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Articles

Physicochemical water variations in a big Mexican hydroelectric dam, central semi-arid region

Variaciones fisicoquímicas del agua de una gran presa hidroeléctrica mexicana, región centro semiárida

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Abstract

The Zimapan hydropower plant built in 1995 was the first project to take advantage of Mexico's City wastewater for electric power generation. This tropical reservoir receives pollutants that affect water quality from municipal, agricultural, and industrial wastewater through the Tula and San Juan rivers. The study considered the changes in the physicochemical parameters (surface to 20 m depth) for May (wet warm), November (wet cold-after rains), and February (dry cold) in seven dam sites: two lotic, two transitional, and three lentic sites. Mean values ranges were temperature 20.71-24.38 °C, 1.59-7.56 mg/l dissolved oxygen, Secchi disk transparency 2.26-3.98 m, pH 7.12-8.40, electrical conductivity 48-1334 μS/cm, total nitrogen 14.20-30.74 mg/l, total phosphorus 10.45-15.83 mg/l, and dissolved organic carbon 9.11-20.63 mg/l. In November, all the reservoir surface water was hypoxic due to increased dissolved organic carbon by river input. Even though dissolved oxygen has a seasonal variation, this reservoir has a sustainable fishery of tilapia and black bass (~400 tons/y). The dam is meromictic and hypereutrophic, with seasonal water quality variations with no significant spatial variations. Water quality variation observed in this study can be useful to

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Mexican decision-makers on water and fisheries management, prevent massive fish kills, and be a support guide for commercial and sport fishers.

Keywords: Hydroelectric dam, semi-arid, meromictic, hypoxic waters, fisheries.

Resumen

La central hidroeléctrica Zimapán, construida en 1995, fue el primer proyecto en aprovechar las aguas residuales de la Ciudad de México para generar energía eléctrica. Este embalse tropical recibe contaminantes que afectan la calidad del agua, y que provienen de los escurrimientos municipales, agrícolas e industriales transportadas por los ríos Tula y San Juan. Este estudio registró cambios en los parámetros fisicoquímicos (superficie a 20 m de profundidad) para mayo (cálido húmedo), noviembre (frío húmedo, después de las lluvias) y febrero (frío seco) en siete sitios de represas: dos lóticos, dos de transición y tres sitios lénticos. Los valores medios fueron temperatura 20.71-24.38 °C, oxígeno disuelto 1.59-7.56 mg/l, transparencia del disco Secchi 2.26-3.98 m, pH 7.2-8.40, conductividad eléctrica 48-1334 µS/cm, nitrógeno total 14.20-30.74 mg/l, fósforo total 10.45-15.83 mg/l y carbono orgánico disuelto 9.11-20.63 mg/l. En noviembre, toda el agua superficial en el embalse estaba hipóxica luego de un aumento en la entrada del río de carbono orgánico disuelto. A pesar de que el oxígeno disuelto varía estacionalmente, el embalse sostiene una pesquería de tilapia y lobina negra (~400 ton/y). La presa es meromíctica e hipereutrófica, con variaciones estacionales en la calidad del agua y sin variaciones espaciales significativas. Las

variaciones en la calidad del agua registradas en este estudio pueden ser de utilidad para los tomadores de decisiones en México sobre el manejo del agua y la pesca en la prevención de muertes masivas de peces, y como guía de apoyo para los pescadores comerciales y deportivos.

Palabras clave: presa hidroeléctrica, semiárido, meromíctico, aguas hipóxicas, pesquerías.

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Introduction

During the operation of hydroelectric dams, decreases in their water levels are generated; its location in semi-arid climates with long periods of drought and short periods of rain, it is expected that there will be considerable fluctuations in its water levels, both seasonal and interannual, with an effect on the processes of mixing, stratification and consequently on the limnological dynamics and aquatic biodiversity.

Primary producers' dynamics are influenced by changes in light conditions and nutrient availability (Leira & Cantonati, 2008; Costa, Attayde, & Becker, 2016). Reservoirs in semiarid regions have high turbidities, extreme hydrological variability, and relatively stable climatological factors, compared with temperate reservoirs (Thornton & Rast, 1993).

Hydropower dams cause adverse effects on aquatic ecosystems such as alterations in the natural river flow, sediment retention, high nutrient loads, and water quality changes. In tropical and subtropical countries, the construction of dams has been extensive. Excessive input of pollutants from urban, agricultural, livestock, and industrial wastewater impacts the water quantity and quality (Delazari-Barroso, Barroso, Huszar, & Oliveira, 2009; Kazi *et al*., 2009; De Anda & González-Farías, 2013; Rubio-Franchini, López-Hernández, Ramos-Espinosa, & Rico-Martínez, 2016). That condition affects the aquatic biota and human health, particularly in reservoirs near large human settlements with deficient infrastructure for wastewater treatment (Kazi *et al*., 2009; Cunha, Calijuri, & Lamparelli, 2013; Fontana *et al*., 2014).

Mexico has more than 6 325 reservoirs, of which 210 are big dams (Conagua, 2020; World Commission on Dams, 2000), so limnological information on those reservoirs has become an essential aspect of public policy development (Alcocer & Bernal-Brooks, 2010).

This study focused on physicochemical parameters' spatial and temporal changes at seven sites along a tropical semi-arid hydroelectric dam, after the entrance of two rivers with different pollution sources. This study will be the base for understanding the effect of wastewater of the urban and industrial affluents from River Tula and River San Juan on the physicochemical water conditions of dam Zimapán.

Materials and methods

Study area

The Zimapan Hydropower dam is between the states of Queretaro and Hidalgo, Central Mexico **(Figure 1)**, at 1 870 m.a.s.l., with a BS1kw climate (García-Amaro, 2004), dry semi-arid, warm with an annual average temperature of 16.0 °C, being May the warmest month (18.7 °C) and January the coldest (12.6 °C). The average annual rainfall is 591 mm, and the rainy season runs from May to October, with the highest rainfall in September (106 mm) and the lowest in February (8 mm) (Climate-Data, 2020).

