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

Limnological Variations of a Tropical Semi-arid River Dam System, Central México

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Abstract

This study focused on the basic limnological variations of the Tula River-Zimapán dam under different climatic conditions (rains, post-rains, and dry cold). The sampling included three river sites and seven sampling sites in the reservoir. These included dam sites, water temperature, dissolved oxygen, total dissolved solids, water column profiles, nitrogen, and total phosphorus of composite samples from a 0.3-3 m layer. In the river, the same parameters are at 20 cm in depth. Physicochemical and nutrient spatial variations showed that the three riparian sites are a separate group from the reservoir sites as a response to different temperatures, oxygen, transparency, total dissolved solids, and nutrients; similarly, well-defined zones of the reservoir in June and February: riparian, transitional, and lacustrine. The temperature variation in each site water column was low; however, dissolved oxygen significantly varied in June and October. In surface water in June with initial rains, physical and chemical data peaked; in May and February, oxygen >4 mg/l, suitable for fish production, but not convenient in November because of frequent hypoxia conditions. Total nitrogen and phosphorous on the Tula River had values above 14 mg/l in the entrance of wastewater, decreasing in the remaining river sites with spring waters nearby; in the reservoir, values were high for phosphorous and lower for nitrogen. The limnological conditions of the river dam system respond to the permanent entry of wastewater with organic matter, dissolved oxygen producers-consumers, and the potential nutrient loads generated by anthropogenic activities in the drainage basin and the reservoir surroundings.

Keywords

Hypereutrophic, spring waters, fisheries, wastewaters, spatiotemporal variations.

Introduction

In river-dam systems, one of the problems reflected by the water quality on dams is the accumulation of phosphorus and nitrogen whose primary source is particulate organic matter or dissolved organic matter carried by currents and runoff, as well as indigenous organic material, mainly vegetal, accumulated in the river basins. Depending on the climatic and land use conditions in the basin, the quantity and quality of the tributaries to the reservoir, there is an influence on the loading rates of sediments, minerals, and nutrients, accelerating the natural process of eutrophication with excessive growth of algae in natural or artificial systems, influencing water quality; each reservoir can respond differently regarding water quality to changing local and regional climatic conditions (Delazari-Barroso et al., 2009; Kazi et al., 2009). The sources of these compounds come from the urban population center as well as from agricultural and livestock areas with excessive nutrient loads from urban, farming, livestock, and industrial wastewaters have put at risk the different uses of water, aquatic biota, and human health; particularly in large human settlements where there is a deficient infrastructure for wastewater treatment (Kazi et al., 2009; Cunha et al., 2011, 2013; Fontana et al., 2014).

The Tula River feeds the Zimapán hydroelectric dam with wastewater. The high wastewater source originates from the megalopolis México City. This water is considered a high risk for human health due to a wide range of contaminants and emerging substances, as well as a high load of organic matter and nutrients, increased after intensive precipitation events.

The changes in water quality in dry and rain conditions can lead to several limnological spatiotemporal changes in physicochemical parameters in the water column, during the mixing and stratification patterns, water transparency, pH, and nutrients in the photic zone in the dam, and through the altitudinal gradient in the river. There are few studies at that level of detail in subsequent periods of drought and rainfall; water quality variations of tributaries may present spatial gradients along reservoirs in their riparian, transitional, and lacustrine zones (Thornton, 1990; Geraldes & Boavida, 2004; Olds et al., 2011; Azalina et al., 2012).

The study focused on determining under three different weather conditions (dry cold, rain, post-rain) the limnological spatiotemporal variations on the water temperature, dissolved oxygen, total dissolved solids, pH, water transparency, total nitrogen, and phosphorous in the river-dam system. This limnological spatiotemporal variations knowledge will be helpful in the prevention of diseases in fish and aquaculture activities caused by water quality and oxygen fluctuations, as well as water quality for farming activities using a pumping floating system.

Study Site

The Zimapán reservoir, built for hydroelectric purposes in 1995, is located between the States of Queretaro and Hidalgo (Central Mexico); at a height of 1,870 m, it was considered the first project to take advantage of 95 % of México City wastewater for electric power generation. The main wastewater contributions to the reservoir come from the Tula and San Juan rivers. The reservoir has a storage volume estimated at 1,354 mm^3 and an approximate surface of 2,300 ha, with an average depth of 50-60 m and a maximum depth of 170 m in the curtain (20°40'N; 99°30'W).

The main affluent Tula River, in the state of Hidalgo, promotes high agricultural productivity in the Mezquital Valley, which 40 years earlier was an area of low farming yields due to the semi-arid climate and scarce surface water. The river also receives waste from cement, oil, thermoelectric industries, hospitals, and urban activities (Ramos et al., 2018). The second affluent San Juan River (state of Querétaro) drains the wastewater from the cities of San Juan del Río and Tequisquiapan, with chemical, metal, textile, and wine industries (López et al., 2021). This study works in the Tula River because it is a permanent affluent with an estimated flow of 12.3 m^3/s compared with the estimated flow of 2 m^3/s of the San Juan River.

The area has climate type BWh, very dry and warm, with average annual temperatures >22°C and the coldest month <18°C, with a summer rainfall regime and a prolonged dry season https://sma.gob.mx; May is the hottest month of the year with some rains; the annual temperature variation is 6.8°C. The average yearly rainfall is 432 mm, and the rainy season is from April to September. In June, the highest rainfall is an average of 79 mm; the lowest is in February and March, with an average of 8 mm, and the lowest temperature is 16°C. The outside vegetation of the dam is primarily thorny scrub and, to a lesser extent, grassland; the native plant communities are xerophilous scrub: submontane scrub, desert crash-cause scrub, and desert rosette scrub (González-Medrano, 2003).

Tula River wastewater contains a high load of organic material and organic pollutants, heavy metals, and pharmaceutical waste (Siemens et al., 2008; Sols et al., 2009; Rubio-Franchini et al., 2016; Lesser et al., 2018). Given the high organic load that the dam has, the Riparian communities from the year 1997 have taken advantage of this reservoir for commercial fishing based mainly on tilapia (*Oreochromis* spp.). Later, sport fishing, besides productive activities, irrigated agriculture by pumping water inside the dam, incipient realty, and recently, ecotourism (López et al., 2007).

Material and Methods

On a temperature-rain climate basis, wet (June), post wet (October), cold dry (Feb), physical and chemical data were sampled in seven sites considering the three reservoir zones (Thornton, 1990), one riparian San Juan River, one riparian Tula River, two transitional, and three lacustrine); on the river, three sites: México's wastewater entrance after the Requena dam, one after spring waters zone, and one before the entrance to the reservoir (Figure 1).

