Topics of limnological research in Mexico

Coordinator
Alfredo Pérez Morales

UNIVERSIDAD DE COLIMA

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This book is dedicated to
Dr. Singaraju Sri Subrahmanya Sarma,
in gratitude for all his teachings in the world of limnology.

Index

Phytoplankton from Two Dams in Central Mexico

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Abstract

Reservoirs are environments where phytoplankton develop and sustain food webs. This study explores the structure of the phytoplankton community in two dams and its relationship with six limnological variables from El Llano and Taxhimay reservoirs during September and October 2022. Microalgae were collected in surface layer in three sampling sites with a 20 µm net mesh opening, which were preserved with formaldehyde. The specific richness, the Shannon-Wiener index, the canonical correspondence analysis (CCA), the association quotient, organic contamination, and diatom index were determined. The samples obtained during the two months were markedly different; both ecosystems recorded a warm temperature from 15 to 22°C, pH between 7-8, well oxygenation (5.8 to 9.6 mg/l), low mineralization, and conductivity. Fifty-five species were determined, and six are new records for Mexico. The abundance by taxonomic classes in all the sampling stations was markedly higher for Bacillariophyceae; in particular, observed in Taxhimay in T1 October, with 21,476 cell/ml. *Asterionella formosa* was dominant in both reservoirs, with 79.9 to 96.4 % of the abundance. The H' was recorded from 0.21 to 1.54 bits/ind., it represents variation between the sampling stations and the study months. The CCA positively related conductivity and temperature with *Aulacoseira granulata* var. *angustissima*, *A. granulata* f. *curvata*, *Monactinus simplex,* and *Microcystis panniformis*. The three indexes indicate eutrophic environments. Furthermore, it is recommended to monitor phytoplankton, in particular, the abundance of *Microcystis* and other Cyanophyceae, as they are harmful algae.

Keywords

Abundance, *Asterionella formosa*, *Aulacoseira granulate*, Bioindicators, Specific richness, State of Mexico.

Introduction

In Mexico, there are more than 10,000 dams that are used for the generation of electrical energy, irrigation, flood control, food production, storage of drinking water, and ecotourism, among others (Arredondo-Figueroa & Flores-Nava, 1992; De la Lanza-Espino & García-Calderón, 2002); the study of these ecosystems is essential to know their relevance and impacts, as well as maintaining the availability of the ecosystem services they provide (Domínguez, 2019), which are essential for maintaining human society's well-being and sustaining life in general. However, despite their recognized importance, inland aquatic environments are among the most threatened ecosystems around the world (WWF, 2022). Climate change, domestic and industrial waste dumping, pollution from pesticides, invasions by exotic species, eutrophication and habitat destruction are the main threats to water bodies (Ghangrekar & Chatterjee, 2018). The diversity of species living in these ecosystems is dominated by organisms with poor swimming ability, such as plankton (Dodds & Whiles, 2010). Within this group, phytoplankton is a diverse community of microorganisms composed of different phyla, such as Cyanobacteria, Bacillariophyta, Chlorophyta, Charophyta, Chrysophyta, Dinoflagellata, Euglenophyta, among others (Wehr et al., 2015). They are important since they fix atmospheric carbon, produce oxygen, and generate biomass through photosynthesis, which is why they constitute the basis of the food webs of aquatic ecosystems (Carrasco-Vargas et al., 2014). Some phytoplankton species are used as biological indicators of water quality due to their short life cycle, and they are sensitive to changes in temperature, dissolved oxygen, pH, turbidity, conductivity, alkalinity, phosphorus, nitrogen, and silica (De Lanza-Espino & García-Calderón, 2002).

Phytoplankton as a bioindicator is a powerful tool that has been used to determine water quality where some change in conditions causes variation in the presence, absence, or abundance of some species, which provides us with information about the trophic state of the habitat where they are found (Bellinger & Sigee, 2010). Bioindicators may have different degrees of tolerance to deterioration; some species are tolerant, while others are pretty sensitive, which helps determine conditions of contamination or eutrophication. In this way, there will be indicator species of good water quality with low levels of eutrophication and other abundant species in eutrophic environments (Nguyen, 2003). For example, some studies have reported that *Microcystis*, *Aphanizomenon*, *Planktothrix*, *Dolichospermum*, *Cylindrospermopsis,* and *Oscillatoria* (Cyanobacteria); are indicators of eutrophic habitat. While, diatoms such as *Melosira* and *Fragilaria* have been found in waters contaminated with organic matter (Valeriano-Riveros et al., 2014), and Chlorophyta such as *Pandorina* and *Scenedesmus* are referred to contaminated with domestic sewage water (Chandel et al., 2023).

In the central area of Mexico, there are some limnological and phytoplankton analyses from the Zimapan Dam, Querétaro-Hidalgo where González-Fernández et al. (2023) indicated that phytoplankton richness suggests a eutrophic system with dominance of diatoms, Cyanophyta, and Chlorophyta with proliferations of *Microcystis aeruginosa*, *Botryococcus,* and *Stephanocyclus*. In another study, Ortega-Murillo et al. (2007) investigated the trophic state of the Mintzita Dam (Michoacán), based on the cellular concentration and distribution of phytoplankton, where they determined a mesotrophic to eutrophic condition with a dominance of *Ulnaria ulna* and *Cocconeis placentula* var. *euglypta*. In Puebla, González-Fernández et al. (2013) analyzed the composition of phytoplankton in three eutrophic reservoirs: the La Laguna, Los Reyes, and Necaxa dams, where the dominant species were *Woronichinia naegeliania*, *Microcystis wesenbergii*, *M. aeruginosa*, *Aulacoseira granulata*, *Fragilaria crotonenesis,* and *Asterionella formosa*. For Morelos, Carrasco-Vargas et al. (2014) studied the phytoplankton of the eutrophic-hypereutrophic El Abrevadero reservoir with representatives of Euglenophyceae, Chlorophyceae, Cyanophyceae and Bacillariophyceae.

The State of Mexico is one of the entities where a high number of phytoplankton species has been recorded, with 668 species distributed in 14 classes, 40 orders, 81 families, and 209 genera, with greater dominance of green algae (307 species), followed by diatoms, cyanoprokaryotes, euglenids, with 262, 65 and 13 species, respectively (Garduño-Solórzano et al., 2009). For the tropical reservoir Valle de Bravo, the composition is dominated by *Cyclotella ocellata*, *Fragilaria crotonensis*, *Woronichinia naegeliana,* and *M. wesenbergii* that generate high biomass as a result of the trophic conditions of the system, in particular when the temperature and nutrient levels are high. In contrast, when the water level drops to a difference of up to 12 m, an increase in the biomass of planktic diatoms and a decrease in harmful algae have been evidenced (Valeriano-Riveros et al., 2014). Also, we know that this reservoir supplies drinking water to Mexico City through the Cutzamala system and that the cyanobacteria that develop as *Microcystis smithii*, *M. aeruginosa*, *M. viridis*, *M. flos-aquae*, *Aphanocapsa formosa,* and *Dolichospermum crassum* are species that produce microcystins with maximum values of 71 μg/l from July to September. Based on this information, the ecosystem requires constant monitoring to evaluate water quality (Martínez-Jerónimo et al., 2022). In particular, El Llano and Taxhimay dams in the State of Mexico are sources for social development and economic activities. Razo-Paredes et al. (2016) analyzed the environmental and microbiological variables in El Llano Dam from July 2015 to May 2016, where the physical and chemical conditions favored the presence of diatoms and cyanobacteria. Additionally, Toledo-Trejo and Razo-Paredes (2018) indicated that the nutrients SO_4^{-2}, NO_3^{-}, and PO_4^{-3} contributed to the growth of *M. aeruginosa* from the Taxhimay Dam. This reveals that knowledge of microalgae in these reservoirs is scanty, so this work explores the structure of the phytoplankton community in two dams (El Llano and Taxhimay) and its relationship with some limnological variables during September and October 2022.

