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THE GENUS *NAVICULA SENSU STRICTO* IN THE UPPER LERMA BASIN, MÉXICO. I

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In order to characterize and analyze the distribution of species of the genus *Navicula sensu stricto* in the Lerma River and its tributaries, biannual samplings (wet and dry seasons) for the period 2003 to 2005 were made at eleven locations in the Upper Lerma basin, central-western México. Twenty-two species of *Navicula* Bory, were identified, of which fourteen represent new records for México and five were new to the study area. Most of the species of *Navicula s. str.* observed in the study area are tolerant to high contents of organic matter, which is incorporated into the aquatic ecosystems as a product of agricultural and industrial activities and from cities and towns with deficient treatment facilities. Cosmopolitan species with broad tolerances to organic pollution and eutrophic conditions, such as *Navicula antonii, N. germainii, N. perminuta, N. rostellata* and *N. erifuga* were present throughout the year. *N. tripunctata* and *N. veneta*, widely reported as tolerant to pollution from industrial activities in other regions of the world, were present at the sites most affected by these activities.

INTRODUCTION

When *Navicula* Bory was erected, it included the biraphid and most bilateral symmetrical diatoms (Round *et al*. 1990). During the last part of the 20th century, the systematical position of the genus was reviewed and the generic description was amended by Cox (1979) to restrict the genus *Navicula* to the species of the old Section *Lineolatae,* in agreement with the type species *Navicula tripunctata* (O. F. Müller) Bory. With the contributions of Cox (1979, 1987) and Mann & Stickle (1991), among others, new differential morphological, cytological and reproductive characters were discovered and a large number of species was clustered and transferred to new (*Luticola* Mann, *Fallacia* Stickle & Mann, *Cavinula* Mann & Stickle) or resurrected genera (*Craticula* Grunow, *Dickieia* Berkeley).

Lange-Bertalot (2001) subdivided *Navicula* in two Sections, based on the curvature of the central fissures of the raphe. In the Section *Alinea* the central raphe ends are clearly deflected to the primary side of the valve while in the Section *Navicula*, the central pores of the raphe are deflected to the secondary side of the valve, or they are straight or indistinct.

Most of the 250–300 known species of *Navicula s. str.* are epicontinental (fresh and brackish waters). It is important to state that a high number of species are still unidentified/ undescribed and there remain substantial taxonomical problems in the genus (Lange-Bertalot 2001).

In México, *Navicula* is a poorly known genus, with scarce records and less detailed descriptions. Moreover, of the forty-four species of *Navicula s. l.* recorded for México, twenty-one (47.7%) belong to *Navicula s. str.* and the remaining ones have to be reassigned to other genera.

The Lerma–Chapala basin is located in the central-western region in México (Fig. 1). This region is situated at the confluence of the Neartic and Neotropical biogeographic zones and presents a high biological richness including large species diversity (CONABIO, 1998; Moncayo-Estrada *et al*. 2001). Unfortunately, biological richness has decreased during the last decades due to the intense human activity within the basin.

Only two previous diatom studies have occurred in the Lerma river basin (Oliva-Martínez *et al.* 2005, Valadez *et al.* 2005), thereby making an intensive taxonomical and ecological research in this region necessary. For these reasons, a project was financed by CONACyT (SEP-2003-CO2-44693/A-1), to characterize the Lerma river diatoms.

Among the forty-seven diatom genera that were identified in the river basin, the genus *Navicula s. str.* showed interesting species richness and morphological diversity. As a consequence, the objectives of this paper were to analyze the morphological and morphometric characteristics of the representatives of this genus in the area; to compare the taxonomical features of the species and to analyze their ecological requirements in relation to the environmental characteristics of the basin.

Study area

The Lerma River originates with the Almoloya del Río springs in the Nevado de Toluca volcano, at 4680 m asl; and terminates in Chapala Lake in the state of Jalisco (1560 m asl). The river is shallow, not navigable, and is dammed in many points. Two big water reservoirs along the river are used for electrical energy generation (Tepuxtepec and Solis). The Lerma river, with an approximate length of 700 km and a catchment area of 52500 km^2, flows through several large cities (Toluca, Querétaro, León, Irapuato, Salamanca, and Morelia) (Waitz 1943, Aparicio 2001) (Fig. 1).

The river receives wastewater from more than two thousand industries (mainly concentrated in the Upper Lerma basin), from 170,573 Ha of cultivated areas and from urban zones (eight large towns with high population density: 100,000 inhabitants) with inadequate treatment facilities (INE, 2003, Sedeño-Diaz *et al*. 2007). As a consequence all pollutants (mainly heavy metals as Cd and Zn and nutrients produced by farming) generated enter into the soil and underground water (INE 2003, León-Mojarro *et al.* 2001).

According to the geological nature of the area (Waitz 1943, Pasquaré *et al.* 1991), fish distribution (Moncayo-Estrada *et al*. 2001) and topographical features (Sedeño & López 2007), the river basin was subdivided into three sub-basins: upper, middle, and low.

The Upper Lerma basin (19º37'30"–20º08'32"N; 100º35'43" W, 1744 m asl) extends from its origins to the Bajío of Guanajuato region, running across four central Mexican states (México, Guanajuato, Querétaro and Michoacán). Geologically, this sub-basin is located in the Transmexican Volcanic Belt geological province, composed of mainly basaltic and andesitic rocks, which were emitted from several characteristic stratovolcanoes and cineritic cones that accumulated beginning during the late Miocene 13.5 Ma and continuing through Holocene times (Aguirre-Díaz 1995). The last volcanic deposits were covered by alluvial deposits. The volcanism emerged along extensional faults that configure the course of the river. The main materials observed along the river consist of alluvial deposits, constituted of unconsolidated sands, gravels and conglomerates (Israde-Alcántara 1999).

In the Upper Lerma, different soils types can be recognized including Phaeozem, Vertisol and Acrisol (SPP, 1985) (Table1). The studied region has an average temperature of 18º C in valleys and lowlands, and of 12.5º C in the Mil Cumbres highlands and the central Meseta Tarasca. The annual precipitation ranges between 646–1,642 mm and the vegetation is dominated by fir forest, pine forest and pine-oak forest (SPP, 1985).