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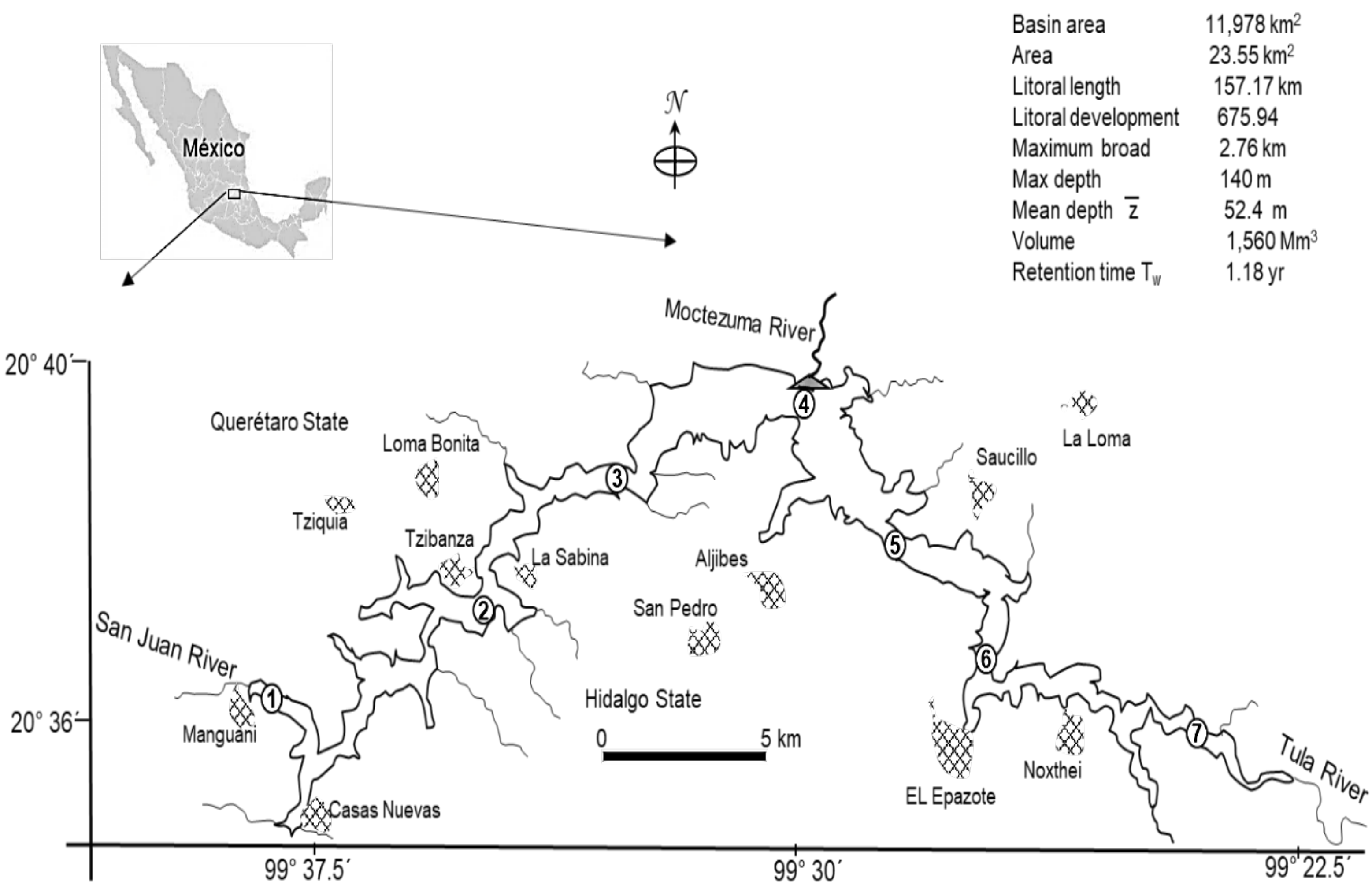

Figure 1. Location of the study area and sampling sites (1 to 7). Geological and hydrological features and main villages are presented.

The principal affluents to the reservoir are the Tula (12.3 m^3/s) and San Juan (2 m^3/s) rivers, which drain into the reservoir untreated urban wastewater generated in Mexico and Tequisquiapan cities, respectively.

The Tula River irrigates the Mezquital Valley whose economy is mainly agriculture based on wastewater from México City; wastewater is regulated for irrigation by the Requena and Endho dams for irrigation of the Mezquital Valley in its northern part. The dam Endho has the extra role of primary treatment of wastewater because acts as an oxidation lagoon, and three dams below Endho, with the same role, act as a cascade reservoir system.

Also added are the drainages of the urban areas of five cities, an industrial corridor that includes an oil refinery, a thermoelectric plant, and several cement plants (Coplain Ingenieros Civiles S.A de C.V., 1985) before the entrance to the Zimapán hydroelectric dam, the river maintains lotic conditions and turbulent flow and also receives urban and agricultural runoff, as well as tributaries of springs used in spas.

The San Juan River transports water with pollutants of urban and industrial origin as it passes through the city of San Juan del Río, as well as from activities of agricultural activities such as wine, cheese, and pottery production in the tourist area of Tequisquiapan. The San Juan River also receives hot spring waters along its course, around 30 km upstream from the dam curtain.

In the reservoir, the maximum storage volume is 1 460 Mm^3 on a surface of 2 300 ha, with an average depth of 50 m and a maximum of 170 m at the curtain (Randell-Badillo, 2008; Agua, 2010). Due to the high organic matter and nutrients that this dam receives from wastewaters, the nearby communities pump water for vegetable and corn crops and develop commercial aquaculture of detritivores fishes, mainly tilapia (*Oreochromis* spp.), and sport fisheries of black bass (*Micropterus salmoides*). Some towns near the dam take water by pumping for vegetable and corn crops; there is incipient tourism with boat rides, and there is little housing development with scenic views on private properties.