Materials and Methods

Study Area and Sampling

El Llano Dam belongs to the physiographic province of the Trans-Mexican Volcanic Belt, and is located at the geographical coordinates 19°39’24”N 99°30’28”W (Fig. 1A), in the town of San Jerónimo Zacapexco in the municipality of Villa del Carbón, State of Mexico. It is an ecotourism park with an area of 40 thousand m^2, at 2,800 m a.s.l. It is one of the primary sources of water supply for the nearby community. According to the Köppen classification, the climate is temperate-cold (Cw), located in a forested area surrounded by rivers (Toledo-Trejo & Razo-Paredes, 2018). The vegetation is mixed forest, pine forest, oak forest, and induced grassland, including cropped and reforested areas, and 73 species of vertebrates are known from the area (Moreno-Díaz, 2014).

The Taxhimay Dam is between 19°49’51’’N and 99°23’46’’W (Fig. 1B) in Villa del Carbón, at 2,200 m a.s.l. The water body covers an area of 365 ha, with 42 billion m^3. It is characterized by being an area of important outcrops of springs that spring up in the wooded region due to the high forest cover that the Cerro de la Bufa and its foothills have; it has a high permeability caused by the predominance of igneous materials, which favor high rainwater retention (Toledo-Trejo & Razo-Paredes, 2018).

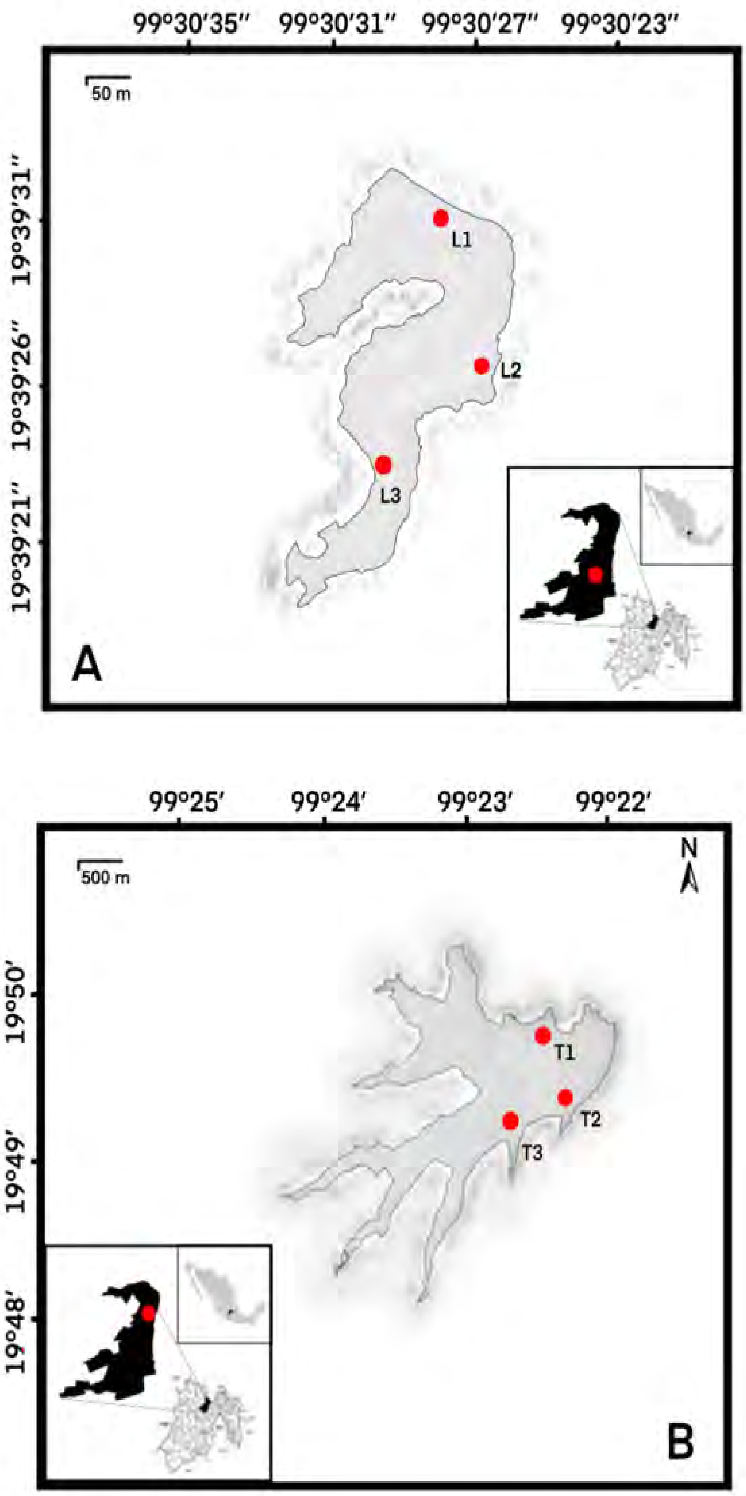

Figure 1. Study Area A) El Llano Dam L1, L2, L3;
B) Taxhimay Dam T1, T2, T3, Red Dots Indicate the Sampling Stations.

Sampling sites were selected randomly in both dams (Table 1) in months with markedly different precipitation records; for September 2022 it was 150.5 mm and for October 2022 with 69 mm of precipitation (Conagua, 2023). 12 samples were obtained from the surface layer, where 10 l of water was filtered for each one with a net mesh size of 20 µm. From the above, in a final volume of 50 ml, the biological material was preserved with formaldehyde at a final concentration of 4 %.

Limnological Variables

A multiparametric model HANNA HI-9146 was used to record temperature, dissolved oxygen, and the percentage of dissolved oxygen saturation. The determination of total alkalinity was carried out by titration (APHA et al., 2005). In addition, the pH was measured using a Cole Parmer potentiometer, model Digi-sense, and the electrical conductivity with a Hanna equipment, model HI98312, in the surface layer of the water column.