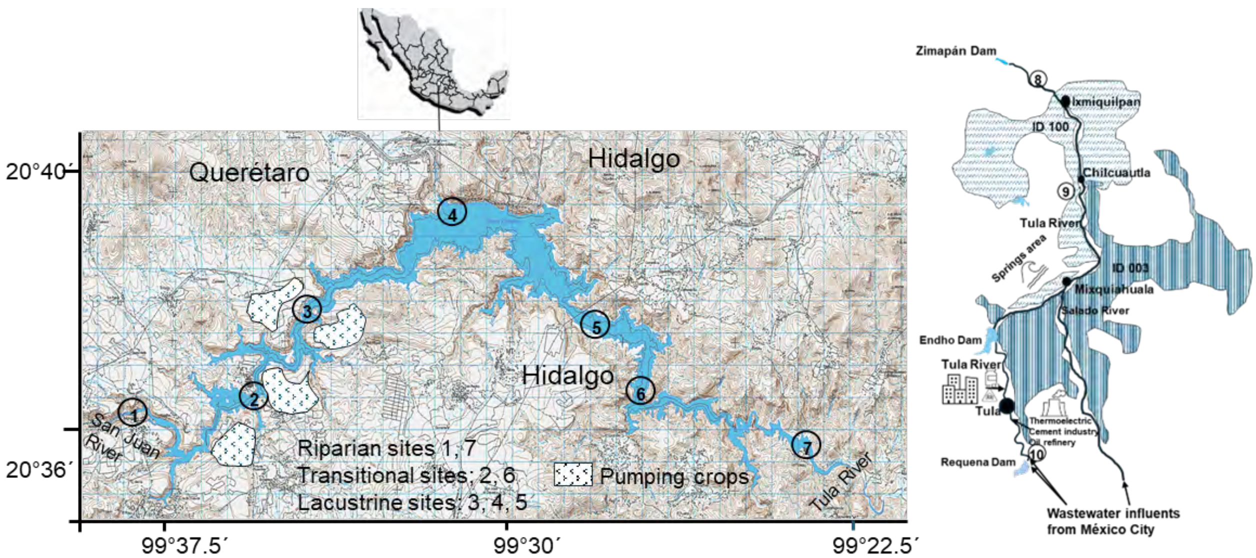

Figure 1. Location of Study Area River Tula with Sites 8, 9, and 10 (right) showing the Wastewater Influents, Irrigation Districts (ID) for Permanent Agriculture, Spring Waters Zones, and Important Cities; the Zimapán Dam with Sites 1-3 (Querétaro State) and Sites 4-7 (Hidalgo State), Pumping Crops Areas.

Composite samples from 0.3-3 m layer from water were collected using a PVC tube (3" Ø x 3 m). Historic temperature and rainfall data characterize the wet (June), post-wet (October), and cold drought (February) months in terms of the hydrological conditions of the reservoir—the following environmental variables at the site: water transparency on the reservoir was measured using a 21 cm diameter Secchi disk, on the river, with a 1 m long plastic transparent tube with a small 2 inches similar plastic Secchi at the bottom. In the water column, dissolved oxygen (mg/l), temperature (°C), pH, and total dissolved solids (g/l) using a multiprobe YSI (model YSI 556), water column registered 0.3-20 m depth.

Total nitrogen (mg/l) and total phosphorous (mg/l) were analyzed with a spectrophotometer Hach DR/2010, according to procedures in APHA (1995). The unfiltered water samples were on ice before being analyzed in the laboratory.

To evaluate the variability of each parameter in the water column of each site in different climatic conditions, average, standard deviation, and the coefficient of variation in % statistics were used. We considered that a %CV>20 would indicate considerable variations, allowing variations between sites in each study month, Spearman correlation, and the ordination diagram with Cluster analysis (Euclidean distance measure) using raw water column data. The Factorial F test gave us the significance of differences between seasons in the dam-river zones, with an average confidence of 95 %, and the Tukey confirmatory test (95 % confidence, 0.05 error). We get the graphing and analyses with Microsoft Excel and Statistica 10 software.

Results

Descriptive statistics with average, standard deviation, and significant differences based on CV% of water column study variables among seven sampling sites for each sampled month are in Table 1.

Table 1. Variations of Water Temperature, Dissolved Oxygen, and TDS (Total Dissolved Solids) by Month Considering Water Column (0-20 m). Underlined= CV% <20, Significant Variation

Temperature °C	1	2	3	4	5	6	7
February							
Average	18.08	17.63	17.69	17.87	18.24	18.37	18.76
Std. Dev	1.01	0.22	0.36	0.62	0.95	0.62	0.48
n	13	13	13	13	13	13	13
CV %	5.60	1.26	2.06	3.47	5.23	3.40	2.56
June							
Average	27.05	23.11	23.49	23.07	23.31	23.09	21.11
Std. Dev	2.41	1.20	0.26	0.93	1.39	1.20	0.67
n	5	13	13	13	13	13	13
CV %	8.92	5.20	1.09	4.01	5.95	5.19	3.18
October							
Average	22.37	22.20	22.15	21.81	21.76	21.65	21.27
Std. Dev	0.94	0.93	0.50	0.21	0.42	0.49	0.66
n	11	12	12	13	13	13	13
CV %	4.19	4.19	2.25	0.98	1.95	2.28	3.08

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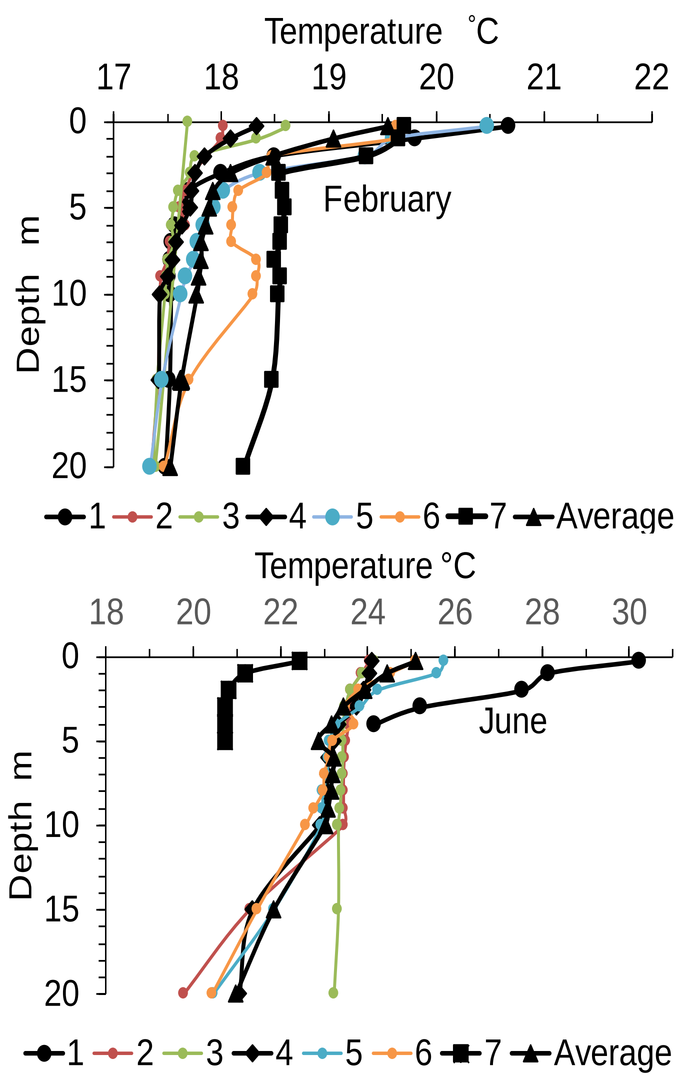
Dissolved oxygen mg/L							
February							
Average	6.74	6.88	6.88	6.84	6.68	6.64	6.52
Std. Dev	0.36	0.12	0.13	0.21	0.31	0.21	0.14
n	13	13	13	13	13	13	13
CV %	5.36	1.72	1.86	3.05	4.58	3.20	2.20
June							
Average	2.70	6.27	5.24	4.74	4.58	4.81	4.11
Std. Dev	0.51	0.87	0.70	1.11	1.43	1.61	0.38
n	5	13	13	13	13	13	13
CV %	18.90	13.79	13.45	23.46	31.29	33.36	9.13
October							
Average	4.56	5.52	5.18	5.05	2.74	3.25	2.36
Std. Dev	1.34	1.43	1.60	1.02	0.36	0.58	0.90
n	11	12	12	13	13	13	13
CV %	29.26	25.87	30.95	20.20	13.26	17.96	38.11
TDS g/L							
February							
Average	1.50	1.51	1.60	1.62	1.62	1.75	1.85
Std. Dev	0.12	0.04	0.00	0.00	0.01	0.07	0.06
n	13	13	13	13	13	13	13
CV %	7.68	2.43	0.26	0.10	0.65	4.24	3.27
June	1.53	2.25	2.51	2.54	2.65	2.66	2.77
Average	0.39	0.03	0.01	0.03	0.06	0.05	0.05
Std. Dev	25.65	1.17	0.46	1.06	2.26	1.88	1.69
n	5	13	13	13	13	13	13
CV %	65.59	44.50	39.82	39.31	37.73	37.54	36.12
October							
Average	1.41	1.42	1.61	1.63	1.67	1.69	1.67
Std. Dev	0.12	0.13	0.01	0.00	0.00	0.05	0.06
n	10	12	12	10	13	13	13
CV %	8.43	9.05	0.32	0.27	0.26	3.15	3.79