Water sampling and water analysis

The seven sampling sites distributed in the reservoir considered physical and chemical water data in three different limnological zones on dams. (Thornton, 1990), *i.e.*, lotic (sites 1 and 7), transitional (sites 2 and 6), and lentic (sites 3, 4, and 5) (Figure 1). Three sampling campaigns took place considering climatic conditions: Wet-warm (May 2014), wet-cold after rains (November 2014), and dry-cold (February 2015) (Climate-Data, 2020). We consider that due to the environmental conditions of wind, temperature, and precipitation of this semi-arid area, the months selected for the study will reflect the physicochemical conditions of the reservoir.

Dissolved oxygen (DO), temperature (T), and electrical conductivity (EC) were measured in situ using a multiprobe YSI (model YSI 556) at different depths (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15 and 20 m). Secchi disk transparency (SDT) with a 30 cm diameter Secchi disk; pH with multiprobe YSI, model YSI 556, measured only in surface water. Water column composite samples from surface to 3 m depth were taken using an adapted PVC tube (3' Ø x 3 m) for chemical analysis of total nitrogen (TN), total phosphorus (TP), and dissolved organic carbon (DOC). TN and TP were analyzed with a spectrophotometer Hach DR/2010, APHA-AWWA-WPCF (1995), while DOC with a multiprobe WTW (model MIQ/C184 XT).

Fundamental statistical analysis was applied to evaluate the physical and chemical conditions of the water in the different sampling sites. A multivariate cluster analysis with Ward's Euclidean distances considered all parameters used to evaluate longitudinal patterns in the reservoir and explore the similarities among the seven sampling sites for May 2014, Nov 2014, and Feb 2015. For spatial-seasonal variations for each environmental parameter, an analysis of variance MANOVA and Wilks' lambda ($P < 0.05$) and a posteriori Tukey test were performed when ANOVA differences among the tested factors were statistically significant ($P < 0.05$). No transformations of environmental variables data before statistical analysis (Statgraphics Centurion XVI).

Results

Through time the reservoir presented depth variations due to the balance of water input by rivers, runoff, rain, and the output by evaporation and intermittent water release through the hydroelectric dam gates. Depth variation affected the hydrological parameters' behavior, mainly in the lotic and transitional sampling sites, which are shallower than the lentic sites; depth variation for lotic and transitional sites was up to 10 m and 20 m, respectively. Lentic sites always present more than 70 m in depth, so water columns tend to be more stable. The essential variations occurred from the surface to twenty meters deep; later, the values did not change significantly. We present the results of the layer (surface to 20 m depth) with the most significant variation. Descriptive statistics of measured parameters (T, DO, EC, SDT, pH, TN, TP, and DOC) are in Table 1.

Table 1. Mean, standard deviation, % coefficient variation, minimum, and maximum of the parameters were measured in surface water (0-20 m) and composite samples (0-3 m) in the Zimapan Dam.

Parameter	Month	Mean	Std Dev	% CV	Max	Min
Surface water						
Temperature (°C)	May	24.38	2.63	10.81	29.85	21.67
	November	20.71	1.33	6.45	23.65	19.78
	February	22.04	1.68	7.06	25.13	20.26
Dissolved oxygen (mg/l)	May	7.56	1.06	14.09	8.58	1.20
	November	1.59	0.23	14.97	2.34	0.74
	Feb-15	6.25	1.73	27.82	9.73	2.34
Secchi disk transparency (m)	May-14	5.60	2.63	66.26	7.00	0.52
	Nov-14	2.55	0.79	30.65	4.18	1.68
	Feb-15	2.70	0.68	26.56	3.41	1.21
pH	May-14	8.40	0.00	0.05	8.41	8.40
	Nov-14	7.90	0.08	1.03	8.00	7.80
	Feb-15	7.12	0.14	2.10	7.32	6.96
Electrical Conductivity (µS/cm)	May-14	753	99.25	13.18	847	444
	Nov-14	48	2.2	4.58	56	34
	Feb-15	1334	143	10.76	1700	820
Composite sample						
Total nitrogen (mg/l)	May-14	14.20	4.07	28.67	19.7	9.70
	Nov-14	17.69	1.61	9.10	18.80	14.40
	Feb-15	30.74	3.71	12.07	35.6	26.80
Total phosphorous (mg/l)	May-14	15.83	5.57	35.21	24.6	9.71
	Nov-14	10.45	0.94	8.99	11.9	8.90
	Feb-15	13.90	1.76	12.66	16.2	11.90
Dissolved organic carbon (mg/l)	May-14	9.11	1.44	15.84	11.1	7.52
	Nov-14	20.63	5.22	29.37	32.4	18.11
	Feb-15	17.54	3.59	20.44	24.10	12.74

Temperature (T)

Air temperature in semiarid regions and seasonal changes are important in large reservoirs for the detection of stratification and circulation processes, the solubility of OD, as well as in fish reproduction, which sustains fishing Commercial, or sporting in the reservoir. In May the average air temperature was 28 -22 °C and 14-10 °C in November. The decreasing thermal gradient along the reservoir in May sites 1-7 was 30-22 °C, and November had a lower mean temperature of 21 °C. February, temperature increased between 22 and 25 °C, except in sites 2 and 3.

Stratification conditions with the epilimnion were detected at 2 m in May and 5 m in February, considering the surface to 70 m depth, the hypolimnion occupies more than 80 % of the total water column. May present temperatures ranged 22-30 °C from surface to 5 m depth, then discontinuous decreases until 20 °C at 20 m. In the mixing process, November is practically 4-20 m depth 20 °C with no changes; February with thermocline similar to May but with a lower temperature of 20-26 °C, the surface to 5 m, in hypolimnion without changes of 20 °C to 70 m.

