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Environmental determinants of diatom assemblages along a North African wadi, the Kebir-East, North-East Algeria

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ABSTRACT

A total of 322 benthic diatoms with the majority being cosmopolitan species was recorded during a survey of the catchment area of the Kebir-East wadi, northeast Algeria. The spatial distribution patterns of diatom communities in relation to environmental gradients were examined using Co-Inertia Analysis (CIA) for ascertaining the interdependence between physico-chemical descriptors and diatom assemblages in 182 samples, collected over a period of 3 years, across 23 sampling stations. There was a significant covariance between the environmental data set and the benthic diatom data set with the CIA highlighting correlations between environmental factors and diatom species. A clear longitudinal gradient was a main driver of diatom communities with upstream sites characterized by high dissolved oxygen concentrations and downstream sites characterized by high organic load and nutrient enrichment of the water. A further factor influencing the shape of diatom assemblages was related to the conductivity, and the high values possibly reflected the close proximity of the sea to the downstream sites. An anthropogenic impact was also most evident in structuring diatom assemblages at sites close to Lake Oubeïra where agriculture was concentrated.

Key words: Diatoms, environmental gradients, intermittent streams, anthropogenic pressure, water quality, North Africa

1. INTRODUCTION

The River Continuum Concept (Vannote *et al*. 1980) has provided a stimulating theoretical framework for the research on ecological structural properties in running water systems (Hynes 1970; Junk 1999; Stanford & Ward 1988). Spatial patterns of diatom species assemblages and environmental factors driving diatom species communities have been targeted by several studies (Biggs 1990; Pipp & Rott 1994; Reavie & Smol 1998; Rott *et al*. 1998; Pan *et al*. 1999, 2000; Potapova & Charles 2003; Soininen 2002). These studies highlight the dominant role of chemical constituents and ion composition in the shaping of the structures of diatom communities (Johansson 1982; Soininen 2004). Knowledge of North African rivers or wadi is relatively poor and these water systems remain some of the least studied Mediterranean ecosystems. These limnological systems are subjected to harsh climatic conditions and, as they are located in a semi-arid region, are likely to experience marked physical and biological changes in the near future (Hulme *et al*. 2001). There is, however, a potent lack of knowledge about possible physical and biological changes that these hydrosystems are likely to experience in the light of climatic changes. Most studies of Algerian wadi have been confined to physico-chemical characteristics and macro-invertebrates (Lounaci *et al*. 2000; Belaidi *et al*. 2004) while studies on algae are rare (Baudrimont 1973).

Diatom species composition has been shown to be affected by anthropogenic pressures (Van Dam *et al*. 1994; Kelly & Whitton 1998; Kovacs *et al*. 2006) and diatoms have been used routinely across the world to monitor water quality in rivers and streams (Schoeman 1979; Coste *et al*. 1991; Whitton & Kelly 1995; Jüttner *et al*. 2003). The increasing demand for environmental impact assessment and the reliance on benthic diatoms as a tool to monitor the ecological quality of rivers have been highlighted by the European Water Framework Directive (European Commission 2000). Knowledge of how the interactions of geographical and environmental factors drive the distribution pattern of benthic diatom species is crucial for the development of water-quality assessment based on diatom monitoring. The aim of this study was two-fold: (1) to survey the diatom flora of the Kebir-East wadi, and (2) to relate the distributional patterns of benthic diatom species assemblages to environmental variables.

2. METHODS

The Kebir-East wadi originates at an altitude of 1200 m in the Ghora Mountain, Numidia, close to the Algerian-Tunisian border (Samraoui & de Bélair 1998). The climate of the Kebir-East basin, northeastern Algeria, is typically Mediterranean with a dry and hot summer and with rainfall occurring mostly during the winter months. The sites sampled on the Kebir-East wadi (Fig. 1) and its effluents (streams) have a wide range of con-

