RESEARCH ARTICLE

Development of the Diatom Ecological Quality Index (DEQI) for peri-urban mountain streams in the Basin of Mexico

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Abstract

In the Basin of Mexico, one of the most important economic regions in the country with over 22 million inhabitants, peri-urban streams have been transformed into sewers, drains, and pipes to avoid flooding or unsanitary conditions; the change affects not only the ecosystem's goods and services but also the aquatic communities that support the natural ecological processes. We aimed to develop a diatom-based diagnosis of the ecological quality of these aquatic ecosystems through the study of epilithic diatom response to regional environmental gradients. Samples of epilithic diatoms and water were collected in 45 sites representing 12 perennial streams, and multivariate analyses were performed on environmental and biological data. The ecological quality gradient to which diatoms responded was related to oxygen saturation, soluble reactive phosphorous, dissolved inorganic nitrogen, and hydromorphological quality. Three species groups were recognized according to their ecological preferences along CCA1 axis, indicators of high and low ecological quality, and tolerant species. By assigning an indicator value to each species group, we calculated the DEQI using the formula adapted from Pantle and Buck, indicating five different ecological quality classes. This index is proposed for complementing the ecological quality evaluation as a biological metric that responds to multiple regional stressors of the structure and function of these peri-urban streams in the Basin of Mexico.

Keywords Peri-urban streams · Biomonitoring · Ecological quality · Epilithic diatoms · Bacillariophyta · Basin of Mexico

Introduction

Ecological quality (EQ) in aquatic ecosystems is defined by its structure and function, and it is evaluated using physical, chemical, hydromorphological, and biological indicators (EC 2000). In this sense, different biological groups have been used for assessing and monitoring freshwater ecosystems. Among them, epilithic diatoms are recognized worldwide as

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valuable indicators of environmental conditions as they respond directly and sensitively to specific physical, chemical, and biological changes (Wetzel 1983; EC 2000; Hill et al. 2001; Lobo et al. 2004, 2016; Stevenson et al. 2010). A substantial number of diatom indices have been developed in various geographic areas in the world based on species relative abundance and their sensitivity to environmental gradients, allowing numeric values to be assigned as measures of the response of diatom species to abiotic factors in order to obtain a quantitative, cost-effective, fast, and accurate EQ bioassessment (Kelly and Whitton 1995; Gómez and Licursi 2001; Lobo et al. 2004, 2015, 2016, 2019; Ector and Rimet 2005; Álvarez-Blanco et al. 2013).

Diatom distribution patterns and some species ecological preferences respond not only to changes in water quality but also to regional and physiographical factors, affecting the effectiveness of indices when these are applied in regions other than that where species-environment relationships were originally assessed to construct the metrics (Potapova and Charles 2007; Álvarez-Blanco 2013). Consequently, to improve bioassessments, it is important to perform studies on an ecoregional level (areas with similar climate, landscape,
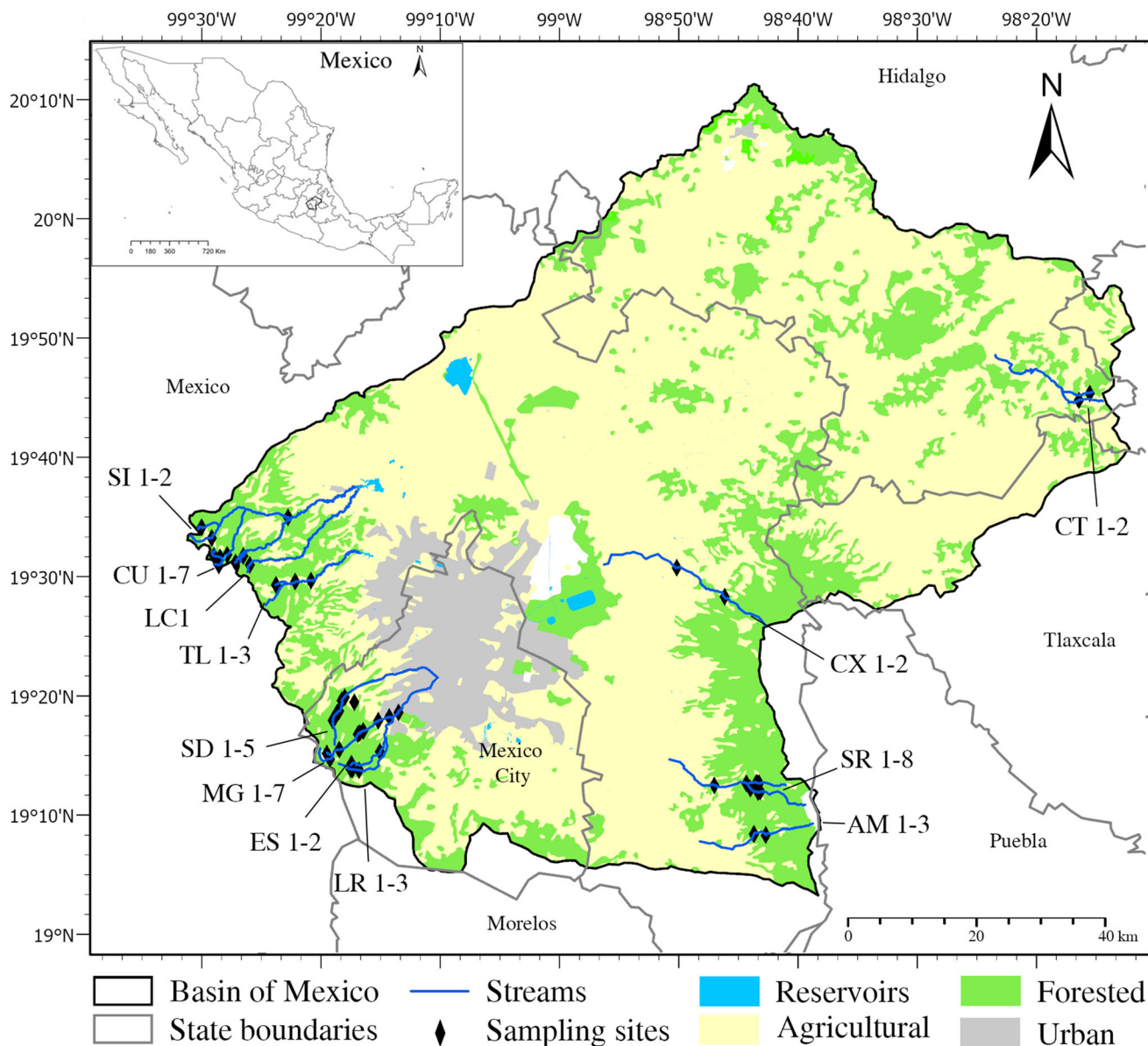
Fig. 1 The Basin of Mexico, land use, and distribution of the 12 sampled streams and 45 sites. (1) Coatlaco (CT1–2), (2) Coaxcacoaco (CX1–2), (3) San Rafael (SR1–8), (4) Ameca (AM1–3), (5) Las Regaderas (LR1– 3), (6) Eslava (ES1–2), (7) Magdalena (MG1–7), (8) Santo Desierto (SD1–5), (9) Tlalnepantla (TL1–3), (10) La Caldera (LC1), (11) Cuautitlán (CU1–7), and (12) San Ildefonso (SI1–2)

vegetation, or land use), recognizing regional floras and its species distributions along local environmental gradients using datasets representative of the areas where metrics want to be applied to assess aquatic ecosystems EQ (Solninen et al. 2004; Leira and Sabater 2005; Álvarez-Blanco et al. 2011). The foregoing is extremely important in Latin America, where regional studies continue exploring diatom biodiversity, species ecological preferences, and some less conventional metrics to measure changes in diatom assemblages in urban-impacted streams like nuclear abnormalities or ecological guilds (Lobo et al. 2019; Nicolosi-Gelis et al. 2020).

In the Basin of Mexico (BM), with over 22 million inhabitants, aquatic ecosystems have been transformed into drains,

converted into sewers or piped to avoid flooding and unsanitary conditions (Legorreta 2009; CONAGUA 2018). Streams in this region flow from natural protected areas (PA) at high elevations, being exposed to different human activities along their course through the BM. Not only the ecosystem's goods and services are affected but also the aquatic communities that support the natural processes in these environments (Mazari-Hiriart et al. 2014). According to the Mexican National Monitoring Network established by the National Water Commission (CONAGUA), the assessments of contamination levels in aquatic systems are based on physical, chemical, and bacteriological variables (CONAGUA 2018), not necessarily integrating the EQ (Rocha 1992; Karr et al. 2000; Carmona-

Table 1 Physicochemical and hydromorphological characteristics of sampling sites in the BM

