Epilithic diatoms (Bacillariophyceae) as indicators of water quality in the Upper Lerma River, Mexico

Diatomeas epilíticas como indicadores de la calidad del agua en la cuenca alta del río Lerma, México

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ABSTRACT

The upper Lerma River is the most economically important basin of Mexico because it is the region where 80 % of the commercial activity of the country takes place, with 3500 industries, 750,000 Ha of irrigated land and 14 cities with populations over 100,000 inhabitants. Despite this relevance, little or no waste water treatment is done in the basin, which results in high contamination levels. The present paper deals with the taxonomy and ecology of epilithic diatoms collected at 11 sites in the basin in the dry and post-rainy seasons of the 2003-2005 period. This is the first study in an environmental direction of the diatoms of the upper Lerma River basin and the information generated will be used to propose, in the short-term, a Lerma River diatom index (IDL), supporting water quality monitoring programs. 178 taxa were recognized, of which 112 taxa (63%) were cosmopolitan or widely distributed. The genera with most species were *Nitzschia* (34), *Navicula* (19), *Gomphonema* (15), and *Pinnularia* (11). The dominant species in the studied locations and study period were *Eolimna subminuscula* (Manguin) Moser, Lange-Bertalot *et* Metzeltin, *Gomphonema parvulum* (Kützing) Kützing, *Navicula veneta* Kützing, *Nitzschia capitellata* Hustedt, *N. sublinearis* Hustedt, *N. umbonata* (Ehrenberg) Lange-Bertalot and *Sellaphora pupula* (Kützing) Mereschkowsky, which are characterized as tolerant to α-mesosaprobic to polysaprobic conditions, and to high nitrogen content. Trends in distribution of diatom species in the sampling sites were explained by variations in environmental parameters such as depth, conductivity, pH, temperature, and total dissolved solids.

Key words: Diatoms, Bacillariophyta, Lerma River, environmental quality, Mexico.

RESUMEN

La cuenca alta del río Lerma es la más importante de México desde el punto de vista económico, ya que en ella ocurren el 80 % de las actividades comerciales del país, con 3500 industrias diversas, 750,000 hectáreas de tierras de riego y 14 ciudades con poblaciones de más de 100,000 habitantes. El escaso o nulo tratamiento de las aguas residuales, trae como consecuencia una elevada contaminación. Este trabajo abordó el estudio taxonómico y ecológico de diatomeas epilíticas colectadas en 11 localidades de ésta cuenca, entre los años 2003-2005. Se trata del primer estudio con una orientación ambiental que se realiza sobre diatomeas de la cuenca alta de este río, y la información generada permitirá proponer en el corto plazo un índice diatomológico para el Río Lerma (IDL), que posibilite emprender programas de monitoreo de la calidad del agua. Se reconocieron 178 especies, de las cuales 112 taxones (63 %) fueron de amplia distribución. Los géneros con mayor número de especies fueron *Nitzschia* (34), *Navicula* (19), *Gomphonema* (15) y *Pinnularia* (11). Las especies dominantes en las localidades de estudio y en las épocas de recolecta fueron *Eolimna subminuscula* (Manguin) Moser, Lange-Bertalot *et* Metzeltin, *Gomphonema parvulum* (Kützing) Kützing, *Navicula veneta* Kützing, *Nitzschia capitellata* Hustedt, *N. sublinearis* Hustedt, *N. umbonata* (Ehrenberg) Lange-Bertalot y *Sellaphora pupula* (Kützing) Mereschkowsky, que se caracterizan por ser tolerantes a condiciones α-mesosapróbicas a polisapróbicas con alto contenido de nitrógeno. La distribución de las especies de diatomeas fueron explicadas por las variaciones en parámetros como profundidad, conductividad, pH, temperatura y sólidos disueltos totales.

Palabras clave: Diatomeas, Bacillariophyta, Río Lerma, calidad ambiental, México.

INTRODUCTION

The research about algae in Mexico considering the diatoms in lotic environments has emphasized floristic aspects (Cantoral & Montejano, 1993; Cantoral *et al*., 1997; Valadez-Cruz *et al*., 1996; Ramírez *et al*., 2001; Novelo *et al*., 2007), taxonomy (Cantoral, 1997; Oliva *et al*., 2006, 2008; Segura-García *et al*., 2010), geographical distribution (Ramírez & Cantoral, 2003) and ecological topics, as well as their use as biological indicators (Bojorge & Cantoral-Uriza, 2007; Cantoral-Uriza & Mora, 2012; in press).

The Lerma-Chapala basin has had a remarkable economical growth and generates many products for the country. Furthermore, 80% of the national commercial activity takes place in the basin (Mestre-Rodríguez, 1997) in which 3500 diverse industries, 750,000 Ha of irrigated fields, and 14 cities with more than 100,000 inhabitants are located. All this makes it the more densely populated region in the country with over 9'000,000 inhabitants (INEGI, 1983; INE, 2003).

These agricultural, industrial, and urban activities taking place without adequate and integrated water management converted the Lerma River into one of the most polluted of Mexico, causing negative effects that have not been completely quantified such as the disappearance of flora and fauna in some regions (Medina-Nava, 2003).

Due to the importance of the basin both as a center of species origin and diversification (Díaz-Pardo *et al.,* 1993; Moncayo *et al*., 2001), and as a site of abundant natural resources, it is a priority to propose methods for identifying bioindicator organisms that could reflect the prevailing environmental conditions, enable their monitoring, and allow for the evaluation of water quality; all of which would facilitate ecosystem management decision making.

The present study provides information to increase the knowledge of diatoms in the region, together with a proposal of their use in future monitoring programs.