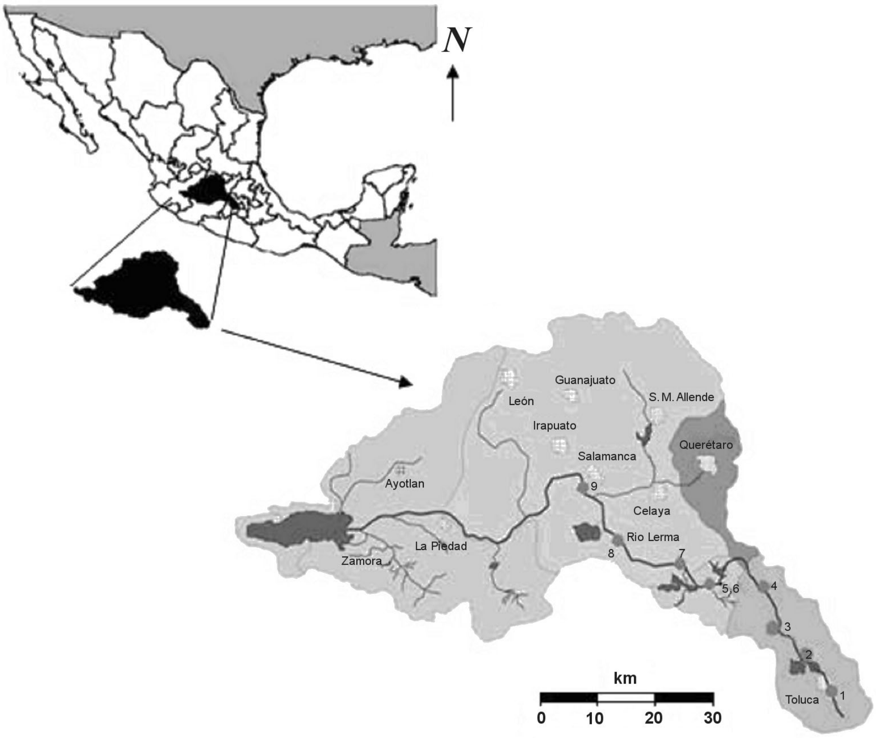


Fig. 1. Location of sampling sites on Upper Lerma basin. 1-Lerma-Toluca bridge, Mex.; 2-Ixtapatongo, Mex.; 3-Tlacotepec, Mex.; 4-Temazcalcingo bridge, Mex.; 5-El Pedregal, Mich.; 6-Pedregal spring, Mich.; 7-Chamacuaro, Gto.; 8-El Capulin, Gto.; 9-Uruetaro, Gto.

MATERIALS AND METHODS

Sampling sites were selected every ca. 10 km in the Upper Lerma basin. Eight sampling sites were located on the main river course and in a spring before its confluence with the river (Fig. 1, Table 1). Sampling stations were chosen according to the different human activities and land uses in the area, in order to have samples collected upstream and downstream of every town. Two water and epilithon samples were taken every year from April 2003 to December 2005.

The sampling was carried out in a free flowing area during dry and rainy seasons and the following parameters were measured in all the seasons. Depth was measured with an electric sounding line, water temperature, electric conductivity and pH were measured with a Conductronic (PC-18) potentiometer, dissolved oxygen and percent oxygen saturation with a portable YSI (51-B) meter, solar radiation ($\mu E \cdot m^{-2} \cdot s^{-1}$) with a LICOR (LI-1000) photometer, and current velocity was measured at each site with a Gurley Pigmy Current Meter (622).

Table 1. Sample localities, main characteristics of geology, soils, and riparian vegetation. Us – urban sewage, A – Agrochemical, I –industrial activity, P – Pottery, Ts – touristic site, L – livestock use.

Sample Nº	Sampling sites	Geology	Soils	Vegetation	Land Use
1	Lerma River-Toluca bridge.	Lacustrine, pumice	Phaeozem	*Bouteloa curtipendula* *Tripsacum dactyloides*	Us, A, I
2	Lerma River-San Jeronimo Ixtapatongo.	Piroclastic flows , pumice	Vertisol	*Salix bonplandiana* *Urtica dioica*	Us, A, I
3	Lerma River-San Lorenzo Tlacotepec, (México St.)	Basalts, andesites	Acrisol	*Urtica dioica* *Lepidium virginicum* *Salix bonplandiana*	Us, A, I
4	Lerma River-Temazcalcingo bridge, (México St.)	Basalts, andesites	Acrisol	*Taxodium mucronatum*	A, I, P
5	Lerma River-El Pedregal (Michoacán St.)	Andesite dacite	Vertisol	*Taxodium mucronatum*	A
6	El Manantial (spring) at Pedregal (Michoacán St.)	Andesite, piroclastic acid flows	Vertisol	*Taxodium mucronatum*	Ts
7	Lerma River-Chamacuaro (Guanajuato St.)	Basalts	Vertisol	*Oenothera rosea* *Salix bonplandiana* *Tagetes* sp	Us, A
8	Lerma River-El Capulin (Guanajuato St.).	Andesites and basalts	Vertisol	*Argemone ochroleuca*	Us, A
9	Lerma River-Uruetaro (Guanajuato St.)	Andesites	Vertisol	*Taxodium mucronatum* *Salix bonplandiana*	Us, I

Table 2. A. Environmental variables of Upper Lerma, México, dry/postrainy season, 2003-2005. Sampling sites: (PL)-Lerma-Toluca bridge, state of México; (Ixt)-San Jerónimo Ixtapatongo, state of México; (Tl)-San Lorenzo Tlacotepec, state of México; (Tz)-Temazcalcingo bridge, state of México; (P)-El Pedregal, state of Michoacán; (Ps)-Pedregal spring, state of Michoacán; (Ch)-Chamácuaro, state of Guanajuato; (C)-El Capulín, state of Guanajuato; (U)-Uruétaro, state of Guanajuato. d: dry season; p-r: postrainy season. B. Dry and Post-rainy seasonal physical and chemical variables of the Upper Lerma River.

A	Depth (cm)		Temperature (ºC)		Conductivity (µS cm-1)		pH		Dissolved oxygen (mgL^{-1})		Oxygen saturation (OS) (%)	
	d	p-r	d	p-r	d	p-r	d	p-r	d	p-r	d	p-r
PL	20	20-30	18.2-23.1	14-15.7	728-911	316-720	5-10.8	6.7-7.4	0.5-0.8	0.1-1	5.6-8.9	1-10.9
Ixt	40-50	50-60	18.4-21.9	16.5-19.2	443-750	450-917	6-9.2	7.1-8.5	1.4-7.9	0.4-5.7	15.6-88	18-47.5
Tl	40-60	50-60	17.9-20.9	14.9-17.1	423-883	153-467	6.8-7.9	7-7.4	2-2.2	2-4.8	23.2-64.5	28.2-52
Tz	100-150	142-200	18.4-19	15-17.6	396-683	137-431	7-8	6.8-7.7	5.4-8.4	5.6-8	67-91.3	69-93.5
P	150	200	16-18.9	16-17.5	352-780	232-756	7-8.1	7.2-7.6	6.5-8.9	6-6.9	86-95.6	80-90
Ps	20-30	30-40	24-24.1	23.9-24.5	254-262	244-527	6-8	7-7.8	5.8-6.5	4.8-9.4	66-78.6	55.5-102
Ch	130-140	150	17.5-18.9	17.7-19	275-613	117-570	6.9-7.9	6.9-8.6	5.2-10	4.5-5.6	58-111.5	53-64
C	10-20	30-35	20-21.3	18.1-19.4	340-395	157-568	6.7-7.9	6.7-8.2	3-7.5	3.6-5	35-67.5	43.5-54.5
U	40-60	50-70	21.4-23.3	18.3-19.3	526-691	344-487	7	6.9-7.6	3-4.8	2.4-4	35.5-45.5	29-45
Range	10-150	20-220	16-24.1	14-24.5	254-911	117-917	5-10.8	6.7-8.6	0.5-10	1-9.4	5.6-111.5	17-102
($\chi\pm\sigma$)	(67±51)	(89±68)	(20.3±2.2)	(18±3)	(537±201)	(401±196)	(7.3±1)	(7.4±0.5)	(5±3)	(4.4±2.3)	(57±30)	(55±25)

