Topics of limnological research in Mexico

Coordinator
Alfredo Pérez Morales

UNIVERSIDAD DE COLIMA

Topics of limnological research in Mexico

Coordinator
Alfredo Pérez Morales

Universidad de Colima

Topics of Limnological Research in Mexico

Avenida Universidad 333
C.P 28040, Colima, Colima, México
Dirección General de Publicaciones
Telephone numbers: 312 316 1081 and 312 316 1000, extension: 35004
Email: publicaciones@ucol.mx
www.ucol.mx

ISBN electrónico: 978-968-9733-13-3
DOI: 10.53897/LI.2025.0032.UCOL
5E.1.1/317000/308/2024 Edición de publicación no periódica

Cover and interior photographs: Juan Franco Rodríguez

Certified Publishing Process with ISO since 2005
Double blind ruling and editing are registered in the PRED Electronic Publishing System

Registration: LI-020-24
Received: September 2024
Dictamination: November 2024
Published: December 2025

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

Index

On the Relevance of Monitoring the Thermal Structure, Community Metabolism and Phytoplankton Ecology of Inland Waters of Mexico in the Context of Global Change

Patricia Margarita Valdespino-Castillo[1,2]
Jorge Alberto Ramírez-Zierold[2]
Rocío Jetzabel Alcántara-Hernández[3]
Mariel Barjau-Aguilar[2,3]
Mario Alberto Neri-Guzmán[4]
Paola Julieta Cortés-Cruz[5]
Oscar Alejandro Gerardo-Nieto[2]
Martín Merino-Ibarra[2]

[1] Escuela Nacional de Ciencias de la Tierra, Universidad Nacional Autónoma de México, Circuito de la Investigación científica, Mexico City, 04510, Mexico. valdespinopm@encit.unam.mx.

[2] Unidad Académica de Ecología y Biodiversidad Acuática, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Circuito exterior s/n. Mexico City, 04510. Mexico

[3] Instituto de Geología, Universidad Nacional Autónoma de México, Circuito interior s/n, Mexico City, 04510, Mexico

[4] Facultad de Estudios Superiores Zaragoza, Universidad Nacional Autónoma de México, Batalla 5 de Mayo S/N, Ejército de Oriente Zona Peñón, Iztapalapa, Mexico City, 09230, Mexico

[5] Escuela Superior de Ingeniería y Arquitectura Unidad Ticomán, Instituto Politécnico Nacional, Calz. Ticomán 55, Mexico City, 07738, Mexico

Abstract

The relevance of aquatic bodies on global biogeochemical cycles has been recently highlighted. Thus, limnological research is increasingly needed to improve the models of ecosystems functioning. We also need to face Climate and Global Change. As the information on tropical systems is still scarce, tropical limnology is providing interesting elements to understand ecosystem's responses to environmental change. Particularly relevant are long-term monitoring efforts. Here we revise recent research on tropical limnology of aquatic ecosystems of Mexico that contribute to understand emergent and complex challenges in a panorama of water crisis, particularly, the rise of temperature and increased eutrophication, Our analyses showed long-term, interdisciplinary monitoring of ecosystems of the Mexican highlands are providing novel findings that contribute to global research questions in areas

like: community metabolism and carbon dioxide fluxes, physical forcing, water-level fluctuations, internal proceses that affect vertical nutrient exchange, biodiversity, phytoplankton ecology, eutrophication progressions, plankton interactions, and phytoplankton blooms. This research contributes to the understanding of eutrophication and oligotrophication under warming scenarios, as well as aims to provide elements to mitigate and adapt to the increasing drought, and water crisis in Mexican territory.

Keywords

Tropical limnology, global change, thermal stratification, eutrophication, net heterotrophy, long-term monitoring.

Introduction

In recent decades, the linkage of aquatic systems functioning and Climate Change has been increasingly studied (IPCC, 2001). For example, it has been determined that changes in vertical stratification and the rise (upwelling) of water in different regions are related to warming of the surface layer. Baseline studies to understand these processes included research showing a strong positive relationship between the temperature of surface water and that of the surrounding air, at regional scales (*e.g.*, Livingstone, 2003; O'Reilly et al., 2003). Aside from exploring the largest spatial scale possible, the access to time-series monitoring studies has been critical. For example, the study conducted by Boyce et al. (2010) shows a trend, in the last century, of decreasing chlorophyll coverage. Their results indicate this trend is related to the increase in surface layer temperature. They concluded that these trends may be linked to changes in vertical stratification and water upwelling, mainly because of elongation (or increase in depth) of surface layers, and limitation in nutrient supply from deep layers, as has been delineated by other studies, see Robertson et al. (1990), Falkowski et al. (1998), Behrenfeld et al. (2006), and Martínez et al. (2009).

Epicontinental aquatic systems have been useful models to observe the impact of global warming on the thermal characteristics of water bodies since epilimnetic temperature experiences a direct and rapid response to climatic conditions (Lee et al., 2012). Temperature also shapes the density gradient in the water column, therefore, if climatic conditions change, epilimnetic warming would induce changes in the intensity and duration of stratification, thermal stability, and the depth of the thermocline (McCormick and Fahnenstiel, 1999; Livingstone, 2003; Coats et al., 2006). In fact, lakes have recently been tagged as "sentinels" of Global Climate Change because they are sensitive to climate, respond quickly to change, and integrate information about changes in their watersheds (Pham et al., 2008; Williamson et al., 2008; Adrian et al., 2009). Examples of these observable changes are evapotranspiration, infiltration, water retention by soils, surface and subsurface runoff, and underground recharge. The aquatic communities also experience short-term responses in this context, some examples include prokaryoplankton, phytoplankton, and zooplankton compositional changes related to turbulence, water-level fluctuations or nutrient availability, that frequently are related to some species blooms (*e.g.* Ramírez-García et al., 2002; Ramos-Higuera et al., 2008; Jiménez-Contreras et al., 2009; Ramos-Olvera et al., 2009; Valdespino-Castillo et al., 2014, 2017; Valeriano-Riveros et al., 2014; Nandini et al., 2019). Yet, much research is needed to understand the water bodies internal processes and their implications in ecosystem's functioning.

The increase in temperature is related to processes that have important ecological effects such as: the decrease in oxygen saturation due to the increase in temperature, or the alteration in the frequency of extreme wind/weather events (Mooij et al., 2005, Blenckner et al., 2007). Indirectly, temperature is also related to changes in trophic structure (Gyllström et al., 2005; Beklioglu et al., 2007; Jeppesen et al., 2007; Meerhoff et al., 2007), and complex interactions between temperature, nutrient recycling, and physical forces (Jeppesen et al., 2009; Jones et al., 2010; Merino-Ibarra et al., 2021) that are often determined by the conditions of each ecosystem. Moreover, temperature increase may determine the net metabolism of water bodies, for example by increasing respiration and carbon exportation to the atmosphere (Guimarais et al., 2019).

There is convincing evidence that much of the variation in ecological and biogeochemical functioning of natural waters is related to changes in climate (Livingstone and Dokulil, 2001; Blenckner et al., 2007; Jones et al., 2010). As the studies are very limited in tropical inland waters, Lake Tanganyika, East Africa, is one of the most studied tropical systems. Its fisheries have crucial economic importance for the region. In a very paradigmatic study, O'Reilly et al. (2003) studied the sediments of the lake and concluded climate warming is diminishing productivity in Lake Tanganyika. By analysing C isotope records (delta ^{13}C) in the sediments, their results show that primary productivity in Lake Tanganyika, may have decreased by around 20 % (from the 1950's to date), implying a decrease of approximately 30 % of the fishing load (O'Reilly et al., 2003).