Stream/site (code)	Elevation	T	pH	DO	OS	K_{25}	SRP[1]	DIN[1]	V	HQ
Coatlaco										
Rancho Nuevo Alto (CT1)	2895	11.2	7.4	6.6	86	61	0.38	0.16	0.2	100
Rancho Nuevo Bajo (CT2)	2799	13.5	6.8	3.9	53	68	1.20	0.10	0.3	82
Coaxcacoaco										
Santa Catarina (CX1)	2855	13.1	7.1	7.1	94	134	0.40	0.31	0.3	98
Molino de flores (CX2)	2345	15.7	7.7	4.1	56	546	7.73	17.03	0.2	74
San Rafael-Tlalmanalco										
Inicio Canal (SR1)	2895	9.9	7.5	7.9	100	138	0.48	0.14	0.5	118
San Rafael Canal (SR2)	2865	11.3	6.8	6.9	89	136	0.51	0.96	0.9	94
La Compañía (SR3)	2941	10.6	6.9	6.6	85	121	0.49	0.2	0.4	120
Cascada Compañía (SR4)	2847	10.7	7.2	7.8	100	154	0.34	0.10	0.4	112
Agua Dulce (SR5)	2773	10.9	6.8	6.3	80	110	0.52	0.27	0.9	100
Cosamala (SR6)	2757	14.6	7.0	4.9	68	99	0.51	0.61	0.5	92
Dos Aguas (SR7)	2676	14.9	7.0	4.2	58	137	0.40	1.05	0.6	66
Estación UAM (SR8)	2429	15.0	6.8	3.0	40	143	5.55	2.22	0.8	72
Ameca-Canal Nacional										
La Castañeda Alto (AM1)	2900	8.3	7.3	7.4	90	255	0.27	0.08	0.5	120
La Castañeda (AM2)	2625	9.3	7.0	8.3	100	175	0.36	0.05	0.5	104
La Castañeda Bajo (AM3)	2647	11.0	7.2	4.8	60	201	0.62	0.17	0.6	96
Las Regaderas										
Montealegre Alto (LR1)	3364	12.8	7.2	7.1	100	41	0.31	0.1	0.3	108
Montealegre (LR2)	3341	9.4	7.3	7.5	100	47	0.28	0.67	0.2	82
Montealegre Bajo (LR3)	3292	16.9	7.2	6.4	98	47	0.25	0.72	0.1	77
Eslava										
Manantial (ES1)	3261	8.7	5.7	3.4	43	112	0.19	0.53	0.2	110
Cascada (ES2)	2872	12.3	6.9	6.3	84	58	0.12	0.43	0.4	90
Magdalena										
Magdalena Alto (MG1)	3448	11.9	7.4	7.2	100	94	0.31	0.19	0.4	98
Chautitle alto (MG2)	3357	5.0	6.7	8.1	98	64	0.49	0.12	0.2	116
Truchero Alto (MG3)	3278	7.6	7.2	6.6	82	63	0.28	0.24	0.2	88
Segundo Dinamo (MG4)	2835	10.0	7.2	8.0	100	90	1.03	0.78	0.3	90
La Cañada (MG5)	2553	12.9	6.9	7.2	90	140	0.31	0.41	0.6	88
Confluencia (MG6)	2465	12.0	7.1	4.1	50	86	0.39	2.78	1.0	54
Santa Teresa (MG7)	2492	12.8	7.6	3.4	43	80	0.54	4.85	0.6	52
Santo Desierto-Mixcoac										
Santa Rosa Alto (SD1)	3050	16.0	8.0	6.0	89	75	0.28	0.04	0.2	116
Santa Rosa Bajo (SD2)	2960	7.5	7.0	7.8	93	79	0.31	0.07	0.3	104
Convento (SD3)	2925	9.4	6.6	7.9	99	77	0.29	0.71	0.5	65
Escuela Ambiental (SD4)	2777	5.5	7.3	7.8	87	83	0.27	0.74	0.3	80
Valle de Monjas (SD5)	2700	7.4	6.6	6.1	69	100	0.34	0.63	0.3	79
Tlalnepantla										
Las Manzanas (TL1)	3095	11.8	6.8	7.4	100	86	0.12	0.28	0.2	116
San Luis Ayucán (TL2)	2704	10.8	6.6	4.4	55	60	0.97	1.71	0.8	68
San Luis Bajo (TL3)	2600	12.3	6.7	6.1	78	68	0.24	0.73	0.9	88
La Caldera										
Xopachi (LC1)	2867	11.0	7.6	7.3	94	42	0.26	0.08	0.2	114
Cuautitlán										
Organillos (CU1)	3378	11.2	6.4	5.9	81	126	0.47	0.68	0.1	106
Nacimiento Presa Iturbide (CU2)	3339	14.4	7.5	6.7	99	52	0.48	0.56	0.3	110
Manantial San Pedro (CU3)	3305	12.4	7.4	6.5	92	54	0.29	0.06	0.2	118
Truchero Presa Iturbide (CU4)	3300	11.8	6.7	5.0	69	62	1.42	1.45	0.3	70
Cortina Presa Iturbide (CU5)	3271	13.2	6.5	5.6	80	53	0.96	1.54	0.7	78
Cortina Presa Capoxi (CU6)	3158	12.7	6.4	3.5	49	48	1.30	1.45	0.5	108
Transfiguración (CU7)	2496	12.7	7.5	7.8	100	63	1.67	3.23	0.7	88
San Ildefonso										
Manantial las Palomas (SI1)	3417	11.8	7.0	7.1	100	49	0.23	0.43	0.2	120
Truchero Don Álvaro (SI2)	3236	12.5	7.7	7.2	100	55	0.36	0.29	0.3	108

Elevation (m a.s.l.); *T* water temperature (°C), *DO* dissolved oxygen (mg L^{-1}), *OS* oxygen saturation (%), K_{25} specific conductivity (μS cm^{-1}), *SRP* soluble reactive phosphorous (mg L^{-1}), *DIN* dissolved inorganic nitrogen (mg L^{-1}), *V* water velocity (m s^{-1}), *HQ* hydromorphological quality (pts.)

Jiménez and Caro-Borrero 2017). Recently, through a study of macroscopic algae and macroinvertebrate communities in streams of BM, Carmona-Jimenez and Caro-Borrero (2017)

established a preliminary characteristic baseline of the potential ecological reference conditions, defined as a set of conditions that are similar to those finding in ecosystems free from
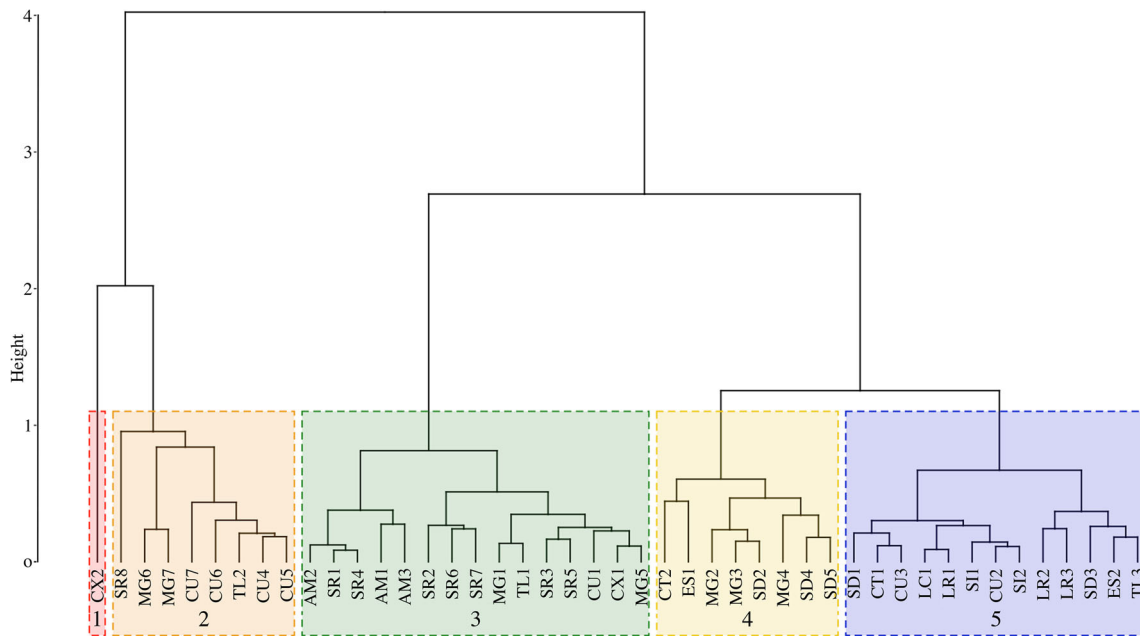
Fig. 2 Hierarchical agglomerative cluster recognizing five clusters of sites based on environmental data. Site codes in Table 1

anthropogenic influences, with a "natural" biota. In this context, the research aimed at developing the Diatom Ecological Quality Index (DEQI) for mountain streams located in the Basin of Mexico, providing a scientific basis for the implementation of diatom-based diagnoses of these ecosystems ecological quality.

Material and methods

Study area

The BM (Fig. 1) is an endorheic basin located in Central Mexico within the morphotectonic region of the Trans-
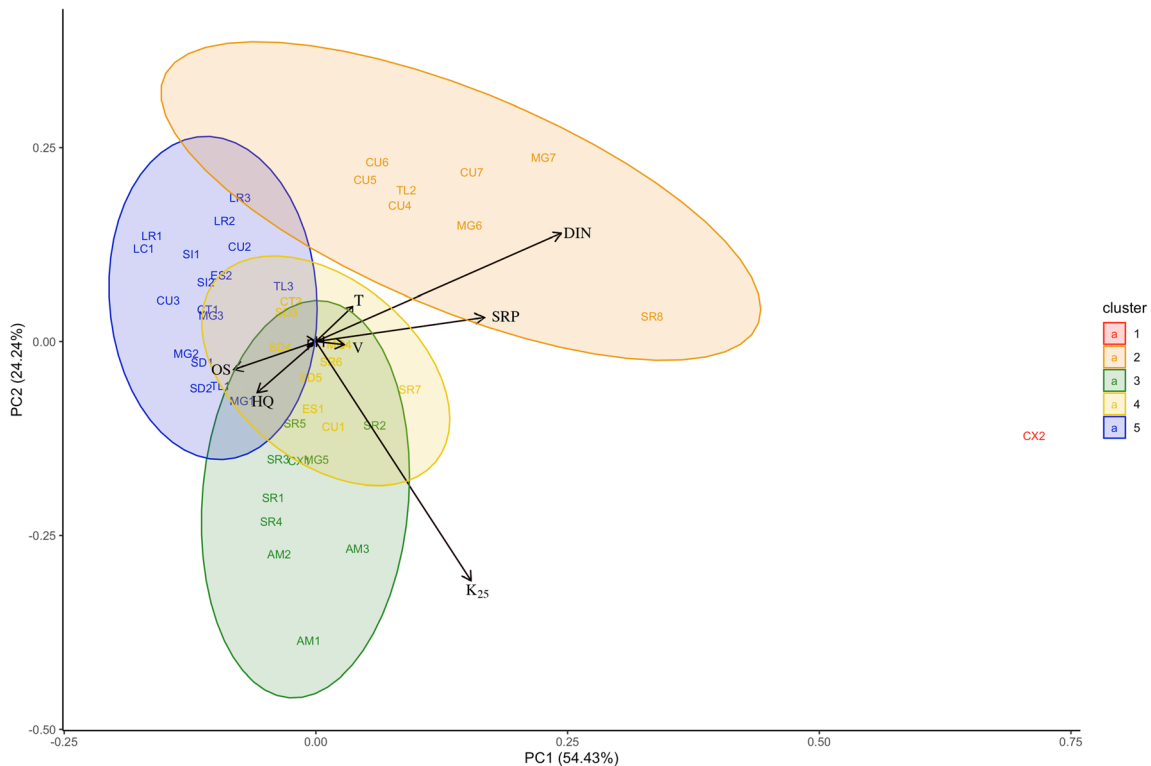
Fig. 3 PCA ordination biplot of sites along PC1 and PC2, based on environmental data with overlaid clustering results. See Table 1 for sites and environmental variables codes
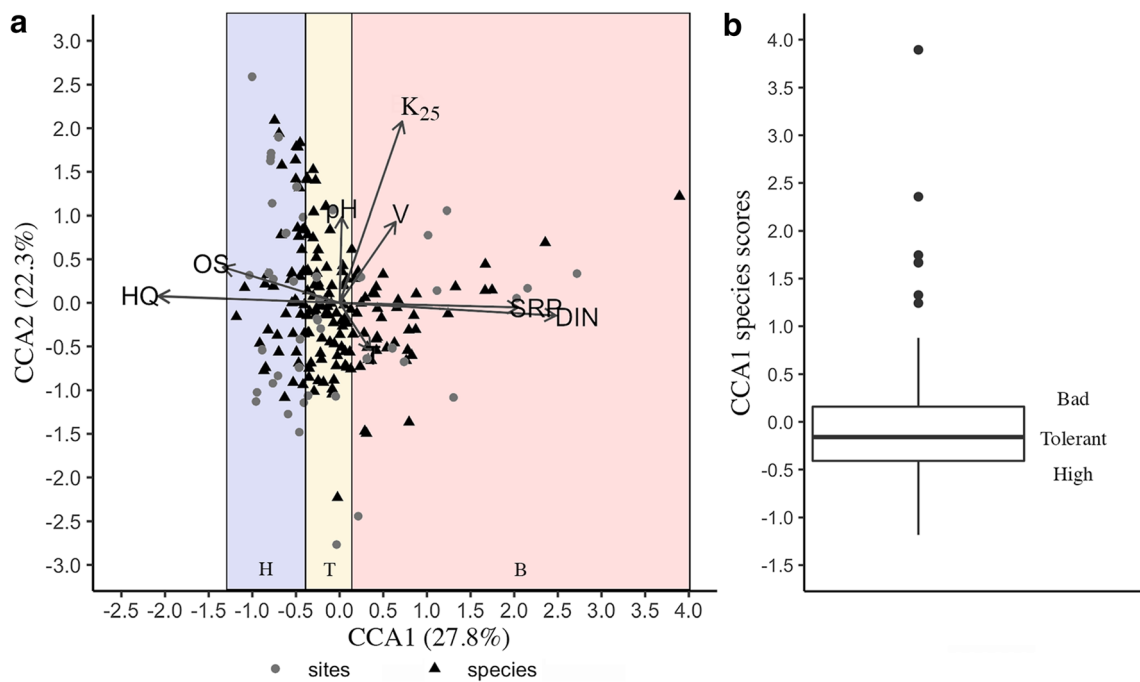
Fig. 4 CCA scatterplot showing the ordination of species and sites along axis 1 and 2. **a** Ordination of species clustered in three groups according to their ecological optima along axis 1 EQ gradient (H, high; T, tolerant; B, bad). **b** Box plot of species scores in axis 1, species scores below 25% quartile indicated high EQ, those in the interquartile range were considered tolerant species, and those above the 75% quartile indicated bad EQ. Environmental variable codes in Table 1