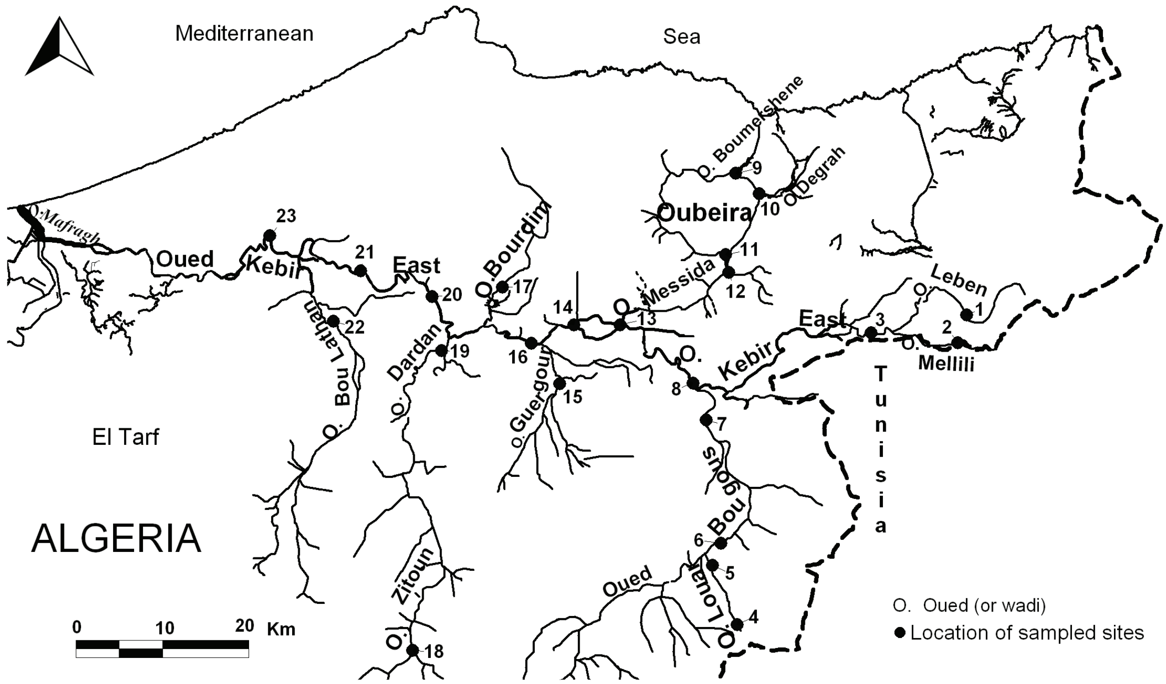

Fig. 1. Map of the Kebir-East hydrosystem in northeast Algeria with location of the sampled stations.

ductivity (0.1-3.0 mS cm^{-1}), water depth, and hydroperiod (Zouini 1997). The list of sampled sites is provided in table 1.

Tab. 1. List of the sampled sites.

N°	Name of Site	N°	Name of Site
1	Leben	13	Messida amont
2	Mellili	14	Kebir at Aïn Khiar
3	Kebir at R'Mel Souk	15	Guergour
4	Louar amont	16	Kebir at Guergour
5	Louar aval	17	Bourdim
6	Bougous amont	18	Zitoun
7	Bougous aval	19	Dardan
8	Kebir at Aïn Assel	20	Kebir at Anènes
9	Oubeïra 3	21	Kebir at Righia
10	Oubeïra 2	22	Boulathan
11	Oubeïra 1	23	Kebir at Sebaa
12	Messida aval		

Over a period of 3 years (spring 2005 to winter 2008), a total of 174 samples were collected along the main course of the Kebir-East wadi and its 10 principal tributaries (Tab. 1) in northeastern Algeria (Fig. 1). No sampling took place in the summer of 2006. Sampling sites were selected on the basis of land-use information with the aim of sampling across a broad gradient of altitude (from 8 m to 650 m a.s.l.) and pollution levels (from near-pristine to heavily urbanized areas).

Samples of diatoms were collected according to a standardized method (NFT90-354) (AFNOR 2000), from five randomly chosen stones representing a total surface area of 1 m^2. The stones were scraped with a toothbrush and the pooled material was kept in 500 mL dark bottles containing 5% formaldehyde.