All year-round surface water T in the Zimapan reservoir was higher than 20 °C (Table 1), like other tropical water bodies in Mexico (Torres-Orozco & Zanatta, 1998; De Anda, Quiñones-Cisneros, French, & Guzmán, 1998; De Anda & Shear, 2013; Sigala *et al*., 2017). At depths greater than 30 meters, the temperature remained constant at 18.5 °C (Figure 2).

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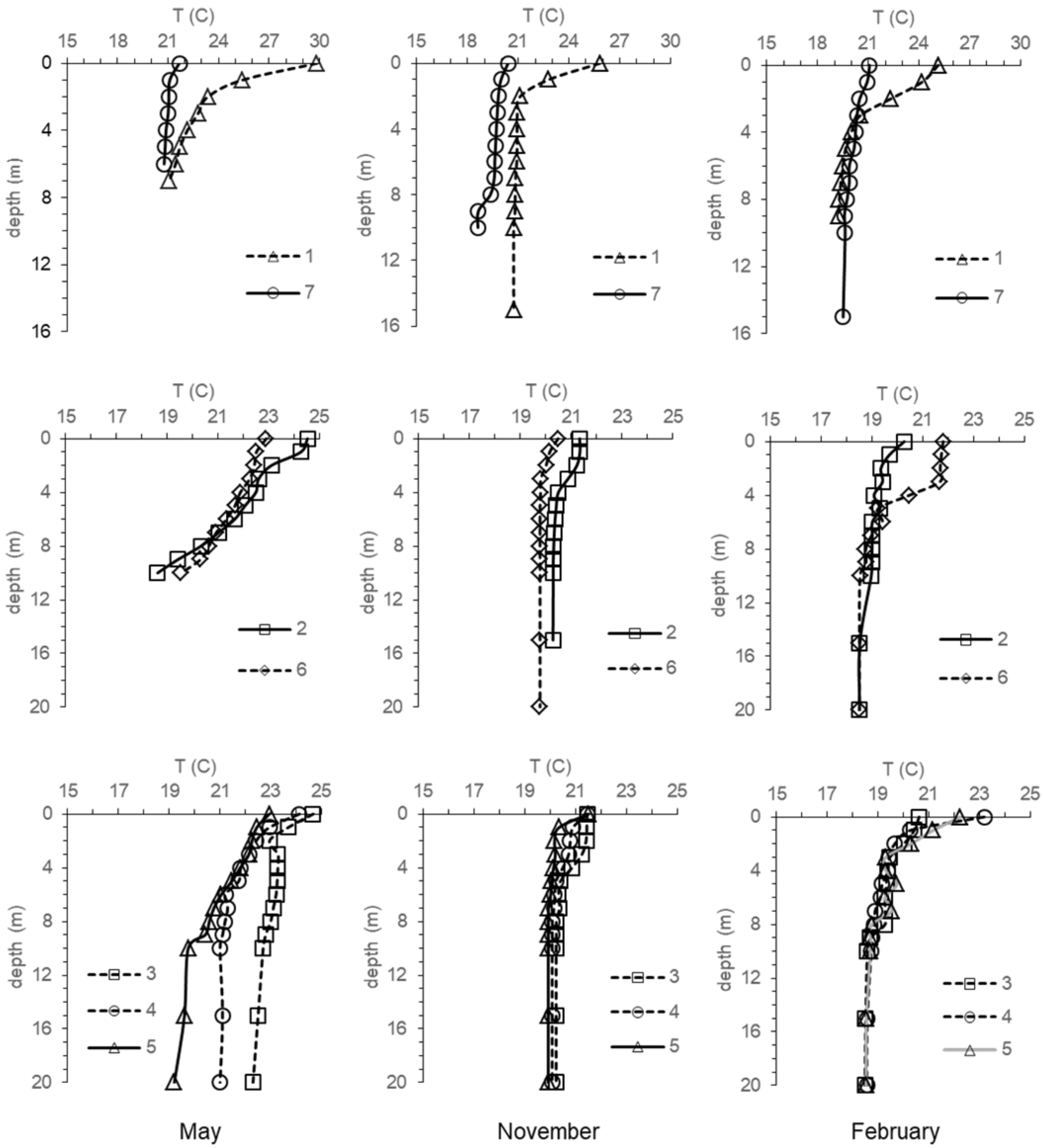

Figure 2. Temperature (°C) profiles of lotic (1 and 7), transitional (2 and 6), and lentic (3, 4, and 5) sites for May 2014, November 2014, and February 2015.

The presence of thermal waters (38 °C) close to riparian site 1 (San Juan River) influenced the highest temperatures (22-30 °C), conversely inlets in site 7 (Tula Tula) caused the lowest values (21-24 °C) (Figure 2).

Dissolved oxygen (DO)

DO profiles of lotic (1 and 7), transitional (2 and 6), and lentic (3, 4, and 5) sites are in Figure 3. DO mean values (Table 1) were high for May 2014 (7.56 mg/l) and Feb 2015 (6.25 mg/l) and very low for Nov 2014 (1.59 mg/l). In general, DO in surface water in May 2014 and Feb 2015 was around 4 mg/l, while in Nov 2014 was utterly different from the other months. The highest value was 2.34 mg/l in surface water at lotic site1, or the rest of all sites and depths, DO below 2.00 mg/l (Figure 3).