Phytoplankton

The phytoplankton was quantified by recording the volume of one ml of sample, and transferred to a preparation where it was placed on the stage under 200X and 400X in a Leica optical microscope (Semina, 1978). In addition, images were obtained with a 10 MP Rising Cam model C3CMOS 10000KPA camera. The works of Bourrelly (1981), Comas (1996), Komárek and Anagnostidis (2002), John and Tsarenko (2002), Figueroa-Torres et al. (2008), Bellinger and Sigge (2010), Wehr et al. (2015), Bicudo et al. (2016), Bicudo and Menezes (2017), Ponce-Márquez et al. (2019), and Bojorge-García and Cantoral-Uriza (2021) were used for taxonomic determination based on the classification indicated in the algae database (Guiry and Guiry, 2023).

Statistical Analysis

To determine phytoplankton diversity, specific richness, and the Shannon-Wiener index, we used Magurran (2004). To categorize the phytoplankton species, an Olmstead-Tukey analysis was carried out according to Sokal and Rohlf (1981). The following criterion was applied: 1) Species with abundance and frequency values above the median were considered dominant; 2) Species with abundance values below the median, but above the median frequency were considered constant; 3) Species that showed values above the median abundance, but below the median frequency were occasional; 4) Species that recorded values below the median of both abundance and frequency were categorized as rare.

For Canonical Correspondence Analysis (CCA) we used the CANOCO 4.5 program (Ter-Braak, 1986). To normalize the data and ensure homoscedasticity, environmental variables (except pH) and phytoplankton abundances were transformed using the log (x+1) function. Forward selection, coupled with a Monte Carlo permutation test, was employed to assess the statistical significance of the relationships between environmental variables and species abundance.

To analyze the water quality of the dams from phytoplankton, different water quality indices were applied: *i*) The “association quotient” (CA) based on the criteria of Thunmarck (1945), Nygaard (1947) and Gayral (1954) which is calculated with the following formula CA=Cy+Ch+Ce+Eu/De, where the number of species is represented by Cy=Cyanophyceae, Ch=Chlorophyceae (Chlorococcales), Ce=Central diatoms, Eu=Euglenophyceae and De=Chlorophyceae (Desmidiales), where the CA is interpreted as <1=oligotrophic, 1.1 to 2.5=mesotrophic, 2.6 to 2.9=eutrophic and >3.0 saprotrophic (Ortega et al., 1994). *ii*) The organic pollution index (IP) of Palmer (1969), which is based on the reference of 20 phytoplankton genera that have been considered in 165 publications as tolerant to organic pollution in continental water bodies. The classification considers genera with a value of one when it is shallow organic contamination. At the same time, two indicates low organic contamination, three indicates intermediate conditions, four indicates moderate contamination, and five indicates high organic contamination. Based on the above, the following criterion was used: IP values ≥20 indicate environments with high organic contamination, IP values between 15 and 19 probable organic contamination, and IP <15 indicates low organic contamination. Finally, *iii*) Diatom Index (ID=Central diatoms/Pennal diatoms), which is based on the richness of Central and Pennal diatoms, where values above 0.2 are considered characteristic of eutrophic waters (Nguyen, 2003).

Results

Environmental Variables

Table 1 shows the values of the six physical and chemical variables examined at each station in both dams during September and October. Both reservoirs are well-oxygenated environments between 4.4 and 9.6 mg/l, poorly mineralized with 20-40 mg/l $CaCO_3$, with a general pH of 7.0 to 8.0, temperature between 15 and 22°C, and conductivity of 62 and 171 µS/cm.

Table 1. Values of the Physical and Chemical Variables in each Sampling Station of the El Llano (L) and Taxhimay (T) Dams, during September and October 2022.

Limnological parameter	September/2022			October/2022		
	L1	**L2**	**L3**	**L1**	**L2**	**L3**
1. Temperature (°C)	15.4	17	17.2	16.5	15.8	21.2
2. pH	7	9.1	8.8	7	7	7
3. Dissolved Oxygen (mg/l)	6.9	6.5	6.6	4.4	6.8	5.6
4. % Oxygen Saturation	67.5	107	95	41	64	52
5. Alkalinity (mg/l $CaCO_3$)	24	24	24	30	42	34
6. Conductivity (µS/cm)	62	68	67	70	70	70
	T1	**T2**	**T3**	**T1**	**T2**	**T3**
1. Temperature (°C)	21.2	21.8	20.5	19.9	19.3	19.2
2. pH	7.9	8	7.8	8	8	7
3. Dissolved Oxygen (mg/l)	5.8	6.1	5.3	7.7	8	9.6
4. % Oxygen Saturation	93.1	107	88.8	118	79.1	94.9
5. Alkalinity (mg/l $CaCO_3$)	30	20	48	80	50	60
6. Conductivity (µS/cm)	171	146	146	141	147	140

1, 2, 3 correspond to the sampling stations (station 1, station 2 and station 3).

Composition of Phytoplankton

Table 2 shows the specific richness for both dams, which totals 55 *taxa*, 45 for El Llano, and 36 for Taxhimay (Fig. 2), where 26 species were recorded in both dams.

Table 2. Phytoplankton Determined in each of the Selected Stations: L1, L2, L3 (El Llano Dam) and T1, T2, T3 (Taxhimay Dam) for September and October 2022, Where "X" Indicates the Presence and "0" Absence of the Taxon. The Olmstead-Tukey O-T Value for El Llano (L) /Taxhimay (T); Where C=Constant, D=Dominant, O=Occasional, R=Rare; * Corresponds to New Records for the Mexico, and ** New Records for the State of Mexico

		El Llano (L)						**Taxhimay (T)**					
Taxa	O-T L/T	L1	L2	L3	L1	L2	L3	T1	T2	T3	T1	T2	T3
		September/2022			October/2022			September/2022			October/2022		
Phylum Cyanobacteria ***Clase Cyanophyceae***													
Dolichospermum planctonicum (Brunnthaler) Wacklin, L. Hoffmann & Komárek 2009	C/D	X	0	0	X	X	0	0	0	X	X	X	X
**Coelomoron microcystoides Komárek 1989	C/-	X	0	0	X	0	0	0	0	0	0	0	0
Microcystis aeruginosa (Kützing) Kützing 1846	-/D	0	0	0	0	0	0	X	0	X	X	X	X
Microcystis botrys Teiling 1942	-/D	0	0	0	0	0	0	X	X	0	X	X	X
Microcystis panniformis Komárek, Komárkova, Komárkova-Legnerová, Sant'Anna, Azevedo & Senna 2002	-/D	0	0	0	0	0	0	X	X	X	X	X	X
Oscillatoria sp. Vaucher ex Gomont	-/R	0	0	0	0	0	0	X	0	0	X	0	0
Planktothrix agardhii (Gomont) Anagnostidis & Komárek 1988	-/D	0	0	0	0	0	0	0	X	0	X	X	0
Pseudanabaena sp. Lauterborn, 1915	R/O	X	0	0	0	0	0	X	0	X	0	0	0
**Radiocystis fernandoi* Komárek & Komárková-Legnerová 1993	R/R	X	0	0	0	0	0	X	0	0	0	0	0
Sphaerocavum sp. Azevedo & Sant'Anna, 2003	R/O	X	0	0	0	0	0	0	0	X	0	X	0
Synechocystis sp. Sauvageau, 1892	R/R	X	0	0	0	0	0	0	X	0	X	0	0
Woronichinia naegeliana (Unger) Elenkin 1933	-/D	0	0	0	0	0	0	0	0	0	X	X	X