Diatom species were identified at 1000× magnification using Zeiss light microscope with 400 valves per slide according to Krammer & Lange-Bertalot (1986-1991), by examining permanent slides of cleaned diatom frustules, digested in boiling H_2O_2 (30%) and HCl (35%) and mounted in a high refractive index medium (Canada Balsam, RI = 1.55). Species and genera were identified according to Süsswasserflora von Mitteleuropa (Krammer & Lange-Bertalot 1985-1991) in addition to some complementary works (Patrick & Reimer 1966, 1975; Germain 1981; Hartley *et al.* 1996; Kelly 2000). Simultaneous with the collection of diatoms, physico-chemical data were collected. From the three-years collection period, average values were calculated for each environmental variable. All physico-chemical parameters were recorded on the sampling date from 1.5 L samples collected from a free flowing area near the middle of the stream. The samples were stored at 4 °C and then analyzed within 48 hours, according to standardized protocols (AFNOR 2000).

The ecological determinants of diatom assemblages along the Kebir-East were subjected to Co-Inertia Analysis (CIA), a two-table ordination method similar to Canonical Correlation Analysis (CCA), using the ADE-4 package (Thioulouse *et al.* 2004). This multivariate analysis tool (Dolédec & Chessel 1994) has been used to ordinate samples by researching a co-structure between physico-chemical variables and diatom species. The co-structure in CIA was determined by the maximization of the covariance, instead of correlation as in CCA, between the two new sets of projected coordinates. The significance of the resulting correlation (*R* value) between the two sets of coordinates resulting

