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Construction of wetlands in La Piedad Lagoon: a strategy to mitigate climate change in Mexico

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ABSTRACT

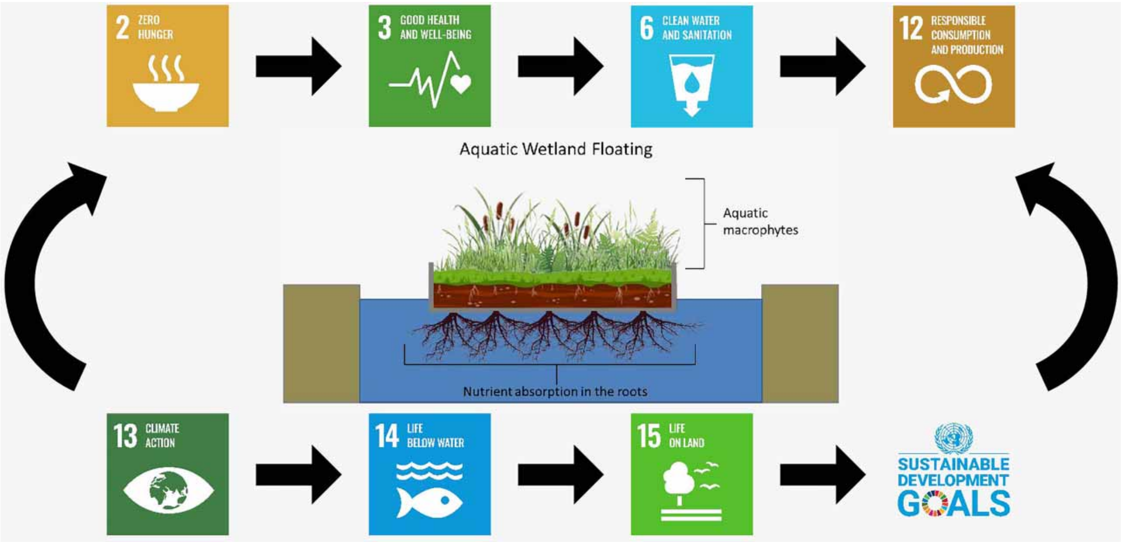
The freshwater systems located within the Metropolitan Area of Mexico City (Mexico City and the State of Mexico) are depleted. La Piedad Lagoon is recognized as a critical water resource as it serves as a run-off reservoir during the rainy season. However, the Lagoon is highly contaminated by untreated wastewater discharge due to disorderly and unplanned urban development. Inadequate sanitation has caused significant biodiversity loss and negatively impacted the population's health. Climate change models estimate that surface water availability could be reduced by over 30% in the short term, increasing the risk of a regional water crisis. This complex situation is urgent and demands the ecological restoration of La Piedad Lagoon as it provides an alternative source of water for Mexico City. Here, the intervention and efforts currently performed to rescue La Piedad Lagoon are described, involving its transformation and analysis of the environmental conditions of the area, land uses and ownership, as well as available infrastructure. Finally, it examines key environmental parameters for the construction of wetlands in the Lagoon. The removal contamination capacities of *Eichhornia crassipes* and *Lemna minor*, two aquatic plants in the area, were assessed. The lessons learned from this intervention can provide valuable lessons.

Key words: climate change impacts, constructed wetlands, environmental parameters, environmental restoration, freshwater systems, untreated wastewater

HIGHLIGHTS

- Inadequate water management practices caused environmental degradation.
- Environmental, social, and economic considerations must be addressed to ensure the long-term success of this intervention.
- Amounts of nutrients discharged into the systems must be considered in the design of wetlands that work as biofilters.
- The advantages of constructed wetlands include their low costs of operation and maintenance compared to conventional systems.
- Constructed wetlands can create opportunities for developing new economic activities.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The main obstacle to achieving comprehensive water management in Mexico is the failure to manage water transference, use, contamination, and extraction without the water being retained, treated, and reused. Due to this mismanagement, the Metropolitan Area of Mexico City (MAMC) is experiencing a water crisis due to the overuse of aquifers, contamination of surface and groundwater, and frequent floods and droughts (Chen & Bilton 2022). In the last decade, the entire territory of the MAMC, where Mexico City and the State of Mexico are located, has experienced a moderate drought (NMS 2023); this situation highlights the challenges that the government must address to provide sufficient water for the population and for economic activities. Increasing demands include not only access to water but also for improved sanitation. Unfortunately, water management agencies have dealt with these problems focusing only on using gray infrastructure without recognizing the contribution that green infrastructure could provide for more sustainable water management. Additionally, the urgency of treating wastewater has been ignored for most water bodies in the region, and these water bodies have been used for receiving untreated wastewater discharges. These problems highlight the need for coordination between water management and land management, recognizing the relevant environmental functions of water bodies and their associated ecosystems, wetlands being the most important. Currently, a supply-oriented vision of water continues to dominate, forcing authorities to import water from increasingly distant sources, as well as the overexploitation of groundwater to meet growing demand, incurring high environmental, social, and economic costs (García-Sánchez & Güereca 2019). The costs involved in transporting water have risen, but at the same time, vast volumes of raw sewage and stormwater are disposed of without being collected, treated, reused, or recycled, making water management in the MAMC unsustainable even in the short term. The difficulty of finding solutions for water problems in the MAMC continues to escalate due to demographic and urban increase, poor waste management, and wasteful water use (Sosa-Rodríguez *et al.* 2022).