Limnological Variations in the Water Column Zimapán Dam

Temperature in the water column (0.3 to 20 m), temperature values were 17.3 to 20.6°C in February and 20.3 to 26°C in June, with the influence of hot water springs (38°C) in site 1 with 30°C. The temperature variability between the seven sites occurred in the first 2 to 5 m depth, with a thermocline of 24°C in June from 5 to 10 m and in February with 22°C between 2 and 10 m. The variation is low, with CV less than 20 % at each site, with the most significant variation in June at site 1, with 8.9 % close to the hot water springs (Table 1 Fig. 2).

Dissolved oxygen had the lowest variability in February with a range of 6 to 7 mg/l, the most significant variability in space and time in June with values between 3 and 7 mg/l between the surface and 10 m depth, with oxycline between 10 to 15 m and with 3 to 7 mg/l, with a subsequent decrease between 2 and 3 mg/l; October presented two zones, lower concentrations 1 to 4.5 mg/l between sites 5 to 7, and 3 to 7 mg/l between sites 1 to 4, site 7 stands out where the river enters. Then, hypoxia at 10 m, there was an increase to 3 mg/l at 15 m and up to 5 mg/l at 20 m. The most remarkable changes were in June in the influence of the Tula River in sites 4 to 6 with CV of 23.3 to 33.4 %; October presented significant variations in the area influenced by the San Juan River, from site 1 to site 4 (Table 1, Fig. 2).

Total dissolved solids presented the lowest values in October and February, with the range 1.2 to 1.9 g/l, and the highest values in June, with 1.0 to 2.9 g/l: the variations with CV% were less than 20, except June in site 1, with CV% 25.6. The lowest values were between sites 1 and 4 in the three months and the highest in sites 5 and 7 in the Tula River influence area (Table 1, Fig. 2).



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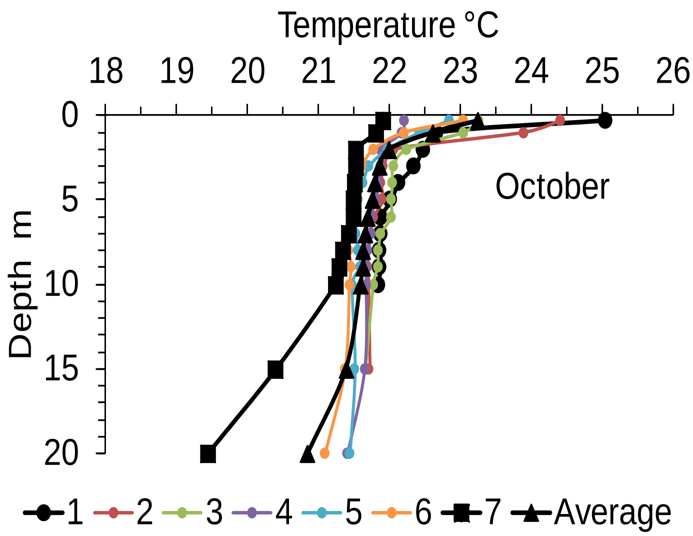