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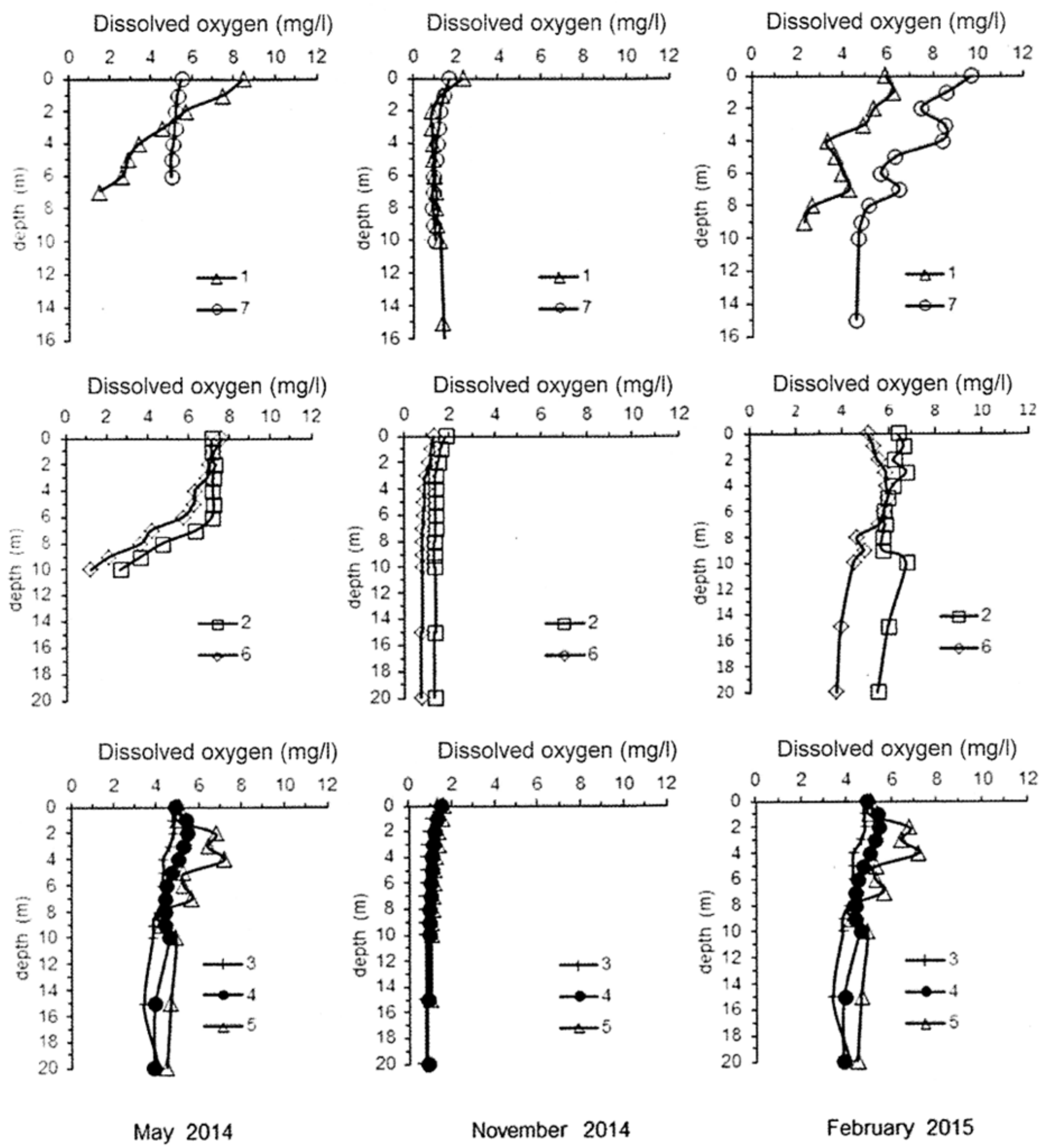

Figure 3. Dissolved oxygen (mg/l) profiles of lotic (1 and 7), transitional (2 and 6), and lentic (3, 4, 5) sites for May 2014, November 2014, and February 2015.

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Secchi disk transparency (SDT)

As for DO, the SDT (Table 1) was also affected by the high wastewater volume input in Nov 2014. In May 2014, at the beginning of the rainy season, lotic sites 1 and 7 showed the lowest SDT, 0.52 and 1.15 m, respectively, due to storm runoff which is the primary source of suspended material in the water bodies (Kemdirim, 2005). The SDT increased at the transition sites 2 and 6, to 5.90 m and 2.10 m, respectively, due to the sedimentation of suspended particles caused by a depth increase and width of river channels in those sites (Figure 1), and consequently a decrease in river current speed. The deeper lentic zone of the reservoir, which allows precipitation of suspended matter, always presented SDT values higher than 5.60 m.

pH

The mean pH of surface water was 8.40 in May 2014 and diminished to 7.90 and 7.12 in Nov 2014 and Feb 2015, respectively (Table 1). In May 2014, the whole surface water presented a homogeneous basic pH due to the system's primary productivity, influenced by high solar irradiation and temperature. The pH decrease in Nov 2014 and Feb 2015 (Figure 4A) was due to less primary productivity and an increase in DOC that increased CO_2 concentration through its chemical and biochemical degradation (Roldán-Pérez & Ramírez-Restrepo, 2008). Zimapan basin with carbonate-rich limestone rocks influenced the reservoir pH values, ranging between 6.96 and 8.40 (Table 1). Our pH was similar to those in

Aguamilpa dam, Nayarit state, 6.46-8.43 (Rangel-Peraza & González-Farias, 2013), and in Danxhó dam, State of Mexico, 6.90-8.90 (Oliva-Martínez, Ramírez-Martínez, Garduño-Solórzano, Cañetas-Ortega, & Ortega, 2005).