According to the Global Water Security Index, the State of Mexico is considered one of the most critical cases in Mexico (Arreguin-Cortes *et al.* 2020) due to the challenges attributed to ensuring access to water and sanitation for the population and economic activities. Currently, renewable water reaches 2/3 of the volume allocated. This situation has deepened the dependence on increasingly distant sources and relies on the overexploitation of five of its nine aquifers. For now, three-quarters of the state's water requirements depend on groundwater extraction; thus, the recharge periods of the aquifers have not been respected. These inadequate water management practices have made the state's water resources vulnerable to contamination from wastewater discharges. Extracted water contains diverse pollutants (i.e., emerging, metals, micro-plastics) that cannot be removed when water is reinjected to the aquifer (US-EPA 2002). These problems are expected to worsen with the projected temperature increase and the reduction of precipitation expected due to climate change. The existing infrastructure in the

State of Mexico is experiencing low operational efficiency and must be improved to meet water needs (Sosa-Rodríguez *et al.* 2022).

The hydrological cycle of this region has been profoundly modified; and this has led to more significant conflicts over water, which are expected to increase due to climate change. The scenarios project reductions in water availability in the State of Mexico of up to 42% by 2,100, a situation that could result in a water crisis (Sosa-Rodríguez 2019). Therefore, it is imperative to consider the hydrological and biological functionality of water bodies with a basin approach to begin restoration in the MAMC. Despite the long history of ecological transformation in the Basin of Mexico, a high degree of biological variety remains, providing great potential for conservation efforts (CONABIO & SMADF 2016); nevertheless, this goal will be achieved if it has political and social support.

The study firstly describes the history of the transformations in La Piedad Lagoon, including its contamination, biodiversity loss, and negative impacts on health and economic activities. Secondly, it explores the environmental conditions of the Lagoon, its land use and ownership, and available infrastructure. Thirdly, it details the intervention processes conducted for the ecological rescue of La Piedad Lagoon. Finally, it analyzes vital environmental parameters for wetlands installation in La Piedad Lagoon.

2. HISTORICAL BACKGROUND AND CHARACTERIZATION OF LA PIEDAD LAGOON

A documentary review was carried out in the Historical Water Archive of the National Water Commission (CONAGUA) to build the historical background of La Piedad Lagoon. Likewise, historical documents from the archives of the municipality of Cuautitlán Izcalli and the Ejidos of Huilango and Tepojaco, located in the State of Mexico, were analyzed. Ejidos are communal land use properties in Mexico, whose main economic activities are agriculture. La Piedad Lagoon is located within these Ejidos. In declaration No. 6062 of April 8, 1922, it was established that water bodies located in the Basin of Mexico are the responsibility of Federal Water Authorities, including direct or indirect tributaries of Lakes Texcoco, Xochimilco, Chalco, and Zumpango. Since La Piedad Lagoon is a tributary of Zumpango Lagoon, it is considered a property of the Mexican Nation (MARH 1978).

The relationship of La Piedad Lagoon with Zumpango Lagoon is stated in the Declaration of Zumpango Lagoon Water Sanctuary, whose extension for the conservation of water bodies includes La Piedad. Therefore, since May 4, 1959, La Piedad Lagoon has been officially considered a federal water body (Government of the State of Mexico 1959). This Lagoon is part of the Cuautitlan sub-basin, located northeast of the Basin of Mexico. There is high potential for environmental recovery, with relevant social and economic impacts (Figure 1) (CONAGUA 2022).