The problem of scale is an additional challenge to study the effects of Climate Change on natural waters. In their study, Boyce et al. (2010) recognize that climate variability at a regional scale can induce variations on the large observed trends. Currently, different models are used to explore system responses to Climate Change in different regions (*e.g.*, Peeters et al., 2002; Bell et al., 2006; Komatsu et al., 2006), and yet the variation associated with applying the models to different types of lakes receives little attention (Jones et al., 2010).

In this context of environmental change, we will briefly explore the global warming scenarios for Mexico. We will focus on the populated Central Highlands to frame the scenarios of change of the aquatic systems on this area in the context of Climate Change. This area concentrates recent limnological efforts in Mexico.

Mexico, Global Change and Inland Waters

The Mexican territory is currently experiencing intense transformation related to human activities such as industry, commerce, minery, tourism, cattle raising, and agriculture. In this chapter, we do not intend to perform a general diagnosis on anthropogenic activities; instead, we shall briefly summarize the general scenarios of change in the panorama of Climate Change. Additionally, some authors have stated that in general, the regional impacts of global Climate Change on the functions and services of aquatic ecosystems may be even greater than the impacts of local anthropogenic activities (O'Reilly et al*.,* 2003).

Climate Change models for the tropics foresee increases in temperature and evaportranspiration, conditions that generally translate into droughts of different magnitudes. Actually, the most likely general scenario for much of the Mexican territory is this (Hernández-Cerda & Valdez-Madero, 2004), as well as changes in the regime and magnitude of runoff, soil moisture, and evaporation (Mendoza et al*.,* 2004). Drought could limit nutrient export to aquatic systems through altered weathering. And, although considerably smaller in magnitude, atmospheric transport of nutrients like P could increase (see Paytan & McLaughlin, 2007). The presence of extreme events could also alter the seasonality of nutrient export. Under a somewhat different approach, the model of Malmaeus et al. (2006) considers that mixing, mineralization, diffusion, and bio-absorption are temperature dependent. Their work highlights that lakes whose water has longer residence times will be more sensitive to increased temperatures.

Even under certain limitations, most atmospheric general circulation models based on Mexican territory, project different percentage decreases of precipitation in Mexico. For example, in the regionalized precipitation panorama for the period 2070-2099, a drier condition is expected, mainly in the Baja California Peninsula and in northwest and central Mexico (in terms of the percentage of average annual accumulated rainfall [see Martínez & Fernández, 2004]).

The 2023 drought monitor of INEGI (Mexican National Institute of Statistics, Geography, and Informatics [www.inegi.org.mx]) integrates a time-series collection of climatic information of the Mexican territory. By comparing drought indicators through space and time, users of this platform may learn about the recent high-water vulnerability accross the Central and Northern regions of the country. The drought indications depict heterogeneity in time, with a non-periodical distribution (Fig. 1; Conagua, 2023). Statistically, the States with the highest drought index are Durango, Chihuahua, and Coahuila. In the second order, Nuevo León, Zacatecas, San Luis Potosí, Aguascalientes, and Guanajuato, located in the Central Highlands. The central region of Mexico depicts the highest population density and experiences relevant pressure over agriculture soils, rivers, reservoirs, and aquifers.

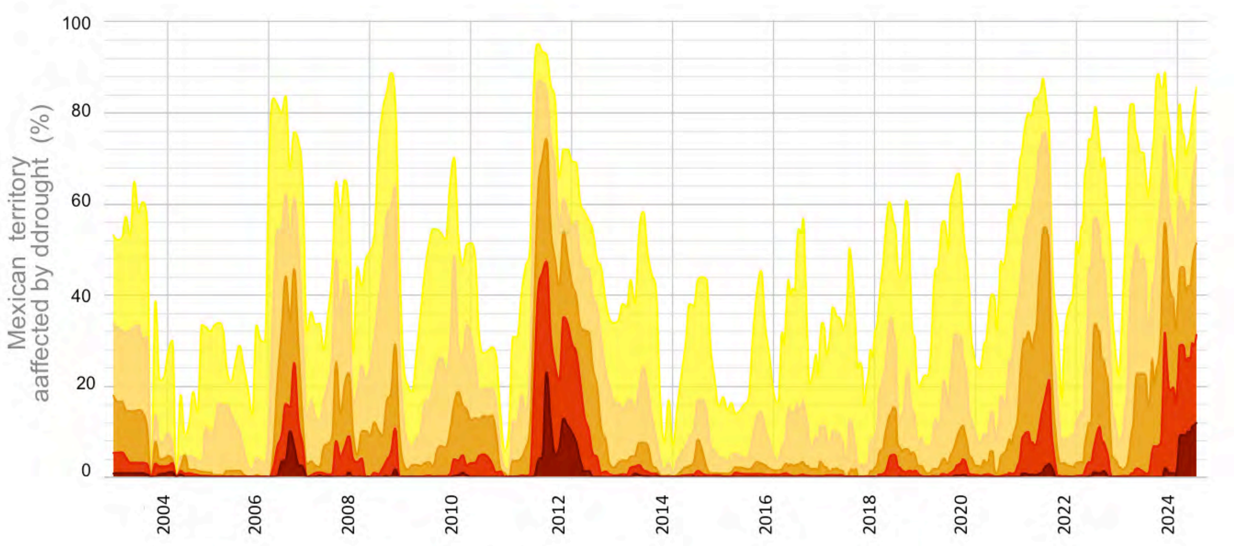

Figure 1. Percentage of Mexican Territory Afected by Drought through Time. Darker Colors (Towards Red and Brown) Depict the Highest Drought Intensity. Source: Modified from Monitor de Sequía en México, Conagua.

Emerging Lessons Learned from Long-term Monitoring in Mexican Inland Waters. Case of study: Comunity Metabolism Monitoring in Valle de Bravo Reservoir

Long-term monitoring of freshwater in Mexico includes only a few study cases, such as the more-than-two-decades interdisciplinary monitoring of Lake Alchichica (a soda, crater lake), and interdisciplinary monitoring of the Amanalco-Valle de Bravo Basin. The Valle de Bravo reservoir is also subject of remote sensing monitoring coupled with field work sampling (Arias-Rodriguez et al., 2020). As relevant research efforts comprehend the limnology of Lake Chapala (*e.g.*, Moncayo-Estrada et al., 2012), and those of the Pátzcuaro lake (Ramírez-Herrejón et al., 2014), Zimapán reservoir (Bravo-Inclan et al., 2008), and Laja rivers (e.g., Mercado-Silva et al., 2006) in previous decades, long-term research efforts are still scarce for Mexican inland waters. Next, we will describe Valle de Bravo with more detail, as the first case of study.

Valle de Bravo (VB) is the last vase of the Cutzamala System, a system that interconnects seven reservoirs and a treatment plant and supplies close to 25 % of the freshwater suply to the superpopulated Central Mexican Highlands (including Mexico City and Toluca, see *e.g.*, Ramírez-Zierold et al., 2010). A long-term monitoring of VB and its tributaries has taken place in the last two decades, by an academia-society partnership (see Nuestro lago, science divulgation series [Merino-Ibarra & Monroy-Ríos, 2004]). VB behaves as a warm monomictic water body that has experienced drastic changes in water level in the last decade due to its management (fluctuations up to 10 m). Extraction and injection of water between the reservoirs of the Cutzamala system respond to urban water requirements. These water level fluctuations (WLF) affect tourism and all user's activities, as well as ecological structure and are related to drought conditions. For example, WLF have been related to changes in the plankton composition (Ramírez-García et al., 2002; Valdespino-Castillo et al., 2014; Valeriano-Riveros et al., 2014; Nandini et al., 2019), and to community metabolism (Valdespino-Castillo et al., 2014; Guimarais et al., 2019), and biogeochemical N and P cycling (Barjau et al., 2022). In summary, in the warm season of the year (typically stratified during the warmest part of the year, from March to October), mixing events have occured; these convey exchange of water (and nutrients) between the mixed surface layer and deeper layers, affecting reservoir's biota.