B	Salinity (ppt)	pH	tH Tot. hardness (mg L^{-1})	HCO_3 (mg L^{-1})	Si-SiO_2 (mg L^{-1})	P-PO_4 (mg L^{-1})	N-NO_3 (mg L^{-1})	N-NO_2 (mg L^{-1})	DO (mg L^{-1})	OS (%)	BOD_5 (mg L^{-1})	COD Chemical Oxigen Demand (mg L^{-1})
PL	0.3	6.8	150	71	36	3.9	3.1	0.09	0.1	21.5	61	75
Ixt	0.1	8.5	154	81	39	3.8	4.1	0.01	5.7	70	41	75
Tl	0.2	7.4	122	61	38	2.7	4.5	0.01	2	28	15	37
Tz	0	6.8	136	49	36	2.5	9.2	0.01	5.6	69	17	47
P	0	7.2	100	26	23	0.4	0.5	0.01	6.5	86	61	94
Ps	0.1	7.8	92	34	58	0	1.9	0.01	4.8	55.5	5	8
Ch	0.3	7.5	158	13	50	0.8	0.8	0.01	5.4	62	10	15
C	0.3	8.2	168	75	44	0.8	3	0.01	3.6	43.5	6	11
U	0.3	7.6	166	63	32	1	2.5	0.02	2.4	29	15	23

Water samples taken for chemical analysis were filtered through 0.45 µm membranes (Millipore type HA) and preserved at 4°C, then analyzed within 24 hours according to standardized APHA protocols. Other parameters such as salinity, turbidity, total dissolved solids, alkalinity, hardness, ammonia, nitrates, orthophosphates, chloride, silica, sodium and potassium, BOD5, and QOD concentrations were measured at a certificated laboratory (Centro de Estudios sobre el Medio Ambiente, CEMA) (Table 2).

Sample collection and processing

Duplicates of epilithon samples were collected and processed for diatom analysis following the procedures of Iserentant *et al*. (1999) modified by Israde-Alcántara *et al.* (2002). Known areas (10 cm^2) of submerged rocks were scraped with disposable toothbrushes. Diatoms were removed from the substrata by repeated washes and rinsed with distilled water; washed material was stored in plastic flasks and preserved *in situ* with 4% formaldehyde solution.

In the laboratory, samples were transferred to 250 ml glass beakers. Carbonates were removed with 30% hydrochloric acid and heated on a hot plate at 100 ºC until total digestion. In order to remove the organic material, 150 ml of 30% hydrogen peroxide was added and samples heated until evaporation and then repeatedly washed with distilled water until neutralized. When necessary, 20 mg of potassium permanganate was added to remove remaining organic matter and washed again with distilled water until neutralization of the final suspension (Iserentant *et al*. 1999). After treatment, the diatoms were mounted in Naphrax® (R. I. = 1.74). Untreated and treated samples, and permanent slides were deposited in the Diatom Collection of Earth Sciences of the Instituto de Investigaciones Metalúrgicas of the Universidad Michoacana de San Nicolás de Hidalgo.

Taxonomic identifications were based on specialized literature (Cantoral-Uriza 1997, Cox 1996, Díaz Pardo & Maidana 2005, Gasse 1980, 1986, Germain 1981, Krammer 1997, Krammer & Lange-Bertalot 1997a, b, 2004a, b, Lange-Bertalot 2001, Metzeltin & Lange-Bertalot 1998, 2002, Metzeltin & García-Rodríguez 2003, Metzeltin *et al*. 2005, Novelo-Maldonado 1998, Novelo-Maldonado *et al.* 2007, Patrick & Reimer 1966, 1975, Rumrich *et al.* 2000, Werum & Lange-Bertalot 2004). Morphometric parameters were measured on at least 20 specimens for each taxon in the same locality.

Apical and transapical axis, and striae density were measured on at least 20 specimens for each taxon in the same locality and minimum and maximum values, average and standard deviation for each parameter were estimated. Diatoms were observed with light microscopes (LM) (Reichert-Jung-Polivar and Olympus Bimax 50) equipped with Nomarski optics and digital photographic cameras (Sony Cibershot and Olympus DP12).

Weighted averaging (WA) using the program "C2" (Juggings 2003) was used to determine the optima and tolerances of the species for the most important environmental variables.

RESULTS AND DISCUSSION

The Lerma River can be considered as a subtropical water body with temperatures from 14 to 24.5°C in the post-rainy season and between 16–24.1°C during the dry season. Conductivities were characteristic of fresh waters with low to moderate mineralization (117–917 µS cm^{-1}) and pH varied from 5 to 10.8. The dissolved oxygen (OD mg L^{-1}) and oxygen saturation percent (OS%) ranged from hypoxic conditions (0.1 mg L^{-1} and 1% of saturation) in localities with industrial corridors, arrival of agrochemical sludge from cultivation fields and elevated eutrophication degree, to very well oxygenated waters (10 mg L^{-1}; and 115% OS) in sites where there are geomorphologic changes favoring the increase of current velocities. The minimum river depth occurred during the dry season (10 cm) and the maximum, in the post-rainy season (220 cm, El Pedregal) (Table 2).

Upstream sites (1-Lerma-Toluca bridge, 2-San Jerónimo Ixtapatongo, 3-San Lorenzo Tlacotepec, 4-Temazcalcingo Bridge) showed elevated pollution levels. These shallow sites had low concentrations of oxygen, low pH and low conductivities. Lerma-Toluca bridge (PL; Table 2) was the most polluted site, with both low depth and current velocity; due to the constant flux of mainly non treated industrial sewages into the river. The waters had wide intervals of pH, anoxic conditions, high temperatures and moderate to high conductivities.