MATERIALS AND METHODS

Study area. The Lerma-Chapala Basin, located in central Mexico between 19° 03' to 21° 34' N and 99° 16' to 103° 31' W, has an area of 53,591 Km^2 from the Lerma River headwaters in the Nevado de Toluca at 4600 m a.s.l. to its mouth in the Chapala Lake at 1600 m a.s.l., and covers territory from five states (State of México, Guanajuato, Querétaro, Michoacán and Jalisco; Cotler *et al.,* 2004; Cotler *et al*., 2006).

The present research focused on the upper Lerma River sub-basin (19° 37' 30" to 20° 08' 32" N and 100° 35' 43" W) located in the Trans Mexican Volcanic Belt that was originated by the subduction of the Pacific and Cocos Plate under the North American Plate (Israde-Alcántara, 1999; Fig. 1, Table 1). It is formed by stratovolcanoes, cineritic cones and calderas that emitted volcanic breccias, tuffs and detrictic materials that accumulated since the Neogene and throughout the Holocene.

Different types of soils are distinguished in the sub-basin, the most abundant being Luvic Feozem, Luvisol, Planosol and Andosol, while Vertisol and Litosol are less represented (SPP, 1985). The climate is temperate with average temperatures of 18 °C in the valleys and plains and of 12.5 °C in the mountains (Mil Cumbres). The annual precipitations range between 646 to 1642 mm and the vegetation types include fir (*Abies*), pine (*Pinus*) and pine-oak (*Pinus-Quercus*) forests, gallery forests (*Salix bonplandiana* Kunth, *Taxodium mucronatum* Ten.), and altered subtropical shrub (SPP, 1985).

Sample collection. Samples of water and epilithic diatoms were collected during the dry (April to June) and post-rainy (November-December) seasons of the 2003-2005 period. The chosen sampling sites were approximately 10 Km apart from each other and near populated areas, according to the criteria established by Israde-Alcántara *et al.* (2007). We considered the province division of the Lerma River proposed by Moncayo *et al.* (2001) based on the highly endemic ichthyofauna. Eight sites were sampled in the main course of the river, and three more in the tributaries.

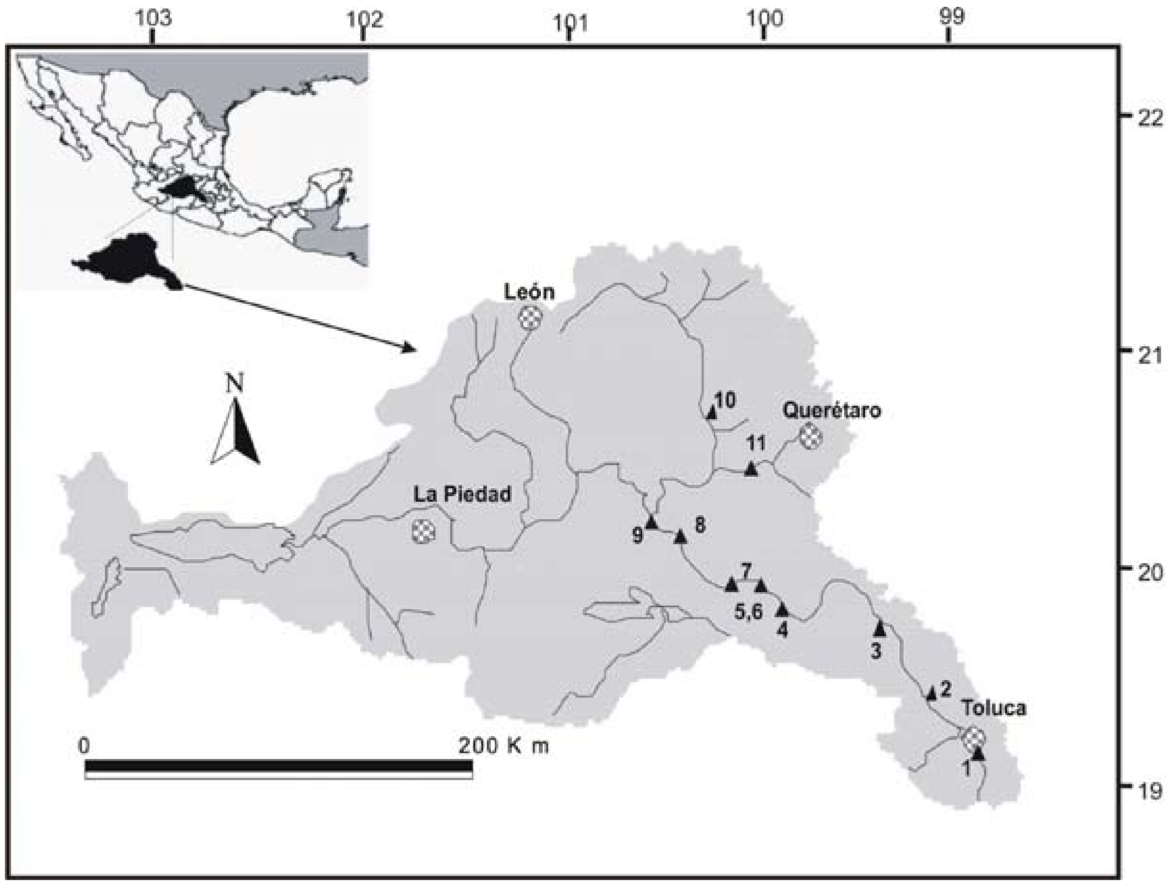

Figure 1. Location of study sites. Legend: 1- Puente Lerma-Toluca, State of Mexico; 2- Ixtapatongo, State of Mexico; 3- Tlacotepec, State of Mexico; 4- Puente Temazcalcingo, State of Mexico; 5- El Pedregal, Michoacán; 6- Manantial el Pedregal, Michoacán; 7- Chamácuaro, Guanajuato; 8- El Capulín, Guanajuato; 9- Uruétaro, Guanajuato; 10- Río la Laja, Guanajuato; 11- Río Querétaro, Querétaro.