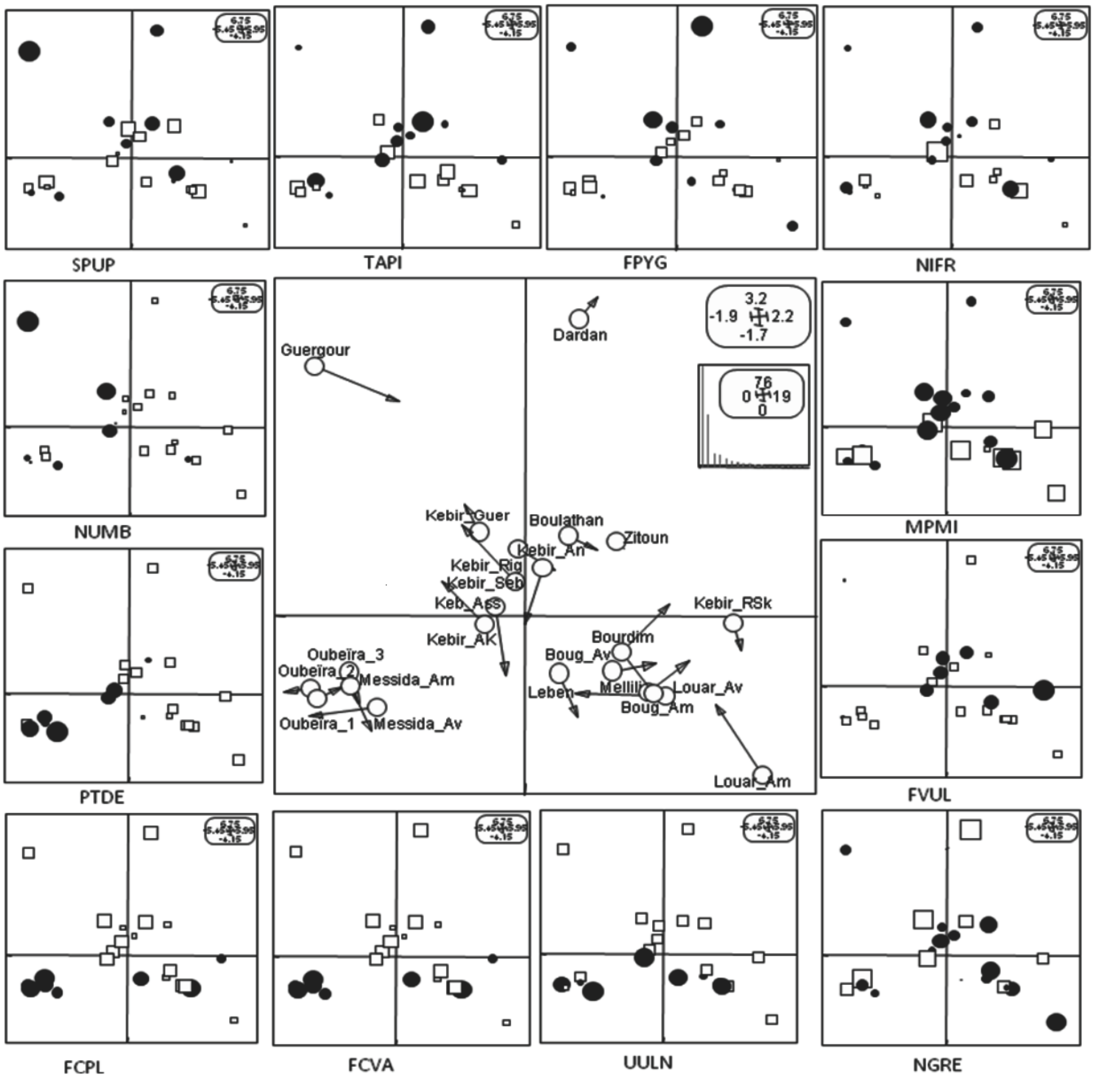

Fig. 2. F1xF2 factorial plane of CIA with arrows linking stations according to physico-chemical variables (base of arrows) and diatom species (end of arrows). Surrounding the central plot are projections of selected diatoms plotted on the same factorial map with abundance proportional to the area of circles (positive values) or squares (negative values). Eigenvalues are displayed on the inset.

Tab. 2. Summary of the Co-Inertia Analysis for wadi Kebir-East. (Covaria: covariance of the two sets of coordinates projected on to Co-Inertia axes. Varian1: inertia of the environmental table projected on to Co-Inertia axes. Varian2: inertia of the diatoms table projected on to Co-Inertia axes. Correla.: correlation between the two new sets of coordinates resulting from the CIA. INER1: maximal projected inertia of the environmental table. INER2: maximal projected inertia of the diatoms table).

Num.	Covaria	Varian1	Varian2	Correla.	INER1	INER2
1	8.662	7.577	10.970	0.950	7.762	13.400
2	6.215	4.248	10.360	0.937	4.125	12.020

from the CIA was tested by carrying out 10,000 Co-Inertia Analyses of the environmental descriptors and the diatom data sets after random permutations of their rows (Dolédec & Chessel 2004).

3. RESULTS

The results of the CIA between habitat characteristics represented by measured environmental variables, and diatom species of the Kebir-East wadi are presented in figure 2. As shown by Monte Carlo simulations, the co-inertia was statistically highly significant (p <0.001). The first two axes of the CIA accounted for 48.6% and 25.0% respectively of the total covariance (Tab. 2).

Every arrow shown in the figure indicates a site with its environmental descriptors (the circled numbers at the base of the arrow) and its species (the end of the arrow).

Tab. 3. Summary table of chemical and physical environmental variables in wadi Kebir-East during the study period (n=174).

	Unit	Mean	SE	Median	Min.	Max.
NO_3^-	mg L^{-1}	13.3	8.4	9.8	1.1	32.4
NO_2^-	mg L^{-1}	0.5	0.4	0.4	0.0	1.8
NH_4^+	mg L^{-1}	0.8	0.7	0.6	0.0	3.4
PO_4^{3-}	mg L^{-1}	0.9	1.0	0.7	0.0	5.6
Turbidity	FTU	224.9	283.0	129.8	0.8	967.0
Flow velocity	cm s^{-1}	28.0	20.3	22.6	0.3	81.4
O_2 saturation	%	117.5	27.6	111.0	45.3	182.0
O_2 dissolved	mg L^{-1}	12.8	3.4	11.7	4.2	28.5
Temperature	°C	12.6	4.2	11.3	6.4	25.5
Cl^-	mg L^{-1}	153.8	87.3	127.9	46.0	586.0
Conductivity	µs cm^{-1}	622.0	195.5	604.5	140.0	1511.0
Alcalinity (TAC)	mg L^{-1}	117.0	76.6	92.5	5.0	367.3
pH	U	7.0	0.6	6.9	5.4	9.4
SO_4^{2-}	mg L^{-1}	110.2	57.6	117.0	3.2	237.0
Ca^{2+}	mg L^{-1}	86.8	44.2	76.0	17.0	235.0
Mg^{2+}	mg L^{-1}	57.6	47.3	32.4	10.0	175.0
Total hardness (TH)	mg L^{-1}	171.2	64.4	165.0	58.0	456.0

Tab. 4. Acronyms and full names of the widespread species over the Kebir-East hydrosystem and its tributaries.