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Phylum Chlorophyta* *Clase Chlorophyceae													
**Coenocystis* sp. Korshikov, 1953	C/R	0	0	X	X	0	0	0	0	0	X	0	0
Crucigenia sp. Morren, 1830	C/-	0	0	0	X	0	X	0	0	0	0	0	0
Eudorina sp. Ehrenberg 1832	D/-	0	X	X	X	X	X	0	0	0	0	0	0
Haematococcus lacustris (Girod-Chantrans) Rostafinski 1875	D/R	X	0	0	0	0	X	0	0	X	0	0	0
Hariotina reticulata P.A. Dangeard 1889	D/-	X	X	0	X	X	0	0	0	0	0	0	0
Monactinus simplex (Meyen) Corda	-/D	0	0	0	0	0	0	X	0	X	0	X	X
Mucidosphaerium pulchellum (H.C. Wood) C. Bock, Proschold & Krienitz 2011	D/D	X	X	X	X	X	X	0	X	0	X	X	X
***Neospongiococcum* sp. Deason, 1971	R/-	0	0	0	0	0	X	0	0	0	0	0	0
Nephrocytium sp. Nägeli, 1849	D/-	X	0	X	X	0	X	0	0	0	0	0	0
Oedogonium sp. Link ex Hirn, 1900	C/-	0	0	0	X	0	X	0	0	0	0	0	0
Oocystis sp. Nägeli ex A.Braun, 1855	D/R	X	X	X	X	X	X	X	0	0	X	0	0
Pandorina morum (O.F. Müller) Bory 1826	D/-	X	0	X	0	0	X	0	0	0	0	0	0
**Paulschulzia pseudovolvox* (P. Schulz) Skuja 1948	D/-	X	X	0	X	0	X	0	0	0	0	0	0
Sphaerocystis schroeteri Chodat 1897	D/-	X	X	X	X	0	X	0	0	0	0	0	0
**Yamagishiella* sp. H. Nozaki, 1992	D/-	X	X	0	0	X	0	0	0	0	0	0	0
Phylum Charophyta* *Clase Zygnematophyceae													
Cosmarium sp.1 Corda ex Ralfs, 1848	D/-	X	X	X	0	X	X	0	0	0	0	0	0
Cosmarium sp.2 Corda ex Ralfs, 1848	D/-	X	0	0	X	0	0	0	0	0	0	0	0
Mougeotia sp. C. Agardh, 1824	D/-	X	X	X	X	X	X	0	0	0	0	0	0
Staurastrum cingulum (West & G.S. West) G.M. Smith 1922	D/R	X	X	X	X	X	X	0	X	0	X	0	0
Staurastrum sp. Meyen ex Ralfs, 1848	R/R	0	0	0	X	0	0	0	0	0	0	0	X
Phylum Charophyta* *Clase Klebsormidiophyceae													
Elakatothrix sp. Wille, 1898	R/-	0	X	0	0	0	0	0	0	0	0	0	0

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Phylum Euglenophyta Clase Euglenophyceae													
Phacus sp 1 Dujardin, 1841	D/-	0	X	0	0	X	X	0	0	0	0	0	0
Phacus sp 2 Dujardin, 1841	C/-	0	X	0	X	0	0	0	0	0	0	0	0
Trachelomonas hispida (Perty) F. Stein 1878	D/R	0	0	X	0	0	X	0	0	0	X	0	0
Trachelomonas volvocina (Ehrenberg) Ehrenberg 1834	D/O	X	X	0	0	0	0	X	0	0	X	X	0
Trachelomonas rugulosa var. *rugulosa* (F. Stein) G.A. Klebs	C/R	X	X	0	0	0	0	0	0	0	X	0	0
Phylum Dinoflagellata Clase Dinophyceae													
Ceratium hirundinella (O.F. Müller) Dujardin 1841	R/D	0	0	X	0	0	0	0	0	X	X	X	0
Peridinium willei Huitfeldt-Kaas 1900	D/D	0	X	X	0	X	0	X	X	0	X	X	X
Peridinium sp.	-/R	0	0	0	0	0	0	0	0	0	X	0	0
**Peridiniopsis* sp. Lemmermann, 1904	C/R	0	X	X	0	0	0	0	0	0	X	0	0
Phylum Heterokontophyta Clase Chrysophyceae													
Dinobryon cylindricum O.E. Imhof 1887	D/D	X	X	X	X	0	X	0	0	0	0	0	0
Dinobryon sp.1 Ehrenberg, 1834	D/D	0	0	X	X	X	X	0	0	0	0	0	0
Mallomonas sp. Perty, 1852	D/D	X	X	X	0	0	X	X	0	X	X	0	X
Clase Mediophyceae													
**Acanthoceras cf. zachariassii* (Brun) Simonsen 1979	-/D	0	0	0	0	0	0	0	X	X	X	0	X
Clase Bacillariophyceae													
Achnanthes sp.	O/-	0	0	X	0	0	0	0	0	0	0	0	0
Asterionella formosa Hassall 1850	D/D	X	X	X	X	X	X	X	X	X	X	X	X
Cymbella mexicana	-/R	0	0	0	0	0	0	0	X	0	0	0	0
Fragilaria crotonensis Kitton 1869	C/C	X	X	0	0	0	0	X	X	X	0	0	0
Epithemia sp. Kützing, 1844	C/-	0	X	0	0	X	0	0	0	0	0	0	0
Frustulia sp. Rabenhorst, 1853	C/R	X	0	X	0	0	0	0	0	0	0	0	0
Navicula sp. Bory, 1822	R/R	0	0	0	X	0	0	X	0	X	0	0	0
Clase Coscinodiscophyceae													
Aulacoseira granulata f. *curvata* Simonsen, 1979	C/D	X	X	0	0	0	0	X	X	X	X	X	X
Aulacoseira granulata var. *angustissima* (O. Müller) Simonsen 1979	R/D	0	0	0	0	0	X	X	X	X	X	X	X