Twenty one species of *Navicula s. str*. were identified, of which sixteen (76%) belong to Section *Navicula* (*N. antonii* Lange-Bertalot; *N. capitatoradiata* Germain; *N. cincta* (Ehrenberg) Ralfs in Pritchard; *N. cryptocephala* Kützing; *N. cryptotenella* Lange-Bertalot; *N. libonensis* Schoeman; *N. microcari* Lange-Bertalot; *N. perminuta* Grunow in Van Heurck; *N. recens* (Lange-Bertalot) Lange-Bertalot; *N. rhyncocephala* Kützing; *N. tripunctata* (O. F. Müller) Bory; *N. trivialis* Lange-Bertalot; *N. upsaliensis* (Grunow) Peragallo; *N. veneta* Kützing; *N. vilaplanii* Lange-Bertalot & Sabater; *N. wildii* Lange-Bertalot) and the remaining five belong to Section *Alinea* (*N. erifuga* Lange-Bertalot; *N. germainii*; *N. riediana* Lange-Bertalot & Rumrich; *N. rostellata* Kützing; *N. simulata* Manguin).

Navicula antonii (sampling sites 1, 2, 3, 5, 6); *N. capitatoradiata* (2, 3, 4); *N. cryptocephala* (2, 7); *N. erifuga* (1, 2, 3, 4, 5, 7, 8, 9); *N. germainii* (1, 2, 6); and *N. veneta* (1, 2, 3, 4, 5, 7, 8, 9) showed the highest percentages and all of them are good indicators of heavily eutrophic waters, with a broad spectrum of conductivity tolerances. Among them, *N. antonii* is considered as a good indicator of anthropogenically affected waters (eutrophic to hypereutrophic) and *N. veneta* is very tolerant to polysaprobic conditions dominant in industrially polluted water (Lange-Bertalot 2001).

From the middle to the lower part of the river (from Pedregal to Uruétaro), the measured physical-chemical data and the diatom assemblages suggested a dilution of contaminants that allows for an increase of the species richness. Important to these sites was the increases in depth, pH values, and oxygen concentrations, favored by the higher current velocity (Table 2).

At Temazcalcingo Bridge, on the bank of Pedregal, the riparian forest, constituted mainly by *Taxodium mucronatum*, allowed for the development of sciophylous diatoms. This section of the river has mineralized waters, greater slopes, and turbulent flux generated by geomorphic changes, which somewhat aided in self-purifying the system and increasing Oxygen Demand (OD). The species found in Pedregal were *N. antonii, N. cryptotenella*, *N. germainii*, *N. microcari*, *N. recens*, *N. riediana*, *N. tripunctata* and *N. wildii*, which indicate oligotrophic to eutrophic waters with average electrolyte content (Lange-Bertalot 2001).

The spring at Pedregal (site 6) showed no evident human impact and was situated on the riverbank. It had higher silica concentrations because the water flowed through a regional aquifer where it leached acidic pyroclastic rocks. Water temperatures were high and conductivity values were low, OD values were the lowest recorded for the upper Lerma Basin. This sampling zone had oligotrophic to mesotrophic waters. The most characteristic species were: *N. cryptotenella, N. recens*, and *N. simulata.*

Chamácuaro (site 7), has also a riparian forest and is characterized by slightly acid to alkaline waters with the maximum registered dissolved oxygen value (10 mg L^{1}), resulting from an extensive rapids zone. The farming activities in the area caused high nitrate concentrations, allowing the development of species like *N. erifuga, N. rostellata, N. simulata*, and *N. cryptocephala*.

Capulín (site 8) and Uruétaro (site 9) have low oxygen content, depth, and conductivities and there is a tendency for increased hardness (Si, Ca and Mg) due to leaching from mafic plagioclases found in the surrounded volcanic rocks. The agricultural activity and the residual waters from villages enhanced the eutrophic conditions in the area. The most abundant species of these localities were *N. antonii, N. veneta, N. erifuga, N. recens* and *N. rostellata*.

Some interesting species for the area

Twenty-one species of *Navicula sensu stricto* were found in the Upper Lerma basin, of which sixteen have not been previously reportedly found in México (Table 3). The species' optima and range of tolerance to environmental factors are resumed in Table 3.

Navicula antonii Lange-Bertalot *in* Rumrich *et al.* (Figs 27, 28, 32, 33)

In the Upper Lerma it was found in waters with low dissolved oxygen concentrations, high organic pollution derived mainly from industrial and farming activities; alkaline, electrolyte-rich waters; indifferent to current velocity; sciophylous. These conditions are similar to that reported by Lange-Bertalot (2001).

Navicula capitatoradiata Germain (Figs 2, 3, 4, 14)

In the Lerma basin, this species was found in alkaline, highly contaminated, low oxygenates waters with high mineral content. Rheophyl, sciophylous. These conditions were also reported by Cantoral-Uriza (1997) for other basins in México.

Navicula cincta (Ehrenberg) Ralfs in Pritchard 1861 (Fig. 37)

This species behaved as tolerant to minimal oxygen concentrations and high levels of contamination in alkaline to slightly acidic waters with low to moderate conductivities, in agreement to that mentioned by Lange-Bertalot (2001) and Cox (1996). New record for México.

Navicula cryptocephala Kützing (Figs 43, 49–51)

Species found in a wide range of environmental conditions, as stated for other areas in México by Cantoral-Uriza (1997), Novelo-Maldonado (1998), and Ramírez *et al*. (2001). Tolerant to very low oxygen concentrations and to severe pollution by organic matter and agrochemicals, in neutral waters with low content of electrolytes. Rheophyl in rapids.

Navicula cryptotenella Lange-Bertalot (Figs 10–13)

Species found in conditions of severe pollution. Has been reported from similar conditions in other states of México (Cantoral-Uriza 1997) and Central Europe (Cox 1996, Lange-Bertalot 2001). In agreement with its tolerance range, found in waters with low to medium oxygenation, slightly acid to alkaline and medium conductivity. According to our observations, it is sciophylous and indifferent to current velocity.