The long-term monitoring effort in the last two decades has contributed to the knowledge of the effects of Climate Change over tropical waters. Recent studies show that these effects are related to: a) community metabolism and carbon emmision to the atmosphere (Guimarais et al., 2019), and b) related to internal functioning, particularly to vertical heat and nutrient flux (Merino-Ibarra et al., 2021).

When VB water level is low, the frequency of the mixing increases due to boundary mixing, related to the geomorphology of the reservoir and the daily-wind regime of VB. Thus, whole-column or partial mixing may occur even in months when stratification typically occurs (*e.g.*, Merino et al., 2003; Valdespino-Castillo et al., 2014). The mixing events promote the oxidation of organic matter in this eutrophic to hipertrophic system. By studying the photosynthesis:respiration ratio at ecosystem scale, Guimarais et al. (2019) detected that, over a decade of observations, net heterotrophy prevailed. Their results show that increase in the reservoirs' temperature was directly, and significantly related to ecosystem respiration. The estimation of carbon released to the atmosphere corresponded, in average, to 3.29 g C m^{-2} d^{-1}. This value lies within the range of carbon released to the atmosphere by aquatic systems, considering the global average. Other conclusions of this work highlight the need of long-term monitoring in tropical systems, in order to generate better models on the role of continental waters on global carbon cycling.

Vertical Nutrient Exchange in a Warming Scenario

Nutrient concentration in surface waters is the result of allochtonous inputs, as well as of internal processes. While as nutrient runoff has been measured for decades in a large number of limnological studies, the processes governing nutrient inputs through vertical mixing remain obscure for the most part. This knowledge gap is a relevant handicap to fully understand the biogeochemistry and ecology of large-scale inland and ocean waters.

Recent research in VB has been useful to study these processes in a warming scenario (Merino-Ibarra et al., 2021). These authors studied heat budgets to assess vertical nutrient transport within the reservoir for more than two decades. They revealed that internal waves can cause vertical transport of heat and nutrients without breaking the stratification. Their results show that as a result of mixing, the hipolimnetic temperature increases (in the range of 0.009-0.028ºC day^{-1}). By estimating a water and nutrient balance, the authors built a physical-biogeochemical model to estimate vertical exchange between the epilimnion and the hypolimnion. The results of these balances during stratification show progressive hypolimnetic warming (Fig. 2a), and also that vertical exchange (and nutrient recycling) can increase up to fivefold when VB water level drops over 12 m in depth (Fig. 2b). Altogether, these efforts provide novel strategies to understand and to model eutrophication and oligotrophication in natural waters in a warming scenario.

a)

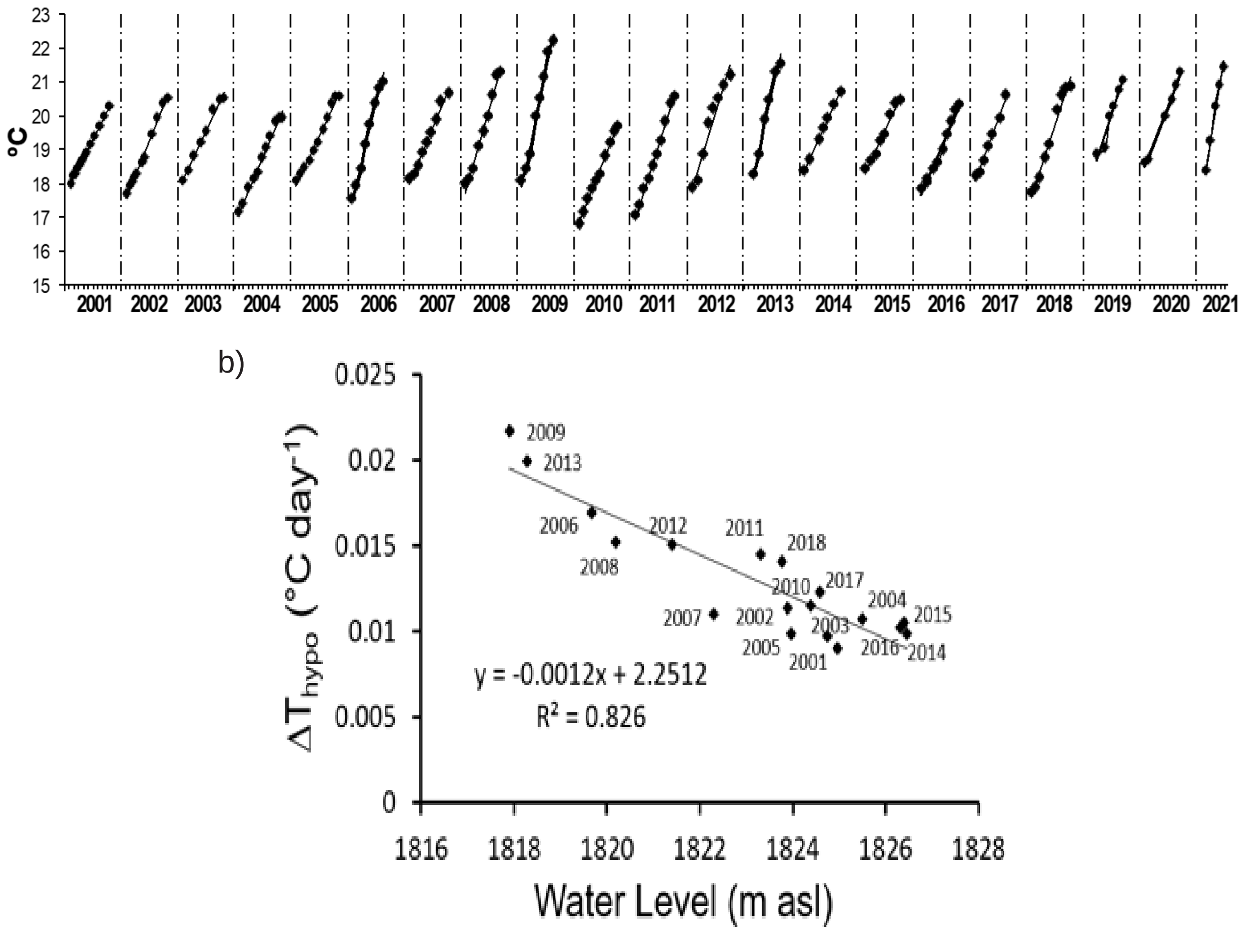

Figure 2. Hypolimnetic Water Warming and Water Level Relationship in VB: a) Hypolimnetic Temperature Variation during Each Stratification Period Sampled from 2001 to 2021 [The Slopes of the Regressions Were Used to Assess the Mean Hypolimmnetic Warming Rate for Each of the Stratifications], and b) Mean Hypolimnetic Temperature Increase Rate During Each Annual Stratification Period Plotted Against the Mean Water Level Throughout 2001-2018. Modified from Merino-Ibarra et al., 2021.

Case of study: Lakes of the Mexican Central Highlands, Perspectives in a Panorama of Climate Change

As meteorological data has provided evidence of a recent regional warming trend (*e.g.*, since 2000 *sensu* Caballero et al*.,* 2016; or during 1966 to 2018 *sensu* Alcocer et al*.,* 2022), paleolimnological data and phytoplankton studies have evidenced the ecological changes in different lakes of the Mexican highlands.