Mexican Volcanic Belt. It occupies territories from five states: Mexico City, Mexico, Hidalgo, Tlaxcala, and Puebla. Considering the total surface of 9600 km², 57% are mountainous terrains that rise above 2400 m a.s.l. Also, the basin contains 45 perennial or ephemeral streams (Ferrusquía-Villafranca 1998; Legorreta 2009). The climate of the region is sub-humid, with an annual median temperature of 13.4 °C, abundant rains from June to October, and dry season from November to May (annual median precipitation between 1200 and 1500 mm) (García 2004). Its geological traits consist of alternating andesitic to basaltic lavas (Ferrusquía-Villafranca 1998). Forests of *Abies religiosa* (Kunth) Schltdl. & Cham., *Pinus hartwegii* Lindl., and *Quercus* spp. grow in the upper area of the watershed, with mixed forests in the middle and lower areas (Ávila-Arkerberg 2010).

Sampling and data analysis

Twelve perennial streams were selected in the BM, and through several campaigns during dry seasons (2013–2017), we collected 45 sites in order to represent all different conditions from pristine areas to human-altered urban areas (each site was visited once). Samples of epilithic diatoms and water were collected simultaneously. The following physicochemical parameters were recorded in situ (whit daylight) with a Hanna Multiparameter probe 991300 (Dallas, USA): water temperature, specific conductivity, and pH. In addition, oxygen saturation as a proxy for organic pollution (YSI-85 meter, YSI, OH,

Table 2 Diatom taxa included in the DEQI and their indicator value (v)

Taxa	v
Achnanthes coarctata (Brébisson ex Kützing) Grunow	3
Achnanthidium exiguum (Grunow) Czarnecki	3
Achnanthidium minutissimum (Kützing) Czarnecki	1
Adlafia minuscula (Grunow) Lange-Bertalot	3
Amphora copulata (Kützing) Schoeman & R.E.M. Archibald	1
Amphora pediculus (Kützing) Grunow ex A. Schmidt	1
Aulacoseira ambigua (Grunow) Simonsen	1
Caloneis bacillum (Grunow) Cleve	1
Caloneis fontinalis (Grunow) Lange-Bertalot & Reichardt	5
Caloneis silicula (Ehrenberg) Cleve	3
Caloneis stauroneiformis (Amossé) Metzeltin & Lange-Bertalot	3
Cavinula cocconeiformis (Gregory ex Greville) D.G. Mann & A.J. Stickle	1
Cavinula lapidosa (Krasske) Lange-Bertalot	5
Cavinula pseudoscutiformis (Hustedt) D.G. Mann & A.J. Stickle	1
Chamaepinnularia submuscicola (Krasske) Lange-Bertalot in Moser et al.	3
Cocconeis placentula Ehrenberg	1
Craticula subminuscula (Manguin) Wetzel & Ector	5
Cyclotella menenghiniana Kützing	5
Cymbella mexicana (Ehrenberg) Cleve	5
Cymbella tumida (Brébisson) Van Heurk	5
Cymbopleura naviculiformis (Auerswald ex Heiberg) Krammer	3
Decussata placenta (Ehrenberg) Lange-Bertalot & Metzeltin	1
Diploneis smithii (Brébisson) Cleve	3
Diploneis subovalis Cleve	5
Discostella pseudostelligera (Hustedt) Houk & Klee	5
Encyonema lange-bertalotii Krammer	5
Encyonema minutum (Hilse ex Rabenhorst) Mann	3
Encyonema muelleri (Hustedt) Mann in Round et al.	1
Encyonema silesiacum (Bleisch) D.G. Mann	3
Encyonema ventricosum (Kützing) Grunow in Schmidt et al.	1
Encyonema sp.	1

Table 2 (continued)

Taxa	v
Epithemia adnata (Kützing) Brébisson	5
Epithemia turgida (Ehrenberg) Kützing	3
Eunotia arcus Ehrenberg	5
Eunotia bilunaris (Ehrenberg) Schaarschmidt	3
Eunotia implicata Nörpel, Lange-Bertalot & Alles	3
Eunotia minor (Kützing) Grunow	3
Eunotia paratridentula Lange-Bertalot & Kulikovskiy	1
Fragilaria capucina Desmazières	3
Fragilaria crotonensis Kitton	5
Fragilaria vaucheriae (Kützing) J.B. Petersen	3
Frankophila sp.	1
Frustulia crassinervia (Brébisson) Lange-Bertalot & Krammer	1
Frustulia vulgaris (Thwaites) De Toni	3
Geissleria acceptata (Hustedt) Lange-Bertalot & Metzeltin	3
Gomphonema acuminatum Ehrenberg	3
Gomphonema angustatum (Kützing) Rabenhorst	1
Gomphonema capitatum Ehrenberg	5
Gomphonema clavatum Krammer & Lange-Bertalot	1
Gomphonema commutatum Grunow	5
Gomphonema exillisimum (Grunow) Lange-Bertalot & E. Reichardt	1
Gomphonema gracile Ehrenberg	3
Gomphonema lagenula Kützing	1
Gomphonema minutum f. *pachypus* Lange-Bertalot & Reichardt	1
Gomphonema parvulum (Kützing) Kützing	5
Gomphonema subclavatum (Grunow) Grunow	1
Gomphonema tenuissimum Fricke in Schmidt et al.	5
Halamphora montana (Krasske) Levkov	5
Halamphora veneta (Kützing) Levkov	3
Hantzschia amphioxys (Ehrenberg) Grunow	3
Hantzschia calcifuga Reichardt & Lange-Bertalot	5
Humidophila contenta (Grunow) Lowe et al.	3
Humidophila perpusilla (Grunow) Lowe et al.	3
Iconella linearis (Smith) Ruck & Nakov	3
Lemnicola hungarica (Grunow) T.E. Round & P.W. Basson	3
Luticola goeppertiana (Bleisch) D.G. Mann	5
Luticola mutica (Kützing) D.G. Mann	3
Luticola nivalis (Ehrenberg) D.G. Mann	3
Mayamaea atomus (Kützing) Lange-Bertalot	3
Melosira varians C. Agardh	5
Meridion constrictum Ralfs	3
Navicula angusta Grunow	3
Navicula aurora Sovereign	1
Navicula cryptocephala Kützing	3
Navicula cryptotenella Lange-Bertalot	3
Navicula gregaria Donkin	3
Navicula lundii Reichardt	1
Navicula radiosa Kützing	3
Navicula rhynchocephala Kützing	3
Navicula seibigiana Lange-Bertalot	3
Navicula symmetrica Patrick	3
Navicula tenelloides Hustedt	1
Navicula veneta Kützing	5
Navicula vilaplanii (Lange-Bertalot & Sabater) Lange-Bertalot & Sabater	3
Neidium ampliatum (Ehrenberg) Krammer	3
Neidium sacoense Reimer	3
Nitzschia acidoclinata Lange-Bertalot	5
Nitzschia acula (Kützing) Hantzsch	3
Nitzschia archibaldii Lange-Bertalot	1
Nitzschia bacillariaeformis Hustedt	5
Nitzschia clausii Hantzsch	5
Nitzschia communis Rabenhorst	5
Nitzschia costei L. Tudesque, F. Rimet & L. Ector	1
Nitzschia dissipata (Kützing) Grunow	5
Nitzschia fonticola (Grunow) Grunow	3
Nitzschia frustulum (Kützing) Grunow	1

Table 2 (continued)