Acronym	Species	Acronym	Species
AAMB	*Aulacoseira ambigua* (Grunow) Simonsen	NDUB	*Nitzschia dubia* W.M.Smith
ADM	*Achnanthidium minutissimum* (Kützing) Czarnecki	NERI	*Navicula erifuga* Lange-Bertalot
AGCU	*Aulacoseira granulata* (Ehr.) Simonsen morphotype curvata	NFIL	*Nitzschia filiformis* (W.M.Smith) Van Heurck var. *filiformis*
APED	*Amphora pediculus* (Kützing) Grunow	NGRE	*Navicula gregaria* Donkin
AUGR	*Aulacoseira granulata* (Ehr.) Simonsen	NIFR	*Nitzschia frustulum* (Kützing) Grunow var. *frustulum*
BBRE	*Brachysira brebissonii* Ross in Hartley ssp. *brebissonii*	NLAN	*Navicula lanceolata* (Agardh) Ehrenberg
BPAX	*Bacillaria paxillifera* (O.F. Müller) Hendey var. *paxillifera*	NPAL	*Nitzschia palea* (Kützing) W.Smith
CAFF	*Cymbella affinis* Kützing var. *affinis*	NRAD	*Navicula radiosa* Kützing
CEUG	*Cocconeis euglypta* Ehrenberg	NRCH	*Navicula reichardtiana* Lange-Bertalot var. *reichardtiana*
CMEN	*Cyclotella meneghiniana* Kützing	NRCS	*Navicula recens* (Lange-Bertalot) Lange-Bertalot
COCE	*Cyclotella ocellata* Pantocsek	NROS	*Navicula rostellata* Kützing
CPLA	*Cocconeis placentula* Ehrenberg var. *placentula*	NRST	*Nitzschia rosenstockii* Lange-Bertalot
CTPU	*Ctenophora pulchella* (Ralfs ex Kütz.) Williams et Round	NSIG	*Nitzschia sigma* (Kützing)W.M.Smith
DVUL	*Diatoma vulgaris* Bory	NSYM	*Navicula symmetrica* Patrick
ENMI	*Encyonema minutum* (Hilse in Rabh.) D.G. Mann	NTRV	*Navicula trivialis* Lange-Bertalot var. *trivialis*
FCPL	*Fragilaria capitellata* (Grunow in Van Heurck) J.B. Petersen	NUMB	*Nitzschia umbonata* (Ehrenberg) Lange-Bertalot
FCVA	*Fragilaria capucina* Desmazieres var. vaucheriae (Kützing) Lange-Ber	NVEN	*Navicula veneta* Kützing
FFAM	*Fragilaria famelica* (Kützing) Lange-Bertalot var. *famelica*	PLLE	*Plagiotropis lepidoptera* (Gregory) Kuntze
FPYG	*Fallacia pygmaea* (Kützing) Stickle & Mann ssp. *pygmaea* Lange-Ber	PTDE	*Planothidium delicatulum* (Kütz.) Round & Bukhtiyarova
FVIR	*Fragilaria virescens* Ralfs	RABB	*Rhoicosphenia abbreviata* (C.Agardh) Lange-Bertalot
FVUL	*Frustulia vulgaris* (Thwaites) De Toni	RGIB	*Rhopalodia gibba* (Ehr.) O.Muller var. *gibba*
GMIN	*Gomphonema minutum* (Ag.)Agardh f. *minutum*	RUNI	*Reimeria uniseriata* Sala Guerrero & Ferrario
GOLI	*Gomphonema olivaceum* (Hornemann) Brébisson var. *olivaceum*	SBRE	*Surirella brebissonii* Krammer & Lange-Bertalot var. *brebissonii*
GPAR	*Gomphonema parvulum* (Kützing) Kützing var. *parvulum* f. *parvulum*	SBRI	*Surirella brightwellii* W.Smith var. *brightwellii*
GYAT	*Gyrosigma attenuatum* (Kützing) Rabenhorst	SPUP	*Sellaphora pupula* (Kützing) Mereschkowksy
LGOE	*Luticola goeppertiana* (Bleisch in Rabenhorst) D.G. Mann	TAPI	*Tryblionella apiculata* Gregory
MPMI	*Mayamaea permitis* (Hustedt) Bruder & Medlin	TLEV	*Tryblionella levidensis* Wm. Smith
MVAR	*Melosira varians* Agardh	UUAC	*Ulnaria ulna* (Nitzsch.) Compère var. *acus* (Kütz.) Lange-Bertalot
NCTV	*Navicula caterva* Hohn & Hellerman	UUAN	*Ulnaria ulna* Sippe *angustissima* (Grunow) Lange-Bertalot
NDIS	*Nitzschia dissipata* (Kützing)Grunow var. dissipata	UULN	*Ulnaria ulna* (Nitzsch.) Compère

