any animals or human participants.

Financial and Non-financial interests The authors have no relevant financial or non-financial interests to disclose.

Consent for publication Not applicable.

Consent to participate Not applicable.

Appendix 1

See Table 4.

Table 4 Full names and percentage of abundance of the identified species

Species names	Species codes	Abundance (%)
<i>Achnanthes exigua</i> Grunow in Cleve et Grunow var. <i>exigua</i>	AEXG	0.64
<i>Achnantheidium minutissimum</i> (Kützing) Czarnecki var. <i>minutissimum</i>	ADMI	3.80
<i>Amphora copulata</i> (Kützing) Schoeman & Archibald var. <i>copulata</i>	ACOP	0.49
<i>Amphora pediculus</i> (Kützing) Grunow var. <i>pediculus</i>	APED	1.70
<i>Bacillaria paxillifera</i> (O.F. Müller) Hendey var. <i>paxillifera</i>	BPAX	0.75
<i>Cocconeis euglypta</i> Ehrenberg	CEUG	1.49
<i>Cocconeis pediculus</i> Ehrenberg	CPED	1.04
<i>Craticula subminuscula</i> (Manguin) Moser Lange-Bertalot & Metzeltin	ESBM	1.98
<i>Craticula accomoda</i> (Hustedt) D.G. Mann in Round et al	CRAC	1.28
<i>Cyclotella meneghiniana</i> Kützing	CMEN	1.88
<i>Cyclotella ocellata</i> Pantocsek	COCE	0.92
<i>Cymatopleura solea</i> (Brébisson in Breb. et Godey) W. Smith var. <i>solea</i>	CSOL	0.52
<i>Encyonopsis microcephala</i> (Grunow) Krammer var. <i>microcephala</i>	ENCM	0.88
<i>Eolimna minima</i> Grunow) Lange-Bertalot	EOMI	1.04
<i>Fallacia pygmaea</i> (Kützing) A.J. Stickle & D.G. Mann in Round et al	FPYG	0.68
<i>Gomphonema gracile</i> Ehrenberg var. <i>gracile</i>	GGRA	0.47
<i>Gomphonema minutum</i> (Agardh) Agardh f. <i>minutum</i>	GMIN	0.32
<i>Gomphonema olivaceum</i> (Hornemann) Brébisson var. <i>olivaceum</i>	GOLI	0.65
<i>Gomphonema parvulum</i> var. <i>parvulum</i> f. <i>parvulum</i> (Kützing) Kützing	GPAR	4.09
<i>Gomphonema parvulum</i> var. <i>parvulum</i> f. <i>saprophilum</i> Lange-Bertalot & Reichardt	GPAS	2.54
<i>Gomphonema pumilum</i> (Grunow) Reichardt & Lange-Bertalot var. <i>pumilum</i>	GPUM	0.64
<i>Gyrosigma acuminatum</i> (Kützing) Rabenhorst	GYAC	0.59
<i>Halamphora montana</i> (Krasske) Levkov	HLMO	0.90
<i>Halamphora veneta</i> (Kützing) Levkov var. <i>veneta</i>	HVEN	1.01
<i>Hantzschia abundans</i> Lange-Bertalot	HABU	0.36
<i>Luticola goeppertiana</i> (Bleisch in Rabenhorst) D.G. Mann in Round Crawford & Mann	LGOE	3.36
<i>Mayamaea permitis</i> (Hustedt) Bruder & Medlin	MPMI	2.44
<i>Melosira varians</i> Agardh	MVAR	1.22
<i>Navicula cryptocephala</i> Kützing var. <i>cryptocephala</i>	NCRY	0.39
<i>Navicula cryptotenella</i> Lange-Bertalot var. <i>cryptotenella</i>	NCTE	0.64
<i>Navicula erifuga</i> Lange-Bertalot in Krammer & Lange-Bertalot	NERI	0.99
<i>Navicula germainii</i> Wallace	NGER	0.68
<i>Navicula gregaria</i> Donkin var. <i>gregaria</i>	NGRE	1.59
<i>Navicula phyllepta</i> Kützing	NPHY	2.88
<i>Navicula rostellata</i> Kützing var. <i>rostellata</i>	NROS	1.51
<i>Navicula simulata</i> Manguin	NSIA	2.13
<i>Navicula tripunctata</i> (O.F.Müller) Bory var. <i>tripunctata</i>	NTPT	0.45
<i>Navicula veneta</i> Kützing	NVEN	5.04
<i>Nitzschia amphibia</i> f. <i>amphibia</i> Grunow var. <i>amphibia</i>	NAMP	1.60
<i>Nitzschia capitellata</i> Hustedt in A.Schmidt & al. var. <i>capitellata</i>	NCPL	3.99
<i>Nitzschia denticula</i> Grunow in Cleve & Grunow var. <i>denticula</i>	NDEN	0.57
<i>Nitzschia desertorum</i> Hustedt	NDES	0.31
<i>Nitzschia dissipata</i> subsp. <i>dissipata</i> (Kützing) Grunow var. <i>dissipata</i>	NDIS	2.11
<i>Nitzschia dubia</i> W. M. Smith var. <i>dubia</i>	NDUB	0.64
<i>Nitzschia filiformis</i> (W. M. Smith) Van Heurck var. <i>filiformis</i>	NFIL	1.55
<i>Nitzschia frustulum</i> (Kützing) Grunow var. <i>frustulum</i>	NIFR	0.87