In the Alberca de Tacambaro lake, sediments and phytoplankton (2008 to 2011) were studied to investigate the effects of “El Niño” Southern Oscillation (ENSO). The results shown by Caballero et al. (2016), revealed changes in the hydrological cycle of the lake. A longer circulation period originated a relatively longer period of deoxygenation of the water column due to oxydation of a high organic matter load during warmer conditions. In consecuence, this low-oxygen mixing period was significantly correlated to lower diatom diversity. Their results agree with the impacts of extreme climatic conditions associated to large-scale climatic oscillations like ENSO or the Pacific Decadal Oscillation (*e.g.,* Wachnicka et al*.,* 2013). Sediment changes were also correlated with the ENSO oscillation in the paleolimnological study reported by Ortega et al. (2021). Further evidence of changes in the phytoplankton composition related to Climate Change has also been reported in Lake Alchichica.

Lake Alchichica represents one of the few tropical lakes where long-term monitoring has occurred in Mexican territory. The results of this research have enlightened our understanding of protozooplankton, phytoplankton, zooplankton, hydrology, and biogeochemistry (*e.g.*, Alcocer et al*.,* 2000, 2007; Oliva et al*.,* 2001, 2009; Ramos-Higuera et al*.,* 2008; Ramos-Olvera et al*.,* 2009). Alchichica is the largest of the Axalapascos lakes in the Cuenca Central, in the Mexican Highlands. This area is exposed to intense industrial and agricultural development. In a recent analysis of two decades of observations, Alcocer et al. (2020) showed the lake’s water temperature rose from 1993 to 2003 and remained similar until 2013. Phytoplankton time series analyses also showed that as the temperature Increased, large-size phytoplankton (represented by the diatom *Cyclotella alchichicana*) abundance and biomass increased. In contrast, small-size phytoplankton as well as adult copepods decreased. The author concluded increase in temperature could have favoured the large-size over the small-size phytoplankton. And also affected zooplakton, negatively affecting calanoid copepods physiology and diminish the copepods’ food resource because large size phytoplankton was favored.

In the lakes of the Cuenca Oriental, Mexican highlands, planktonic dynamics and in particular, modifications in the annual pattern of blooms have been observed. Particularly critical are Lake Alchichica’s blooms, related to the cyanobacteria *Nodularia affine spumigena (e.g.,* Macek et al*., 2009)*. The occurrence of these blooms in Alchichica has been related to the increase in surface temperature and nutrient availability (Oliva et al*.,* 2009) which has effects on community structure and dynamics (Macek et al., 1994, 2009). The idea that Lake Alchichica may be sensitive to climatic fluctuations through changes in its mixing-stratification regime was explored in sedimentary cores by Caballero et al. (2003), however the favoring of diatom silica dissolution limits the potential for paleolimnological studies.

Being located in a region that may become hotter and drier, rapid responses to changes in climate are very likely to occur in lakes of the Mexican highlands. Under warming conditions of the Central Highlands of Mexico, conditions such as increase in epilimnion temperature, changes in thickness of the mixed layer, greater intensity and duration of stratification, and effects on vertical water exchange which may occur in a warming scenario, leading to oligotrophication should be studied. Moreover, diverse studies show that many aquatic systems have responded similarly to warming climate, regardless of their dimensions (see Adrian et al., 2009, and Williamson et al., 2009).

The wind regime appears to be an important source of supplementary energy (sensu Margalef, 1983) to aquatic systems. Therefore, if regional wind pattern is modified, the dynamics of biogeochemical processes, in particular nutrient recycling, could change significantly. It has been shown that the cold fronts (called “Nortes” in Mexico) may influence the dynamics of the mixed layer of the Gulf of Mexico (Villanueva et al., 2010) and can promote the vertical exchange of water to supply the nutrients that feed the production of the layer mixed. Its effect on the Mexican epicontinental bodies is still a subject of exploration, as are the possible changes in its frequency or intensity in Climate change scenarios (see CCA, 2011). If the frequency and intensity of these events increase, the stability of the stratification could be affected in water bodies, and the vertical exchange of water as well as the input of nutrients to the surface could be promoted. In this case, the effect of these meteorological phenomena could act against those that accentuate stratification (increased air temperature and greater drought).

Increasing Eutrophication in Mexican Inland Waters

Limnological work has been reporting a global trend of increasing eutrophication and phytoplankton blooms (*e.g.*, Pearl & Huisman 2008).

The information of Mexican ecosystems regarding eutrophication and phytoplankton blooms is heterogeneous and disperse. An useful effort to gather limnological experiences in the country took place in 2014, when more than 300 studies participated in the National Congress of Limnology, held in Mexico City. The presented studies focused on freshwater systems, such as lakes, rivers, reservoirs, wetlands, and groundwater. The abstract Conference book shows numerous studies that document signs of eutrophication in Mexican waters.

However, a comprehensive survey of nutrients concentration and eutrophication indicators in inland waters of Central Mexico is still needed. The map on Figure 3 sumarizes the concentration of total phosphorus (TP) in aquatic systems of Central Mexico. In this exploration (Neri-Guzmán, in press), 51 studies of water systems of Central Mexico were considered. When data were grouped into different categories, 72.55 % of the samples were in the range >3 µm of TP (Fig. 3), which corresponds to eutrophy and hypereutrophy (*sensu* Carlson and Simpson, 1996).

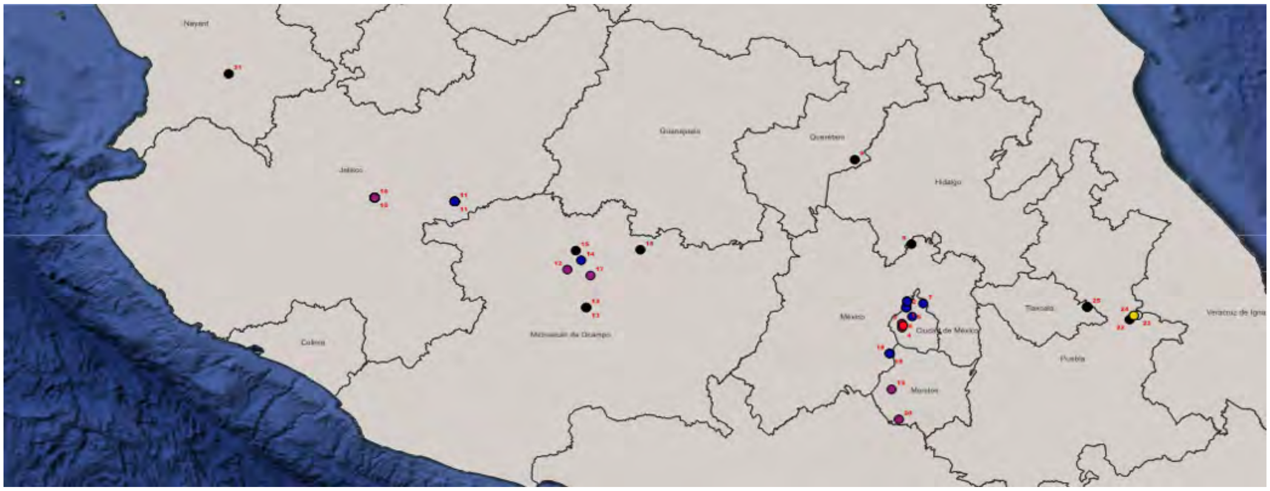

Figure 3. Total Phosphorus (uM) in Water Systems of Central Mexico.
Dark Blue Sample Color Indicates TP Concentration>3 µm.