Navicula erifuga Lange-Bertalot (Figs 29, 30, 35, 36)

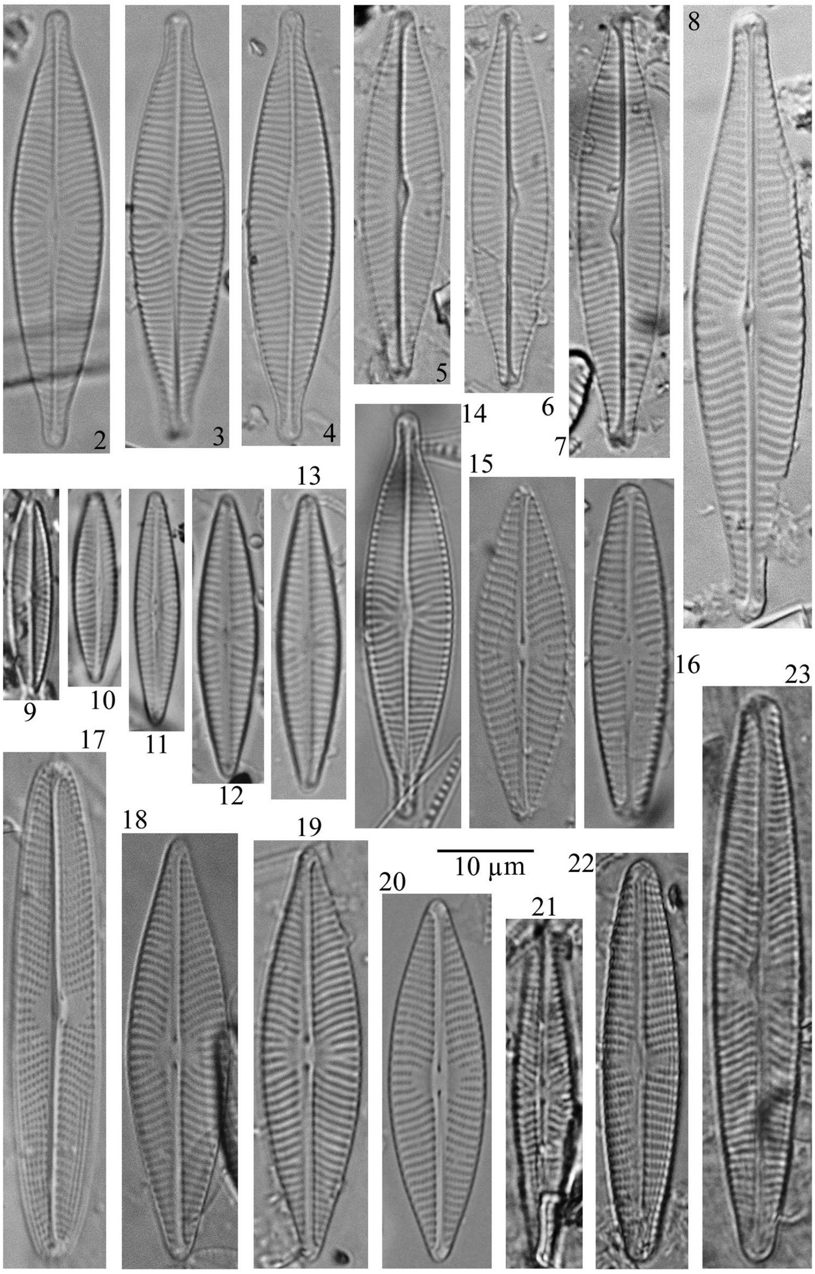
Species found in an ample range of oxygenation and pollution conditions similar to those mentioned by Lange-Bertalot (2001), i.e., waters with high content of organic matter, industrial and agricultural discharges, neutral to alkaline and low conductivity. Rheophyl and sciophylous.

Navicula germainii Wallace (Figs 5–7)

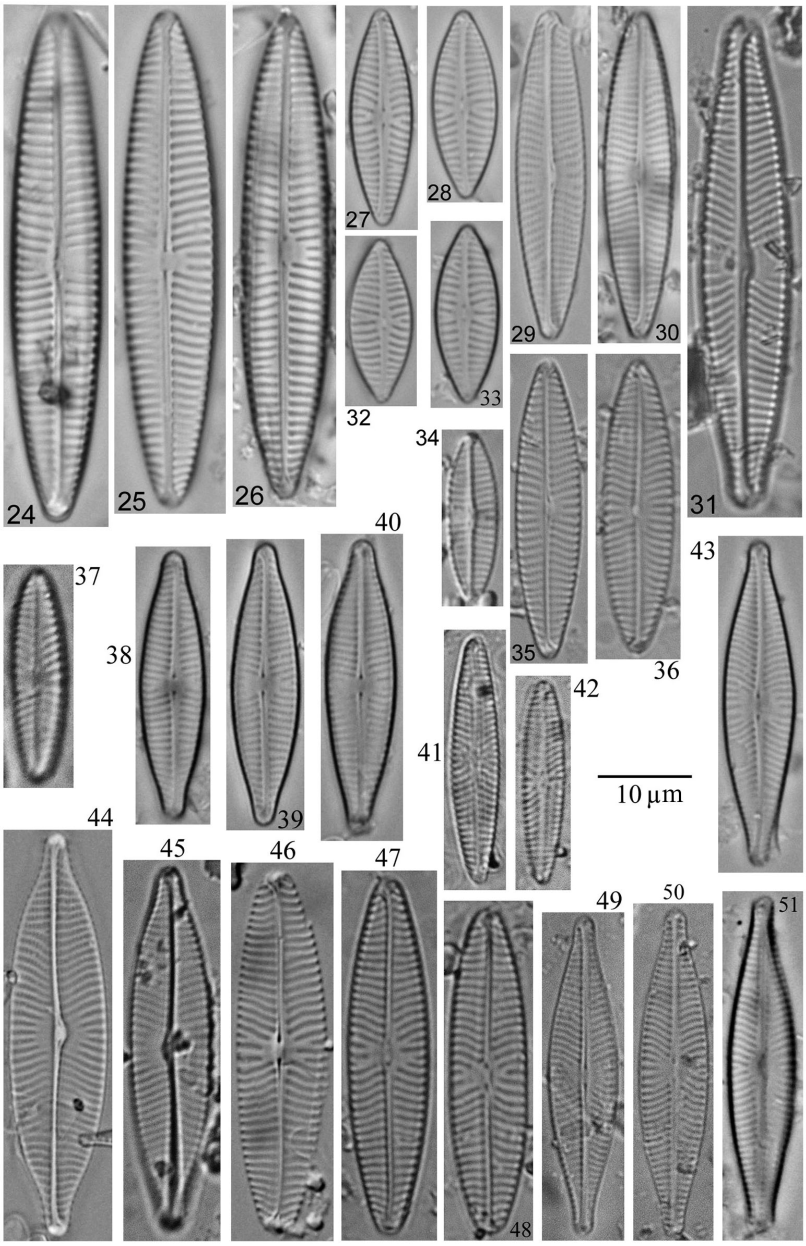
A species that could be considered to be tolerant to water with low oxygenation and high pollution; neutral to alkaline water with low conductivities, similar conditions to those reported for the species in Central Europe (Lange-Bertalot 2001). New record for México**.**

Navicula libonensis Schoeman (Figs 16, 22)

Lange-Bertalot (2001) assigns this species to eutrophic waters with critical levels of pollution, conditions that agree with those recorded in the Upper Lerma. Considered as adapted to severe pollution and medium to low oxygen concentration; slightly acid to neutral waters with low to medium conductivity. Rheophyl. New record for México.