| Taxa	v
Nitzschia linearis W. Smith	3
Nitzschia palea (Kützing) W. Smith	5
Nitzschia paleacea (Grunow) Grunow in Van Heurck	5
Nitzschia pusilla (Kützing) Grunow	3
Nitzschia recta Hantzsch ex Rabenhorst	3
Nitzschia solgensis Cleve-Euler	3
Nitzschia soratensis E.A. Morales & M.L. Vis	5
Nitzschia supralitorea Lange-Bertalot	3
Nitzschia umbonata (Ehrenberg) Lange-Bertalot	5
Nupela praecipua (Reichardt) Reichardt	1
Odontidium mesodon (Kützing) Kützing	3
Odontidium rostratum Z. Levkov & I. Jüttner	3
Orthoseira roeseana (Rabenhorst) O'Meara	1
Pinnularia acoricola Hustedt	1
Pinnularia anglica Krammer	3
Pinnularia appendiculata var. *amaniana* Krammer	3
Pinnularia bertrandii Krammer	1
Pinnularia borealis Ehrenberg	3
Pinnularia divergens W. Smith	5
Pinnularia divergentissima (Grunow) Cleve	3
Pinnularia erratica Krammer	3
Pinnularia frequentis Krammer	3
Pinnularia inconstans A.Mayer	3
Pinnularia johndonatoi Metzeltin & Lange-Bertalot	3
Pinnularia microstauron (Ehrenberg) Cleve	3
Pinnularia nodosa (Ehrenberg) W. Smith	3
Pinnularia peragalli Kulikovskiy, Lange-Bertalot & Metzeltin	5
Pinnularia reichardtii Krammer	5
Pinnularia sinistra Krammer	3
Pinnularia subcommutata var. *nonfasciata* Krammer	3
Pinnularia sp.	5
Planothidium biporomum (Hohn & Hellerman) Lange-Bertalot	1
Planothidium cryptolanceolatum Jahn & Abarca	1
Planothidium frequentissimum (Lange-Bertalot) Lange-Bertalot	3
Platessa conspicua (A.Mayer) Lange-Bertalot	1
Prestauroneis protractoides (Hustedt) Liu & Kociolek	1
Pseudostaurosira brevistriata (Grunow in Van Heurk) Williams & Round	5
Pseudostaurosira sp.	3
Reimeria sinuata (Gregory) Kociolek & Stoermer	3
Rhoicosphenia sp.	1
Rhopalodia rupestris (W. Smith) Krammer	3
Rossithidium nodosum (Cleve) Aboal	3
Sellaphora cosmopolitana (Lange-Bertalot) Wetzel & Ector	5
Sellaphora laevissima (Kützing) D.G. Mann	3
Sellaphora nigri (De Not.) C.E. Wetzel & Ector	3
Sellaphora pseudopupula (Krasske) Lange-Bertalot	3
Sellaphora pupula (Kützing) Mereschkowsky	5
Sellaphora saugerresii (Desmazières) C.E. Wetzel & D.G. Mann	5
Sellaphora sp. 1	1
Sellaphora sp. 2	3
Simonsenia delognei (Grunow ex Van Heurk) Lange-Bertalot	3
Stauroneis kriegeri Patrick	3
Stauroneis phoenicenteron (Nitzsch) Ehrenberg	3
Stauroneis subgracilis Lange-Bertalot & Krammer	3
Stauroneis thermicola (J.B. Petersen) Lund	3
Staurosira venter (Ehrenberg) Cleve & Möller	3
Staurosirella sp.	1
Stephanodiscus minutulus (Kützing) Cleve & Möller	1
Stephanodiscus niagarae Ehrenberg	1
Stephanodiscus oregonicus (Ralfs) Håkansson	1
Surirella angusta Kützing	3
Surirella krammeri Metzeltin & Lange-Bertalot	5
Ulnaria acus (Kützing) M. Aboal	5
Ulnaria ulna (Nitzsch) P. Compère	1
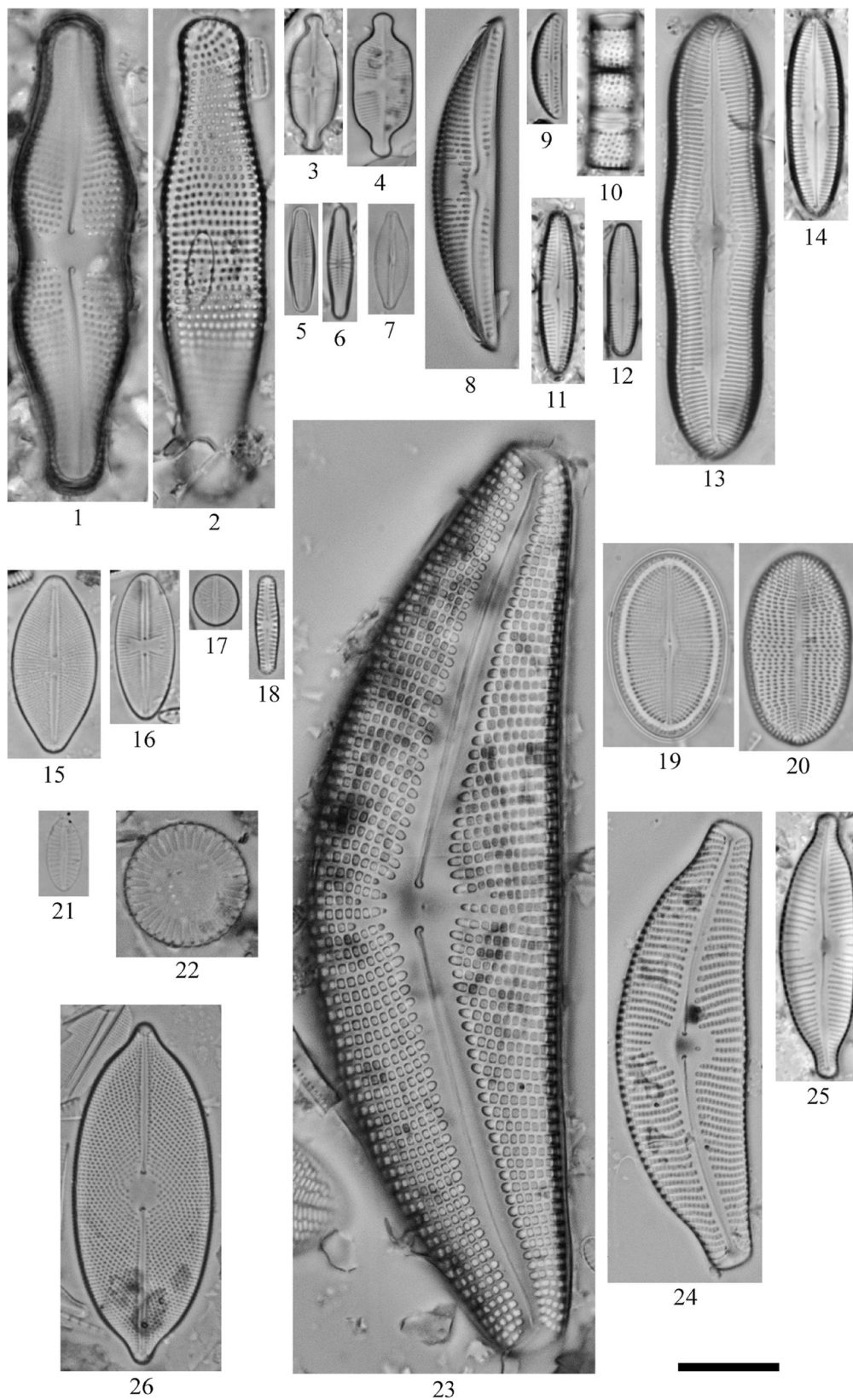
Fig. 5 Abundant and frequent diatoms in the BM included in the DEQI. 1–2, *Achnanthes coarctata*; 3–4, *Achnanthidium exiguum*; 5–6, *A. minutissimum*; 7, *Adlafia minuscula*; 8, *Amphora copulata*; 9, *A. pediculus*; 10, *Aulacoseira ambigua*; 11, *Caloneis bacillum*; 12, *C. fontinalis*; 13, *C. silicula*; 14, *C. stauroneiformis*; 15, *Cavinula cocconeiformis*; 16, *C. lapidosa*; 17, *C. pseudoscutiformis*; 18, *Chamaepinnularia submuscicola*; 19–20, *Cocconeis placentula*; 21, *Craticula subminuscula*; 22, *Cyclotella menenghiniana*; 23, *Cymbella mexicana*; 24, *C. tumida*; 25, *Cymbopleura naviculiformis*; 26, *Decussata placenta*. Scale bar = 10 μm
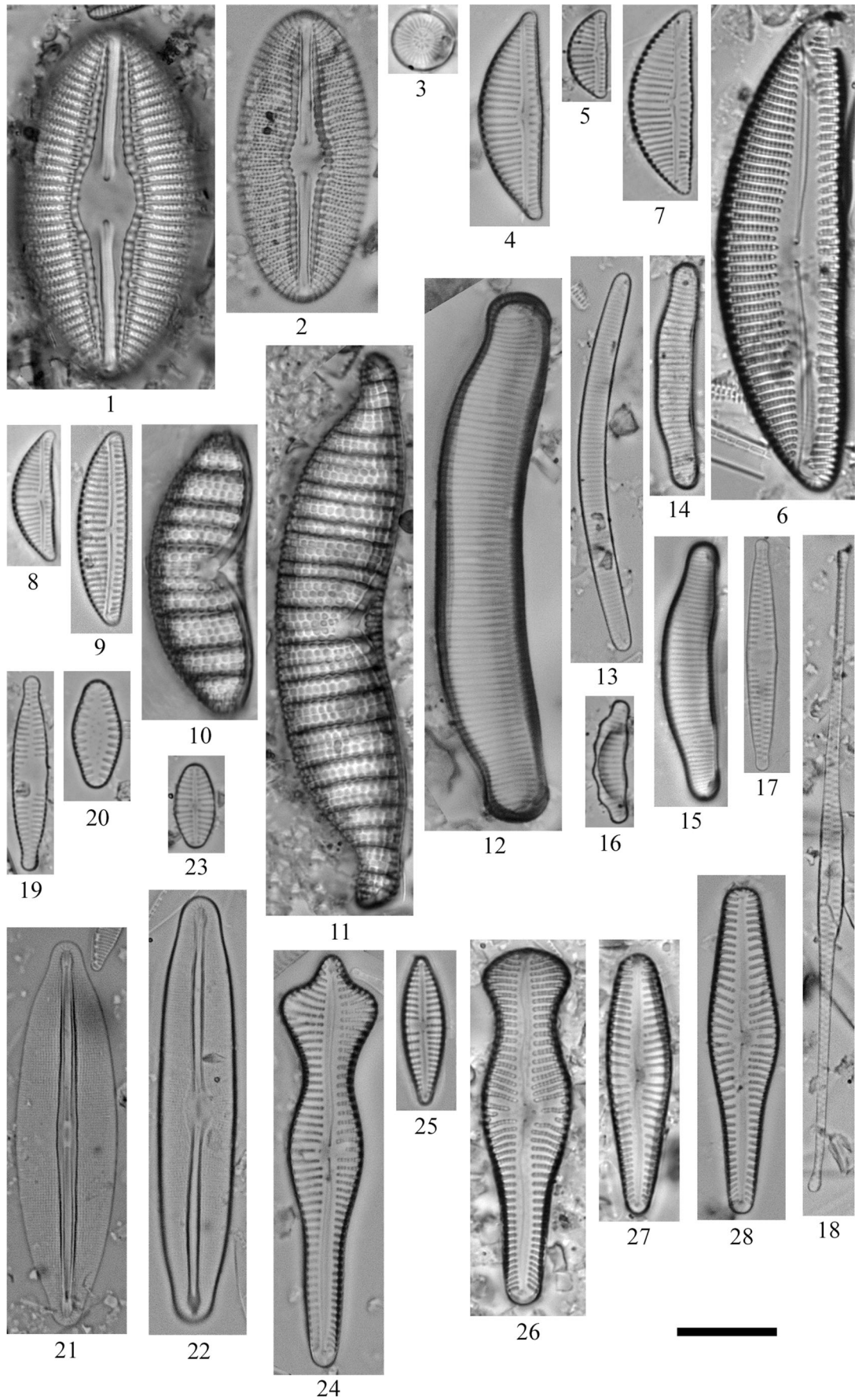
Fig. 6 Abundant and frequent diatoms in the BM included in the DEQI. 1, *Diploneis* smithii; 2, *D. subovalis*; 3, *Discostella pseudostelligera*; 4, *Encyonema lange*-bertalotii; 5, *E. minutum*; 6, *E. muelleri*; 7, *E. silesiacum*; 8, *E. ventricosum*; 9, *Encyonema* sp.; 10, *Epithemia adnata*; 11, *E. turgida*; 12, *Eunotia arcus*; 13, *E. bilunaris*; 14, *E. implicata*; 15, *E. minor*; 16, *E. paratridentula*; 17, *Fragilaria capucina*; 18, *F. crotonensis*; 19, *F. vaucheriae*; 20, *Frankophila* sp.; 21, *Frustulia crassinervia*; 22, *F. vulgaris*; 23, *Geissleria accepta*; 24, *Gomphonema acuminatum*; 25, *G. angustatum*; 26, *G. capitatum*; 27, *G. clavatum*; 28, *G. commutatum*. Scale bar = 10 μm

USA) and water velocity (Global Water FP111, TX, USA) were recorded. At each sampling site, 500 ml samples of water were filtered in situ and analyzed in the laboratory according to the criteria established by the official Mexican guidelines and international standards (DOF 2003; Baird et al. 2017). Nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), dissolved inorganic nitrogen (DIN), and soluble reactive phosphorous (SRP, PO_4-P) were analyzed with a DR 3900 laboratory spectrophotometer (Hach, Loveland, CO; Hach 2003). The trophic status was recognized as oligo-mesotrophic or mesotrophic-eutrophic according to Dodds et al. (1998) and Dodds (2003). Hydromorphological quality (HQ) was evaluated with the Ecological Quality of Andean Rivers Index (Acosta et al. 2009), method that assesses 24 basin attributes, hydrology, reach, and riverbed and that fluctuates from 24 to 120 points (> 96 high, 76–95 good, 51–75 moderate, 26–50 poor, < 25 bad). The conservation status of riparian vegetation was evaluated according to local descriptions (Ávila-Akerberg 2010; Espinosa and SarukÁn 1997; Rzedowski and Rzedowski 2001).