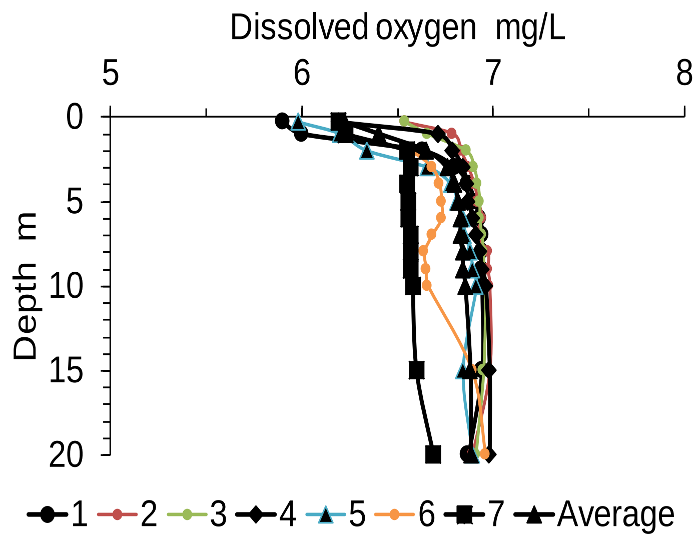

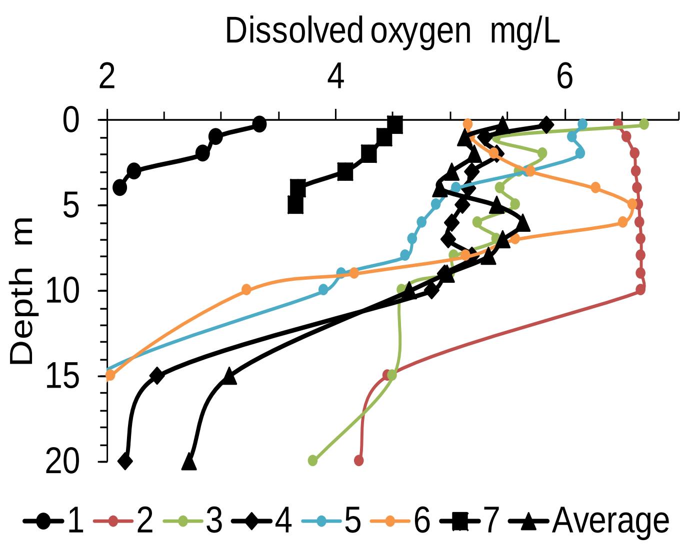

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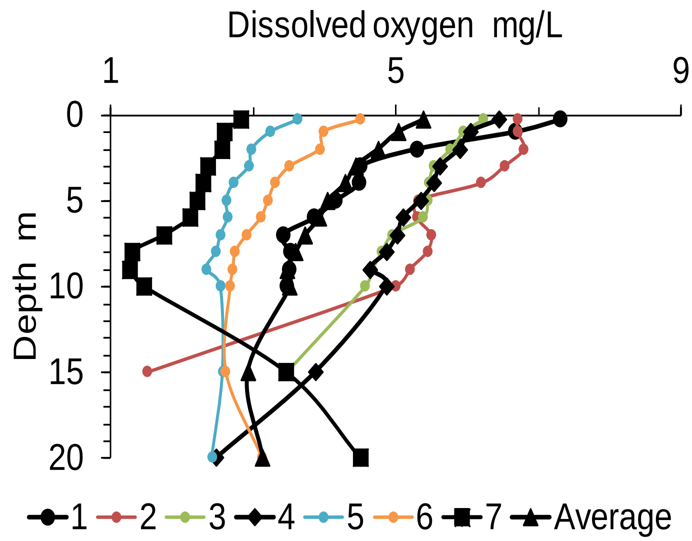

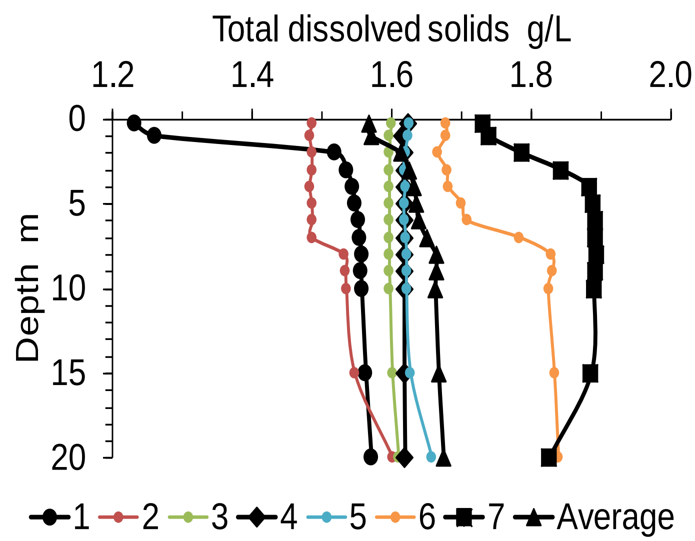

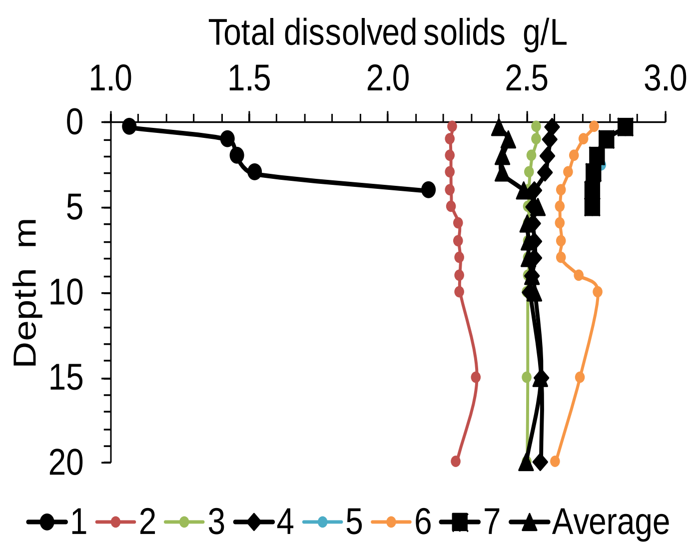

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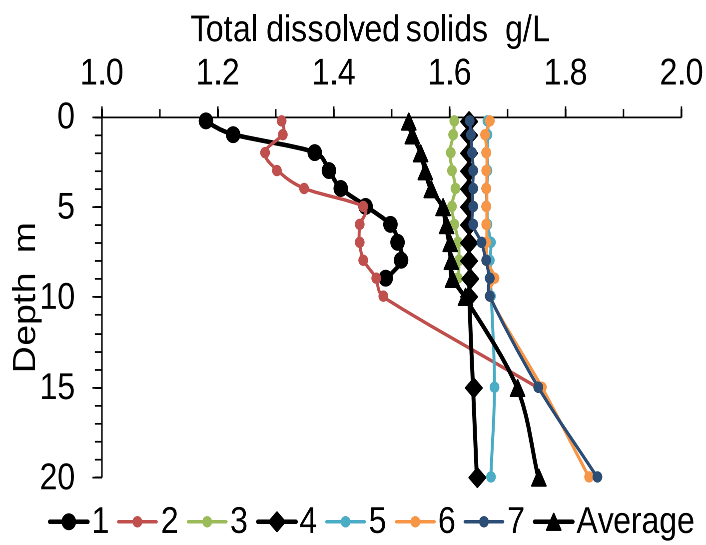


Figure 2. Water Column (Surface-20 m Depth) variations of temperature (°C), dissolved oxygen (mg/L), and total dissolved solids (g/L).

Zimapán Dam-Tula River system

In the composite water sample (surface at 3 m) from sites 1 to 7 of the dam and in surface water (0.20 m) from sites 8 to 10 in the river, the water temperature of the river dam system presented variations between each month of study. However, the river dam did not show significant variations between the months studied, $F(6,18)=1.0637$, $p=0.4193$. At the dam, the lowest values were in February, with averages of 18.6 to 20°C, and in June, with high temperatures, 24.8 to 25.4°C. The river had the lowest temperature values, ranging between 18 and 21°C. In the dam, there were no significant differences between the three areas in June and October $F(4, 12)=0.2263$, $p=0.9184$; the lowest temperatures were in February, with significant differences $F(2, 12)=15.723$, $p=0.0004$) (Fig. 3A).

The changes in dissolved oxygen concentrations also did not present significant differences by study area and month $F(6,18)=0.3958$, $p=0.87204$. The dam areas had the highest records in February but with a variation of 6.0-6.4 mg/l in June and October, with averages in the range of 3.7-6.4 mg/l; the river, with lower concentrations than the dam areas, with a range of 3.5-4.6 mg/l. The dam had no significant differences between the three zones $F(4, 12)=0.5152$, $p=0.7262$; the lowest oxygen concentrations were recorded in the riparian zone, while the highest were in the three zones in February (Fig. 3B).