La Piedad Lagoon is a permanent water body that is fed by rainwater that drains into the Cuamatla Canal to the Guadalupe Dam, which is later discharged into the Aurora Canal, and then into the Lagoon (Government of the State of Mexico 1959). It is a natural regulating vessel of the Cuautitlan River, with an extension of 3.4 km^2 and a storage capacity of 800,000 m^3 (CONAGUA 2022). Its water is used for irrigation and carp fishing by the Ejidos of San Jose Huilango and San Francisco Tepojaco (CONAGUA 1971; MAHR 1978).

Unfortunately, at present, the federal authority responsible for water management in Mexico currently denies that La Piedad Lagoon is a federal water body; therefore, CONAGUA has stated that its conservation is the responsibility of other state and local authorities. Consequently, no authority is taking care of the Lagoon; this has favored its contamination and the loss of over 20% of its original extension in favor of the Ejido San Francisco Tepojaco due to land use changes explained by the urban growth of the MAMC. The Lagoon faces increasing pressure from the real estate sector, which seeks to build precarious housing. Fortunately, the ejido's defense has allowed more than 5.64 km^2 around the Lagoon to remain undeveloped. Thus, the ecological recovery of La Piedad Lagoon is a unique opportunity to contribute to the hydraulic equilibrium of the Basin of Mexico, in addition to being an alternative water source for MAMC.

There are 12 wastewater treatment plants (WWTP) in the municipality of Cuautitlan Izcalli, whose installed capacity is 1.796 m^3/s. However, only three are in operation and treat a volume of 0.328 m^3/s, representing 18.25% of the total installed capacity. The lack of operation of the WWTP has been the cause of the discharge of 44.68 million m^3 of untreated wastewater into different water bodies; this has increased the contamination of all water bodies in the area, with severe impacts on people's health and economic activities (Government of Cuautitlan Izcalli 2019). Table 1 lists the WWTP in the municipality of Cuautitlan Izcalli.

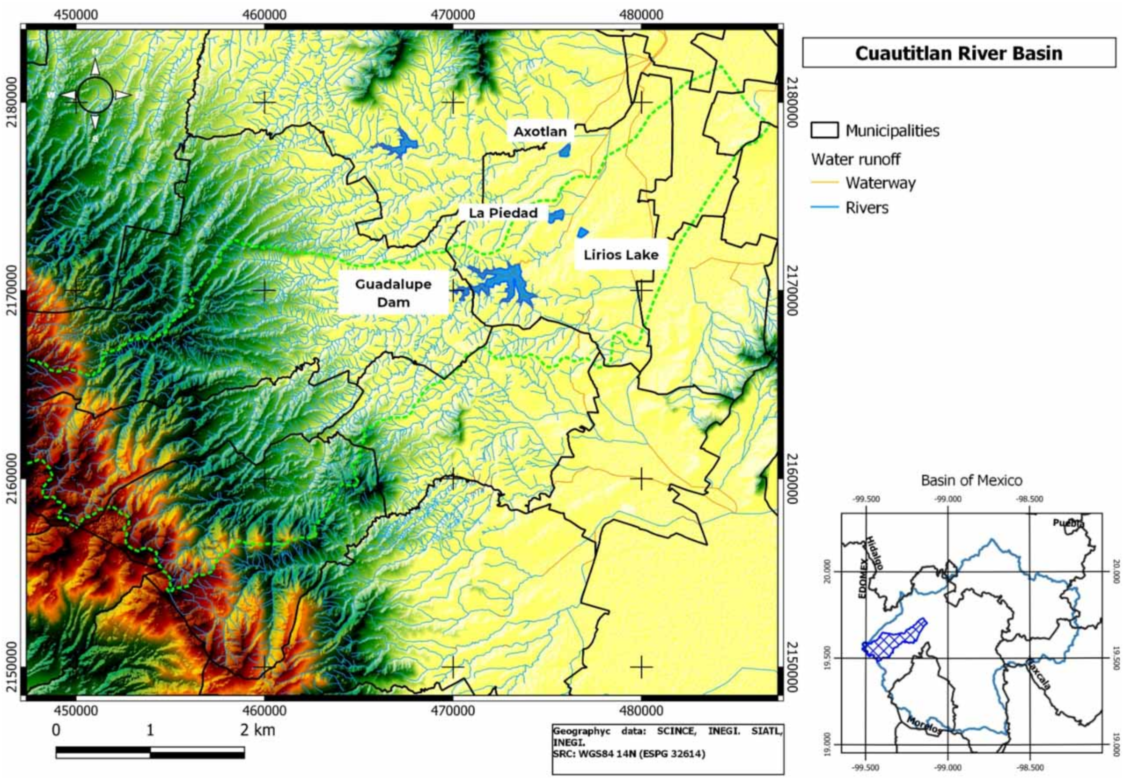


Figure 1 | Cuautitlan River sub-basin, Basin of Mexico, Mexico. The map was created using the Free and Open Source QGIS.