Epilithic diatom samples were collected by brushing off 10 cm^2 with a toothbrush from the upper surface of five submerged stones along a 10-m transect and fixed with ethanol (70%) in independent samples. Before chemical treatments, we observed the samples to make sure that empty frustules were always rare (< 1%) to avoid overestimating species abundances. The 225 samples were oxidized with the hydrogen peroxide method following Kelly (2001), and three subsamples were mounted into permanent preparations (675 slides) in the high refraction index mounting medium Naphrax® for species quantification. In each slide, we counted 500 valves following random transects using an Olympus BX51 microscope. Microphotographs were taken with an Olympus DP12 digital camera (Olympus, Tokyo, Japan). Plates were edited using Adobe® Photoshop Elements 14.1. For species identification, the following taxonomic references were used: Krammer and Lange-Bertalot (1986–1991), Metzeltin and Lange-Bertalot (1998, 2007), Krammer (2000), Rumrich et al. (2000), Metzeltin and García-Rodríguez (2003), Metzeltin et al. (2005), and Cantonati et al. (2017). The abundant species were selected for analyses following the criterion of Lobo and Leighton (1986), which

consider those species whose number of individuals is higher than the average (statistically) value of the total number of individuals in a sample. Since this was a regional study, we made a presence/absence matrix of species by stream to calculate the mean distribution of species in the basin and selected those with higher values than the average. Lastly, voucher samples were stored in the F.C.M.E. Herbarium at the Science Faculty, UNAM.

DEQI development

The DEQI was developed by analyzing environmental differences in sampling sites and diatom ecological preferences using multivariate techniques following Bahls et al. (2008) and Lobo et al. (2015). All statistical analyses were performed using RStudio (RStudio team 2019) with the packages vegan (Oksanen et al. 2019) and ggplot2 (Wickham 2016). Environmental factors were tested for collinearity to avoid correlation among variables, and those selected for further analyses were transformed by $\log(x + 1)$, except for pH.

For environmental characterization, we searched for groups of sites with similar environmental characteristics using hierarchical agglomerative clustering analysis based on the Ward method (Ward 1963). A principal component analysis (PCA) was performed to analyze which environmental gradients were ordering the sites among groups.

We analyzed how species (previously selected by their abundance and distribution) were ordered along environmental gradients with a canonical correspondence analysis (CCA) to recognize diatom ecological preferences. CCA global results, by axis and by variable, were tested for significance by 999 permutations. The variance partitioning was calculated to understand the contribution of physicochemical and hydromorphological aspects in diatom response. Species score distributions along axis 1 in CCA were used to separate them in three groups according to their ecological preferences, and an indicator value was assigned to each group. These were used to calculate the DEQI using the formula adapted from Pantle and Buck (1955): $DEQI = \frac{\sum (v\, h)}{\sum h}$, where v is the species indicator value and h is the species relative abundance in the sample.

DEQI validation

We used a new test set with twelve samples from seven streams within the BM collected during dry season in 2017. The HQ, physicochemical parameters, and diatom samples were obtained as previously described, and the DEQI was calculated for each site. To validate the index performance
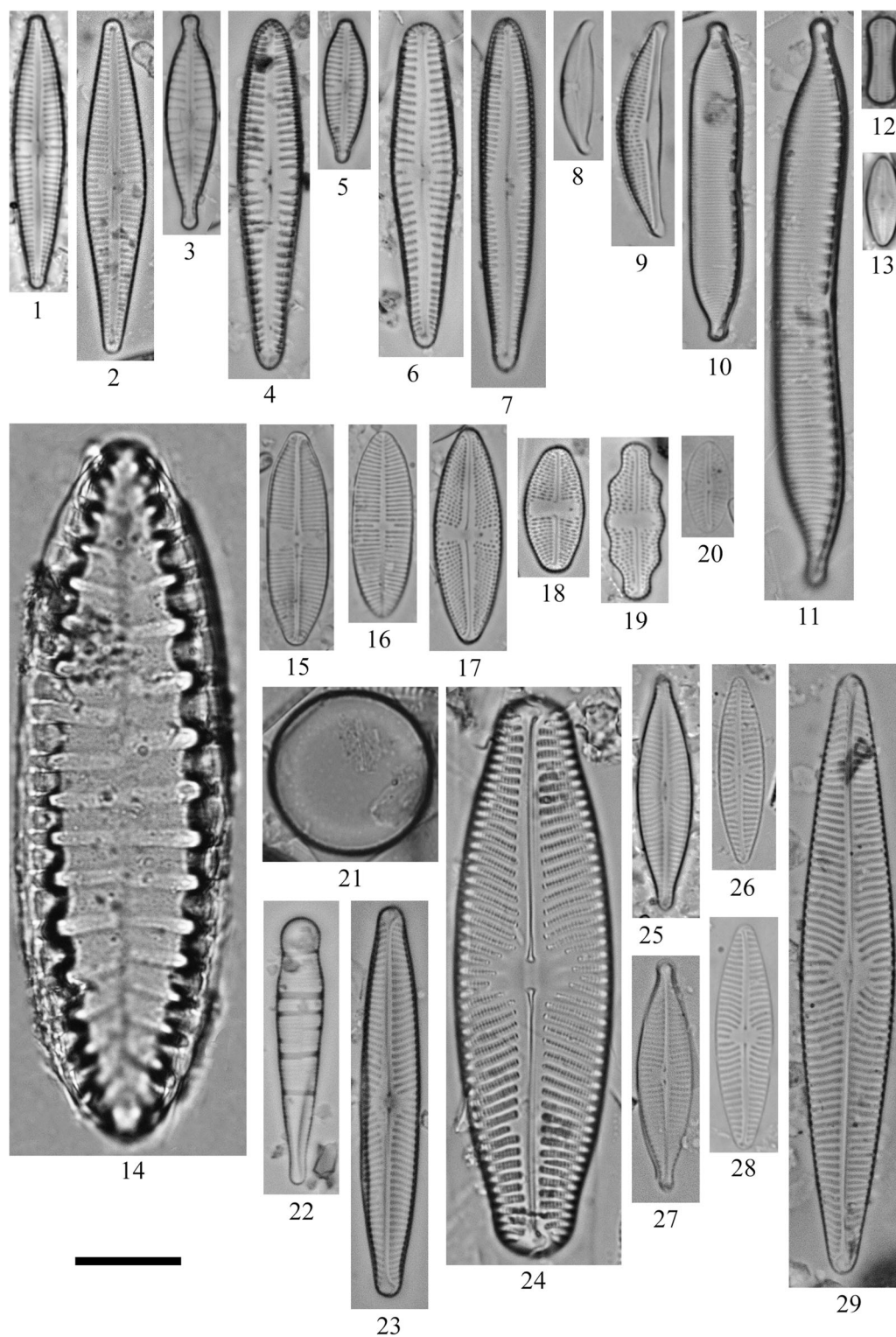
Fig. 7 Abundant and frequent diatoms in the BM included in the DEQI. 1, *Gomphonema exillisimum*; 2, *G. gracile*; 3, *G. lagenula*; 4, *G. minutum* f. *pachypus*; 5, *G. parvulum*; 6, *G. subclavatum*; 7, *G. tenuissimum*; 8, *Halamphora montana*; 9, *H. veneta*; 10, *Hantzschia amphioxys*; 11, *H. calcifuga*; 12, *Humidophila contenta*; 13, *H. perpusilla*; 14, *Iconella linearis*; 15–16, Lemnicola hungarica; 17, Luticola goeppertiana; 18, *L. mutica*; 19, *L. nivalis*; 20, Mayamaea atomus; 21, Melosira varians; 22, *Meridion constrictum*; 23, Navicula angusta; 24, *N. aurora*; 25, *N. cryptocephala*; 26, *N. cryptotenella*; 27, *N. gregaria*; 28, *N. lundii*; 29, *N. radiosa*. Scale bar = 10 µm

summarizing the EQ, we calculated Spearman's rank correlation coefficients of the DEQI with nutrient concentrations (DIN and SRP), oxygen saturation, specific conductivity, and HQ.

Results

Environmental characterization

The mountain streams in the BM were collected at an elevation range of 2345–3448 m a.s.l. (2941.8 ± 311.3) and presented water with cold to temperate temperature, 5–16.9 °C (11.5 ± 2.6); circumneutral pH, 5.7–8.0 (7.0 ± 0.4); mostly highly oxygenated, 40–100% (81.8 ± 19.2), and mostly electrolyte poor, 41–546 μS cm^{-1} (102.9 ± 81.6); with variable concentrations of SRP, 0.1–7.7 mg L^{-1} (0.7 ± 0.3) and DIN, 0.04–17.03 mg L^{-1} (1.1 ± 2.6); and a water flow that ranged from slow laminar to fast flowing, 0.1–1.0 m s^{-1} (0.4 ± 0.2). The HQ in sites ranged from 52 to 120 pts. (94.2 ± 18.7), with 23 sites recognized with high, 14 sites with good, and eight sites with moderate HQ, and four sites with oligo-mesotrophic conditions (DIN < 0.7 mg L^{-1} and SRP < 0.25 mg L^{-1}) and seven sites with meso-eutrophic accordingly (DIN > 1.5 mg L^{-1} and SRP > 0.75 mg L^{-1}).

After analyzing collinearity among environmental variables, we removed the elevation and dissolved oxygen, since these strongly reflected water temperature and oxygen saturation; no other environmental variable was removed for further analyses, as their collinearity values were below 10 (1.3–3.7). Through the hierarchical agglomerative clustering, sites were grouped in five different clusters based on their environmental characteristics (Fig. 2). Cluster 1 contained only one site (CX2), which presented the highest values for K$_{25}$, DIN, and SRP. Cluster 2 grouped eight sites (lower reaches) with high concentrations of K$_{25}$, DIN, and SRP and low OS and HQ. Cluster 3 included 15 sites (some headwaters and middle reaches) with intermediate concentrations of K$_{25}$, low DIN and SRP concentrations, and high OS and HQ. Cluster 4 grouped eight sites (middle reaches) with low K$_{25}$, moderate DIN and SRP concentrations, high OS, and moderate HQ. Finally, cluster 5 included 13 sites (headwaters) characterized by high OS, low K$_{25}$, DIN, and SRP concentrations, and very good HQ.

The ordination of sites in the PCA revealed 78.66% of total data variance explained in the first two components. The first component indicated 54.43% of explained variance ($\lambda = 0.3$), mainly related to DIN (0.69), SRP (0.47), and K$_{25}$ (0.43) and less to OS (-0.23) and HQ (-0.16). The second component explained 24.24% of variance ($\lambda = 0.2$), with K$_{25}$ (-0.87) and DIN (0.39) as the main related variables. The PCA biplot (Fig. 3) shows a gradient left to right along PC1 of decreasing environmental EQ: increased DIN and SRP concentrations and K$_{25}$ and decreased OS and HQ; while the gradient from top to bottom along axis 2 represents how K$_{25}$ increases and NID concentrations decreases in some sites, especially in those from the streams San Rafael-Tlalmanalco and Ameca-Canal Nacional grouped in cluster 3.