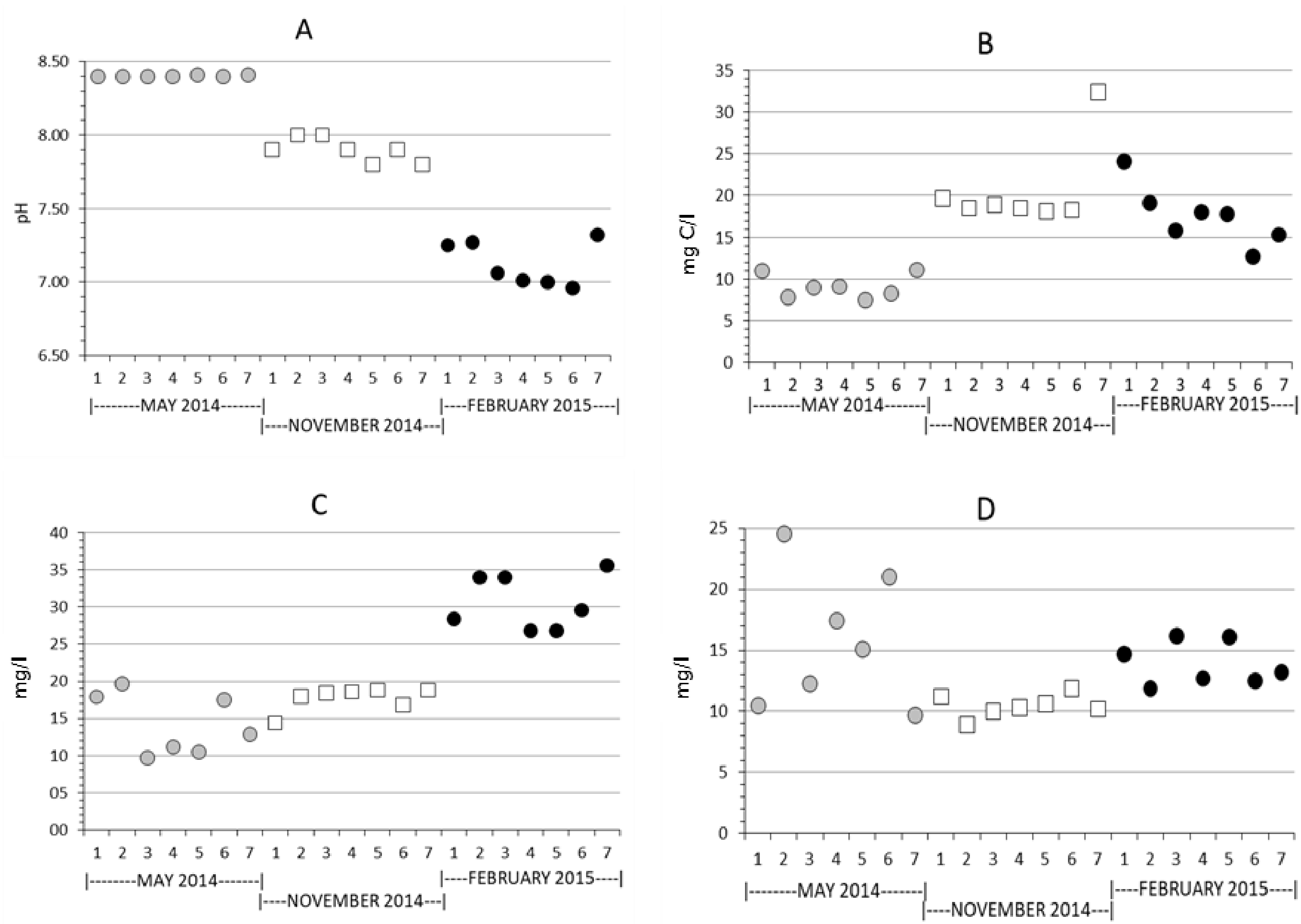

Figure 4. Surface profiles of: A) pH; B) dissolved organic carbon (mg/l); C) total nitrogen (mg/l); and D) total phosphorus (mg/l) in all sampling sites (1 to 7) in May 2014, November 2014 and February 2015.

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Electrical conductivity (EC)

The reservoir presented a significant variation of EC mean values through time, 747 µS/cm in May 2014, 48 µS/cm in Nov 2014, and 1 268 µS/cm in Feb 2015 (Table 1). EC variations at the lotic sites 1 and 7 always presented significant differences among them and in depth. The increase in EC in Feb 2015 was due to the entrance through sites 1 and 7 of N residues of fertilizers applied in the irrigation districts DR003 (Tula River) and DR023 (San Juan River) (Sagarpa, 2015) was reflected in the high concentration of TN in the reservoir (Figure 5C).

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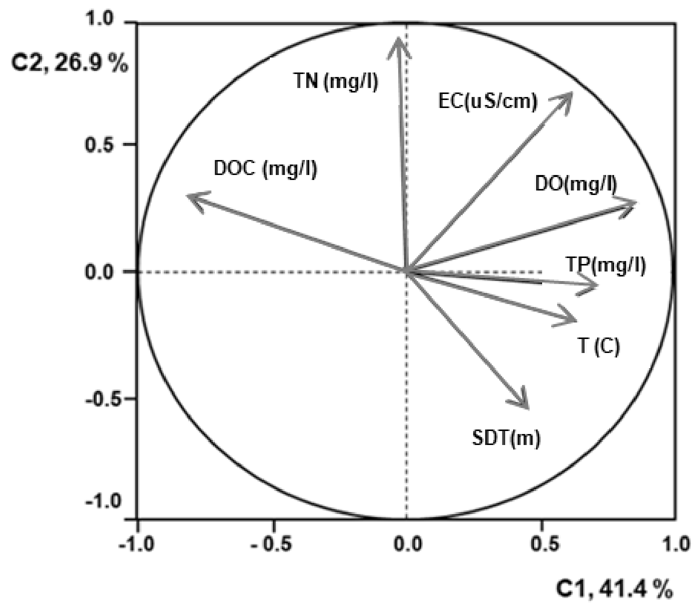
	C1	C2
DO (mg/L)	**0.51486**	0.20172
T (C)	0.37133	- 0.13675
EC (uS/cm)	0.35460	**0.52531**
SDT (mg)	0.26545	- 0.39888
TN (mg/l)	- 0.01464	**0.67424**
TP (mg/l)	0.42041	- 0.04505
DOC (mg/l)	**- 0.47315**	0.22120