The sampling sites were chosen taking into account the different human activities and land uses occurring in the basin, and attempting to obtain samples from sites located both upstream and downstream, and from villages or cities.

Depth was measured with an electric sounding line. Water temperature, specific conductivity (K_{25}) and pH were measured with a Conductronic (PC-18) potentiometer. Dissolved solids were recorded using a HORIBA Multiparameter meter and dissolved oxygen concentration, with a portable YSI (51-B) meter (Table 2).

Epilithic diatoms were collected according to the method proposed by Iserentant *et al.* (1999), by brushing 10 cm^2 area of submerged rocks with disposable tooth brushes. The samples were stored in plastic bottles and fixed *in situ* with 4% formaldehyde solution.

In the laboratory, carbonates were removed by addition of 30% hydrochloric acid and heating to 100 °C until total digestion in approximately 10 minutes. The remaining organic matter was removed adding hydrogen peroxide and heating until evaporation, afterwards repeatedly washing with distilled water until neutralization. In cases in which organic matter remained adhered to the frustules, 20 mg of potassium permanganate were added, and samples were subsequently washed with distilled water until neutralization (Iserentant *et al.*, 1999). Finally, samples were mounted on Naphrax® (Refraction Index = 1.74). Cleaned and uncleaned samples, and permanent slides were deposited in the Diatom Collection of Geology Department of the Instituto de Investigaciones Metalúrgicas, Universidad Michoacana de San Nicolás de Hidalgo (IIM-UMSNH), México.

Diatoms were observed with light microscopes (LMs) (Reichert-Jung-Polivar and Olympus Bimax 50) equipped with Nomarski interference optics, and digital photographic cameras (Sony Cyber-shot and Olympus DP12). Apical and transapical axis lengths, and striae density were measured on at least 20

Table 1. Location of study sites and main land uses in the Upper Lerma River sub-basin. Notes: (Md- municipal discharges, A- agricultural chemicals, I- industrial ceramics, Uc- used for cattle, L- livestock use, Lt- local tourism, A/E- affluent-effluent).

Study sites	Acronym	Location	Altitude (masl)	Anthropogenic influence
1. Puente Lerma-Toluca, Estado de México	PL	19° 16′ 45.08″ N 99° 38′ 56.13″ W	2587	Md, A, I
2. San Jerónimo Ixtapatongo, Estado de México	Ixt	19° 32′ 01.52″ N 99° 46′ 06.72″ W	2523	Md, A, I
3. San Lorenzo Tlacotepec, Estado de México	Tl	19° 48′ 56.99″ N 99° 55′ 32.01″ W	2502	Md, A, I
4. Puente Temazcalcingo, Estado de México	Tz	19° 55′ 0.21″ N 100° 01′ 09.89″ W	2347	A, I, Uc
5. El Pedregal, Michoacán	P	19° 57′ 15.12″ N 100° 17′ 05.71″ W	2357	A
6. Pedregal, Michoacán	Pm	19° 57′ 15.12″ N 100° 17′ 05.71″ W	2357	Lt
7. Chamácuaro, Guanajuato	Ch	20° 06′ 18.32″ N 100° 49′ 53.3″ W	1838	Md, A
8. El Capulín, Guanajuato	C	20° 16′ 14.6″ N 100° 59′ 02.16″ W	1729	Md, A
9. Uruétaro, Guanajuato	U	20° 16′ 14.6″ N 100° 59′ 02.61″ W	1744	Md, A, I
10. Río Laja, Guanajuato	LAJ	20° 57′ 53″ N 100° 50′ 08.41″ W	1797	A/E, Md, I, L
11. Río Querétaro, Querétaro	QRO	20° 44′ 02.05″ N 100° 33′ 20.51″ W	1731	A/E, Md, A, I, L

specimens for each species in the same locality. Minimum and maximum values, average, and standard deviation for each morphometric parameter were estimated to show the variation in populations. When necessary for taxonomic identification, the scanning electronic microscopes (SEMs) Phillips XL 30 (Museo Argentino de Ciencias Naturales, Buenos Aires, Argentina), and JEOL JSM 6400 (IIM-UMSNH) were used.

Taxonomic identifications were based on Patrick and Reimer (1966); Gasse (1980, 1986); Germain (1981); Ehrlich (1995); Cox (1996); Cantoral (1997); Krammer (1997); Krammer and Lange-Bertalot (1997a, b; 2004a, b); Metzeltin and Lange-Bertalot (1998, 2002); Novelo (1998); Rumrich *et al.* (2000); Lange-Bertalot (2001); Metzeltin and García-Rodríguez (2003); Werum and Lange-Bertalot (2004); Díaz and Maidana (2005); Metzeltin *et al.* (2005); Oliva-Martinez *et al.* (2005), and Novelo *et al.* (2007). The environmental preferences of taxa were also consulted in the above-mentioned references.

For the statistical analysis, 400 valves were counted per slide (Kelly *et al.*, 1998) in all samples for obtaining the relative abundance of taxa. To explore the relations between species and environmental variables a Canonic Correspondence Analysis (CCA) was performed considering the frequencies of the most abundant species (>3%) (CANOCO program; ter Braak, 1990). The significance of the canonical axes was tested using a Monte Carlo permutation test of samples.