Table 1. Limnological Parameters Summarized per State in Central Mexico (Modified from Neri-Guzmán, in Press).

Mexican State	SD	Chl-a	TP	TN	BOD5	CDO	TSS
	(m)	(mg m^{-3})	(mg L^{-1})				
Mexico City	0.11 - 0.53	81 - 1320	0.37 - 10.65	1.27 - 46.69	9 - 102	169.4	8 - 140
Mexico City - Estado de México	0.32 - 0.63	54.9 - 6.1	8.03 - 28.61	1.11 - 4.53	NA	NA	NA
Estado de México	0.30 - 3.92	1.12 - 29.2	0.0002 - 0.32	NA	2	14	NA
Hidalgo	1.44 - 2	6.43 - 57.9	0.07 - 13.59	2.18 - 31.9	1.6 - 20.34	10.7 - 107	43.5 - 353.33
Jalisco	NA	NA	0.4 - 2.31	NA	1.9 - 25	2.18 - 76	59.5
Jalisco - Michoacán	NA	NA	0.62	1.34	6.36	46.92	NA
Michoacán	0.15 - 1.3	2.2 - 120	0.029 - 2	2.2	5.82 - 229	28.3 - 748	53.68
Morelos	0.09 - 5.20	0.04 - >100	0.003 - 5.5	NA	30.02	88.94	NA
Puebla	NA	0.2 - 2.2	0.02 - 0.05	NA	NA	NA	NA
Puebla -Tlaxcala	Nula - Total	NA	NA	NA	NA	NA	NA
Tlaxcala	0.08 - 0.2	NA	NA	NA	NA	NA	NA
Overall	0.08 - 5.20	0.04 - >1000	0.0002 - 28.61	1.11 - 46.69	1.6 - 229	2.18 - 748	8 - 353

SD (Secchi Disk Depth), Chl-a (chlorophyll a), TP (Total Phosphorus), TN (Total Nitrogen), BOD (Biologiccal Oxygen Demand), CDO (Chemical Oxygen Demand), NA (Not Available), and TSS (Total Suspended Solids).

In the exploration of water bodies of Central Mexico, Neri-Guzmán (in press) sumarized the parameters considered to calculate the trophic state index (*sensu* Carlson and Simpson, 1996), per state. The integrated conditions indicate that most of the studied water bodies have reached conditions of eutrophy and hypertrophy (Table 1 and Table 2).

Table 2. Indication of Trophic State (*Sensu* Carlson and Simpson, 1996), Shown per State in Central Mexico (Modified from Neri-Guzmán, in Press).

Mexican State	TSI SD	TSI Chl-a	TSI TP	Trophic State
Mexico City	69.15 - 91.80	73.70 - 101	89.48 -137.96	Eutrophic - Hypertrophic
Mexico City - Estado de México	66.65 - 76.42	69.90 - 70.10	133.89 - 152.22	Eutrophic - Hypertrophic
Estado de México	40.31 - 77.35	31.71 - 63.70	0 - 87.38	Mesotrophic - Hypertrophic
Hidalgo	50 - 54.74	48.85 - 70.41	65.45 - 141.48	Mesotrophic - Hypertrophic
Jalisco	NA	NA	90.60 - 115.91	Hypertrophic
Jalisco - Michoacán	NA	NA	96.93	Hypertrophic
Michoacán	56.22 - 87.33	38.33 - 77.56	52.74 - 113.83	Mesotrophic - Hypertrophic
Morelos	36.24 - 94.70	0 - >75.77	20 - 128.42	Oligotrophic - Hypertrophic
Puebla	NA	NA	47.37 - 60.60	Mesotrophic - Hypertrophic
Puebla - Tlaxcala	NA	NA	NA	NA
Tlaxcala	83.20 - 96.40	NA	NA	Hypertrophic
Overall	36.24 - 96.40	0 - 101	0 - 152.22	Mesotrophic - Hypertrophic

TSI (Trophic State Index), SD (Secchi Disk Depth), Chl-a (Chlorophyll *a*), TP (Total Phosphorus), and NA (Not Available).

In the abstract collection of the 2014 National Congress of Limnology of Mexico, thesis and published studies, the study of cyanobacteria and other planktonic microbes that form massive blooms was frequent. Some examples of events of massive blooms listed on the book include: Valle de Bravo Reservoir, lakes of Central Mexico such as Zirahuén, Atexcac, Alchichica, Lake Texcoco, and Lake Chapultepec, as well as the coastal systems Pom-Atasta and Palizada del Este, in the Gulf of Mexico litoral.

One of the main challenges for Mexican freshwater ecosystems is related to the growth and toxicity of cyanobacteria. Among other phytoplankton species, cyanobacteria are the main biological agents related to blooms, and their development and ecological success is reported to benefit from warmer temperature (Pearl and Huisman, 2008). Recent studies on tropical limnology are contributing to the global understanding on the diversity, physiology, and ecology of cyanobacteria and lake's microbiota. Some of these studies reveal a remarkable diversity in our territory, that includes in most cases, uncharacterized specia (*e.g.*, Becerra et al., 2020; Carmona et al., 2023). The toxic potential of some freshwater cyanobacteria and their impacts on different trophic levels has been also addressed, for example by Vasconcelos et al. (2010), Mendoza et al. (2012), Alillo-Sánchez et al. (2014), Pineda et al. (2019), and Ávila-Torres et al. (2023). Deep characterizations, such as genomic or metabolomic, of bloom forming plankters are still pending, in order to better understand the metabolic and ecological particularities of these organisms.

Conclusions

In this mini review, we summarize some emerging findings of tropical limnology, focused on the studies of aquatic systems of Mexico that contribute to the global understanding of the effects of Climate Change on aquatic systems. Long-term, interdisciplinary monitoring of ecosystems of the Mexican highlands are providing integrated approaches of community metabolism and carbon dioxide fluxes, physical forcing, water-level fluctuations, internal proceses that affect vertical nutrient exchange, biodiversity, phytoplankton ecology, eutrophication progressions, plankton interactions, phytoplankton blooms, and paleolimnological reconstruction, among others. Altogether, this research aims to contribute to the understanding of eutrophication and oligotrophication under warming scenarios. Increased drought risk, and water crisis in the Mexican territory highlight the relevance of interdisciplinary monitoring in inland waters of Mexico.

We also conclude that biogeochemical and chemical insights, as well as ecological studies based on long-time monitoring, are crucial to better understand ecosystems functions and responses. With this knowledge we will have more efficient toolboxes to mitigate and adapt to the environmental change we are facing.

Acknowledgements

We acknowledge F. Sergio Castillo Sandoval, Julio A. Lestayo González, and Andrea Guzmán Arias for technical support. This work was funded by CONAHCYT (project CF-2023-G-155, Postdoctoral scholarships to O.G-N, P.M.V-C and J.A.R-Z), UNAM (PAPITT IN111321 and PASPA, DGAPA, UNAM to M.M-I.), and (PAPIIT IA103324 to P.M.V-C) for their funding.

Authors' Contributions

PMVC, MMI and JARZ conceptualization, first draft writing and editing. RJAH, MBA and OAGN data integration and editing. JPCC and MANG compilation, data visualization and editing.