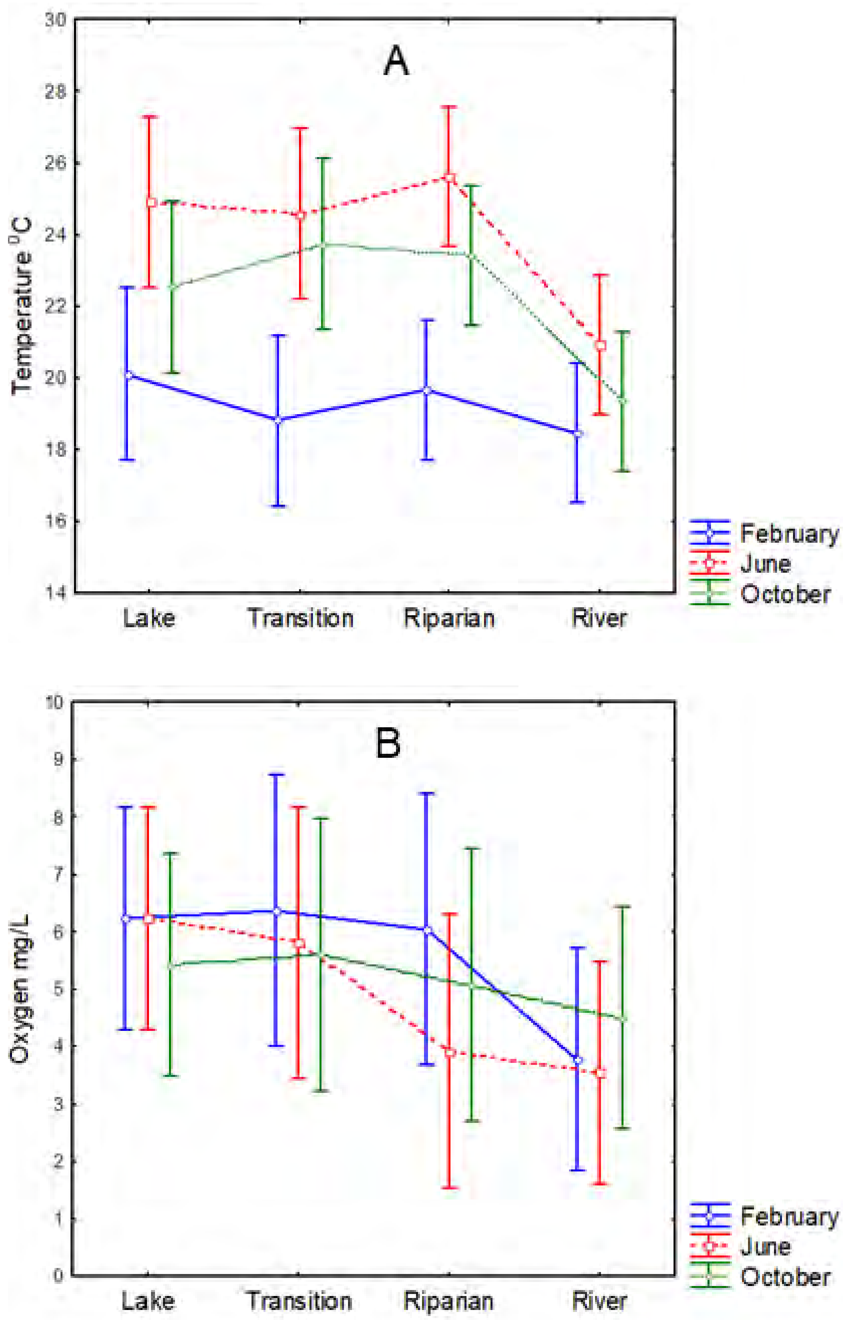
Water transparency also had no significant differences between the months and study areas $F(6,18)=1.6665$, $p=0.1867$. At the dam, the lake zone had the highest records, 6.0 m in February and 6.4 m in June, the lowest in the riparian zone, 1.1-2.8 m; the river, its average values were almost the same, in the range of 0.5-0.8 m; the dam areas well differentiated from each other and the river with lower transparency. Between the areas and months of collection at the dam, there were no significant differences in the transparency values recorded $F(4, 12)=1.5767$, $p=0.2433$. The lowest transparency values were recorded in the riparian zone, while the most significant transparency depth in the lake zone corresponded to February and June (Fig. 3C).

The average pH varied from basic conditions 7.7 to 8.7 in June and October, and February with values between 7.1 and 8.2 to neutral conditions 7.1; there were no significant variations $F(6,18)=1.1180$, $p=0.3907$ between the months and the areas of the river-dam system; The riparian zone shows the influence of river water, with values between 7.3 and 8.1, higher than those of the transition and lake zones. The river with the highest average values is 8.2 to 8.7. Between the areas and months of collection at the dam, there were no significant differences in pH values $F(4, 12)=0.5389$, $p=0.7102$. The lowest pH values were in the three areas in February (Fig. 3D).

In TP, the highest concentrations were in the river, 7 to 22 mg/l. The dam areas had values close to 3 mg/l. There were significant differences $F(6,18)=3.2314$, $p=0.0247$ in the river dam system, with the river having the highest concentrations in the three months of the study. Between the areas and months of collection in the dam, there are no significant differences in total phosphorus values $F(4, 12)=0.3633$, $p=0.8301$. The lowest total phosphorus values were in the transition and riparian zone in June and the highest in February in the riparian zone (Fig. 3E).

The TN, the highest values were in the river, 24 to 36 mg/l, and the dam areas, with values between 2 and 7 mg/l; there were significant differences $F(6,18)=2.8097$, $p=0.0414$ in the river-dam system. There were no significant differences in the dam $F(4, 12)=0.8137$, $p=0.54$. The highest total nitrogen values were recorded in the riparian zone in February, while the lowest was in June and October in the three collection areas (Fig. 3F).

The limnological variables showed spatial changes in their values but were not significant or relevant compared with temporal changes between the three climatic conditions.