Table 4 (continued)

Species names	Species codes	Abundance (%)
<i>Nitzschia inconspicua</i> Grunow	NINC	3.12
<i>Nitzschia linearis</i> (Agardh) W.M.Smith var. <i>linearis</i>	NLIN	1.06
<i>Nitzschia palea</i> (Kützing) W.Smith var. <i>palea</i>	NPAL	9.91
<i>Nitzschia umbonata</i> (Ehrenberg) Lange-Bertalot	NUMB	3.41
<i>Nitzschia vermicularis</i> (Kützing) Hantzsch in Rabenhorst var. <i>vermicularis</i>	NVER	0.48
<i>Planothidium frequentissimum</i> (Lange-Bertalot) Lange-Bertalot var. <i>frequentissimum</i>	PLFR	2.80
<i>Planothidium granum</i> (Hohn & Hellerman) Lange-Bertalot	PGRN	0.50
<i>Reimeria sinuata</i> (Gregory) Kociolek & Stoermer	RSIN	0.91
<i>Rhoicosphenia abbreviata</i> (C. Agardh) Lange-Bertalot	RABB	1.45
<i>Sellaphora pupula</i> (Kützing) Mereschkowsky var. <i>pupula</i>	SPUP	0.89
<i>Surirella angusta</i> Kützing var. <i>angusta</i>	SANG	0.78
<i>Surirella brebissonii</i> Krammer & Lange-Bertalot	SBRE	0.80
<i>Tryblionella constricta</i> Gregory	TRCO	2.32
<i>Tryblionella levidensis</i> Wm. Smith	TLEV	0.53
<i>Ulnaria ulna</i> (Nitzsch) Compère var. <i>ulna</i>	UULN	1.79
Total abundance of other species in Safsaf watershed		1.42
Total abundance of other species in Kebir watershed		1.26
Total abundance of other species in Guebli watershed		0.98

Species in bold are the common taxa identified from the three watersheds. Abundance (%) was calculated as the average frequency of diatoms in all the watersheds. The sum of the total abundance of other species was calculated for each watershed separately

Appendix 2

See Table 5.

Table 5 Mean values of the environmental variables calculated for 3 seasons and measured at 26 sampling sites along the Coastal Central Constantine between May 2017 and August 2018