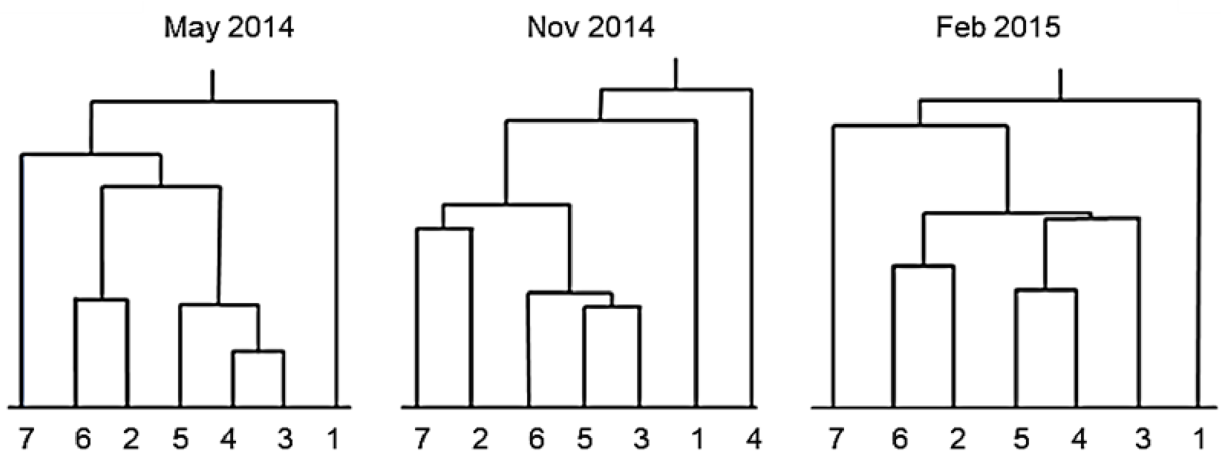


Figure 5. Hydrological similarity dendrogram Bray-Curtis Index on top, and principal component analysis (PCA) at the bottom.

The rest of the sites (2, 3, 4, 5, and 6) presented almost equal EC values through time and depth, probably due to water column homogenization caused by wind and currents generated by dam gates' water release. The EC range of values for Zimapan, 34.0-1700 µS/cm

(Table 1), was similar to Chapala wetland values, 27.4-1570 μS/cm, which receives high volumes of agricultural drains (Chávez-Alcántara *et al*., 2011).

Total nitrogen (TN) and total phosphorus (TP)

TN and TP concentrations for all samples were consistently higher than 9.7 and 8.9 mg/l, respectively (Table 1), so this reservoir is hypereutrophic (Smith, Tilman, & Nekola, 1999; Cunha *et al*., 2013). The highest TN and TP concentrations were measured in Feb 2015 at Station 7 (35.60 mg/l) and May 2014 at Station 2 (24.61 mg/l), respectively (Figures 4C, 4D). Those high concentrations in the reservoir are due to wastewater input from Mexico and San Juan cities and agricultural drainage of fertilizers applied in the irrigation districts DR003-Tula and DR-023 San Juan (Pérez-Díaz *et al*., 2018; Sagarpa, 2015; Saldaña-Fabela, Díaz-Pardo, & Gutiérrez-Hernández, 2011). Zimapan reservoir, like other eutrophic ecosystems, presents a severe degradation in water quality in times of heat and drought, with frequent cyanobacterial blooms of *Microcystis* sp. and *Anabaena* sp. (López-Hernández, Ramos-Espinosa, Figueroa, & Carranza-Fraser, 2007; Montelongo-Casanova *et al*., 2008; Conley *et al*., 2009).

Dissolved organic carbon (DOC)

The origin of DOC in a water body can be autochthonous or allochthonous, carried by rivers, runoffs, and industrial, municipal, and residual agricultural waters. The mean concentrations of DOC were consistently higher than 9.11 mg/l; Nov 2014 presented the highest concentration (32.43 mg/l) (Table 1, Figure 4B). Variation of DOC in the reservoir depends on the wastewater inputs through the rivers at the lotic sites 1 and 7, and by the exportation through the dam penstocks when hydropower is required.

A hydrological similarity dendrogram Bray-Curtis Index (Figure 5) of the sampling sites presented equal similarity group distribution for May 2014 and Feb 2015 and for Nov 2014. There was a slight group change with site 4, where the control of the hydroelectric penstocks strongly influences the dynamics of the water; however, despite the slight difference in Nov 2014, we consider that the sites grouped as expected, i.e., lotic (sites 1 and 7), transitional (sites 2 and 6) and lentic (sites 3, 4 and 5).

Applying the PCA (Bartholomew, 2010) for the sampling period, the reservoir presented two main components that together explain 68.3 % of the variability in the original data (Figure 5); in component 1, there are DO and EC, and in component 2, DOC and TN. Concerning the PCA, the parameters in component 1 (DO and EC) and those in component 2 (DOC and TN) confirmed that the water quality responds to the entry of organic matter (N and P organic compounds), and similar dynamics are reported in other reservoirs (Geraldes & Boavida, 2004).

According to the ANOVA performed on the PCA components, the reservoir surface water presented a considerable variation of water quality parameters among the seasons compared with no spatial variations among the sampling sites (except EC, which presented both season and sites' significant variations). MANOVA with the Wilks test (95 % confidence) applied to months versus sampling sites showed significant differences for the months (p = 0.000027) and no differences for sampling sites; seasonal variation was significant, not so for spatial variation. Tukey contrast confirmatory test (p = 0.05 significance) showed us those significant differences among the months in detail. Seasonal differences were significant for DO and EC for all sampled months, TN differences were also significant in May-Feb and Nov-Feb, and DOC differences were in May-Nov and May-Feb. The T presented the difference only between May-Nov. No significant seasonal differences between SDT and TP.