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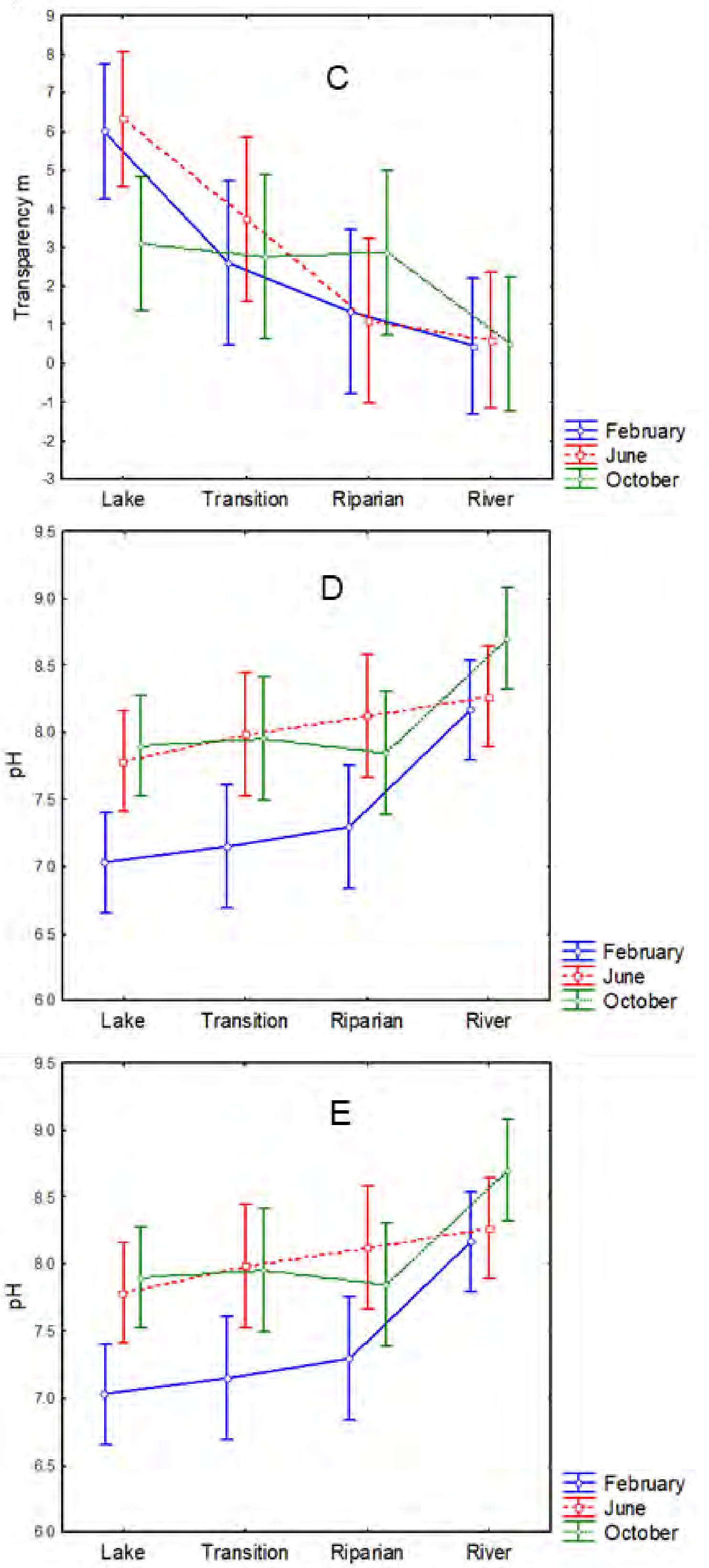

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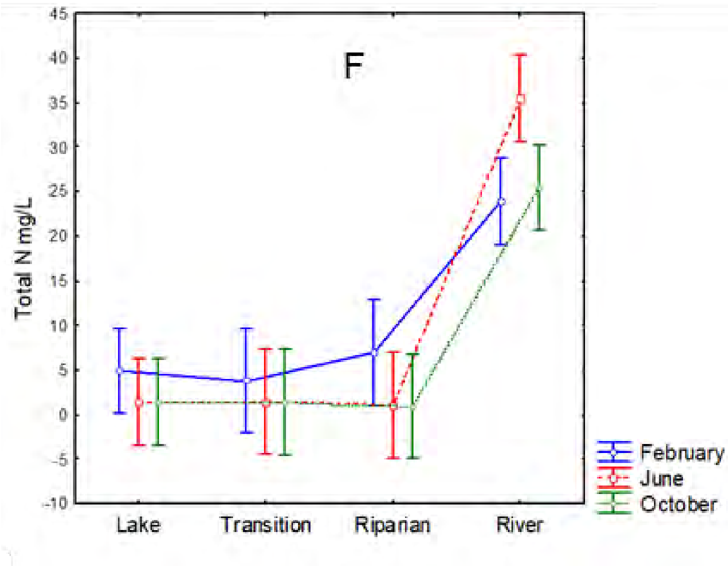


Figure 3 (A, B, C, D, E, F). Comparative Surface Water Variations Months vs Dam Zones and River of Physicochemical and Nutrient. F Factorial Test, Average, Confidence Bars 95%. There Are No Significant Differences in Months vs Zones. The River and the Dam Differ in Limnological Spatiotemporal Transparency, pH, Total P, and Total N Variations.

Tukey confirmatory test, with all the limnological parameters and for the tree climatic conditions studied, showed the river-dam differences in sites 8, 9, and 10 with temperature, oxygen, transparency, and nutrients; there were fewer differences in sites 1 to 7 of the reservoir (Table 2).

Table 2. Tukey Confirmatory Test (N =20, 95 % confidence, 0.05 error), to Detect Significant Differences (in bold) at Work Sites. River Sites 8,9 and 10 are Different in Most of the Parameters, but pH in Sites 5 and 6.

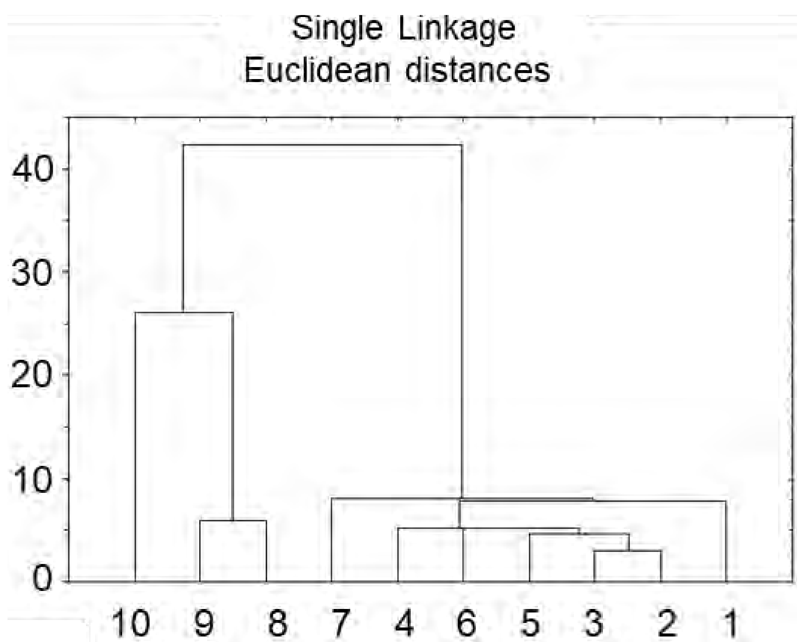
Parameter	1	2	3	4	5	6	7	8	9	10
Temperature 0C	0.90	0.89	0.86	0.87	0.98	0.95	0.74	0.33	0.26	0.21
Oxygen mg/L	1.00	0.96	0.97	0.99	1.00	1.00	0.97	1.00	0.97	0.01
Transparency m	1.00	0.92	0.95	0.89	0.35	0.99	0.99	0.02	0.020	0.01
pH	1.00	0.99	0.99	0.96	0.027	0.036	1.00	0.99	0.00	0.25
Total P mg/L	1.00	1.00	0.99	0.99	1.00	0.99	0.98	0.35	0.13	0.004
Total N mg/L	1.00	1.00	0.99	0.97	0.99	0.96	0.99	0.0002	0.0004	0.0001

The Pearson correlation analysis between the variables in the ten stations in the three different climatic conditions showed that significant negative or inverse proportional variations occurred between dissolved oxygen and total nitrogen nutrients, with r=-0.640, and with total phosphorus, with r=-0.548. Another important correlation was oxygen with pH, with r=-0.587. More TN, TP, and pH, less Oxygen (Table 3).