Diatom ecological preferences

We recognized a diverse diatom flora of 503 infrageneric diatom taxa distributed in 80 genera. The average abundance in the assemblages ranged from 0.6 to 3.1%, and the average distribution of species was 3.5 streams. We selected 160 abundant and frequent taxa above those averages for further analysis and to develop the DEQI. Ordination of sites and species along the CCA first two axis revealed 50.09% of total constrained variance being globally significant ($p < 0.001$) (Fig. 4a). Axis 1 explained 27.75% of variance ($\lambda = 0.41$; $p < 0.001$), showing a response from diatoms towards a decrease in EQ (left to right) given by a decrease in OS (-0.49; $p < 0.05$) and HQ (-0.77; $p < 0.05$), and an increase in SRP (0.76; $p < 0.05$) and DIN (0.92; $p < 0.05$) concentrations. Along this axis, species correlated with high HQ and OS and low concentrations of SRP and DIN are positioned in the left side of the biplot, and species correlated with low HQ and OS and high concentrations of SRP and DIN are positioned towards the right side. Axis 2 explained 22.34% of variance ($\lambda = 0.31$; $p < 0.001$), showing a physical response of diatoms to K$_{25}$ (0.77; $p < 0.05$), pH (0.36; $p < 0.05$), V (0.34; $p < 0.05$), and T (-0.20; $p > 0.05$). Along this axis, species correlated with high K$_{25}$, pH, V, and T are positioned in the upper part of the biplot, while those correlated with low values of these variables are positioned in the lower part. All variables except for T had p values < 0.05. We focused on diatom response along axis 1 since it explains more variation related to EQ.

After variation partitioning from the physicochemical and HQ sets in diatom response, we found that both sets of explanatory variables contributed to the explanation of the species data, although the unique contribution of the physicochemical set (fraction [a], $R^2_{adj} = 0.118$) was much larger than that of HQ (fraction [c], $R^2_{adj} = 0.022$). The variation explained jointly by the two sets (fraction [b], $R^2_{adj} = 0.023$) indicated that the physicochemical and hydromorphological variables were low intercorrelated. Still, HQ was considered a part of the EQ gradient.

We used species scores along axis 1 (EQ gradient) to define species ecological preferences (Fig. 4b). Species with scores below the 25% quartile (-0.41) were considered indicators of high EQ ($n = 44$), as these represent the species whose preferences were restricted to the lowest values in the EQ gradient: low nutrient concentrations (SRP and DIN) and high OS and HQ. Those species with scores within the 25% and 75% percentile ($n = 77$) were considered tolerant species, with preferences in the intermediate values in the EQ gradient. And those species with scores above the 75% percentile (0.15) were considered indicators of low EQ ($n = 40$), as these represent the species whose preferences were among the highest values in the EQ gradient: high nutrient concentrations and low OS and HQ. An indicator value (v) was assigned to each species group
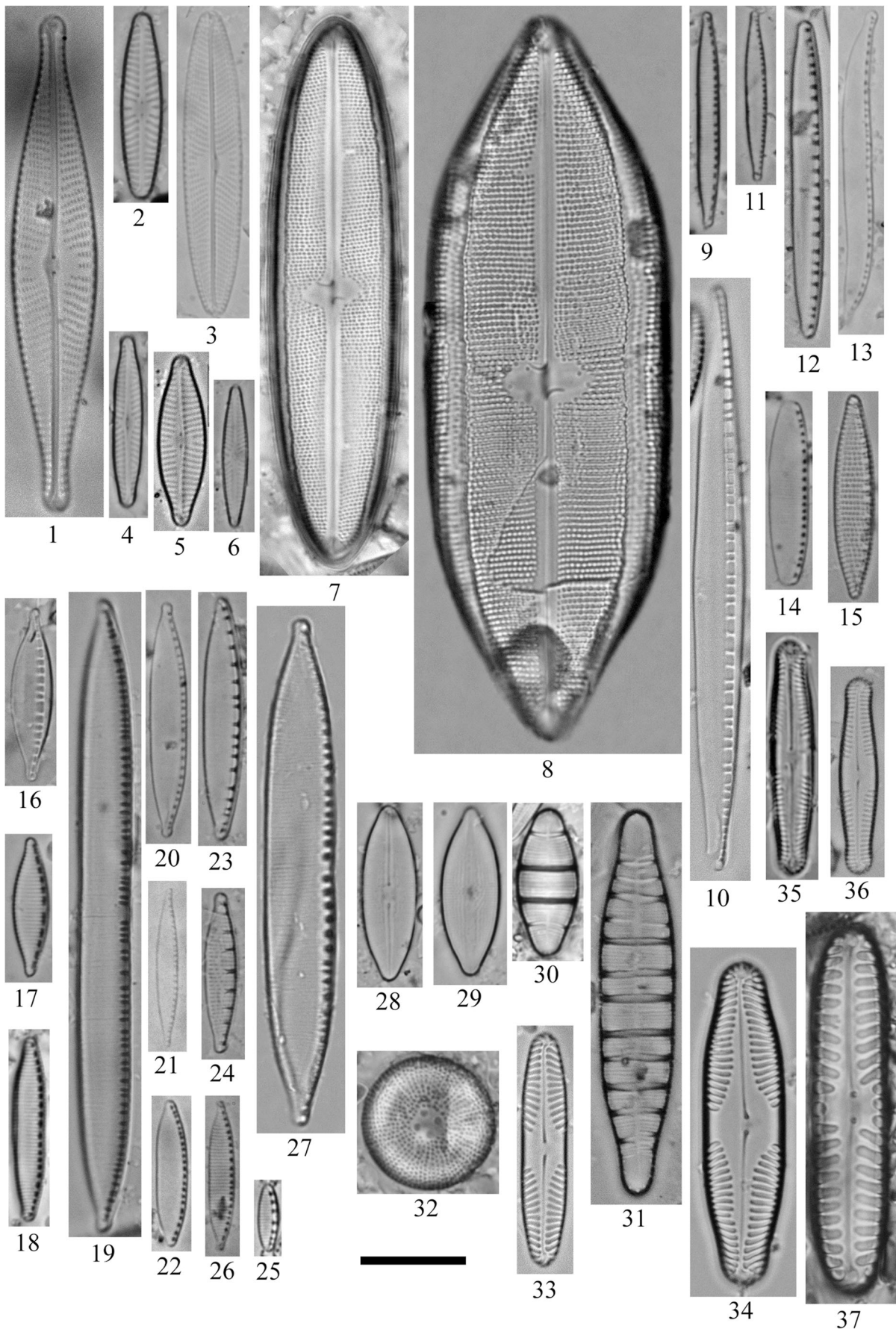
◄ **Fig. 8** Abundant and frequent diatoms in the BM included in the DEQI. 1, *Navicula rhynchocephala*; 2, *N. seibigiana*; 3, *N. symmetrica*; 4, *N. tenelloides*; 5, *N. veneta*; 6, *N. vilaplanii*; 7, *Neidium ampliatum*; 8, *Neidium sacoense*; 9, *Nitzschia acidoclinata*; 10, *N. acula*; 11, *N. archibaldii*; 12, *N. bacillariaeformis*; 13, *N. clausii*; 14, *N. communis*; 15, *N. costei*; 16, *N. dissipata*; 17, *N. fonticola*; 18, *N. frustulum*; 19, *N. linearis*; 20, *N. palea*; 21, *N. paleacea*; 22, *N. pusilla*; 23, *N. recta*; 24, *N. solgensis*; 25, *N. soratensis*; 26, *N. supralitorea*; 27, *N. umbonata*; 28–29, *Nupela praecipua*; 30, *Odontidium mesodon*; 31, *O. rostratum*; 32, *Orthoseira roeseana*; 33, *Pinnularia acoricola*; 34, *P. anglica*; 35, *P. appendiculata* var. *amaniana*; 36, *P. bertrandii*; 37, *P. borealis*. Scale bar = 10 μm

as follows: $v = 1$ to species representing high EQ, $v = 3$ to tolerant species, and $v = 5$ to species representing low EQ. Species and their indicator value are presented in Table 2, and its microphotographs are in Figs. 5, 6, 7, 8, 9, and 10 in order to properly use the DEQI. The five most common and frequent in each group are mentioned below.

We recognized *Achnanthidium minutissimum*, *Cocconeis placentula*, *Gomphonema lagenula*, *Planothidium cryptolanceolatum*, and *Rhoicosphenia* sp. among the species that indicated high EQ ($v = 1$); *Fragilaria capucina*, *Navicula cryptotenella*, *N. gregaria*, *N. rhynchocephala*, and *Reimeria sinuata* in the tolerant species group ($v = 3$); and *Craticula subminuscula*, *Nitzschia palea*, *N. soratensis*, *Sellaphora cosmopolitana*, and *S. saugerresii* as species that indicated low EQ ($v = 5$).

Species relative abundances and their indicator value were used to calculate the Diatom Ecological Quality Index (DEQI) using the formula adapted from Pantle and Buck (1955). The DEQI for a given site was calculated by ascribing an indicator value of 1 to those species not included in Table 4. The index values ranged from 1 to 5 indicating five different EQ following those established by the WFD (EC 2000) (Table 3). High EQ represents almost pristine conditions in reference sites, good EQ represents that there is still a natural structure and function in the aquatic ecosystem, moderate EQ indicates slightly disturbance given by nutrient increase, organic pollution, or hydromorphological alterations, poor EQ indicates severe disturbance, where the structure and function in the ecosystem are almost lost, and bad EQ represents a total loss of these.

From the training set used to develop the DEQI, the index was calculated resulting in four sites with a high EQ, 23 sites with good EQ, 11 sites had moderate EQ, three sites had poor EQ, and four had bad EQ (Table 4).

DEQI validation

We tested the DEQI to prove its performance summarizing the EQ in a new test set from twelve sites which represented the different conditions in the BM including pristine areas in headwaters to human-altered urban areas

in lower reaches. It presented a strong positive correlation with DIN, moderate positive correlations with K_{25} and SRP, and strong negative correlation with OS and moderate negative correlation with HQ ($p < 0.05$ for all correlations) (Fig. 11). In this sense, as the DEQI scores increased, it reflected an increase in nutrient concentrations (especially DIN over SRP), mineralization (K_{25}), organic pollution (OS as a proxy), and hydromorphological alterations.

Discussion

Different human activities were detected as the streams flowed through the BM, including the presence of hydraulic infrastructure (channels and dams), the construction of bridges or roads, fish farming, agriculture, cattle raising, unregulated tourism, or irregular human settlements, resulting in nutrient enrichment (phosphorous and nitrogen), decrease in dissolved oxygen concentration, and low hydromorphological quality (due to the loss of velocity and continuity of flow). This condition highlights the increase in the degradation of ecological quality, which leads to the loss of habitat and ecosystem services, and in some cases to a risk to human health (Mazari-Hiriart et al. 2014). Yet, we still found some sites (some headwaters) with oligotrophic conditions, permanent water flow, and good hydromorphological quality, recognized as reference conditions in the BM by Carmona-Jiménez and Caro-Borrero (2017), where they found some macroinvertebrate families and macroalgae species associated with these conditions, establishing a preliminary baseline for bioassessment in these aquatic ecosystems in Central Mexico. Since different biological groups respond to different stressors (EC 2000), it would be desired to construct metrics based on these other biological groups to perform an integrated evaluation of the ecosystems ecological quality.