Figs 2–23. LM: ×1500. **Scale:** 10 µm. **Figs 2, 3, 13.** *Navicula capitatoradiata* Germain, Tlacotepec. **Figs 4–6.** *Navicula germainii* Wallace, Ixtapatongo. **Fig. 7.** *Navicula rhyncocephala* Kützing, Lerma–Toluca Bridge. **Fig. 8.** *Navicula vilaplanii* (Lange-Bertalot & Sabater) Lange-Bertalot & Sabater, Ixtapatongo. **Figs 9–12.** *Navicula cryptotenella* Lange-Bertalot, Pedregal. **Fig. 14.** *Navicula upsaliensis* (Grunow) Peragallo, Chamácuaro. **Figs 15, 21.** *Navicula libonensis* Schoeman. 15: Chamácuaro; 21: Ixtapatongo. **Fig. 16.** *Navicula simulata* Manguin, Pedregal. **Figs 17–19.** *Navicula trivialis* Lange-Bertalot. 17. Tlacotepec; 18: Uruétaro; 19: Ixtapatongo. **Fig. 20.** *Navicula wildii* Lange-Bertalot, Pedregal. **Fig. 22.** *Navicula riediana* Lange-Bertalot & Rumrich, Pedregal. **Fig. 23.** *Navicula tripunctata* (O. F. Müller) Bory, Pedregal.



Figs 24–51. LM: ×1500. Scale: 10 μm. **Figs 24, 25.** *Navicula tripunctata* (O. F. Müller) Bory. 24: Pedregal; 25: Lerma–Toluca bridge. **Figs 26, 27, 31, 32.** *Navicula antonii* Lange-Bertalot in Rumrich *et al*. 26: Capulín; 27, 31: Uruétaro; 32: Pedregal. **Figs 28, 29, 34, 35.** *Navicula erifuga* Lange-Bertalot. 28: Chamácuaro; 29: Ixtapatongo; 34: Tlacotepec; 35: Uruétaro. **Fig. 30.** *Navicula riediana* Lange-Bertalot & Rumrich, Ixtapatongo. **Fig. 33.** *Navicula perminuta* Grunow in Van Heurck, Temazcalcingo. **Fig. 36.** *Navicula cincta* (Ehrenberg) Ralfs *in* Pritchard, Lerma–Toluca bridge. **Figs 37–39.** *Navicula veneta* Kützing. 37: Chamácuaro; 38: Tlacotepec; 39: Temazcalcingo. **Figs 40, 41.** *Navicula microcari* Lange-Bertalot. 40: Pedregal spring; 41: Uruétaro. **Figs 42, 48–50.** *Navicula cryptocephala* Kützing, Ixtapatongo. **Figs 43, 44.** *Navicula rostellata* Kützing, Pedregal. **Figs 45–47.** *Navicula recens* (Lange-Bertalot) Lange-Bertalot, Uruétaro.

Table 3. Morphometric characteristics of *Navicula* spp. and their optima and tolerances in the Upper Lerma River.

Species	Identifying Reference	Length (μm)	Breadth (μm)	L/B ratio	Striae/10μm	Sample sites	Depth (cm)	Temperature (°C)	Conductivity (μS cm^{-1})	Dissolved Oxygen (mgL^{-1})	Oxygen Saturation (%)
N. antonii	Rumrich *et al.* (2000)	(12.8)13.7-28.1 (20.7±3.5)	(4.6) 5.6-7.6 (6.1±0.6)	2.4-4.3 (3.4±0.5)	11-15.1 (16) (13.4±1.4)	1, 2, 3, 5, 6	126.8±86.0	17.5±3.0	441.5±132.0	6.9±2.0	75.8±19.1
N. capitatoradiata	L.-Bertalot (2001)	30.7-39.8 (36.1±2.2)	7.1-8 (7.37±0.3)	4.6-5.2 (5±5.2)	13-14.4 (13.6±0.5)	2, 3, 4	88.1±73.5	18.0±2.7	421.0±186.6	5±1.8	17.3±19.1
N. cincta	L.-Bertalot (2001)	19	5	3.8	11	1 (very rare)	25±51.0	18.7±3.1	518.0±126.5	0.5±2.0	87.8±19.1
N. cryptocephala	L.-Bertalot (2001)	26-30 (29±2)	6-6.6 (6.3±0.4)	4.5-4.6 (4.5±0.5)	14.4-17 (16±1.3)	2, 7	112.9±43.2	20.0±2.0	440.9±129.7	6±2.1	27.0±16.7
N. cryptotenella	L.-Bertalot (2001)	17.5-35.3 (25.3±4.2)	4.9–7 (5.5±0.6)	3.5-5.2 (4.6±0.5)	12-15.7 (13.9±0.9)	4, 5, 7, 9	53.6±87.4	19.6±2.0	455.3±52.3	6±1.2	62.1±26.4
N. erifuga	L.-Bertalot (2001)	25-35 (29.1 ± 3)	5.5-7 (6.2 ± 0.5)	4-5.4 (6 ± 0.4)	12-15 (13.4 ± 0.9)	1,2,3,4,5,7,8,9	41.9±37.6	17.6±2.2	435.8±158.0	4.3±1.2	55.8±20.8
N. germainii	L.-Bertalot (2001)	(24.4) 26-37.9 (34.1±3)	(5.4) 6.2-8 (7.2±0.6)	3.8-5.4 (4.7±0.3)	(12.8) 13.7-15 (16) (14.2±0.9)	1, 2, 6	44.5±18.9	17.0±1.7	585.8±83.6	2.5±2.0	65.0±17.1
N. libonensis	L.-Bertalot (2001)	29.2-34.7 (31.8±2.3)	6-6.7 (6.4±0.3)	4.5-5.2 (4.9±0.3)	11.8-12.9 (12.4±0.6)	2, 3, 7	69.1±32.3	17.0±1.7	403.0±158.6	3.7±1.1	45.8±10.3
N. microcari	L.-Bertalot (2001)	17.9-23.1 (20±2.8)	3.7-4.5 (4±0.4)	4.4-5.2 (4.9±0.4)	15-15.7 (15.3±0.4)	6, 7, 9	97.4±48.3	17.0±2.3	387.0±34.0	5.7±2.0	37.4±17.6
N. perminuta	L.-Bertalot (2001)	15	4	3.8	16	4 (very rare)	116.7±51.0	20.0±2.4	553.3±126.5	6.5±2.0	62.4±19.8
N. phyllepta	L.-Bertalot (2001)	26.7-30.3 (28±2)	6.6-8.6 (7.3±1.1)	3.5-4 (4±0.3)	17.2-18.9 (18±0.7)	1, 2	33.4±20.0	16.3±2.0	548.4±72.1	1.3±2.0	33.5±22.3
N. recens	L.-Bertalot (2001)	21.1-36.5 (30.1±4.7)	6.4-9 (7.4±0.6)	2.9-4.9 (4±0.6)	11-13.3 (12±0.8)	1, 2, 5, 6, 9	62.4±39.1	20.0±1.5	516±143.6	4.0±2.0	50.0±19.7
N. rhyncocephala	L.-Bertalot (2001)	51.3	9.3	5.5	10.6	1 (very rare)	20.0±51.0	17.4±2.4	740.0±126.5	0.7±2.0	38.2±15.3
N. riediana	L.-Bertalot (2001) Metzeltin *et al.* (2005)	36.6-56.1 (45.6±4.4)	6.5-8.7 (8±0.5)	5-6.9 (6±0.4)	10-11.9 (11.2±0.5)	1,2,3,5,6,7,8,9	60.5±62.3	18.1±0.4	458.4±106.0	3.4±2.7	42.7±21.4
N. rostellata	L.-Bertalot (2001)	34-42.5 (37.8±2.3)	7.5-9.8 (8.9±0.7)	3.8-4.4 (4.2±0.25)	12-14.6 (13.3±0.7)	1, 2, 3, 8, 9	39.8±15.8	17.0±1.1	504.4±138.8	2.7±1.8	32.5±13.7
N. simulata	L.-Bertalot (2001)	(28.8) 30.4-45.6 (35.8±4.1)	6-8.1 (6.6±0.5)	4.5-6.3 (5.4±0.4)	11-13.5 (13±0.5)	1,2,3,4,5,6,7,9	89.8±67.8	15.8±1.8	475.5±133.4	4.2±2.1	67.4±18.0
N. tripunctata	L.-Bertalot (2001)	47	8	5.9	10	2, 4 (rare)	117±90.0	17.0±1.1	463.5±221.3	5.0±2.5	49.3±21.6
N. trivialis	L.-Bertalot (2001)	32.6-45.5 (39±4.3)	8.6-9.7 (9±0.4)	3.5-4.66 (4.3±0.4)	11.6-13.3 (12.4±0.6)	1, 2, 3, 9	40.0±17.2	17.6±2.0	576.7±137.7	2.1±1.5	76.2±22.7
N. upsaliensis	L.-Bertalot (2001)	29.9-44.8 (36.6±5)	(7.8-8.8) 10.5-11.8 (9.5±1.4)	3.6-4.1 (3.9±0.1)	9 (12-13.9) (11±2)	1, 2, 3, 7	45.2±41.0	15.0±2.0	547.6±86.7	2.1±2.7	45.0±25.5
N. veneta	L.-Bertalot (2001)	14.4-30.1 (21.3±3.3)	4.8-6.4 (5.6±0.4)	2.5-5.6 (4±0.6)	(13) 13.5-15.4 (14.3±0.7)	1,2,3,4,5,7,8,9	62.3±52.4	19.0±2.0	521.5±133.9	4.7±1.8	53.3±23.8
N. vilaplanii	L.-Bertalot (2001)	17-17.9 (17.4±0.5)	3.6-6.1 (4±0.9)	3-4.9 (4±0.8)	17.1-18.4 (17.7±0.6)	2, 5, 8	62.0±70.7	20.4±2.0	561.1±148.6	3.8±1.7	51.7±12.4
N. wildii	L.-Bertalot (1993; 2001)	31	5.5	5.7	12.4	5 (very rare)	206.7±51.0	16.8±2.0	419.3±126.5	6.5±1.9	54.3±17.5