Table 3. Pearson Correlations among All Sites of the River Dam System during Three Different Climatic Conditions. Important Correlation Above r= 0.5

Pearson Correlation, n=30	
Temperature vs Oxygen	0.1164
Temperature vs Total N	-0.2841
Temperature vs Total P	-0.5227
Temperature vs Transparency	0.2231
Temperature vs pH	0.1101
Oxygen vs Temperature	0.1164
Oxygen vs Total N	-0.6401
Oxygen vs Total P	-0.5476
Oxygen vs Transparency	0.3086
Oxygen vs pH	-0.5875

In river-dam surface water, the physicochemical and nutrient variables allowed the definition of two zones: sites 10, 9, and 8 and sites 7 to 1 of the dam. The river group separates site 10, which had lower oxygen and higher TN and TP from the other sites, where oxygen increases and TN and TP decrease. Likewise, the horizontal zoning in the surface water of the dam presented sites 1 and 7 separated from the remaining sites; at the same time, the lake zone through sites 5, 6, and 4, and the area of influence of the San Juan River in sites 2 and 3 (Fig. 4).



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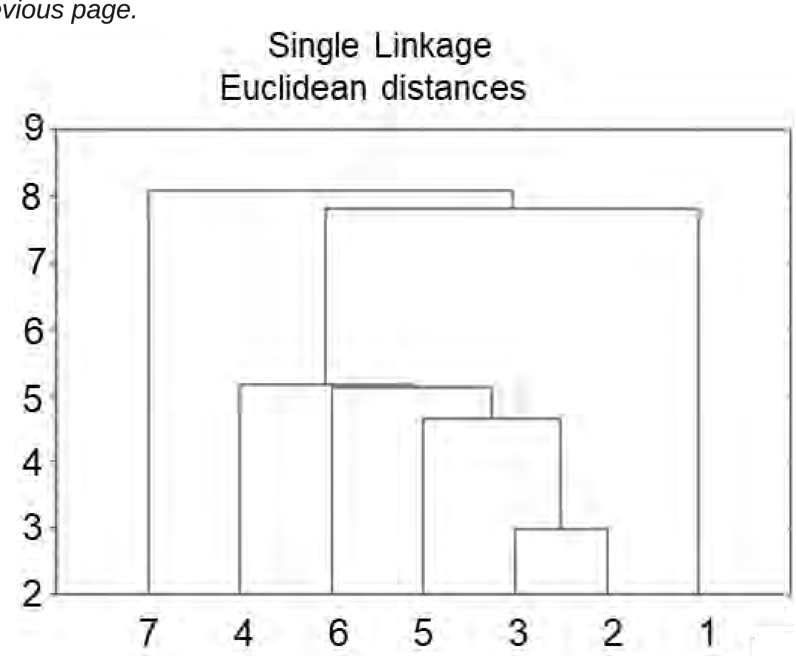

Figure 4. Ordination Diagram with All Study Variables of Sampling Sites, Left Together River and Dam Sites 1-10, Right Only Dam Sites 1-7.

Discussion

Since 1972, the Tula River in the State of Hidalgo has received wastewater from the Megalopolis Mexico City. The water irrigates approximately 45,214 ha of crops in the Mezquital Valley, administered by two central irrigation districts (ID). It is one of the most polluting in the country, generating 40,942 million m^3 of wastewater annually (López et al., 2007).

Comparative drought-rain-pos rain conditions are essential to know the limnological variations in the river dam system. The limnological spatiotemporal variations will help to understand the increase and decrease in values and how to respond to the dam regarding water quality, eutrophication, and environmental quality for fisheries and sport fishing.

The region’s semi-arid climate with ambient temperatures above 22°C and the lowest at 18°C had no significative water column variations (%CV <29) due to its slight annual variation (<6°C).

The environmental temperature, slope, current, bottom, tributaries, thermal springs, depth, and distance from the studied sites determined differences in the temperature, pH, dissolved oxygen, total dissolved solids, and nutrients in the river sites; likewise, in the dam zones, environmental temperature, winds, and the river’s water incoming affect the mixture of temperature, dissolved oxygen, nutrients, and water transparency in the dam.

These vertical patterns varied in time, promoting the formation of thermocline and oxycline in June near the surface and up to 10 or 15 m at greater depths, as well as their breaking in the October mixing process; shallow places were more susceptible to increases in temperature and oxygen concentrations; as depth increased, temperature and dissolved oxygen decreased. When the dam is in the process of stratification and beginning of the mixing process, the oxygen presented significant variations (CV% greater than 20) as a product of the entry of the two rivers, particularly after the rains that transported oxygen-consuming compounds in the wastewater. The low variation of dissolved oxygen in conditions of cold drought in February, the lower entry of sewage, and the lower environmental temperature could be the drivers for the increase in oxygen solubility and the adequate concentrations of dissolved oxygen for aquatic life and aquacultural activities in the dam.

The total dissolved solids also showed differences between river entrances: Site 1 had less concentration than Site 7, and Site 1 had a dilution effect from wastewater from the thermal water spa area 8 km upstream. In contrast, Site 7 received water from the runoff in the area. The Tula River is the main contributor to nutrients, organic matter, and pollutants since it is an outlet conduit for sewage from Mexico City.

The decrease in the transparency at dam riparian sites illustrates the influence of the basin human activities on the water body's physicochemical characteristics; the increased transparency in the internal sites of the reservoir may be due to the suspended solids tending to settle in extended calm areas with high depth. Primary physical dynamics in the reservoir occur in the first 5-15 m of depth, the starting mixing process in October and even in February, causing the decrease of transparency throughout the reservoir. Storm runoff is the primary source of solid suspended material in the water bodies (Kemdirim, 2005). Similar results are for Lake Chapala, Mexico (de Anda et al., 2004) and the Aguamilpa reservoir (Rangel-Peraza et al., 2009).

The reservoir receives wastewater throughout the year. The oxidation of the organic matter that entered, the low water temperature with the lowest photosynthetic efficiency, the mixing conditions, decomposing organic material, and inorganic substances consuming oxygen promoted the decline of dissolved oxygen in riparian zones (Del Sontro et al., 2010). The condition of different turbulence and the mixture from surface to 5 m depth in which thermocline and oxycline occurred conditioned the different oxygen concentrations.

The average dissolved oxygen surface water remained over 4 mg/l in June and February. This finding suggests that the reservoir surface water is suitable for fish production (*e.g.*, tilapia is the main fish caught in the reservoir). However, it is not convenient in November because of continuous conditions under hypoxia (DO <2 mg/l) with occasional sickness and massive fish kill (López et al., 2007).