Organic pollution and eutrophication (using orthophosphate as a proxy) are some factors to which diatoms respond, and thus, several biotic indices have been developed to monitor such factors (Prygiel and Coste 1993; Whitton and Kelly 1995; Kelly and Whitton 1995). Many scientists combine these referring to them as eutrophication in a broad sense as organic pollution and eutrophication of the water are highly cyclical correlated events (Branco 2005; Esteves 2011; Schneider et al. 2014; Dupas et al. 2015; Lobo et al. 2015). Other physical factors dependent of hydromorphology, such as water flow, influence diatom community structure as well (Gomà et al. 2005). In this sense, indices like the Trophic Water Quality Index (Lobo et al. 2015) and the DEQI have been developed using multivariate analysis, to reflect a more consistent, robust, and objective way to determine the ordination of species along local environmental gradients defined by
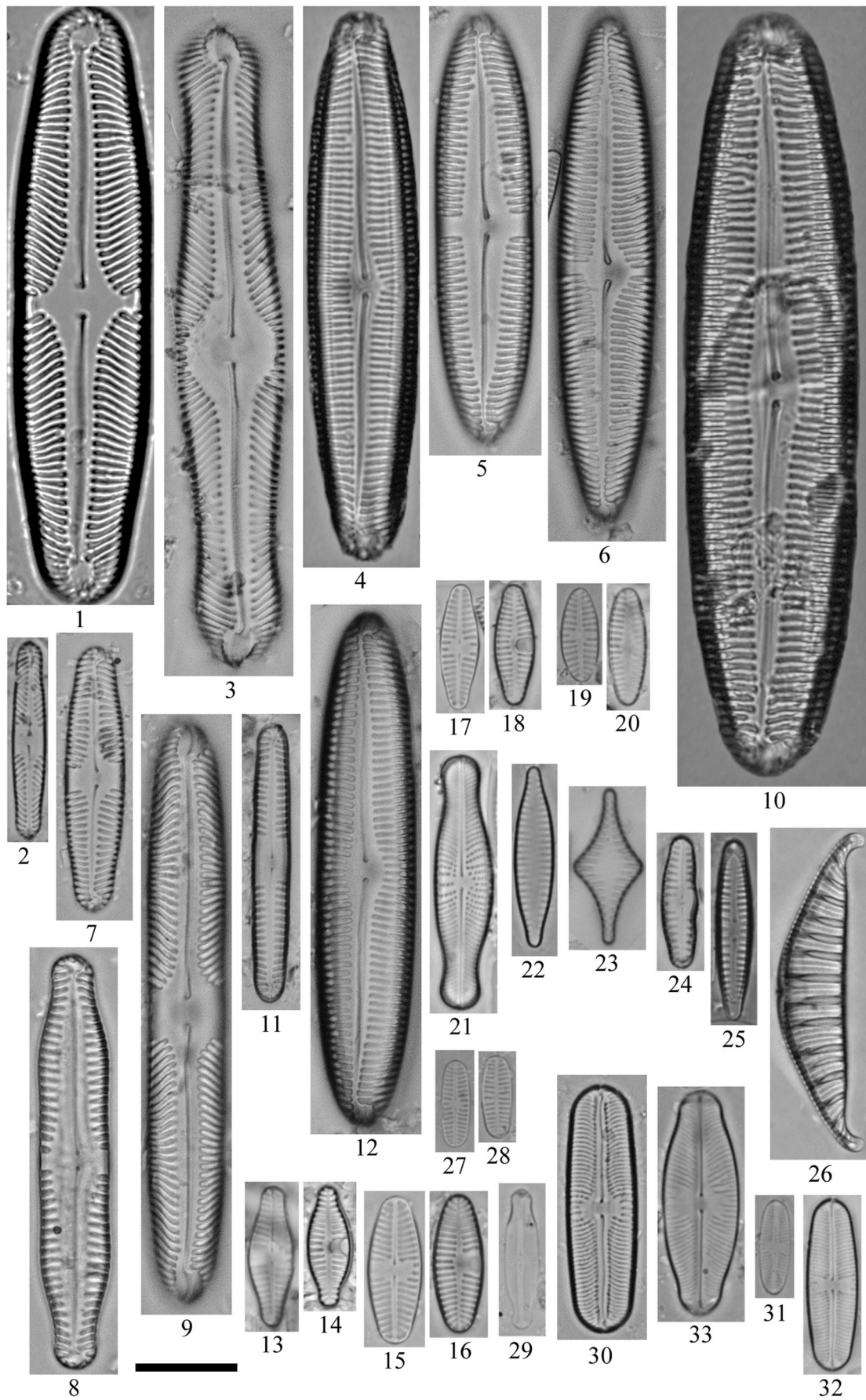
◀ Fig. 9 Abundant and frequent diatoms in the BM included in the DEQI. 1, *Pinnularia divergens*; 2, *P. divergentissima*; 3, *P. erratica*; 4, *Pinnularia* frequentis; 5, *P. inconstans*; 6, *P. johndonatoi*; 7, *P. microstauron*; 8, *P. nodosa*; 9, *P. peragalli*; 10, *P. reichardtii*; 11, *P. sinistra*; 12, *P. subcommutata* var. *nonfasciata*; 13–14, *Planothidium biporomum*; 15–16, *P. cryptolanceolatum*; 17–18, *P. frequentissimum*; 19–20, *Platessa conspicua*; 21, *Prestauroneis protractoides*; 22, *Pseudostaurosira brevistriata*; 23, *Pseudostaurosira* sp.; 24, *Reimeria sinuata*; 25, *Rhoicosphenia* sp.; 26, *Rhopalodia rupestris*; 27–28, *Rossithidium nodosum*; 29, *Sellaphora cosmopolitana*; 30, *S. laevissima*; 31, *S. nigri*; 32, *S. pseudopupula*; 33, *S. pupula*. Scale bar = 10 μm

physical, chemical, and hydromorphological factors acting jointly in the ecosystems.

The suitability of a biotic index relies greatly on how many species are included in it from those integrating the local flora from the region where we want to use it; besides, species distribution and their ecological preferences respond not only to water quality but also to regional and physiographical factors (Álvarez-Blanco et al. 2011). In this matter, it was important to recognize the regional diatom flora in the BM, thus identifying the frequent and abundant species that significantly contributed for determining the community structure. And even though most of the species included in the DEQI are widely distributed in other temperate regions and included in other metrics (Cantonati et al. 2017), it was important to study species response to local environmental gradients, without previous assumptions.

Physicochemical variables explained more variation in diatom assemblages, since these aquatic photosynthetic organisms respond directly to eutrophication gradients (Wetzel 1983; Hill et al. 2001; Lobo et al. 2015; Stevenson et al. 2010). Yet, for a more solid diatom-based assessment, it has been denoted that it is important to quantify the influence of other hydromorphological stressors affecting these ecosystems (Bere et al. 2016) like the native vegetation cover, presence of dams, channel modifications, or human activities, which are included in the HQ evaluation. The greatest example of this was the development of some common planktonic species like *Cyclotella menenghiniana*, *Discostella stelligera*, or *Fragilaria crotonensis* (observed with cell content before chemical oxidation of samples) in sites post-dams. For better understanding of the influence of hydromorphological characteristics in diatom assemblages in the BM, individual variables should be considered to develop a more complete dataset in further campaigns.

The five most abundant species and with grater distribution, representing each indicator group, were used to discuss the ecology of the species present in the index. Within the species included in the group representing high EQ, we found *Achnanthidium minutissimum*, considered a representative of oligotrophic environments and with low tolerance to eutrophication (Kelly and Whitton 1995; Segura-García et al. 2012;

Lobo et al. 2015). *Cocconeis placentula* has been reported as a species tolerant to nutrient enrichment by Van Dam et al. (1994), yet, it also has been reported in low nutrient concentration environments (Kelly and Whitton 1995; Abuhatab-Aragón and Donato-Rondón 2012; Carmona-Jiménez et al. 2016). This species has been described with several varieties, and some authors do not differentiate between them, so the subsuming of them has blurred the autoecology of these taxa (Jahn et al. 2009). In the BM, *C. placentula* was a widespread species, but it was abundant in headwaters with low nutrient concentration. Therefore, until further analyses to distinguish between the *Cocconeis* taxa within the *placentula* species complex in the BM, we considered it as indicator of high EQ. *Gomphonema lagenula* has been recently separated from the broad *Gomphonema parvulum* complex by morphological and molecular data, with an epitype from a close region in Central Mexico (Abarca et al. 2014). In that study, the authors mention that this species occurred in an anthropogenic influenced river, yet no physicochemical information nor abundance information are provided, although they point it with a tropical distribution. In the BM, it was widespread and abundant in headwaters with low nutrient concentrations and high OS and HQ; hence, this is an important opportunity to contribute towards the understanding of this tropical species ecological preference. Another common species in this group was *Planothidium cryptolanceolatum*; this species was used to be identified as *P. lanceolatum* (Brébisson ex Kützing) Lange-Bertalot in the BM (Ramírez-Vázquez et al. 2001; Carmona-Jiménez et al. 2016), a species with a wide ecological amplitude and widely distributed (Cantonati et al. 2017). Yet, Jahn et al. (2017) recently described *P. cryptolanceolatum* through a polyphasic approach including populations from Central Mexico, and our populations are consistent with its morphological and morphometrical characteristics. Our populations were distributed in headwaters and middle reaches of these mountain streams with low nutrient concentrations and good HQ as previously reported by Carmona-Jiménez et al. (2016) (as *P. lanceolatum*). In this matter, we can contribute towards the understanding of the species biogeography and autoecology. *Rhoicosphenia* sp. has previously been recorded as *R. abbreviata* (C. Agardh) Lange-Bertalot in other studies in the Basin of Mexico. Yet, the morphology, morphometry, and autoecology of *Rhoicosphenia* sp. differ from *R. abbreviata*, since the latter has been described to be widely distributed in mesotrophic to eutrophic rivers and thus used as an indicator of eutrophication and pollution (Van Dam et al. 1994; Kelly and Whitton 1995; Levkov et al. 2010). This species was abundant in most headwaters with low nutrient concentration and good hydromorphological quality; therefore, the identity of these taxa should be investigated.