Navicula microcari Lange-Bertalot (Figs 41, 42)

Reported by Lange-Bertalot (2001) only for Israel, Canary Islands (Spain) and Wisconsin (USA). In our study, the species showed tolerance to high pollution by organic matter and industrial and agrochemical spillage; low to medium dissolved oxygen concentration; weakly acid to neutral waters. Indifferent to current velocity, sciophylous. New record for México.

Navicula perminuta Grunow in Van Heurck (Fig. 34)

Found only in highly oxygenated waters and severe industrial, agricultural and pottery pollution; neutral waters with low conductivity. Rheophyl. Lange-Bertalot (2001) mentions this species as inhabiting riverbanks. New record for México.

Navicula recens (Lange-Bertalot) Lange-Bertalot (Figs 46–48)

In the Upper Lerma, found to be tolerant to minimal levels of dissolved oxygen and high levels of organic, industrial and agricultural pollution; slightly acid to neutral waters; middle content of electrolytes; indifferent to current velocity; sciophylous. Reported for eutrophic rivers in Central Europe, Palestine and Jamaica (Lange-Bertalot 2001, Ehrlich 1995), in brackish waters with high electrolyte content. New record for México.

Navicula rhynchocephala Kützing (Fig. 8)

This species was found agree with similar characteristics of those reported by Lange-Bertalot (2001) and Cox (1996). Based wher it was found, it may be considered as tolerant to minimal concentrations of oxygen and to severe pollution; in acid, stagnant waters with low to moderate conductivity.

Navicula riediana Lange-Bertalot & Rumrich (Figs 23, 31)

Found in the Upper Lerma in a wide range of oxygen concentration, high pollution from agrochemical, industrial and pottery discharges; weakly acid to alkaline waters; low to medium conductivity; indifferent to current velocity; may be sciophylous.

Observations: In the Upper Lerma, the valve breadth is wider than those mentioned in the consulted literature. Metzeltin *et al*. (2005) found it in Uruguay with some valves wider (8–8.7 µm) than the European material (usually <8 µm, Lange-Bertalot 2001). The former authors related this difference due to high conductivities (500–1000 µS cm^{-1}) but this was not the case for the samples where *N. riediana* was present, as conductivities varied from low to moderate (232–581 µS cm^{-1}). New record for México.

Navicula rostellata Kützing (Figs 44, 45)

In the Upper Lerma seems to be adapted to several concentration levels of dissolved oxygen; high pollution; acid to neutral waters. May be sciophylous. Tolerance to high levels of pollution which agrees with a previous observation (Lange-Bertalot 2001).

Observations: Although Lange-Bertalot (2001) mentions *N. rostellata* co-occurring with *N. viridula*, this was no observed in the Upper Lerma basin.

Navicula simulata Manguin (Fig. 17)

This species showed a wide tolerance for very low oxygenation levels and severe pollution, an adaptability also mentioned by Van de Vijver and Lange-Bertalot (2009). In slightly acid to alkaline waters with low to medium conductivity, this differs from previous authors who reported it from brackish or electrolyte rich waters. No preference for current velocity was observed. Sciophylous.

Observations: The specimens agreed in almost all respects with the emended diagnosis of Van de Vijver and Lange-Bertalot (2009), however some of the valves were bigger (> 45.6 µm length, 6 to 8.1 µm breadth) with slightly denser areolae: 28.5.–32 (30± 1.4), instead 24 to 28/10 µm.