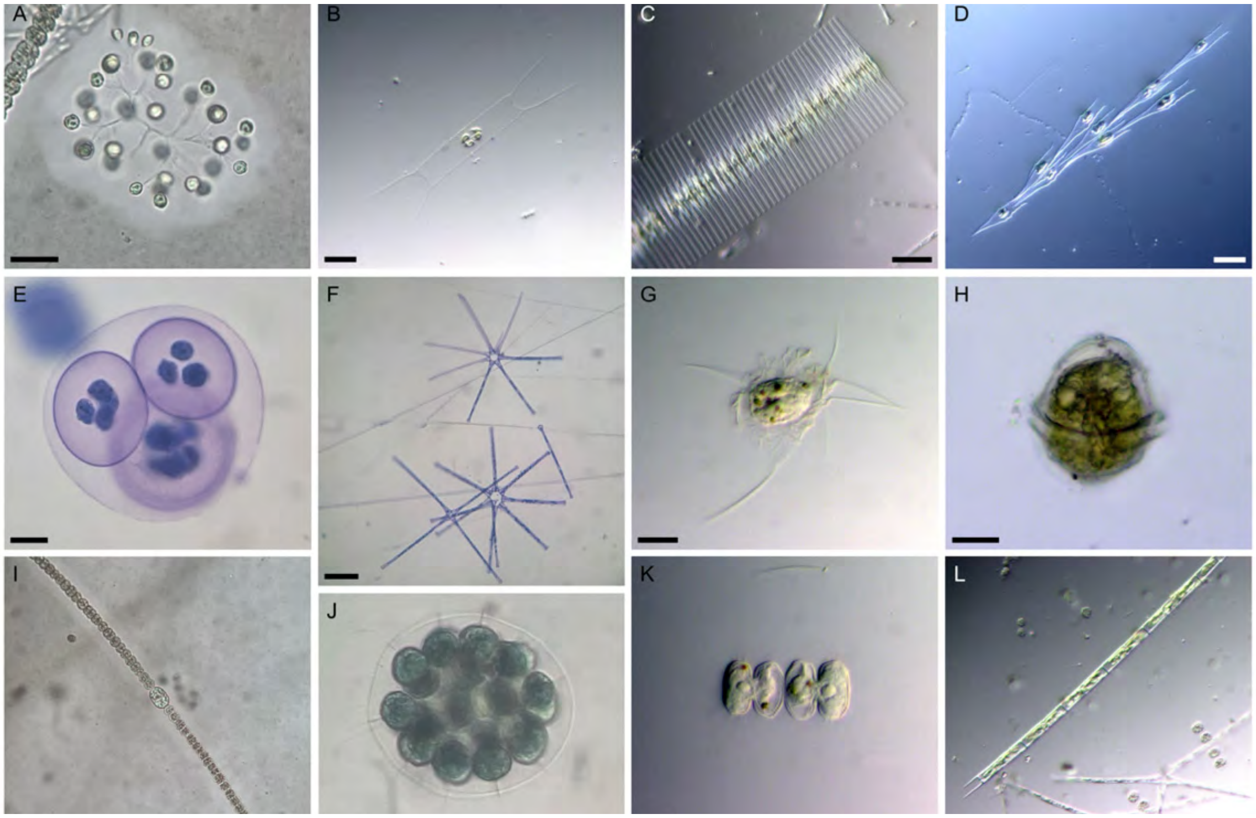


Figure 2. A) *Mucidosphaerium pulchellum,* B) *Acanthoceras cf. zachariassii,* C) *Fragilaria crotonensis,* D) *Dinobryon cylindricum,* E) *Paulschulzia pseudovolvox,* F) *Asterionella formosa,* G) *Mallomonas sp.* H) *Peridinium sp.* I) *Dolichospermum Ç planctonicum,* J) *Pandorina morum,* K) *Cosmarium sp.,* L) *Aulacoseira granulata var. angustissima*. Scale Bars E, G, J, K=10 µm, A, B, D, H=20 µm, C, L=25 µm, F, I = 30 µm.

Taxonomic records for El Llano and Taxhimay dams (Fig. 3) indicate ten classes. The percentages concerning specific richness were the following: Chlorophyceae (27.3 %), Cyanophyceae (21.8 %), Bacillariophyceae (12.7 %), Euglenophyceae and Zygnematophyceae (9.0 %), respectively, Dinophyceae (7.2 %), Chrysophyceae (5.4 %), Coscinodiscophyceae (3.6 %), Mediophyceae, and Klebsormidiophyceae (1.8 %), each.

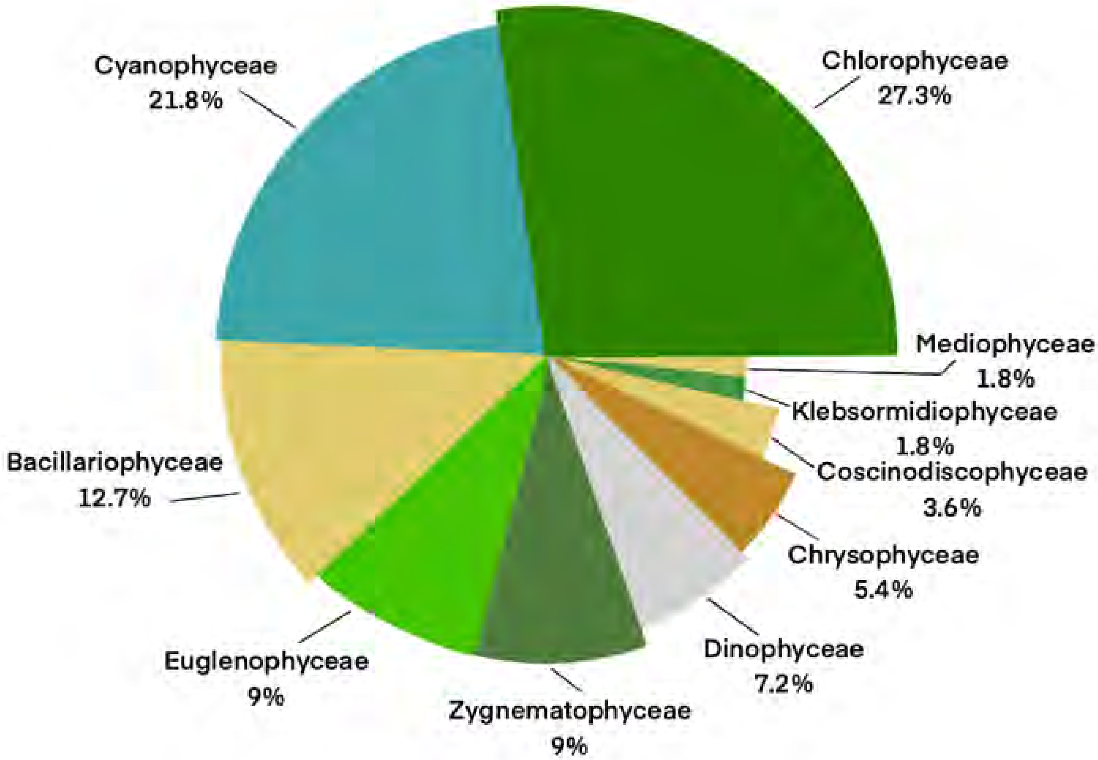


Figure 3. Percentage distribution by Taxonomic Classes of the Phycoflora Richness Recorded in the El Llano and Taxhimay Dams.

Based on the Olmstead-Tukey analysis, the following were recorded in El Llano: 22 dominant species, 12 constant, 10 rare, and 1 occasional. Of them, the most abundant was *Asterionella formo*sa, with a percentage that ranged between 79.9 and 96.4. Meanwhile, *Aulacoseira granulata* f. *curvata,* and *Phacus* sp. 2 were constant. For its part, in Taxhimay, there were 17 dominant species, for example, *Asterionella formosa*, *Microcystis panniformis*, *Woronichinia naegeliana*, *Acanthoceras* cf. *zachariassii*, 14 rare, 3 occasional, and 1 constant.