RESULTS

The physicochemical characteristics of the Lerma River define it as a temperate waterbody with temperatures from 14 to 24.5 °C in the post-rainy season, and between 16-24.1 °C in the dry season. pH varies from 5 to 10.8, and the conductivity values are characteristic of freshwaters with low to moderate mineralization (117-917 µS cm^{-1}). The dissolved oxygen concentration (OD mg L^{-1}) and oxygen saturation percent (OS %) range from hypoxic conditions (0.1 mg L^{-1} and 1 OS %) in localities with industrial activity, agrochemical drainage from farming areas and high eutrophication, to very well oxygenated waters (10 mg L^{-1} and 115 OS %) in sites where geomorphological variations favor the increase of current velocity. The minimum depth was registered during the dry season (10 cm) and the maximum, in the post rainy season (220 cm, El Pedregal) (Table 2).

In the revision with LMs, 53 genera and 178 infrageneric taxa were identified, of which 112 (63%) are cosmopolitan or have wide distribution. The genera with higher number of species were

Table 2. Physicochemical variables of the study area during the dry and post-rainy seasons of the 2003-2005 period.

Sites	Acronym	Depth (cm)		Temperature (ºC)		Conductivity (μScm^{-1})		pH		Dissolved oxygen (mgL^{-1})		Oxygen saturation (%)	
		D	R	D	R	D	R	D	R	D	R	D	R
1. Puente Lerma-Toluca, Estado de México	Pl	20	20-30	18.2-23.1	14.0-15.7	728-911	316-720	5.0-10.8	6.7-7.4	0.5-0.8	0.1-1.0	5.6-8.9	1.0-10.9
2. San Jerónimo Ixtapatongo, Estado de México	Ixt	40-50	50-60	18.4-21.9	16.5-19.2	443-750	450-917	6.0-9.2	7.1-8.5	1.4-7.9	0.4-5.7	15.6-88.0	18.0-47.5
3. San Lorenzo Tlacotepec, Estado de México	Tl	40-60	50-60	17.9-20.9	14.9-17.1	423-883	153-467	6.8-7.9	7.0-7.4	2.0-2.2	2.0-4.8	23.2-64.5	28.2-52.0
4. Puente Temazcalcingo, Estado de México	Tz	100-150	142-200	18.4-19.0	15.0-17.6	396-683	137-431	7.0-8.0	6.8-7.7	5.4-8.4	5.6-8.0	67.0-91.3	69.0-93.5
5. El Pedregal, Michoacán	P	150	200	16.0-18.9	16.0-17.5	352-780	232-756	7.0-8.1	7.2-7.6	6.5-8.9	6.0-6.9	86.0-95.6	80.0-90.0
6. Pedregal, Michoacán	Pm	20-30	30-40	24.0-24.1	23.9-24.5	254-262	244-527	6.0-8.0	7.0-7.8	5.8-6.5	4.8-9.4	66.0-78.6	55.5-102.0
7. Chamácuaro, Guanajuato	Ch	130-140	150	17.5-18.9	17.7-19.0	275-613	117-570	6.9-7.9	6.9-8.6	5.2-10.0	4.5-5.6	58.0-111.5	53.0-64.0
8. El Capulín, Guanajuato	C	10-20	30-35	20.0-21.3	18.1-19.4	340-395	157-568	6.7-7.9	6.7-8.2	3.0-7.5	3.6-5.0	35.0-67.5	43.5-54.5
9. Uruétaro, Guanajuato	U	40-60	50-70	21.4-23.3	18.3-19.3	526-691	344-487	7.0	6.9-7.6	3.0-4.8	2.4-4.0	35.5-45.5	29.0-45.0
10. Río Laja, Guanajuato	LAJ	—	8	—	20.7	—	382	—	8.3	—	0.26	—	2.8
11. Río Querétaro, Querétaro	QRO	—	10	—	21.7	—	1207	—	8.0	—	0.01	—	2.1

Notes: — indicates no data; D, 2003 dry season; R, 2005 post-rainy season.

Nitzschia (34), *Navicula* (19), *Gomphonema* (15), and *Pinnularia* (11). *Cocconeis placentula* var. *euglypta*, *Eolimna subminuscula, Gomphonema parvulum, Navicula veneta, Nitzschia capitellata, N. umbonata*, *N. palea*, and *Sellaphora pupula* were present throughout the period of study (Table 3).

As show in Table 3, the rivers Laja and Querétaro were characterized by low specific richness and the abundance of few taxa, such as *Nitzschia amphibia* and *N. capitellata* in the former, and *N. capitellata* and *N. umbonata* in the latter. In Pedregal Spring a high abundance of some species characteristic of oligotrophic and highly oxygenated waters was observed, such as *Rhoicosphenia abbreviata* and *Eolimna tantula.*

The CCA for the most abundant species (>3%) showed an environment-species correlation of 50.8%, the highest percentage of the explained variation (77.1%) being due to the first two canonical axis. The first eigen values in the Monte Carlo permutation test showed highly significant relations between the species and the chosen variables (p = 0.002). These results suggest that the distribution tendencies of the more abundant species in the sampling sites may be explained by the variables included in the model: depth, conductivity, pH, temperature, and total dissolved solids (Fig. 2).

Axis 1 was negatively correlated with temperature (inter set correlation = –0.68), separating the Pedregal Spring samples. The second important variable in axis 1 was conductivity, which separated the more eutrophic sites of Puente Lerma, Ixtapatongo, Tlacotepec, El Capulín, and Uruétaro, as well as the rivers La Laja, and Querétaro. Axis 2 was positively and very strongly correlated with depth, and it separated the samples from Temazcalcingo, Pedregal, and Chamácuaro. Temporal tendencies were not evident in the analyses.

Temperature was the variable that seemed to be more related with the distribution of *Eolimna tantula*, *Nitzschia microcephala* Grunow and *Planothidium frequentissimum,* while presence of *Eolimna subminuscula, Gomphonema lagenula, G. parvulum, Navicula germainii* Wallace*, Nitzschia capitellata, N. palea, N. um-*

Table 3. Average abundance of main diatom species in study sites in the Upper Lerma River sub-basin, Mexico during the dry and post-rainy seasons of the 2003-2005 period.