Within the tolerant species, we recognized *Fragilaria capucina*, a species with an ecological amplitude not well defined, found in oligotrophic to meso-eutrophic freshwater
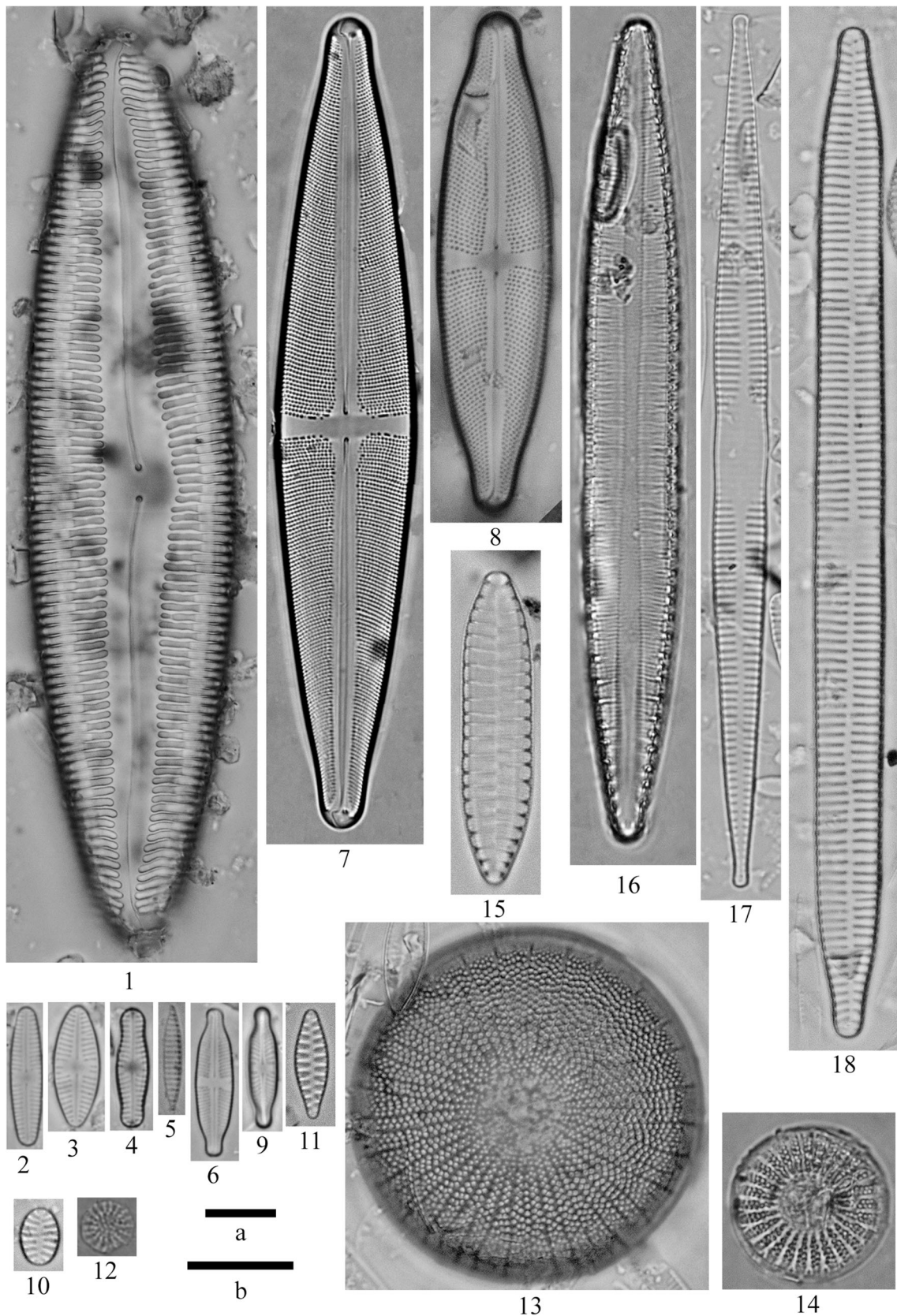
Fig. 10 Abundant and frequent diatoms in the BM included in the DEQI. 1, *Pinnularia* sp.; 2, *S. saugerresii*; 3, *Sellaphora* sp. 1; 4, *Sellaphora* sp. 2; 5, *Simonsenia delognei*; 6, *Stauroneis kriegeri*; 7, *S. phoenicenteron*; 8, *S. subgracilis*; 9, *S. thermicola*; 10, *Staurosira venter*; 11, *Staurosirella* sp.; 12, *Stephanodiscus minutulus*; 13, *S. niagarae*; 14, *S. oregonicus*; 15, *Surirella angusta*; 16, *S. muscicola*; 17, *Ulnaria acus*; 18, *U. ulna*. Scale bar = 10 μm (a, 1 and 7; b, the others)

Table 3 DEQI scores and their ecological quality

DEQI	Ecological quality	Description
1.0–1.5	High	At least 75% of cell abundance are indicator species of high EQ
1.5–2.5	Good	At least 25% of cell abundance are indicator species of high EQ
2.5–3.5	Moderate	At least 50% of cell abundance are tolerant species
3.5–4.5	Poor	At least 25% of cell abundance are indicator species of bad EQ
4.5–5.0	Bad	At least 75% of cell abundance are indicator species of bad EQ

Table 4 Sites ecological quality calculated with the DEQI

EQ	High	Good	Moderate	Poor	Bad
Sites	CU3, LC1, SD1, SI1	AM1–3, CU1–2,CX1, ES1–2, LR1–2, MG1–2,5, SD2,5, SI2, SR1–6, TL1	CT1–2, CU5–7, LR3, MG3, SD4, SR7, TL2–3	CU4, MG4,7	CX2, MG6, SD3, SR8

Sites codes provided in Table 1

habitats (Cantonati et al. 2017). *Navicula cryptotenella*, a cosmopolitan species with a wide spectrum of tolerance to nutrient enrichment and organic pollution (Van Dam et al. 1994; Kelly and Whitton 1995; Lobo et al. 2015), has been reported from oligo to mesotrophic conditions in the upper Lerma Basin, in Central Mexico (Segura-García 2010), which coincides with its distribution within the Basin of Mexico. *N. gregaria* is considered a tolerant species to eutrophication and pollution, also associated with high conductivity (Kobayasi and Mayama 1989; Van Dam et al. 1994; Kelly and Whitton 1995; Lobo et al. 2015; Mora et al. 2017). *Navicula rhynchocephala* has been considered tolerant to eutrophication (Van Dam et al. 1994; Segura-García et al. 2010;

Carmona et al. 2016), occurring in some headwaters and most middle reaches with increased nutrient concentration. Moreover, *Reimeria sinuata* is a widely distributed species in siliceous streams over a wide range of trophic levels (Cantonati et al. 2017).

Within the species included in the group with preference for low EQ, we found *Craticula subminuscula*, considered highly tolerant to eutrophication and with preference for heavily polluted environments (Kobayasi and Mayama 1989; Van Dam et al. 1994; Segura-García et al. 2012; Lobo et al. 2015; Mora et al. 2017). *Nitzschia palea* is a widespread diatom recognized as highly tolerant to organic pollution (found in mesosaprobic to polysaprobic environments) and
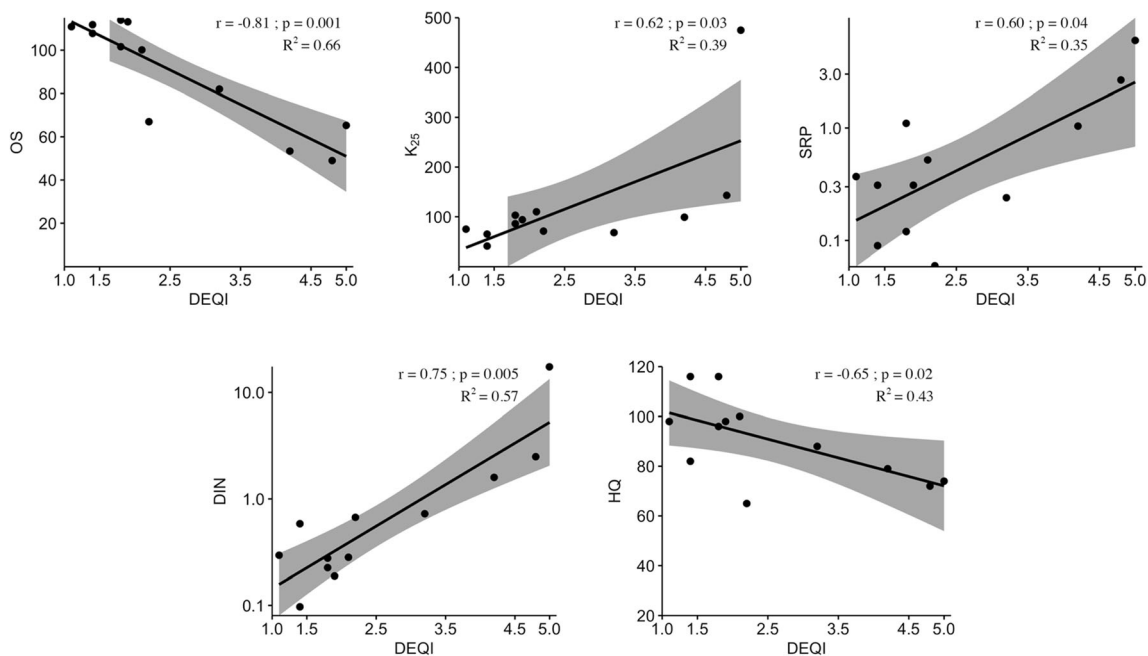

Fig. 11 Spearman's rank correlations between the DEQI and measured environmental variables from the test set

eutrophication (indicator of hypereutrophic conditions) (Lange-Bertalot 1979; Kobayasi and Mayama 1989; Van Dam et al. 1994; Potapova and Charles 2003; Lobo et al. 2010, 2015; Segura et al. 2012; Mora et al. 2017). *N soratensis* has been reported previously as *N. inconspicua* Grunow in some streams of the BM (Carmona-Jiménez et al. 2016), yet with scanning electron microscopy, we identified every population as *N. soratensis*. These two species are easily confused because of their similar valve shape, but they have different environmental preferences. *N. soratensis* is a strictly freshwater species with preference for slightly eutrophic waters (Morales and Vis 2007), whereas *N. inconspicua* extends from freshwater into brackish and marine waters (Trobajo et al. 2013). *Sellaphora cosmopolitana* is described as a tolerant species to both eutrophication and organic pollution (Bey and Ector 2013). Moreover, *Sellaphora saugerresii* is a species occurring in highly eutrophic freshwater habitats (Cantonati et al. 2017).

Comparing the EQ obtained using the DEQI with the trophic status and HQ of the sites from the training set, we could conclude that the trophic status and HQ evaluation were insufficient on their own to reflect all the possible stressors of the ecological status of these systems. In addition, a calibration is needed to establish the reference conditions for nutrient concentrations and HQ, highlighting that the use of biological metrics could provide a suitable framework (Skoulikidis et al. 2004, 2006). Moreover, as the DEQI was developed from the ordering of species along an environmental gradient of multiple factors acting jointly together, it reflected a consistent, robust, and objective way to determine the species response to the local stressors occurring in these peri-urban streams, covering a gap in the need of these methods in Latin America (Lobo et al. 2019).

Conclusions

We found a rich diatom flora in the mountain streams in the Basin of Mexico (BM), and through the analysis of species ecological preferences within the region, we proposed a new metric to assess the ecological quality (EQ) of these aquatic ecosystems. Even though the objective of the campaigns in this study was to cover a large area in the BM to have a representation of different scenarios that occur in the basin (from "pristine" conditions within PAs, rural areas with agricultural, livestock, or fish farming activities, to urban areas), there is still work to do to understand the specific influence of hydromorphological characteristics and seasonal effects on diatom assemblages, which could be integrated in a future calibration of the index. Still, we propose the use of the DEQI to complement the EQ evaluation and improve sustainable management of rivers and streams in Mexico, while filling the gap in the need of biological methods for

environmental biomonitoring in Latin America. Finally, we would like to denote that the evaluation of EQ is not confined to a single taxonomic group but requires understanding of different groups within the basin to conduct an integrative assessment, since different groups respond to different pressures.

Compliance with ethical standards

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