Measured values (mean, median, minimum and maximum) for the physical and chemical variables (n = 174) in the Kebir-East wadi are presented in table 3. A list of the acronyms of the names of the species used in figure 2 are given in table 4.

From 182 samples collected during the period from 2005 to 2008, 322 species were identified. Among the recorded taxa, 100 are considered as frequent (>25%) over the whole length of wadi Kebir-East and its tributaries (Tab. 4). Most are cosmopolites as *Achnantidium minutissimum* (ADMI), *Amphora pediculus* (APED), *Cymbella affinis* (CAFF), *Cyclotella ocellata* (COCE), *Encyonema caespitosum* (ECAE), *Achnanthidium exiguum* ((ADEG), *Amphora oligotraphenta* (AOLG), *Encyonopsis subminuta* (ESUM), and *Gomphonema acuminatum* (GACU) (Fig. 3).

CIA highlighted the links between the physico-chemical characteristics of the wadi and the various diatoms species. The results presented in figure 2 show the mean values of physico-chemical variables for each studied site (Tab. 3), and the widespread species across the 23 sampled sites (i ≥3 sites).

Axis 1 separated upstream from downstream zones of the Kebir hydrosystem: the upstream zone, well oxygenated, was characterized with high flow velocity, and strong mineralization of waters which entailed the presence of species like *Cyclotella ocellata* (COCE), *Navicula gregaria* (NGRE), *Frustulia vulgaris* (FVUL) and