In Fig. 4A, the specific richness (S) is indicated in each of the sites where it is observed that in El Llano, the record with the highest richness was 27 *taxa* (L1 in September), followed by 25 taxa (T1 in October). In contrast, those with the lowest richness were stations T2 in September and L2 in October, with 12 and 14 *taxa*, respectively. In general, the *H'* index was highest in the Taxhimay Dam, with 1.54 bits/ind. in T2 in October, and the lowest was in El Llano, with 0.21 bits/ind. in the L2 in October station.

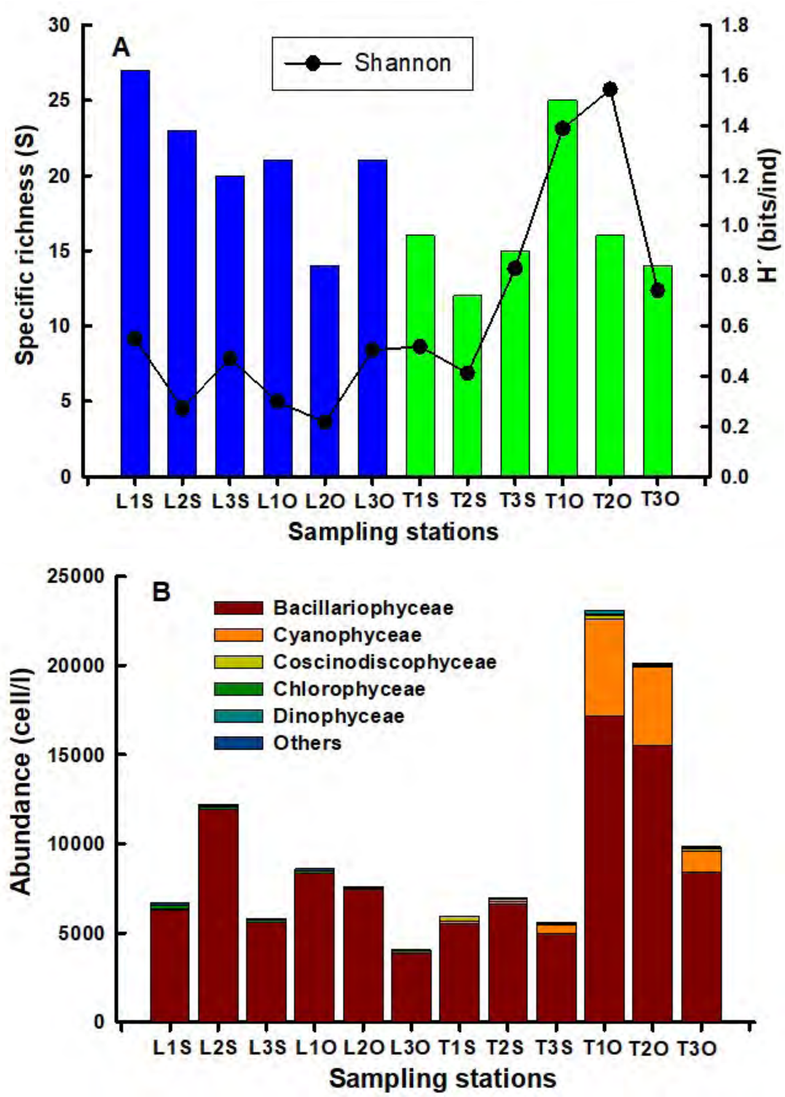
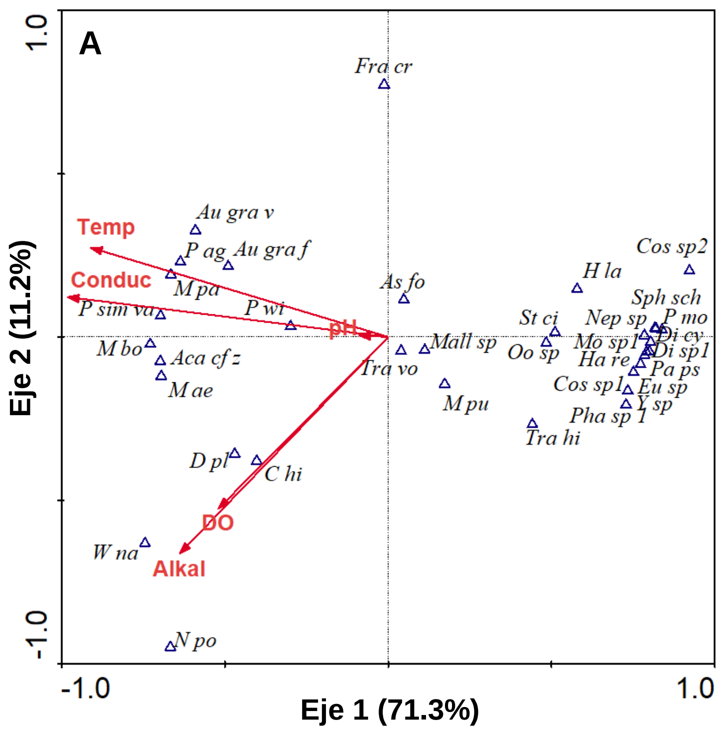


Figure 4. A) Specific Richness and Shannon Index in each of the Study Stations, 4 B) Abundance of Taxonomic Classes Recorded in each of the Dams, where L, Represents El Llano and T, Taxhimay; 1, 2, 3 each of the Stations; Finally, S and O Indicates the Month of Sampling (September and October 2022).

Regarding abundance, the highest record was at station T1 in October, with 21,476 cell/ml. In contrast, the lowest abundance was at station L3 in the same month, with 4,056 cell/ml (Fig. 4B).

The abundance by taxonomic classes in all the sampling stations studied was markedly higher for Bacillariophyceae, represented by the biomass de *Asterionella formosa* with 79.9 to 96.4 % (96,856 cell/ml). Also, during October in Taxhimay, the proliferation of the Cyanophyceae: *Dolichospermum planctonicum*, *Microcystis aeruginosa*, *M. botrys*, *M. panniformis,* and *Woronichinia naegeliana* were notable. Finally, the Chlorophyceae were represented mainly by *Eudorina* sp., *Haematococcus lacustris*, *Mucidosphaerium pulchellum,* and *Yamagishiella* sp.

The CCA explained 82.5 % of the variation in the data where conductivity was significant ($p<0.01$, $F=8.23$, $\lambda=0.54$) and was positively related to *Aulacoseira granulata* var. *angustissima*, *Monactinus simplex*, *Aulacoseira granulata* f. *curvata*, *Planktothrix agardhii*, *Peridinium willei,* and *Microcystis panniformis* from samples collected in September at the Taxhimay Dam. At the same time, this variable was negatively related to *Cosmarium* sp.1, *Dinobryon* sp., *Dynobrion cylindricum*, *Eudorina* sp., *Hariotina reticulata*, *Mallomonas* sp., *Mucidosphaerium pulchellum*, *Nephrocitium* sp., *Oocystis* sp., *Pandorina* sp., *Phacus* sp.1, *Trachelomonas hispida,* and *Yamagishiella* sp. associated with samples from El Llano (Fig. 5A and 5B). It is also observed that the species positively related to conductivity were positively related to temperature. For its part, *W. naege*liana, *D. planctonicum* and *C. hirundinella* are related to alkalinity.