Species	Species Acronym	Site										
		PL	Ixt	Tl	Tz	P	Pm	Ch	C	U	LAJ	QRO
Achnanthidium minutissimum (Kützing) Czarnecki	ACMI	0.0	0.0	0.0	1.8	0.0	12.7	0.0	0.0	0.0	0.0	0.0
Amphora copulata (Kützing) Schoeman *et* Archibald	AMCO	0.0	0.0	0.0	0.0	0.0	16.5	0.0	0.0	0.8	0.0	0.0
Amphora pediculus (Kützing) Grunow	AMPE	0.0	0.0	0.7	0.0	7.8	18.5	1.0	0.0	0.0	0.0	0.0
Amphora veneta Kützing	AMVE	3.5	0.0	0.0	0.0	1.2	11.0	1.0	0.0	0.7	59.0	0.0
Cocconeis placentula var. *euglypta* (Ehrenberg) Grunow	COPL	8.0	1.0	0.0	1.0	13.8	23.2	47.5	3.2	6.5	0.0	0.0
Eolimna subminuscula (Manguin) Moser, Lange-Bertalot *et* Metzeltin	EOSU	17.5	51.8	110.0	145.8	7.0	3.2	16.7	56.5	43.8	8.0	0.0
Eolimna tantula Hustedt	EOTA	0.0	0.0	0.0	4.0	0.0	46.3	0.0	0.0	0.0	0.0	0.0
Fistulifera saprofila (Lange-Bertalot *et* Bonik) Lange-Bertalot	FISA	0.0	8.0	0.0	0.0	0.0	0.0	1.8	1.5	2.7	0.0	0.0
Fragilaria goulardii (Brébisson) Lange-Bertalot	FRGO	0.0	0.0	0.0	0.0	1.6	0.0	27.0	3.0	2.0	0.0	0.0
Gomphonema clavatum Ehrenberg	GOCL	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.3	11.5	0.0	0.0
Gomphonema lagenula Kützing	GOLA	0.0	16.2	8.2	4.4	0.0	0.0	17.0	1.5	17.7	0.0	0.0
Gomphonema parvulum (Kützing) Kützing	GOPA	7.0	13.0	7.7	19.8	0.0	0.0	8.2	10.2	27.7	0.0	0.0
Gomphonema pseudoaugur Lange-Bertalot	GOPS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	59.5	0.0
Gomphonema saprophilum Lange-Bertalot *et* Reichardt	GOSA	0.0	2.8	1.8	1.0	0.0	0.0	4.3	4.3	0.7	0.0	0.0
Luticola goeppertiana Lange-Bertalot	LUGO	0.0	0.0	0.0	0.0	9.8	3.5	0.0	27.0	0.0	0.0	0.0
Luticola mutica Kützing	LUMU	0.0	0.0	0.0	0.0	34.4	0.0	0.0	2.7	0.0	0.0	0.0
Navicula antonii Lange-Bertalot	NAAN	2.0	1.7	2.0	0.0	35.4	7.5	10.8	18.3	1.0	0.0	0.0
Navicula cryptotenella Lange-Bertalot	NACR	0.0	0.0	0.0	0.0	1.2	2.2	0.7	14.0	0.0	0.0	0.0
Navicula erifuga Lange-Bertalot	NAER	0.0	1.5	0.0	0.0	0.0	0.0	0.0	17.7	8.3	0.0	0.0
Navicula recens (Lange-Bertalot) Lange-Bertalot	NARE	0.0	2.3	0.0	0.0	0.0	0.0	2.3	3.2	7.0	0.0	0.0
Navicula veneta Kützing	NAVE	2.0	7.0	1.2	2.2	0.0	1.3	6.3	16.5	19.3	0.0	0.0
Nitzschia amphibia Grunow	NIAM	18.0	0.0	0.7	5.4	18.4	16.3	43.2	41.8	73.5	60.0	0.0
Nitzschia capitellata Hustedt	NICA	81.0	104.7	103.2	76.2	6.8	3.0	41.0	59.7	34.0	164.0	165.5
Nitzschia dissipata (Kützing) Rabenhort	NIDD	0.0	1.0	0.0	0.0	9.4	0.0	6.8	1.7	0.7	0.0	0.0
Nitzschia dissipata var. *media* (Hantzsch) Grunow	NIME	0.0	0.0	0.0	0.0	30.8	0.0	0.7	0.0	1.8	0.0	0.0
Nitzschia frustulum (Kützing) Grunow	NIFR	19.0	0.0	0.0	1.0	38.0	2.7	1.5	1.5	7.3	5.0	0.0
Nitzschia gracilis Hantzsch	NIGR	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.2	0.0	0.0
Nitzschia laevis Hustedt	NILA	0.0	6.8	5.2	2.0	0.0	0.7	0.0	2.8	2.0	0.0	0.0
Nitzschia palea (Kützing) W. Smith	NIPA	0.0	35.8	14.0	2.0	8.2	0.0	13.3	7.3	7.2	9.0	11.5
Nitzschia sublinearis Hustedt	NISB	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	14.8	0.0	0.0
Nitzschia umbonata (Ehrenberg) Lange-Bertalot	NIUM	11.0	43.3	12.7	4.4	0.0	0.0	5.2	10.2	4.8	4.5	77.5
Planothidium frequentissimum (Lange-Bertalot) Lange-Bertalot	PLFR	0.0	0.0	0.0	1.2	4.6	22.7	0.8	8.7	0.0	0.0	0.0
Planothidium lanceolatum (Brébisson ex Kützing) Lange-Bertalot	PLLA	0.0	0.0	2.8	1.0	0.0	7.5	4.8	0.0	2.5	0.0	0.0
Psammothidium subatomoides (Hustedt) Bukhtiyarova *et* Round	PSSU	0.0	1.5	0.0	1.6	0.0	24.2	0.0	0.0	0.0	0.0	0.0
Rhoicosphenia abbreviata (C. Agardh) Lange-Bertalot	RHAB	0.0	0.0	0.0	2.8	97.4	120.5	4.2	0.0	0.0	0.0	0.0
Sellaphora pupula (Kützing) Mereschkowsky	SEPU	67.5	41.8	48.5	77.2	1.4	2.0	13.8	10.8	6.7	0.0	0.0
Stephanocyclus meneghiniana (Kützing) Skabitschevvsky	STME	2.5	0.0	3.8	2.0	0.0	0.0	37.0	14.7	6.8	0.0	0.0
Ulnaria ulna (Nitzsch) Compère	ULUL	6.5	1.5	0.0	1.4	1.0	0.0	8.0	2.2	4.7	0.0	0.0