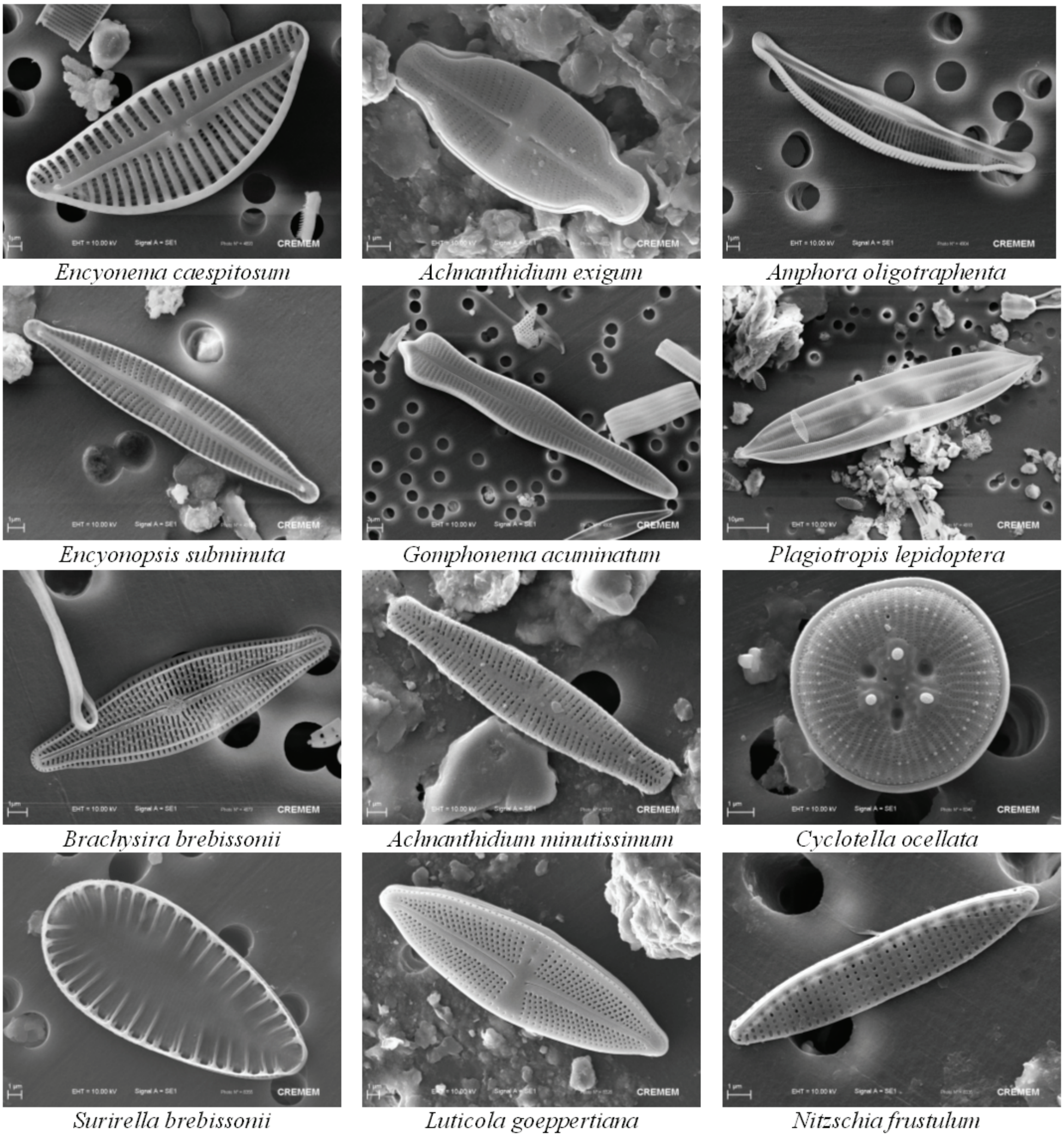

Fig. 3. Photos of mounted diatom frustules taken with MEB.

Plagiotropis lepidoptera (PLLE). The site Bourdim (site 17) exhibited some floral particularities, such as the simultaneous presence of *Fragilaria pulchella* and *Brachysira brebissonii* (BBRE) (Fig. 3).

The sites Zitoun (site 18) and Kebir at R' Mel Souk (site 3) (average water conductivity >700 $\mu S\ cm^{-1}$) were found to house robust forms of *Reimeria uniseriata* (RUNI) with exceptionally strong stria.

Axis 2 of the CIA, displayed distinct differences in water chemistry and diatom community types among downstream sites.

- The downstream reaches (sites 20-23) were characterized by strong water conductivity and chloride concentration and were occupied by species like *Nitzschia frustulum* (NIFR) and *Tryblionella apiculata* (TAPI). Wadis Guergour and Dardan, presented weak current flows, drying up in autumn, and were also similarly associated with salinity (water conductivity (1200 $\mu S\ cm^{-1}$) and chloride concentration (400 mg L^{-1}). These sites were also characterized by the presence of species of anthropogenic ecosystems such as: *Fallacia pygmaea* (FPYG), *Mayamaea permittis* (MPMI) and *Sellaphora pupula* (SPUP).
- The sites located in close proximity to Lake Oubeïra (sites 9-13) (Fig. 1) were associated with low water conductivity, finer substrata (sand, silt) and strong concentrations of NO_3^-, NH_4^+, NO_2^-, PO_4^{3-} (Tab. 3). Local episodes of water pollution were associated

with a transient shift towards the dominance of *Fragilaria capitellata* (FCPL) and *Synedra ulna* (UULN). These sites were also colonized by prostrate diatoms, including several species of *Navicula* (NVEN, NTRV, NRCS) and *Nitzschia* (NUMB, NPAL). In the Messida wadi, an epilithic diatom community was found associated with low water conductivity and gravel substrata, consisting of *Achnanthes* (ADMI, AGCU) as well as stalked taxa like *Gomphonema minutum* (GMIN).