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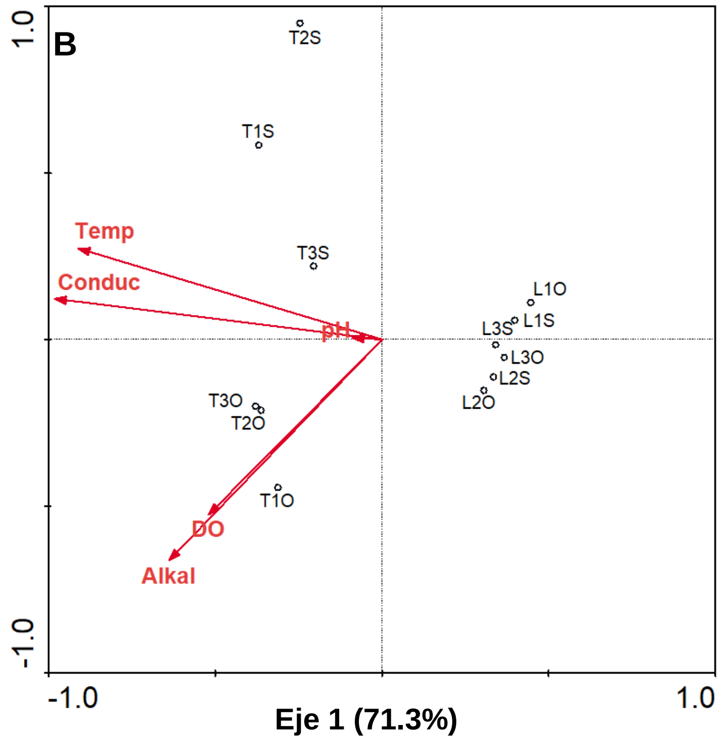

Figure 5. Canonical Correspondence Analysis (CCA) showing A) the Relationship of the Limnological Variables with the Species and B) the Relationship of the Limnological Variables with the Samples Collected in the El Llano and Taxhimay during September and October 2022. *Aulacoseira granulata* f. *curvata* (Au gra f. cur), *Aulacoseira granulata* var. *angustissima* (Au gra var. ang), *Monactinus simplex* (P. sim. var. chl.), *Microcystis panniformis* (M. pan.), *Planktothrix agardhii* (P. ag), *Navicula* sp. (Na sp.), *Oscillatoria* sp. (Os. sp.), *Acanthoceras* cf. *zachariassii (Aca cf. zach), Peridinium willei (P wi), Microcysitis aeruginosa (M ae), Microcystis botrys (M bo), Sphaerocavum* sp. *(Sph sp), Dolichospermum planctonicum (D. pl)*, *Woronichinia naegeliana (W. na), Ceratium hirundinella (C hi)* and *Cymbella mexicana (C. mex).*

Water Quality Indexes

The association quotient (CA) registered values of 6.75 for El Llano (CA=6+14+2+5/4= 6.75), in contrast to 10.5 in Taxhimay (CA= 11+5+2+3/2 = 10.5); which indicates that they are saprotrophic environments. Considering the genera registered in the reservoirs, the IP, based on the genus contamination index obtained values of 6 for El Llano due to the presence of *Navicula* 3, *Pandorina* 1, and *Phacus* 2, which adds up to a total IP of 6; while for Taxhimay, it presented *Oscillatoria* with a value of 5 and *Navicula* 3, which indicated a value of 8. Therefore, based on these biological indicators, during this time of months of high and low rainfall, they were systems with low organic contamination. While, regarding the ID, it was 0.33 (2/6=0.33) for El Llano and 0.50

for Taxhimay (2/4=0.50). Both reservoirs recorded values >0.2, so the environmental condition of the systems indicates eutrophic conditions.

Discussion

Environmental Variables

El Llano and Taxhimay dams are reservoirs of temperate waters, with temperatures typically ranging between 15 and 22°C. Furthermore, mineralization levels remain low, usually between 30 and 80 mg/l $CaCO_3$. This is in contrast to levels observed five years ago in the study area, which ranged from 4 to 162 mg/l $CaCO_3$ (Razo-Paredes et al., 2016). This low mineralization has also been recorded for Lake Zirahuén, Michoacán (Bernal-Brooks, 1998).

The pH levels ranged from neutral to basic (7-9), which were slightly similar to the 6-8.1 range previously documented in the study area by Razo-Paredes et al. (2016). This trend was also observed in the records from Taxhimay during 2018-2019, with values ranging from 7.0 to 9.0 (Saavedra-Martínez, 2020).

Regarding dissolved oxygen, values were from 5.8 to 9.6 mg/l, which indicates that in October 2022, the water surface was well-oxygenated. This suggests an essential photosynthetic activity during the study period and the values of this variable have increased when compared to the records of July 2017, where the values were from 1.0 to 4.6 mg/l (Toledo-Trejo & Razo-Paredes, 2018) and those quantified in Taxhimay between August 2018 and July 2019 with average values between 6.0 to 6.2 mg/l (Saavedra-Martínez, 2020).

The conductivity in both dams, ranging between 62-140 µS/cm was recorded, indicating low conductivity values and confirming the records by Toledo-Trejo and Razo-Paredes (2018) and Saavedra-Martínez (2020). Concerning CCA, temperature and conductivity were positively related to diatoms: *A. granulata* var. *angustissima*, *A. granulata* f. *curvata*; green algae: *Monactinus simplex* and the cyanobacteria: *M. panniformis*. Alkalinity explains the secondary gradient of phytoplankton composition. Conditions that do not coincide with those analyzed for the phytoplankton of Chapala, Jalisco, where sulfate and alkalinity concentrations were the most important variables that determined the composition and richness of the lake's phytoplankton (Mora-Navarro et al., 2004).

The abundance of *Asterionella formosa*, *Aulacoseira granulata,* and *Microcystis aeruginosa* corresponds to species that grow better in eutrophic systems with high amounts of nutrients such as phosphates and nitrates. Information that has been quantified in Taxhimay is between 1.0 to 1.4 mg/l and 0.5 to 0.7 mg/l, respectively (Toledo-Trejo & Razo-Paredes, 2018). In addition, Chl *a* concentration was between 25.4 and 282.8 µg/l when there were blooms; therefore, the limnological and phycological conditions indicate that they correspond to eutrophic systems (Saavedra-Martínez, 2020).

In particular, the development of populations of three *Microcystis* species suggests the establishment of monitoring that includes different climatic periods and sampling sites to learn more about the ecological dynamics of phytoplankton in the reservoirs of Villa del Carbón, State of Mexico, to support the management of alternative drinking water supply systems.