Navicula tripunctata (O. F. Müller) Bory (Figs 24–26)

This species is a good indicator of eutrophic waters (Ehrlich 1995, Cox 1996, Lange-Bertalot 2001), a condition that is present in the Upper Lerma. Seemingly, it has little tolerant to very low dissolved oxygen concentration. In weakly acid to neutral waters with medium ionic concentration. Ehrlich (1995), Cox (1996) and Lange-Bertalot (2001) report it for electrolyte rich waters. Observed as rheophyl and sciophylous.

Navicula trivialis Lange-Bertalot (Figs 18–20)

The species showed tolerance to low concentration of oxygen and severe pollution from wastewaters and industrial discharges, as stated by Cox (1996) and Lange-Bertalot (2001). In acid to alkaline waters; low to medium conductivity, nevertheless Cox (1996) and Lange-Bertalot (2001) report it from electrolyte rich or brackish waters. Indifferent to current velocity. New record for México.

Navicula upsaliensis (Grunow) Peragallo (Fig. 15)

This species was found to be tolerant to low oxygen concentrations and to severe pollution; in acid to neutral waters with low content of electrolytes. Lange-Bertalot (2001) reports it from alkaline waters with high electrolyte content or in estuarine rivers.
New record for México.

Navicula veneta Kützing 1844 (Figs 38–40)

Present in all sampling sites with severe pollution, mainly of industrial origin, and wide oxygenation range, which agrees with observations of Cox (1996) and Lange-Bertalot (2001), although they report the species having higher ionic concentrations than those registered here. Indifferent to current velocity.

Observations: The valve morphological and morphometrical features found fit the description of *Navicula veneta* given in Lange-Bertalot (2001) (length: 14.4–30.1 (21.3±3.3) µm; breadth: 4.8–6.4 (5.6±0.4) µm; length/breath ratio: 2.5–5.6 (4±0.6) µm; striae: (13)13.5–15.4 (14.3±0.7) in 10 µm; lineolae not discernible with LM. However, *Navicula wendlingii* Lange-Bertalot *et al*., a species recently described for Europe by Van de Vijver & Lange Bertalot (2009), has valves relatively similar to *N. veneta* but they are broader (6.0–7.0 µm), with a narrower range of variation of the length (21.7–30 µm) and the lineolae are discernible with LM (27–30 en 10 µm).

Navicula vilaplanii Lange-Bertalot & Sabater (Fig. 9)

This species occurred in eutrophic water which agrees with Lange-Bertalot (2001) observation, however, he found it in high conductivity waters while it occurred here in low to medium concentration.. Tolerant to low oxygen concentration; in neutral waters and indifferent to current velocity. New record for México.

Navicula wildii Lange-Bertalot (Fig. 21)

This species was found at a site having high concentration of oxygen, in neutral waters with low conductivity; rheophyl and sciophylous. Lange-Bertalot (2001) mentions it is a good indicator of unpolluted waters, as was observed here. New record for México.

DISCUSSION

Although *Navicula* (Bory) *s. str*. was not represented by a great number of individuals during the study period, the genus did have high species richness. Up to now only few floristic or taxonomic studies of Mexican river diatom communities have been published however the high morphological variability exhibited by *Navicula* spp was not reported and, frequently, only one or two valves were illustrated. The morphological and morphometric variations found in the Lerma River could be interpreted as adaptations to a highly polluted system, thus pointing out to the importance of having the widest possible survey of the variability of these taxa as part of biomonitoring programs.

Unlike classic freshwater hydrosystems, which show upstream to downstream gradients of eutrophication; the Lerma River has high levels of pollutants from its upper section, immediately downstream from the springs. This feature is due to the activities of a high number of industries (Hansen & Van Afferden 2001) and growing urban developments without wastewaters treatment, which directly influenced the algal assemblages. However, nutrients and ionic concentrations did not increase downstream as occurs in other polluted rivers (Doung *et al*. 2006).

The low densities of *Navicula* species in the Lerma River have also been reported by other authors for other lotic environments influenced by industrial and urban activities around the world (Ehrlich 1995, Ndiritu *et al.* 2006, Krammer & Lange-Bertalot 1997 a,b, 2004a,b, Lange-Bertalot 2001, Patrick & Reimer 1966).

The presence of *N. antonii, N. capitatoradiata*, *N. cryptocephala, N. erifuga, N. germainii*, *N. rostellata*, *N. simulata*, and *N. veneta* associated to *Eolimna subminuscula* (Manguin) Moser *et al*., *Nitzschia capitellata* Hustedt in A. Schmidt *et al., N. amphibia* Grunow*, N. umbonata* (Ehrenberg) Lange-Bertalot, *N. palea* (Kützing) W. Smith*, Gomphonema parvulum* (Kützing) Kützing*, G. lagenula* Kützing, and *G. saprophilum* (Lange-Bertalot & Reichardt) confirm their tolerance to α-mesosaprobic to polysaprobic conditions, and to high nitrogen content (Germain 1981, Lobo *et al*. 1995, Cox 1996, Novelo-Maldonado 1998, Cantoral-Uriza 1997, Krammer and Lange-Bertalot 2007a,b, 2004a,b, Lange-Bertalot 2001, Martínez de Fabricius *et al*. 2003, Szczepocka & Szulc 2006, Dere *et al*. 2006, Ndiritu *et al.* 2006, Novelo-Maldonado *et al.* 2007). Most of these authors have mentioned *that* Navicula species along with other identified species also tolerated high electrolyte contents, a situation that was not been found in the Larma River.

It is important to mention that the strong variations in the riverine slope promoted higher oxygenation in the water that favors the self-depuration, improving the trophic quality of the river; other researchers usually do not report on this parameter, nevertheless, in the present study it seems to be a determinant in the observed species assemblage variations.

WA analysis reveals that for most of the species, their tolerances exceeded the intervals of variation for the physicochemical variables (dissolved oxygen, QOD, pH, etc.) as measured in the Upper Lerma, indicating that species seemed to be well adapted to the environmental conditions.

CONCLUSIONS

Ample morphometric diversity was observed in some species, as in the case of *Navicula capitatoradiata*, *N. riediana* and *N. veneta*. The observed variations in the morphology and morphometry (striae density, frustule length and valve outline) can be related to intense pollution in the area, but it is evident that a deeper analysis of the variability of the populations is needed.

As revealed by the WA analysis, *N. erifuga* seems to be more sensitive to organic pollution while *N. antonii* shows the highest tolerance to all the variables.

More tropical and subtropical studies are required for México to establish the tolerance intervals for most of the diatom species and would be very useful in understanding the consequences of human population growthe and urbanization on Mexican lotic systems and to establish measures for mitigation of river pollution in underdeveloped countries with minimal wastewater discharge controls and monitoring programs.

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