The entrance of wastewater, with its high values of nitrogen, phosphorus, pH, and low transparency, showed the effect of dilution or self-purification after the entry point. The combined action of permanent turbulent flow along the slope and rocky substrates and the constant entry of high volumes of water from the springs between sites 10 and 9 helped reduce those variables' values. Still, high concentrations of nitrogen and phosphorus arrive at the dam. It is a fact that "partially treated" water enters site 1 of the dam, first through the Endho dam (State of Hidalgo), which functions as an oxidation pit, and then due to the permanently lotic character of the river.

The riparian zones in canyons, which have less depth and less exposure to the wind, presented a more significant occurrence of high DO due to primary productivity or low values due to the wastewater effect.

The Zimapán reservoir has the epilimnion in the first 5-10 m and adequate oxygen values for aquatic life (>4 mg/l). In the hypolimnion, temperatures decreased and with values of hypoxia, in conditions of lower temperatures, the concentrations of DO usually lower by reaching hypoxia; with hypoxia and anoxia in the hypolimnion, there are conditions for the release of compounds such as methane, carbon dioxide, hydrogen sulfide, ammonia, iron, manganese, and phosphorus (Rangel-Peraza et al., 2012). Transparency, temperature, and DO are suitable for tilapia and black bass in this reservoir, but only at the first 15 m depth. Previous studies at Dam Zimapán present values of anoxia from 30 or 40 m depth in months from May to September and indicate that the reservoir presents a mixture of only 10-20 m of depth. It is considered a meromictic tropical reservoir with a permanent inlet of wastewater and dissolved oxygen that does not depend on physical and temperature dynamics and can also be important in the microbiological processes of production and consumption; previous studies reveal all physical, chemical, and biological processes occur from surface to 20 m depth, with anoxic waters from 40 to 70 m depth (López et al., 2007; Bravo-Inclán et al., 2008).

The reservoir showed an average pH of 7-8.4, considered a neutral or alkaline water body, consistent with other semi-desert soils with limestone rocks with carbonates and bicarbonate. Most Mexican waterbodies are rarely acidic, alkaline, or nearly neutral (Sarma & Elías-Gutiérrez, 1997; Torres-Orozco & Estrada-Hernández, 1997). Tula's river pH was considered highly alkaline (pH 7.7-9.6) with critically high values at site 10, where wastewater comes from México City; numerous spring waters before and after site 8 could explain pH values below 8.

NT and PT with concentrations, indicating nutrient excess because the source of nitrogen and phosphorus is the wastewater transported by the Tula and San Juan Rivers, as the contributions by livestock waste like those in some reservoirs in Brazil (Nogueira, 2001; Carvalho et al., 2002); the entry of high nutrient rates by river supply, affect water quality (Nogueira, 2001; Delazari-Barroso et al., 2009); the rates of denitrification by the action of anoxic sediments at the bottom and the permanent entry of organic matter are standard processes in dams with anoxic bottoms (Abe et al., 2003).

The TN concentrations in this dam can be part of the processes that promote the frequent algal blooms by cyanobacteria (*Microcystis* and *Anabaena*) in months of drought, high temperature, and little or no wind, resulting in high densities of cyanobacteria (López et al., 2007).

Based on the TP values (Lampárelli, 2004; Cunha et al., 2013), the reservoir always presented a hypereutrophic condition by the permanent inlets of wastewater. Dams like Zimapán, with high inflows of organic matter and accelerated eutrophication by nitrogen and phosphorus, present severe situations of degradation in water quality, with frequent cyanobacteria algal blooms and cyanotoxins, as well as precursors of trihalomethanes, and compounds with strong unpleasant odors generated from the decomposition of the biological material from animals, plants, and microorganisms (Mostofa et al., 2007; Conley et al., 2009).

This river-reservoir system is experiencing a frequently pronounced decline in water quality because of the excessive nutrient inputs delivered in untreated sewage effluents, pollution by metals and toxins from oil, cement, pharmacists, and other human impacts, physical disturbances included. There are similar conditions in other reservoirs (Daughton & Ruhoy, 2009; Fontana et al., 2014); because of this condition, the water from Dam Zimapán is beneficial for crop irrigation and is not considered healthy for human use or recreation.

The values of hypoxia DO in sites 1 and 7 are due to their consumption in the degradation process of the organic material that arrived by the trawls of both rivers and local runoffs in the reservoir surroundings after the rain occurred from June to September.

The self-depurating process in the river and reservoir mixing processes, bacterial activity in the water column, biological fishery actions, and minor rain events have promoted the decline of N and P; at the onset of research activities, the dam had data higher than 5 mg/l in the years 2002-2005 (López-Hernández et al., 2007).

The cluster diagram and Tukey analysis based on physicochemical and nutrients clearly show the separation between the river and the dam based on decreased values from the river and the differences between lotic and lentic systems. The reservoir has a typical pattern; the deeper sites (lake area) are always together regarding total nitrogen and phosphorous dilution. Site 7 receives the highest wastewater volume in the river, and site 1 has less pollutant loading.

This study confirms the water quality response regarding the permanent entry of organic matter, dissolved oxygen producers-consumers, and the potential nutrient loads generated by anthropogenic activities in the drainage basin and the reservoir surroundings. Similar dynamics exist in other Brazilian reservoirs (Geraldes & Boavida, 2003, 2004). In this research, wastewater with high pH, nitrogen, and phosphorous showed a significant negative relation with dissolved oxygen.

Conclusions

Limnological spatiotemporal variations of water temperature, oxygen, dissolved solids, transparency, pH, total nitrogen, and phosphorous were evident between river and dam zones; river site variations had hydrological differences in current, influents, rocky/mud bottom, and anthropic activities in the surroundings. The dam sites, according to depth, wind influence in open and closed areas by mountains, ambient temperature, and the river entrance.

Primary physical dynamics based on temperature transparency and oxygen in the reservoir occur in the first 15 m of depth, the starting mixing process in October and even in February. The average dissolved oxygen surface water remained over 4 mg/l in June and February; surface water is suitable for aquaculture fish activity. However, it is not convenient in November because of continuous conditions under hypoxia (DO <2 mg/l).

The semi-arid climate of the region with ambient temperatures above 22°C, the lowest at 18°C and no significative water column variations, and its slight annual variation.

NT and PT with high concentrations indicate nutrient excess because the source of nitrogen and phosphorus is the wastewater transported by the Tula and San Juan Rivers and other contributions by livestock waste.

The reservoir always presented a hypereutrophic condition based on the total phosphorous values in the permanent inlets of wastewater; the TN concentrations can be part of the processes that promote the frequent algal blooms by cyanobacteria (*Microcystis* and *Anabaena*) in drought with little or no wind.

Zimapán Hydropower Dam, with high organic matter inflows and accelerated eutrophication caused by excessive nutrient inputs delivered in untreated sewage effluents, pollution by metals and toxins from oil, cement, pharmacists, and other human impacts, presents severe situations of degradation in water quality. Water can be used for irrigation purposes, not for human drinking or recreational activities.

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Authors' Contributions

GFF worked with the physicochemical analysis and water column graphics; RAEG and GTP collected samples; LHM and GPA carried out statistical graphics procedures.

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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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