Sites codes	Temperature °C	conductivity $\mu\text{S cm}^{-1}$	DO mg L^{-1}	Nt mg L^{-1}	Phosphates mg L^{-1}	Chlorides mg L^{-1}	Velocity cm.s^{-1}	Altitude M	COD mg L^{-1}	BOD ₅ mg L^{-1}	Pollution	Seasons
SAD_S	24.1	900.00	7.29	288.86	4.33	129.16	1.07	85.00	136.64	10.00	Moderately impacted	Spring
SAD_W	16.5	1565.00	13.44	190.18	1.45	257.36	4.14	85.00	12.00	11.00	Slightly impacted	Winter
SAD_Sm	28.34	1388.00	6.52	167.79	2.55	185.49	0.41	85.00	62.50	8.00	Slightly impacted	Summer
SAU_S	24.12	1400.00	6.70	67.87	0.19	199.15	1.07	89.00	109.31	8.00	Slightly impacted	Spring
SAU_W	13.51	1612.00	12.03	111.27	1.59	258.92	4.13	89.00	24.00	12.00	Slightly impacted	Winter
SAU_Sm	28.27	1401.00	6.31	146.95	2.25	190.83	0.45	89.00	63.01	5.33	Slightly impacted	Summer
SSD_S	22.2	1275.00	0.90	73.01	1.02	97.47	0.88	21.00	156.16	440.00	Bad quality	Spring
SSD_W	16.15	1523.00	0.88	123.75	5.00	194.97	2.66	21.00	68.00	24.00	Slightly impacted	Winter
SSD_Sm	29.24	1378.67	4.05	235.30	7.44	183.45	0.42	21.00	86.20	167.33	Moderately impacted	Summer
SSU_S	24.18	1222.00	5.90	292.41	12.56	166.14	1.10	35.00	117.12	1.00	Moderately impacted	Spring
SSU_W	13.15	2646.00	7.19	95.70	2.52	414.90	3.33	35.00	4.00	25.00	Slightly impacted	Winter
SSU_Sm	29.23	1175.33	5.82	66.82	3.09	140.58	0.52	35.00	70.84	15.67	Slightly impacted	Summer
SZD_S	22.21	2300.00	0.70	294.25	5.38	371.90	0.73	14.00	163.97	430.00	Heavily impacted	Spring
SZD_W	16.14	1531.00	0.98	252.42	4.79	249.56	3.10	14.00	284.00	130.00	Bad quality	Winter
SZD_Sm	29.99	1701.67	0.42	277.23	2.42	278.41	0.49	14.00	177.64	205.67	Bad quality	Summer
SZU_S	24.21	1100.00	5.80	747.74	10.05	246.01	0.44	22.00	99.55	1.00	Heavily impacted	Spring
SZU_W	13.14	1008.00	11.06	145.74	1.09	152.86	4.25	22.00	72.00	4.00	Slightly impacted	Winter
SZU_Sm	29.77	1516.33	5.92	112.55	2.55	246.30	0.23	22.00	53.89	3.33	Slightly impacted	Summer
KAD_W	11.56	1247.00	3.95	594.29	21.85	128.08	0.11	72.00	160.00	61.00	Heavily impacted	Winter
KAD_S	22.78	1200.00	6.20	478.05	36.36	505.87	0.04	72.00	15.36	98.00	Bad quality	Spring
KAD_Sm	29.63	1189.33	2.59	362.14	13.40	134.06	0.13	72.00	70.59	57.33	Bad quality	Summer
KAU_W	14.72	1065.00	4.06	715.75	19.15	101.53	0.08	73.00	60.00	62.00	Heavily impacted	Winter
KAU_S	21.94	1100.00	6.40	417.70	37.26	521.85	0.03	73.00	107.52	110.00	Bad quality	Spring
KAU_Sm	28.15	1140.00	3.77	358.30	8.38	133.85	0.08	73.00	288.60	86.67	Bad quality	Summer
KED_W	11.11	1155.00	16.35	188.38	1.18	118.71	0.17	38.00	57.60	10.00	Slightly impacted	Winter
KED_S	23.06	800.00	5.93	114.73	3.52	152.88	0.13	38.00	60.00	40.00	Slightly impacted	Spring
KED_Sm	30.46	1289.67	4.03	197.59	6.88	117.07	0.44	38.00	58.11	27.00	Moderately impacted	Summer
KEU_W	10.72	1149.00	16.97	157.39	2.36	123.40	0.20	67.00	57.60	14.00	Slightly impacted	Winter
KEU_S	21.94	800.00	6.34	314.72	3.91	223.65	0.17	67.00	11.52	65.00	Moderately impacted	Spring
KEU_Sm	29.26	1420	5.29	193.79	9.93	160.17	0.16	67.00	38.56	74.00	Moderately impacted	Summer
KFD_W	9.39	1806.00	15.56	478.90	12.80	168.70	0.07	94.00	260.00	38.00	Heavily impacted	Winter
KFD_S	22.78	1100.00	7.75	769.71	7.27	179.63	0.05	94.00	65.28	100.00	Heavily impacted	Spring