Notes: PL: Puente Lerma-Toluca, State of Mexico; Ixt: San Jerónimo Ixtapatongo, State of Mexico; Tl: San Lorenzo Tlacotepec, State of Mexico; Tz: Puente Temazcalcingo, State of Mexico; P: El Pedregal, Michoacán; Pm: Pedregal manantial, Michoacán; Ch: Chamácuaro, Guanajuato; C: El Capulín, Guanajuato; U: Uruétaro, Guanajuato; LAJ: Río Laja, Guanajuato: QRO: Río Querétaro, Querétaro.

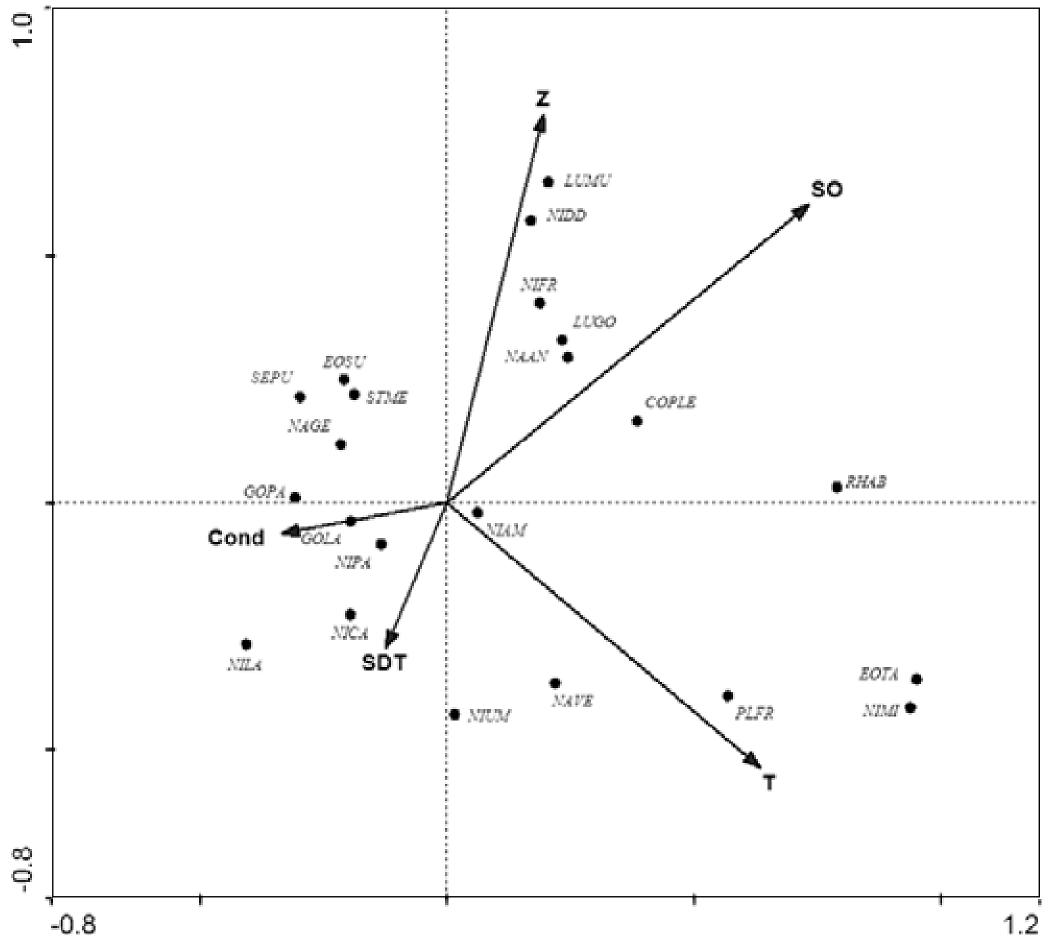

Figure 2. CCA of species and environmental variables in the Upper Lerma River sub-basin. Species acronyms as in Table 3.

bonata, N. levidensis (W.Smith) Grunow*, Sellaphora pupula*, and *Stephanocyclus meneghiniana* was positively and significantly correlated with conductivity. On the other side, *Luticola goeppertiana*, *L. mutica*, *Navicula antonii* Lange-Bertalot, *Nitzschia dissipata* var. *dissipata* (Kützing) Rabenhorst, and *N. frustulum* were positively correlated with depth. In Fig. 3A-Z shows the main diatoms as indicators of water quality in the Lerma River.

DISCUSSION

The Lerma River was characterized as a highly polluted and eutrophic system due to a constant throughout the year drainage of high nutrient content wastewaters from industrial, agricultural, and urban activities.