References

Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Livingstone, D. M., Sommaruga, R., Straile, D. Van Donk, E., Weyhenmeyer, G. A., & Winder, M. (2009). Lakes as sentinels of climate change. *Limnology and Oceanography*, *54*, 2283-2297. https://doi.org/10.4319/lo.2009.54.6_part_2.2283

Alcocer, J., Lugo, A., Escobar, E., Sánchez, M. R., & Vilaclara, G. (2000). Water column stratification and its implications in the tropical warm monomictic lake Alchichica, Puebla, Mexico. *Verhandlungen Internationale Vereinigung für theoretische und angewandte Limnologie*, *27*, 3168-3169. https://doi.org/10.1080/03680770.1998.11898262

Alcocer, J., López-Anaya, D. P., & Oseguera, L. A. (2007). Dinámica del carbono orgánico particulado en un lago tropical profundo. In Hernández de la Torre, B., Gaxiola Castro, G. (Eds.), *Carbono en ecosistemas acuáticos de México*, (pp. 41-50). INE.

Alcocer, J., Lugo, A., Fernández, R., Vilaclara, G., Oliva, M. G., Oseguera, L. A., Silva-Aguilera, R. A., & Escolero, Ó. (2022). 20 years of global change on the limnology and plankton of a tropical, high-altitude lake. *Diversity*, *14*(3), 190. https://doi.org/10.3390/d14030190

Alillo-Sánchez, J. L., Gaytán-Herrera, M. L., Martínez-Almeida, V. M., & Ramírez-García, P. (2014). Microcystin-LR equivalents and their correlation with *Anabaena* spp. in the main reservoir of a hydraulic system of Central Mexico. *Inland Waters*, *4*(3), 327-336. https://doi.org/10.5268/IW-4.3.573

Arias-Rodriguez, L. F., Duan, Z., Sepúlveda, R., Martinez-Martinez, S. I., & Disse, M. (2020). Monitoring water quality of valle de bravo reservoir, Mexico, using entire lifespan of meris data and machine learning approaches. *Remote Sensing*, *12*(10), 1586. https://doi.org/10.3390/rs12101586.

Ávila-Torres, G., Rosiles-González, G., Carrillo-Jovel, V. H., Acosta-González, G., Cejudo-Espinosa, E., Ortega-Camacho, D., Hernández-Zepeda, C., & Moreno-Valenzuela, O. A. (2023). Microcystin concentrations and detection of the *mcyA* gene in water collected from agricultural, urban, and recreational areas in a karst aquifer in the Yucatan Peninsula of Mexico. *Microbiology Research*, *14*(3), 1168-1184. https://doi.org/10.3390/microbiolres14030078

Barjau-Aguilar, M., Merino-Ibarra, M., Ramírez-Zierold, J. A., Castillo-Sandoval, S. F., Vilaclara-Fatjó, G., Guzmán-Arias, A. P., Macek, M., Alcántara-Hernández, R. J., Sánchez-Carrillo, S., Valdespino-Castillo, P. M., Sacristán-Ramírez, A., Quintanilla-Terminel, J. G. Monroy-Ríos, E., Díaz-Valenzuela, J., Lestayo-González, J. A. Gerardo-Nieto, G. A., & González-De Zayas, R. (2022). Nitrogen and phosphorous retention in tropical eutrophic reservoirs with water level fluctuations: A case study using mass balances on a long-term Series. *Water*, 2022, *14*(14), 2144; https://doi.org/10.3390/w14142144.

Becerra-Absalón, I., Johansen, J. R., Osorio-Santos, K., & Montejano, G. (2020). Two new *Oculatella* (Oculatellaceae, Cyanobacteria) species in soil crusts from tropical semi-arid uplands of Mexico. *Fottea*, *20*(2), 160-170. https://doi.org/10.5507/fot.2020.010

Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., Milligan, A. J., Falkowski, P. G., Letelier, R. M., & Boss, E. S. (2006). Climate-driven trends in contemporary ocean productivity. *Nature*, 444, 752-755. https://doi.org/10.1038/nature05317

Beklioglu, M., Romo, S., Kagalou, I., Quintana, X., & Bécares, E. (2007). State of the art in the functioning of shallow Mediterranean lakes, Workshop conclusions. *Hydrobiologia*, *584*, 317–326. https://doi.org/10.1007/s10750-007-0577-x

Blenckner, T., Adrian, R., Livingstone, D. M., Jennings, E., Weyhenmeyer, G. A., George, D. G., Jankowski, T., Jarvinen, M., Aonghusa, C. N., Noges, T., Straile, D., & Teubner, K. (2007). Large-scale climatic signatures in lakes across Europe: A meta-analysis. *Global Change Biology*, *13*,1314-1326. https://doi.org/10.1111/j.1365-2486.2007.01364.x

Bravo-Inclan, L. A., Saldana-Fabela, M. P., & Sanchez-Chavez, J. J. (2008). Long-term eutrophication diagnosis of a high-altitude body of water, Zimapan Reservoir, Mexico. *Water Science and Technology*, *57*(11), 1843-1849. https://doi.org/10.2166/wst.2008.279

Boyce, G., Lewis, M. R., & Worm, B. (2010). Global phytoplankton decline over the past century. Global phytoplankton decline over the past century. *Nature*, 466, 591-596. https://doi.org/10.1038/nature09268

Caballero, M., Vilaclara, G., Rodríguez, A., & Juárez, D. (2003). Short-term climatic change in lake sediments from lake Alchichica, Orienta, Mexico. *Geofísica Internacional, 42*(3), 529-537. https://doi.org/10.22201/igeof.00167169p.2003.42.3.942

Caballero, M., Vázquez, G., Ortega, B., Favila, M. E., & Lozano-García, S. (2016). Responses to a warming trend and “El Niño” events in a tropical lake in western México. *Aquatic Sciences*, *78*, 591-604. https://doi.org/10.1007/s00027-015-0444-1

Carlson, R. E., & Simpson, J. (1996) *A coordinator’s guide to volunteer lake monitoring methods*. North American Lake Management Society.

Carmona Jiménez, J., Caro Borrero, A., Becerra-Absalón, I., Perona Urizar, E., Márquez Santamaría, K., & Mateo Ortega, P. (2023). Description of two new species of *Nostoc* (Nostocales, Cyanobacteria) from central Mexico, using morphological, ecological, and molecular attributes. *Journal of Phycology*, *59*, 1237-1257. https://doi.org/10.1111/jpy.13401

Centro de Ciencias de la Atmósfera (CCA). (2011). *Informe de labores*. UNAM.

Coats, R., Perez-Losada, J., Schladow, G., Richards, R., Goldman, C. (2006). The warming of Lake Tahoe. *Climatic Change*, *76*, 121-148. https://doi.org/10.1007/s10584-005-9006-1

Comisión Nacional del Agua (Conagua). (2023). *Monitor de sequía en México.* https://smn.Conagua.gob.mx/es/climatologia/monitor-de-sequia/monitor-de-sequia-en-mexico

Falkowski, P. G., Barber, R. T., & Smetacek, V. (1998). Biogeochemical controls and feedbacks on ocean primary production. *Science*, *281*, 200-206. https://doi.org/10.1126/science.281.5374.200

Guimarais-Bermejo, M. O., Merino-Ibarra, M., Valdespino-Castillo, P. M., Castillo-Sandoval, F. S., & Ramírez-Zierold, J. A. (2018). Metabolism in a deep hypertrophic aquatic ecosystem with high water-level fluctuations: a decade of records confirms sustained net heterotrophy. *PeerJ, 6*, e5205. https://doi.org/10.7717/peerj.5205

Gyllström, M., Hansson, L.A., Jeppesen, E., Garcia-Criado, F., Gross, E., Irvine, K., Kairesalo, T., Kornijow, R., Miracle, M., Nykänen, M., Nõges, T., Romo, S., Stephen, D., Van Donk, E. & Moss, B. (2005). The role of climate in shaping zooplankton communities of shallow lakes. *Limnology and Oceanography*, *50*, 2008-2021. https://doi.org/10.4319/lo.2005.50.6.2008

Hernández-Cerda, M. E., & Valdez-Madero, G. (2004). Sequía meteorológica. In Martínez J., Fernández, A. (Eds.) *Cambio climático: una visión desde México*. SEMARNAT. INE.