Table 5 (continued)

Sites codes	Temperature °C	conductivity $\mu\text{S cm}^{-1}$	DO mg L^{-1}	Nt mg L^{-1}	Phosphates mg L^{-1}	Chlorides mg L^{-1}	Velocity cm.s^{-1}	Altitude M	COD mg L^{-1}	BOD ₅ mg L^{-1}	Pollution	Seasons
KFD_Sm	30.19	1692.67	3.19	455.59	10.63	150.97	0.04	94.00	272.85	97.67	Heavily impacted	Summer
KFU_W	10.56	1873.00	14.57	400.64	11.17	165.57	0.10	104.00	11.52	22.00	Bad quality	Winter
KFU_S	21.67	1100.00	7.74	31.38	6.07	167.70	0.08	104.00	200.00	90.00	Moderately impacted	Spring
KFU_Sm	29.26	1689.67	3.20	281.18	9.90	151.59	0.06	104.00	58.22	33.33	Moderately impacted	Summer
KKD_W	11.85	1135.00	11.60	99.04	2.77	124.96	0.25	31.00	19.20	13.00	Slightly impacted	Winter
KKD_S	19.76	800.00	6.83	79.87	2.22	130.26	0.17	31.00	48.00	65.00	Slightly impacted	Spring
KKD_Sm	26.81	1402.33	5.42	287.28	3.75	185.96	0.22	31.00	58.28	30.33	Moderately impacted	Summer
KKU_W	13.64	1140.50	10.03	212.68	2.50	127.87	0.29	43.00	31.36	9.00	Slightly impacted	Winter
KKU_S	21.81	900.00	7.02	79.79	3.20	120.90	0.20	43.00	112.00	70.00	Slightly impacted	Spring
KKU_Sm	28.40	1578.50	7.22	226.89	4.91	217.12	0.29	43.00	85.18	39.00	Moderately impacted	Summer
KMD_W	11.39	904.00	16.81	288.36	0.71	104.65	0.25	39.00	57.60	22.00	Moderately impacted	Winter
KMD_S	22.78	300.00	8.55	163.86	1.51	92.04	0.25	39.00	72.00	24.00	Slightly impacted	Spring
KMD_Sm	30.46	933.00	5.91	214.21	2.26	123.41	0.30	39.00	63.27	23.33	Moderately impacted	Summer
KMU_W	10.00	892.00	14.80	85.10	0.58	109.34	0.50	47.00	38.40	5.00	Slightly impacted	Winter
KMU_S	19.50	500.00	8.15	34.41	0.15	89.03	0.20	47.00	38.40	15.00	Slightly impacted	Spring
KMU_Sm	29.54	950.00	5.57	107.73	2.02	107.79	0.27	47.00	35.68	21.33	Slightly impacted	Summer
GBD_W	12.50	463.00	11.31	43.82	0.80	78.10	0.20	46	176.00	212.00	Moderately impacted	Winter
GBD_S	18.75	743.00	7.37	112.68	0.75	104.08	0.33	46	273.64	220.00	Moderately impacted	Spring
GBD_Sm	29.50	850.00	7.48	108.97	1.07	80.90	0.22	46	199.50	123.00	Moderately impacted	Summer
GBU_W	11.05	473.00	10.06	34.30	2.21	103.09	0.33	85	18.00	15.00	Slightly impacted	Winter
GBU_S	15.29	727.00	7.00	45.55	1.31	119.28	0.10	85	125.72	61.00	Slightly impacted	Spring
GBU_Sm	27.50	873.50	7.71	90.98	1.85	81.59	0.29	85	72.29	79.50	Slightly impacted	Summer
GFD_W	12.60	710.00	9.97	33.97	9.77	76.55	0.07	183	194.00	95.00	Slightly impacted	Winter
GFD_S	19.25	835.50	7.53	166.98	0.43	62.80	0.27	183	76.63	10.00	Slightly impacted	Spring
GFD_Sm	28.91	723.95	7.49	260.80	5.89	120.93	0.03	183	148.85	26.00	Moderately impacted	Summer
GFU_W	14.40	744.00	11.73	40.72	8.15	78.10	0.08	201	182.40	77.00	Slightly impacted	Winter
GFU_S	17.00	882.00	7.72	115.26	1.03	90.07	0.08	201	197.42	20.00	Slightly impacted	Spring
GFU_Sm	26.35	1731.50	8.44	247.44	4.57	196.56	0.10	201	135.22	19.50	Moderately impacted	Summer
GGD_W	12.68	530.00	11.56	40.20	1.19	101.53	0.25	54	307.20	216.00	Moderately impacted	Winter
GGD_S	18.82	764.50	8.20	91.07	1.01	124.00	0.09	54	165.57	101.00	Slightly impacted	Spring
GGD_Sm	29.88	969.50	7.26	156.65	1.59	131.42	0.11	54	278.90	177.50	Bad quality	Summer