Discussion

The physicochemical variations in the Zimapan reservoir are influenced by high and low air temperature, wind, dry and rainy conditions, and the depuration process along the Tula River caused by a cascade dams system (five reservoirs), spring waters, and physical aeration by rocks and permanent lotic conditions throughout the river.

The system is also affected by anthropogenic actions (Gerson, Costa-de-Azevedo, & Ferreira, 2011), the most important being the input of wastewater and the intermittent discharge of large volumes of water (~60 m^3/s) through the hydroelectric penstocks (Bravo-Inclán, Saldaña-Fabela, & Sánchez-Chávez, 2012). Simultaneously, the most critical anthropogenic impact was the municipal and agricultural sewage input that promotes nutrient enrichment in the reservoir with significant quantities of N, P, organic matter, and coliform microorganisms (Janssen *et al*., 2017). The environmental parameters influencing water quality are seasonal rains (direct input and runoff), solar irradiance, winds, and temperature.

The epilimnion is at 2 m in May and 5 m in February; considering the surface to 70 m depth, the hypolimnion occupies more than 80 % of the total water column. So fisheries activities are able only in 0-20 m depth.

In warmer months, the thermally stratified water column presented epilimnion with T around 25 °C. Appropriate DO values for aquatic life (> 4 mg/l) in epilimnetic surface waters in May and February. In comparison, the hypolimnion (≥20 m depth) presented T lower than 20 °C (Figure 2) and DO values of hypoxia (2 mg/l) or anoxia (0-1 mg/l) (Figure 3), like other reservoirs (Rangel-Peraza *et al*., 2012; Nishimoto & Mawatari, 2009). Throughout our sampling period, the bottom water mass below 50 m depth never mixed with the upper water layer, so we consider the system to be meromictic (Bravo-Inclán *et al*., 2012).

The fact that DO in epilimnion remained around 5 mg/l in May 2014, and Feb 2015 implies that the reservoir surface water was suitable for fish farming, mainly tilapia, as suggested by Ruiz-Velazco-Arce, Tapia-Varela, García-Partida and González-Vega (2006), but unsuitable in Nov 2014 when hypoxia (DO < 2 mg/l) dominates the whole systems and can lead to massive fish kills in combination with extreme flood conditions like the year 2002 (López-Hernández *et al*., 2007). Fish kills in dams happen due to parasites, anoxic waters, cyanobacteria, and in the hypolimnion, releasing methane, hydrogen sulfide, and ammonia (Rangel-Peraza *et al*., 2012).

Bravo-Inclán *et al*. (2012) reported a maximum SDT in May 2005 of 5.67 m between sites 4 and 5. Our results are similar to those obtained for other water bodies in Mexico, like Lake Chapala (De Anda *et al*., 1998) and the Aguamilpa hydroelectric dam (Rangel-Peraza & González-Farias, 2013). In Nov 2014, SDT was affected by high primary productivity reported for previous years (Bravo-Inclán *et al*., 2012) and the residual runoffs after the rains.

In Feb 2015, the SDT mean value was 2.56 m (Table 1), with the highest value of 3.41 m at site 3 and the lowest at 1.21 m at site 7. In that month, the SDT was affected by the suspended matter carried by the residual waters of Mexico and San Juan del Río cities, and also from agriculture residual waters of the irrigation districts DR003-Tula (50 104 ha irrigated with 928.1 Mm^3) and DR023-San Juan del Río (9 336 ha irrigated with 80.6 Mm^3), that discharge irrigation waters of the autumn-winter crops in the Tula and San Juan rivers, respectively (Conagua, 2018).

Considering that the Zimapan reservoir is a drainage lake with the central water outflow through the turbines, the variable electric demand for this hydroelectric plant will affect the hydrology and the distribution (location and depth) of physicochemical parameters in the system. Janssen *et al*. (2019) showed that lake or reservoir restoration depends on spatial nutrient loading and hydrology aspects. In our case, the organic matter, nutrients, and solids input is through the San Juan and Tula Rivers (sites 1 and 7), so the water outflow manipulation will affect their distribution and concentration, affecting fish farming in the reservoir. In concordance with Janssen *et al*. (2019), continuous flushing of the Zimapan reservoir through the hydroelectric plant turbines might improve water quality, avoiding the concentration of allochthonous pollutants supporting tilapia and black bass aquaculture.

Conclusions

The Zimapan reservoir is a system affected by important volumes of organic matter, nutrients, and solids transported in the Tula River and San Juan River, which promotes nutrient enrichment in the reservoir, conductivity, turbidity, pH, and, dissolved oxygen gradients; contamination must be hight because the rivers receive urban, industrial and agriculture sewage with no treatment.

The system is a tropical meromictic hypereutrophic system that presents seasonal water physicochemical dynamics, with no spatial variation among the sampling sites. The spatial distribution of the different measured parameters is controlled by balancing the wastewater from Mexico and San Juan cities and the output through the hydropower penstocks. Fish farming in the reservoir takes place most of the year, except at the end of autumn after the rainy season (Nov 2014), due to the hypoxic/anoxic conditions in the epilimnion caused by an input increase of DOC and probably a smaller volume of water expelled by the turbines.

With the knowledge of the limnological dynamics of the water masses (epilimnion, metalimnion, hypolimnion) of the physicochemical parameters studied and in particular in the concentrations of dissolved oxygen and inorganic nutrients, there are bases so that decision-makers can prevent the danger to the health of fish and humans from the neurotoxic and neuropathic substances released by cyanophyte microalgae during algal blooms in dry months.

The physicochemical conditions of the Zimapán dam water are related to environmental changes in the semiarid climate of this region; likewise, they allow inferences about the species of fishing importance that can be cultured in cages, as well as the appropriate selection of sites for this fishing activity.

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