Intergovernmental Panel on Climate Change (IPCC). (2001). *Summary of Policymaker, Climate Change: Impacts, Adaptations and Vulnerability. Working group II*. IPCC. https://www.ipcc.ch/report/ar6/wg2/

Jeppesen, E., Meerhoff, M., Jakobsen, B. A., Hansen, R. S., Søndergaard, M., Jensen, J. P., Lauridsen, T. L., Mazzeo, N., & Branco, C. (2007). Restoration of shallow lakes by nutrient control and biomanipulation: The successful strategy depends on lake size and climate. *Hydrobiologia*, *581*, 269-288. https://doi.org/10.1007/s10750-006-0507-3

Jeppesen, E., Kronvang, B., Meerhoff, M., Søndergaard, M., Hansen K. M., Andersen, H. E., Lauridsen, T. L., Bekliglu, A., Özen, A., & Olesen, J. E. (2009). Climate Change Eff ects on Runoff, Catchment Phosphorus Loading and Lake Ecological State, and Potential daptations. *Journal of Environmental Quality, 38*, 1930-1941. https://doi.org/10.2134/jeq2008.0113

Jiménez-Contreras, J. J., Sarma, S. S. S., Merino-Ibarra, M., & Nandini, S. (2009). Seasonal changes in the rotifer (Rotifera) diversity from a tropical high-altitude reservoir (Valle de Bravo, Mexico). *Journal of Environmental Biology*, *30*(2), 191-195. https://geocris.unam.mx/entities/publication/ad9ca04b-3ae1-4025-b442-9b9d4ff34edb

Jones, I., Sahlberg, J., & Persson, I. (2010). Modelling the impact of Climate Change on the thermal characteristics of lakes. In D. G. George (Ed.), *The impact of Climate change on European Lakes. Aquatic Ecology Series 4*. https://doi.org/10.1007/978-90-481-2945-4_7

Lee, H. W., Kim, E. J., Park, S. S., & Choi, J. H. (2012). Effects of climate change on the thermal structure of lakes in the Asian Monsoon Area. *Climatic Change*, *112*, 859-880. https://doi.org/10.1007/s10584-011-0233-3

Livingstone, D. M. (2003). Impact of secular climate change on the thermal structure of a large temperate central european lake. *Climatic Change*, *57*, 205-225. https://doi.org/10.1023/A:1022119503144

Livingstone, D. M., & Dokulil, M. T. (2001). Eighty years of spatially coherent austrian lake surface temperatures and their relationship to regional air temperature and the North Atlantic Oscillation. *Limnology and Oceanography*, *46*, 1220-1227. https://doi.org/10.4319/lo.2001.46.5.1220

McCormick, M. J., & Fahnenstiel, G. L. (1999). Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. *Limnology and Oceanography*, *44*, 530-540. https://doi.org/10.4319/lo.1999.44.3.0530

Macek, M., Vilaclara, G., & Lugo, A. (1994). Changes in protozoan assemblage structure and activity in a stratified tropical lake. *Marine Microbial Food webs*, *8*(1-2), 235-249.

Macek, M., Alcocer, J., Lugo-Vázquez, A., Martínez-Pérez, M. E., Peralta Soriano, L., & Vilaclara-Fatjó, G. (2009). Long term picoplankton dynamics in a warm-monomictic, tropical high-altitude lake. *Journal of Limnology*, *68*(2), 183-192. https://doi.org/10.4081/jlimnol.2009.183

Malmaeus, J. M., Blenckner, T., Markensten, H., & Persson, I. (2006). Lake phosphorus dynamics and climate warming: a mechanistic model approach. *Ecological Modelling, 190*, 1-14. https://doi.org/10.1016/j.ecolmodel.2005.03.017

Martínez, E., Antoine, D., D'Ortenzio, F., & Gentili, B. (2009). Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. *Science*, *326*, 1253-1256. https://doi.org/10.1126/science.1177012

Martínez J., & Fernández, A. (2004) *Cambio climático: una visión desde México*. SEMARNAT. INE.

Meerhoff, M., Clemente, J. M., Teixeira F., de Mello, C., Iglesias, C., Pedersen, A. R., & Jeppesen, E. (2007). Can warm climate-related structure of littoral predator assemblies weaken the clear water state in shallow lakes? *Global Change Biology*, *13*, 1888-1897. https://doi.org/10.1111/j.1365-2486.2007.01408.x

Mercado-Silva, N., Lyons, J., Díaz-Pardo, E., Gutiérrez-Hernández, A., Ornelas-García, C. P., Pedraza-Lara, C., & Zanden, M. J. V. (2006). Long-term changes in the fish assemblage of the Laja River, Guanajuato, central Mexico. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *16*(5), 533-546. https://doi.org/10.1002/aqc.737

Merino, M., Monroy, E., Castillo, S., Ramírez, J., Gallegos, M. E., & Alcocer, J. (2003). Wind-driven upwelling indicated by hydrological variability in a tropical eutrophied reservoir, Valle de Bravo, Mexico. In *4th International Conference on Reservoir Limnology and Water Quality* (pp. 228-231). Cezké Budejovice, Czeck Republic.

Merino-Ibarra, M., & Monroy-Ríos, E. (2004) *Nuestro Lago, serie de divulgación*. Patronato de Valle de Bravo A. C. México.

Merino-Ibarra, M., Ramírez-Zierold, J. A., Valdespino-Castillo, P. M., Castillo-Sandoval, F. S., Guzmán-Arias, A. P., Barjau-Aguilar, M., Monroy-Ríos, E., López-Gómez, L. M., Sacristán-Ramírez, A., Quintanilla-Terminel, J. G., González-De Zayas, R., Jimenez-Contreras, J., Valeriano-Riveros, M. E., Vilaclara-Fatjó, G., & Sánchez-Carrillo, S. (2021). Vertical boundary mixing events during stratification govern heat and nutrient dynamics in a windy tropical reservoir lake with important water-level fluctuations: A long-term (2001–2021) study. *Water, 13*(21), 3011. https://doi.org/10.3390/w13213011

Moncayo-Estrada, R., Lyons, J., Escalera-Gallardo, C., & Lind, O. T. (2012). Long-term change in the biotic integrity of a shallow tropical lake: a decadal analysis of the Lake Chapala fish community. *Lake and Reservoir Management, 28*(1), 92-104. https://doi.org/10.1080/07438141.2012.661029

Mooij, W. M., Hulsmann, S., De Senerpont Domis, L. N. D., Nolet, B. A., Bodelier, P. L. E., Boers, P. C. M., Pires, L. M. D., Gons, H. J., Ibelings, B. W., Noordhuis, R., Portielje, R., Wolfstein, K., & Lammens, E. (2005). The impact of climate change on lakes in the Netherlands: a review. *Aquatic Ecology*, *39*, 381-400. https://doi.org/10.1007/s10452-005-9008-0

Mendoza, V. M., Villanueva, E. E., & Maderey, L. E. (2004). Vulnerabilidad en el recurso agua de las zonas hidrológicas de México ante el Cambio Climático global. In Martínez, J., Fernández, A. (Comp.), *Cambio climático: una visión desde México*. SEMARNAT, INE.

Nandini, S., Sánchez-Zamora, C., & Sarma, S. S. S. (2019). Toxicity of cyanobacterial blooms from the reservoir Valle de Bravo (Mexico): A case study on the rotifer *Brachionus calyciflorus*. *Science of the Total Environment, 688*, 1348-1358. https://doi.org/10.1016/j.scitotenv.2019.06.297

Neri-Guzmán, M. A. (in press). *Evaluación integrada de la eutrofización en sistemas acuáticos del Centro de México.* [Bachelor's thesis]. FES Zaragoza, Universidad Nacional Autónoma de México.