4. DISCUSSION

The distribution of diatom species along environmental gradients has been the focus of numerous studies which have been used to infer processes that determines the structure of communities (Dunson & Travis 1991; Wellborn *et al*. 1996; McPeek & Brown 2000). This is true for lotic systems which have witnessed in the last decades a strong theoretical framework providing guidance in the study of running waters (Townsend & Hildrew 1994). The concept of environmental filters in rivers (Poff 1997), an extension of Southwood's River Habitat Templet (1977), suggests that life history traits strategies are shaped by habitat and disturbance, thus generating predictions to be tested (Townsend & Hildrew 1994; Statzner *et al*. 2004). It is, however, unclear how widespread such patterns are and how broadly these hypotheses apply. As diatom assemblages are thought to be driven by local environmental factors rather than regional processes (Soininen 2004), it may be useful therefore to describe such patterns and identify environmental drivers of species assemblages in different geographical settings, especially in arid regions like North Africa. Mediterranean rivers, especially southern ones, are subjected to a wide spectrum of natural fluctuations and anthropogenic disturbances driven by a seasonal sequence of extreme flooding and drying (Gasith & Resh 1999).

The present study represents the first attempt on typology of benthic diatom assemblages and characterization of their ecological responses to environmental gradients in an Algerian hydrosystem, the Kebir-East wadi. Although the knowledge of Algerian wadi has increased in recent years (Arab *et al*. 2004; Moubayed *et al*. 2007), little attention has previously been given to diatoms. In the present study 322 benthic diatom species were recorded and the majority were cosmopolitan taxa. Because of their small size, diatom assemblages are thought to be dominated by cosmopolitan species (Lange-Bartelot 2000) and this view, despite some criticisms (Kociolek & Spaulding 2000), has been upheld (Bate *et al*. 2004). In line with previous studies in other geographical settings (Potapova & Charles 2002), the CIA revealed a strong longitudinal gradient with upstream sites characterized by high water velocity and dissolved oxygen contrasting with downstream sites characterized by turbid water and affected by a higher level of organic pollution. The ecological impact of P- and N-loading from agricultural activities is most apparent around Lake Oubeïra with a distinct diatom community [*Fragilaria capucina* (FCVA), *Planothidium delicatulum* (PTDE), *Achnanthidium minutissimum* (ADMI) and *Luticola goeppertiana* (LGOE)]. Environmental stressors like livestock grazing and intensive agricultural activities are known to increase nutrient runoff, resulting in downstream eutrophication (Jüttner *et al*. 1996; Brown & May 2000). Diatoms assemblages of the Kebir-East wadi seem also to be most sensitive to conductivity, a variable known to reflect the dominant geological nature of the watershed (Leland & Porter 2000; Rimet *et al*. 2007) and to influence diatom communities (Biggs 1990; Pan *et al*. 1999; Soininen 2004). The downstream sites may also have been influenced by sea intrusions which may be responsible for the higher water salinity.

The present work also represents a first step of attempting to gain a better understanding of the composition and distribution of benthic diatoms in northeastern Algerian rivers. The next step will be to investigate whether similar patterns are found across the varied North African landscapes. The diatom-based water quality indicators of the ecological status of hydrosystems should be developed by testing the applicability of European Indices such as the Diatom Biological Index (Prygiel & Coste 2000) on North African wadi or by adapting such indices to take into account ecological attributes of native taxa.

5. CONCLUSIONS

The combined effects of demography and climate change will only exacerbate the increasing pressure on precious water resources in North Africa. One way to address threats such as pollution is to implement a management strategy with improved monitoring schemes of freshwater habitats. As a prelude to develop diatom-based water quality indicators of the ecological status of hydrosystems, there is a need to improve the knowledge of ecological determinants of diatom assemblages in North Africa. Results show that diatom species composition of wadi Kebir-East is influenced by geological, chemical, physical and anthropogenic factors like agricultural activities and livestock grazing.

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