The physicochemical data showed a clear discrimination of the studied sites having a high conductivity such as Puente Lerma, San Jerónimo Ixtapatango, San Lorenzo Tlacotepec, Pedregal, Uruétaro, and Laja River, in which the discharges of industrial and urban activity of sites within the State of México are very intense, as are those of sewage derived from agricultural activities located in the states of Michoacán and Guanajuato. Sampling sites with both high dissolved oxygen content and high oxygen saturation percent were San Jerónimo Ixtapatongo, Temazcalcingo Bridge, Pedregal Spring, Chamácuaro, and El Capulín, localities in which the river has zones with boulders or large rocks that increase the oxygenation of the system.

Known taxocenoses are dominated by species of the genera *Nitzschia*, *Navicula* and *Gomphonema*, similar to those observed in several lentic bodies named "*bordos*" in the state of Guanajuato near the Lerma River (Cantoral-Uriza & Mora, in press). The presence of a large number of *Nitzschia* species that are tolerant to a wide range of environmental conditions (Dere *et al*., 2006; Cantoral-Uriza & Mora, in press) evidenced the hypereutrophic conditions that predominated in the Lerma River during the research period.

The rivers Laja and Querétaro, considered as referents for highly disturbed conditions, have a low species diversity and are dominated by species characteristic of organic matter enriched waters such as *Nitzschia capitellata* present in both rivers, and

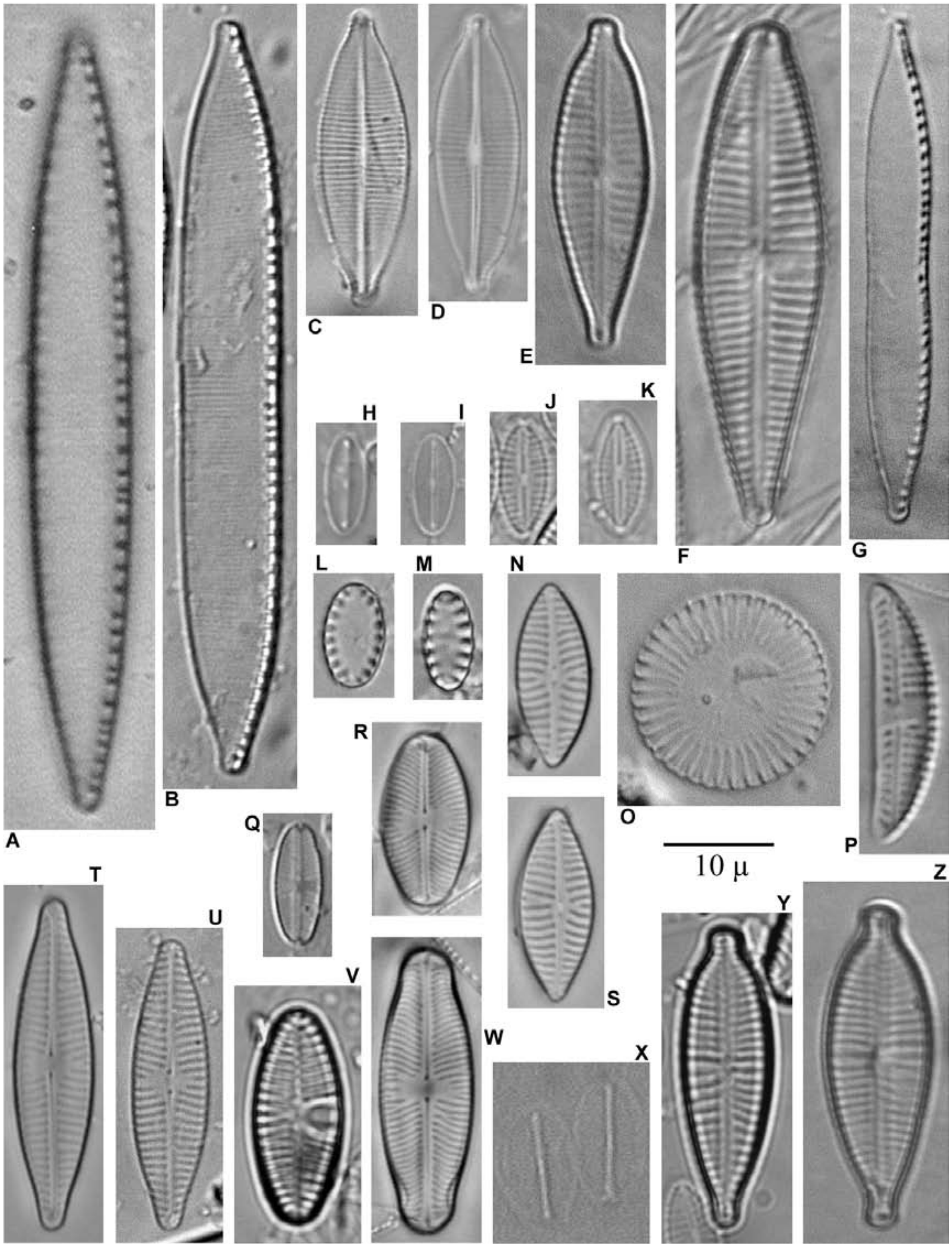

Figure 3A-Z. Diatoms species that are main indicators of water quality in the Lerma River. A-K, R, W, X-Z **Polluted water** (all fotographs on the same scale). A. *Nitzschia palea* (Kützing) W. Smith; B. *Nitzschia umbonata* (Ehrenberg) Lange-Bertalot; C, D. *Craticula accomoda* (Hustedt) D. G. Mann; E-F. *Gomphonema parvulum* (Kützing) Kützing; G. *Nitzschia capitellata* Hustedt; H, I. *Mayamaea atomus* var. *permitis* (Hustedt) Lange-Bertalot; J, K. *Eolimna subminuscula* (Manguin) Moser, Lange-Bertalot *et* Metzeltin; R-W. *Sellaphora pupula* (Kützing) Mereschkowksy. X. *Fistulifera saprophila* (Lange-Bertalot *et* Bonik) Lange-Bertalot; Y-Z. *Gomphonema lagenula* Kützing. L-M, P-Q, V **Clean water**. L-M. *Frankophila similioides* Lange-Bertalot *et* Rumrich. P. *Amphora pediculus* (Kützing) Grunow; Q. *Eolimna tantula* Hustedt; V. *Planothidium frequentissimum* Lange-Bertalot. N-O, S-U **Tolerant species**. N, S. *Navicula antonii* Lange-Bertalot; O. *Stephanocyclus meneghiniana* (Kützing) Skabitschevvsky; T, U. *Navicula veneta* Kützing.