On the other hand, samples obtained during the two studied months have different levels of precipitation, September with 150 mm and October with 69 mm; this correspond according to the stage of ecological succession for reservoirs in the central zone of Mexico indicated by Arredondo-Figueroa and Flores Nava (2012) to the dilution phase in both dams during September, since the precipitation was greater during this period and therefore the phytoplankton community showed greater stability. Meanwhile, the biological material from October, when precipitation decreased (69 mm), increased primary productivity with the abundance of Bacillariophyceae of 36,404 cell/ml and Cyanophyceae with 11,016 cell/ml, so they represent a transition phase, when it is assumed greater amount of nutrients in the water column.

Phycoflora

The specific richness of phytoplankton in both dams was 55 species; for El Llano, there were 45 taxa, while Taxhimay, 32 taxa, and 26 taxa were present in the two reservoirs. The most diverse groups in both were Chlorophyceae, with 27.3 %, Cyanophyceae 21.8 %, and Bacillariophyceae 12.7 %. For the El Llano, 41 taxa cited by Razo-Paredes et al. (2016) coincide; while, in Taxhimay Toledo-Trejo and Razo-Paredes (2018), indicated six *taxa*. Therefore, 26 species correspond to new records for this reservoir.

These environments contain only the 8.4 % phytoplankton diversity recorded from the State of Mexico (Garduño-Solórzano et al., 2009), where the taxa that develop in the two dams were: *D. planctonicum* (Cyanophyceae); *H. lacustris*, *M. pulchellum*, *Oocystis* sp., *S. cingulum* (Chlorophyceae), *A. formosa* (Bacillariophyceae), *A. granulata* f. *curvata,* and *A. granulata* var. *angustissima* (Coscinodiscophyceae); *Trachelomonas hispida*, *T. volvocina,* and *T. rugulosa* (Euglenophyceae); *C. hirundinella*, *P. willeii*, *Peridiniopsis* sp. (Dinophyceae), and *Mallomonas* sp. (Crysophyceae).

The following six *taxa*: *A.* cf. *zachariassii*, *Coenocystis* sp., *P. pseudovolvox*, *Peridiniopsis* sp, *R. fernandoi*, and *Yamagishiella* sp., correspond to new records from México, based in Novelo and Tavera (2023). Also, *Coelomoron microcystoides* and *Neospongiococcum* sp. were new records for the State of Mexico.

In El Llano, the following diatoms were dominant: *Asterionella formosa* and *Aulocoseira granulata* f. *curvata*, which coincides with what was described by Toledo-Trejo and Razo-Paredes (2018), who indicated that *A. formosa* was also dominant in phytoplankton in the study area. Likewise, the dominant species in both dams was *A. formosa*, with abundances of 43 and $53x10^3$ cell/ml for El Llano and Taxhimay, respectively; according to Bellinger and Sigee (2010), values that indicate eutrophic lentic water bodies.

Taxhimay Dam, the development of *A. granulata* var. *angustissima* was dominant during October 2022; conditions that are explained by corresponding to a taxon whose ecological distribution in lentic environments of 13 lakes in central Mexico has been recorded under limnological conditions of average annual temperature of 16.6°C, pH 7.7 and trophic state from meso to hypertrophic (Ramírez-Nava et al., 2022). As well as in eutrophic reservoirs in Brazil (Bicudo et al., 2016). Therefore, this is a bioindicator of eutrophic environments, which allows us to add arguments to indicate the Taxhimay dam under ecological conditions of neutral to slightly basic, with pH between 7-8 and temperature 19.2 to 19.9°C where they grow in high percentages of the taxon, as has been observed in Lake Santa Gertrudis, Jalisco and San Juanico, State of Mexico, with abundances more significant than 31 % (Ramírez-Nava et al., 2022).

Water Quality Indexes

The phycoflora of El Llano is distributed in six species of Cyanophyceae, in contrast to 11 species in Taxhimay. At the same time, the Chlorophyceae in El Llano were 14 *versus* five species in Taxhimay. A composition that allowed different water quality indexes to be considered: CA, IP, and ID, all with results that indicate that they are eutrophic systems. Besides, El Llano has a lower level of eutrophication than Taxhimay. In the latter, the dominant species were *A. formosa* and *M. aeruginosa*; their presence suggests a significant amount of wastewater and, therefore, a high concentration of nutriment. The presence of the same species has been recorded in the following seven dams: Zimapan (Gutiérrez-Hernández, 2003), Mintzita (Ortega-Murillo et al., 2007), La Laguna, Los Reyes, Necaxa (González-Fernández et al., 2013), El Abrevadero (Carrasco-Vargas et al., 2014), and Taxhimay (Toledo-Trejo and Razo-Paredes, 2018).

Conclusions

The environmental conditions were in both reservoirs poorly mineralized (30-80 mg/l $CaCO_3$), low conductivity (62-140 µS/cm), and well oxygenated; during the study of the phytoplankton structure of two months, where there were marked differences of precipitation records from September (150 mm) and October (69 mm).

Considering both dams, a specific richness of 55 species was obtained, of which the percentages concerning the specific richness were from the highest to lowest of Chlorophyceae (27.3 %), Cyanophyceae (21.8 %), and Bacillariophyceae (12.7 %), among other classes of lower record; new records were determined for the study area in Mexico. Also, the H' index was higher in the Taxhimay Dam with 1.54 than in El Llano with 0.21 bits/ind.

The Olmstead-Tukey analysis showed 22 dominant species for El Llano and 17 for Taxhimay. In particular, the abundance in both dams was represented by the Class Bacillaryophyceae, of which *Asterionella formosa* was the most dominant species. In Taxhimay, it also indicated an abundance of the Cyanophyceae (*Microcystis aeruginosa*, *M. botrys*, *M. panniformis,* and *Woronichinia naegeliana*); *taxa* associated with eutrophic water body conditions. The CCA showed positive relations with the conductivity and warm temperature (15 and 22°C), and alkalinity with some species.

Based on the three water quality indexes used, the two dams indicate that they are eutrophic, in addition, the abundance of Cyanophyceae from Taxhimay in October suggests that they should be monitored in different climatic periods, since they can develop harmful proliferations.

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Authors' Contributions

GGS formal analysis and investigation, data curation, writing—original draft preparation and review and editing. GFJM conceptualization, collected the samples, identification, statistical analysis and writing. BVV collected the samples, identification, writing. DLVK collected the samples, identification, writing. CAER conceptualization, collected the samples, original draft preparation, and review and editing. All authors have read and agreed to the published version of the manuscript.

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This book takes a significant step in showcasing the relevance of limnology to our survival. Freshwater habitats, though they cover less than 1 % of the Earth's surface, are home to a substantial portion of the world's biodiversity—at least 10 % of all known species. Freshwater habitats and the biodiversity they support are under threat. Moreover, our survival depends on access to high-quality freshwater. This book not only highlights the beauty of limnology and the scientific methods used to study it, but it also draws attention to the major causes of biodiversity loss in freshwater ecosystems. It shows all readers what it means to deal with inland waters as a scientist interested in understanding ecosystems and protecting them.

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