Oliva, M. G. Lugo, A., Alcocer, J., Peralata, L., & Oseguera, L. A. (2009). Planktonic bloomforming *Nodularia* in the saline Lake Alchichica, Mexico. *Natural Resources and Environmental Issues*, *15*(22). http://digitalcommons.usu.edu/nrei/vol15/iss1/22

Oliva, M. G., Lugo, A., Alcocer, J., Peralta, L., & Sánchez, R. (2001). Phytoplankton dynamics in a deep, tropical, hyposaline lake. *Hydrobiologia*, 466, 299-306. https://doi.org/10.1023/A:1014578024049

O'Reilly, C. M., Alin, S. R., Plisnier, P. D., Cohen, A. S., & McKee, B. A. (2003). Climate change decreases aquatic ecosystem productivity in Lake Tanganyika, Africa. *Nature*, *424*, 766–768. https://doi.org/10.1038/nature01833

Ortega-Guerrero, B., Caballero, M., & Israde-Alcántara, I. (2021). The Holocene record of Alberca de Tacámbaro, a tropical lake in western Mexico: evidence of orbital and millennial-scale climatic variability. *Journal of Quaternary Science*, *36*(4), 649-663. https://doi.org/10.1002/jqs.3316

Paerl, H. W., & Huisman, J. (2008). Blooms like it hot. *Science*, *320*(5872), 57-58. https://doi.org/10.1126/science.1155398

Paytan, A., & McLaughlin, K. (2007). The oceanic phosphorus cycling. *Chemical Reviews*, *107*(2), 563-576. https://doi.org/10.1021/cr0503613

Pham, S. V., Leavitt, P. R., McGowan, S., & Peres-Nato, P. (2008). Spatial variability of climate and land-use effects on lakes of the northern Great Plains. *Limnology and Oceanography*, *53*, 728-742. https://doi.org/10.4319/lo.2008.53.2.0728

Pineda-Mendoza, R. M., Olvera-Ramírez, R., & Martínez-Jerónimo, F. (2012). Microcystins produced by filamentous cyanobacteria in urban lakes. A case study in Mexico City. *Hidrobiológica*, *22*(3), 290-298. https://www.scielo.org.mx/scielo.php?pid=S0188-88972012000300010&script=sci_abstract&tlng=en

Ramírez-García, P., Nandini, S., Sarma, S. S. S., Robles Valderrama, E., Cuesta, I., & Hurtado, M. D. (2002). Seasonal variations of zooplankton abundance in the freshwater reservoir Valle de Bravo (Mexico). *Hydrobiologia, 467*, 99-108. https://doi.org/10.1023/A:1014953119507

Ramírez-Herrejón, J. P., Zambrano, L., Mercado-Silva, N., Torres-Téllez, A., Pineda-García, F., Caraveo-Patiño, J., & Balart, E. F. (2014). Long term changes in the fish fauna of Lago de Pátzcuaro in Central México. *Latin American Journal of Aquatic Research*, *42*(1), 137-149. https://doi.org/10.3856/vol42-issue1-fulltext-11

Ramírez-Olvera, M. A. Alcocer, J., Merino-Ibarra, M., Lugo, A. (2009). Nutrient limitation in a tropical saline lake: a microcosm experiment. *Hydrobiologia*, *626*, 5-13. https://doi.org/10.1007/s10750-009-9733-9

Ramírez-Zierold, J. A., Merino-Ibarra, M., Monroy-Ríos, E., Olson, M., Castillo, F. S., Gallegos, M. E., & Vilaclara, G. (2010). Changing water, phosphorus and nitrogen budgets for Valle de Bravo reservoir, water supply for Mexico City Metropolitan Area. *Lake and Reservoir Management*, *26*(1), 23-34. https://doi.org/10.1080/07438140903539790

Ramos-Higuera, E., Alcocer, J., Ortega-Mayagoitia, E., & Camacho, A. (2008). Nitrógeno: elemento limitante en un lago oligotrófico tropical. *Hidrobiológica*, *18*(1) supplement: 105-113. https://hidrobiologica.izt.uam.mx/index.php/revHidro/article/view/883/473

Robertson, D. M., & Ragotzkie, R. A. (1990). Changes in the thermal structure of moderate to large sized lakes in response to changes in air temperature. *Aquatic Science*, *52*, 360-380. https://doi.org/10.1007/BF00879763

Wachnicka, A., Gaiser, E., Collins, L., Frankovich, T., & Boyer, J. (2010). Distribution of diatoms and development of diatom-based models for inferring salinity and nutrient concentrations in Florida Bay and adjacent coastal wetlands of south Florida (USA). *Estuaries and Coasts*, *33*, 1080-1098. https://doi.org/10.1007/s12237-010-9283-4

WIlliamson, C. E., Dodds, W., Kratz, T. K., & Palmer, M. (2008). Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. *Frontiers in Ecology and the Environment*, 6, 247–254. https://doi.org/10.1890/070140

Valdespino-Castillo, P. M., Merino-Ibarra, M., Jiménez-Contreras, J., Castillo-Sandoval, F. S., & Ramírez-Zierold, J. A. (2014). Community metabolism in a deep (stratified) tropical reservoir during a period of high water-level fluctuations. *Environmental monitoring and assessment, 186*(10), 6505-6520. https://doi.org/10.1007/s10661-014-3870-y

Valdespino-Castillo, P. M., Alcántara-Hernández, R. J., Merino-Ibarra, M., Alcocer, J., Macek, M., Moreno-Guillén, O. A., & Falcón, L. I. (2017). Phylotype dynamics of bacterial P utilization genes in microbialites and bacterioplankton of a monomictic endorheic lake. *Microbial ecology*, *73*, 296-309. https://doi.org/10.1007/s00248-016-0862-1

Valeriano-Riveros, M. E., Vilaclara, G., Castillo-Sandoval, F. S., & Merino-Ibarra, M. (2014). Phytoplankton composition changes during water level fluctuations in a high-altitude, tropical reservoir. *Inland Waters*, *4*(3), 337-348. https://doi.org/10.5268/IW-4.3.598

Vasconcelos, V., Martins, A., Vale, M., Antunes, A., Azevedo, J., Welker, M., López, O., & Montejano, G. (2010). First report on the occurrence of microcystins in planktonic cyanobacteria from Central Mexico. *Toxicon*, *56*(3), 425-431. https://doi.org/10.1016/j.toxicon.2010.04.011

Zamora-Barrios, C. A., Nandini, S., & Sarma, S. S. S. (2019). Bioaccumulation of microcystins in seston, zooplankton and fish: A case study in Lake Zumpango, Mexico. *Environmental pollution*, *249*, 267-276. https://doi.org/10.1016/j.envpol.2019.03.029

Topics of Limnological Research in Mexico, coordinated by Alfredo Pérez Morales, was published in Dirección General de Publicaciones of the Universidad de Colima, avenida Universidad 333, Colima, Colima, México, www.ucol.mx. The edition was completed in December 2025. The Arial family was used for typesetting. Non Periodical Editorial Program: Eréndira Cortés Ventura. Cover Design: Adriana Minerva Vázquez Chávez. English Proofreader: Yul Ceballos. Interior Design: José Luis Ramírez Moreno and Leticia Bermúdez Aceves.

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.

ISBN: 978-968-9733-13-3
9 789689 733133

UNIVERSIDAD DE COLIMA