Table 5 (continued)

Sites codes	Temperature °C	conductivity $\mu\text{S cm}^{-1}$	DO mg L^{-1}	Nt mg L^{-1}	Phosphates mg L^{-1}	Chlorides mg L^{-1}	Velocity cm.s^{-1}	Altitude M	COD mg L^{-1}	BOD ₅ mg L^{-1}	Pollution	Seasons
GGU_W	11.50	527.00	11.42	24.32	1.07	99.96	0.33	80	414.00	230.00	Bad quality	Winter
GGU_S	15.50	761.50	7.70	122.60	0.34	142.68	0.12	80	260.10	200.00	Moderately impacted	Spring
GGU_Sm	31.50	931.50	7.53	156.08	1.22	129.65	0.15	80	275.71	139.50	Moderately impacted	Summer
GMD_W	13.58	835.00	3.39	675.38	7.94	145.26	0.14	238	460.00	243.00	Heavily impacted	Winter
GMD_S	18.65	1011.70	1.99	892.63	11.84	161.87	0.03	238	343.84	110.00	Heavily impacted	Spring
GMD_Sm	31.14	1369.50	2.03	763.48	8.05	166.97	0.13	238	293.87	153.00	Heavily impacted	Summer
GMU_W	10.55	834.00	3.52	693.11	7.75	132.77	0.10	264	280.00	227.00	Heavily impacted	Winter
GMU_S	17.75	1119.50	2.01	741.91	7.56	165.41	0.04	264	391.76	140.00	Heavily impacted	Spring
GMU_Sm	28.91	1335.00	1.94	800.65	10.70	154.70	0.18	264	353.28	205.50	Heavily impacted	Summer
GOD_W	10.49	1045.00	8.47	100.90	8.97	160.88	0.04	72	228.00	110.00	Moderately impacted	Winter
GOD_S	15.65	828.50	5.23	216.93	2.16	181.91	0.02	72	323.24	212.50	Bad quality	Spring
GOD_Sm	29.83	1087.50	1.66	943.27	12.06	251.65	0.01	72	373.90	194.00	Heavily impacted	Summer
GOU_W	12.08	1025.00	10.26	208.90	9.58	156.20	0.05	84	235.84	186.00	Bad quality	Winter
GOU_S	16.45	786.50	7.08	402.22	0.91	122.10	0.03	84	438.60	230.00	Bad quality	Spring
GOU_Sm	30.99	1083.50	1.99	824.75	9.72	131.29	0.02	84	345.92	170.00	Heavily impacted	Summer

DO Dissolved oxygen, Nr: Total nitrogen, COD Chemical oxygen demand, BOD₅ Biochemical oxygen demand in five days, S Spring, W Winter, Sm Summer

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