N. amphibia and *N. umbonata*, occurring in the former and the latter water bodies, respectively. Pedregal Spring, dominated by *Eolimna tantula*, *Amphora copulata* (both exclusive of this location), and *Rhoicosphenia abbreviata*, was the referent for less disturbed waters in the Lerma River. The latter three taxa have been recorded for waters with low nutrient concentrations and conductivities, although *E. tantula* may tolerate hypereutrophic conditions (Lange-Bertalot, 2001; Ramírez & Plata-Díaz, 2008). *A. copulata* and *R. abbreviata* are sensitive to the increase of conductivity (Maidana *et al*., 2005) and may grow in places with high current velocity (Walker & Pan, 2006). *R. abbreviata* may also reflect the continual industrial and urban activity talking place in the basin (Walker & Pan, 2006).

CCA grouped some species that are sensitive to oxygen saturation percent (Fig. 2). This group includes high oxygen concentration demanding species such as *Luticola mutica* (100% saturation), *Nitzschia dissipata* (75%), and *Nitzschia frustulum* (50%) (van Dam *et al*., 1994).

Most of the dominant species (i.e., *Eolimna subminuscula, Gomphonema parvulum, Luticola goeppertiana, Nitzschia amphibia, N. capitellata, N. palea, N. umbonata,* and *Sellaphora pupula*) have been characterized in the literature as being tolerant to high electrolyte contents in rivers highly contaminated with industrial waste (Germain, 1981; van Dam *et al*., 1994; De Wolf, 1982; Lobo *et al*., 1995; Cox, 1996; Cantoral, 1997; Krammer & Lange-Bertalot, 1997b; Novelo, 1998; Lange-Bertalot, 2001; Dere *et al*., 2006; Ndiritu *et al*., 2006; Novelo *et al*., 2007), and thus, the presence of these species could be considered to be indicators of similar conditions in the upper Lerma River.

On the other side, *Achnanthidium minutissimum, Cocconeis placentula, Planothidium frequentissimum, P. rostratum* (Oestrup) Lange-Bertalot, and *Staurosirella pinnata* (Ehrenberg) D. M. Williams *et* Round are species sensitive to contamination (Sczepocka & Szulc, 2006; Ndiritu *et al*., 2006) that were found in the Lerma-Toluca Bridge, San Jerónimo Ixtapatongo, San Lorenzo Tlacotepec and, Temazcalcingo Bridge. In Pedregal Spring, a high number of very small valves of *Achnanthidium minutissimum* and *Planothidium frequentissimum* were observed, which could be associated to shaded habitats (Weilhoefer & Pan, 2006).

Gomphonema parvulum and *Nitzschia palea,* observed in areas of agricultural runoff such as San Jerónimo Ixtapatongo, Temazcalcingo Bridge, El Capulín, and Uruétaro, have also been found in rivers with high concentrations of nitrates and phosphates near agricultural land in the U.S., Japan, Poland, and Germany (Lobo *et al*., 1995; Leland & Porter, 2000; Köster & Hübener, 2001; Sczepocka & Szulc, 2006; Zampella *et al*., 2007).

Species such as *Achnanthidium minutissimum, Rhoicosphenia abbreviata*, and *Navicula antonii* indicate slightly better conditions of oxygenation whitin the Lerma River (Krammer & Lange-Bertalot, 1985, 2004b). While *Nitzschia sublinearis, N. palea*, and *Luticola goeppertiana* are species that may reflect conditions of intermediate pollution, in the present study they were observed to occur only in low relative abundances (Krammer & Lange-Bertalot, 1997b; Salomoni *et al*., 2006).

The observed decrease in biodiversity and the changes in species composition in the most altered zones of the river during the sampling years could be accounted for by changes in water quality due to the increase of pollution in the system given that, as has been shown by Stevenson (1997), communities may adapt themselves to environmental stress througth a change in species composition. Thus, in highly contaminated places of the upper Lerma River, medium to small sized species such as *Eolimna subminuscula* and *Nitzschia palea* were found, while medium to large size individuals of *Ulnaria ulna*, *Nitzschia umbonata*, and *Sellaphora pupula* were found in places with relatively less environmental perturbation; all of the above-mentioned species were found to be amply distributed in the study area, and the latter three are considered as tolerant to moderate organic pollution (Martinez de Fabricius *et al*., 2003).

We concluded that the environmental information based on a precise taxonomic description from the epilithic diatoms and understanding of ecological preferences that was generated in the present study may represent a relevant constribution for a region of great economic importance in Mexico.

As show by the results of CCA, the distribution of epilithic diatoms species in the study area is closely linked to chemical and physical characteristics of water (particularly to depth, conductivity, pH, temperature, and total dissolved solids), and is also associated to the different types and the intensities of human activities taking place along the upper Lerma River sub-basin.

The environmental and taxonomic information of this study will be of aid for designing water quality monitoring programs using epilithic diatoms species that were shown by our study to be bioindicators, and because they provide tools to develop a series of management activities aimed at improving water quality, therefore bettering the quality of life of people that depend on this resource.

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