Table 1 | WWTPs in the municipality of Cuautitlan Izcalli, State of Mexico

Name of the WWTP	Capacity installed (m^3/s)	Treated volume (m^3/s)	State	Process
Mexicana de aguas	0.40	0.16	Active	Muds activated
Cofradía I	0.30	0	Out of operation	Muds activated
Cofradía II	0.18	0	Out of operation	Muds activated
Cofradía III	0.16	0	Out of operation	Muds activated
Ford Motor Company	0.30	0	Out of operation	Biological
Bosques de Alba II	0.30	0.08	Active	Muds activated
La Piedad I	0.04	0	Out of operation	Muds activated
La Piedad II	0.18	0	Out of operation	Muds activated
Lechería	0.40	0.16	Active	Muds activated
Guadalupe Dam	0.75	0	Out of operation	Muds activated
Tepojaco I	0.42	0	Out of operation	Muds activated
Tepojaco II	0.58	0	Out of operation	Muds octivated
	1.796	**0.328**		

Source: CONAGUA (2022).

There are three WWTPs around La Piedad Lagoon that do not operate: La Piedad II (with a capacity of 0.018 m^3/s), Tepojaco II (with a capacity of 0.055 m^3/s), and the Guadalupe Dam Mega Plant (with a capacity of 0.75 m^3/s) (Table 1). The lack of operation of the first two WWTPs has caused the discharge of 0.080 m^3/s of untreated wastewater to La Piedad Lagoon.

The lack of operation of most WWTPs in the municipality of Cuautitlan Izcalli can be explained by the need for more funds from the local governments to be responsible for the operation and maintenance of these infrastructures. Most of the operation costs are associated with the requirements of energy and chemical reagents and the lack of trained personnel to run the plants. These WWTPs technologies are also obsolete and require updating, redesign, and expansion.

Therefore, cleaning up La Piedad Lagoon is crucial to building a marginal collector to collect the untreated domestic wastewater discharged into the Lagoon. The potential volumetric flow of this collector is 0.250 m^3/s, with a diameter of 0.61 m, which requires an approximate investment of USD 764,700. With the construction of this collector and the operation of the Guadalupe Dam WWTP, it is believed that it is no longer necessary to rehabilitate La Piedad I and Tepojaco II WWTPs (Figure 2).

3. LA PIEDAD LAGOON AND ITS ENVIRONMENTAL CONDITIONS

La Piedad Lagoon is part of the region's identity of First Nations groups. The Lagoon presents irregular and peri-urban settlements, although rural activities persist in irrigated and rainfed crop fields. Custody of this water body is overseen by the ejidos Huilango and Tepojaco, which have demanded its recovery from the authorities for several decades.

The Lagoon is located at an altitude of 2,290 m above sea level. It is a shallow water body with a maximum depth of 13 m, an extension of 3.9 km^2, and a storage capacity of 0.8 million m^3 (Government of Cuautitlan Izcalli 2019). Around the Lagoon, urban areas are not evenly distributed due to the lack of land use planning and identifying a material dump and an inactive mine (Figure 1). La Piedad Lagoon receives between 1.5 and 2 million m^3 per year for water exchange from Guadalupe Dam to reduce pollution levels. These volumes are managed by the Cuautitlan Irrigation Unit (CIU) for agricultural purposes (CIU 2023). Unfortunately, the poor quality of the water in the Lagoon has forced peasants to grow oats and alfalfa for livestock feed; this has reduced the income they receive from this activity since no market purchases vegetables and fruits irrigated with untreated wastewater.

The environmental degradation of La Piedad Lagoon is explained by low vegetation cover, pollution, wastewater discharges, soil erosion, cattle grazing, bird hunting, dumps, and the proliferation of irregular settlements. Before the Lagoon was contaminated, the ejidatarios carried out self-consumption, commercial fishing, and recreational activities. Unfortunately, due to urbanization and uncontrolled wastewater discharges from nearby housing units since 2003, the water quality in the Lagoon has declined. As mentioned, three WWTPs near La Piedad Lagoon are not operating: La Piedad II, Tepojaco II, and the Guadalupe Dam Mega Plant. The operation of the first two treatment plants is the responsibility of the local government, which needs more economic and human resources to operate them. The third plant should be operated by the Water Commission of the State of Mexico (WCSM); its construction was concluded, but it has never operated. Due to its abandonment, the

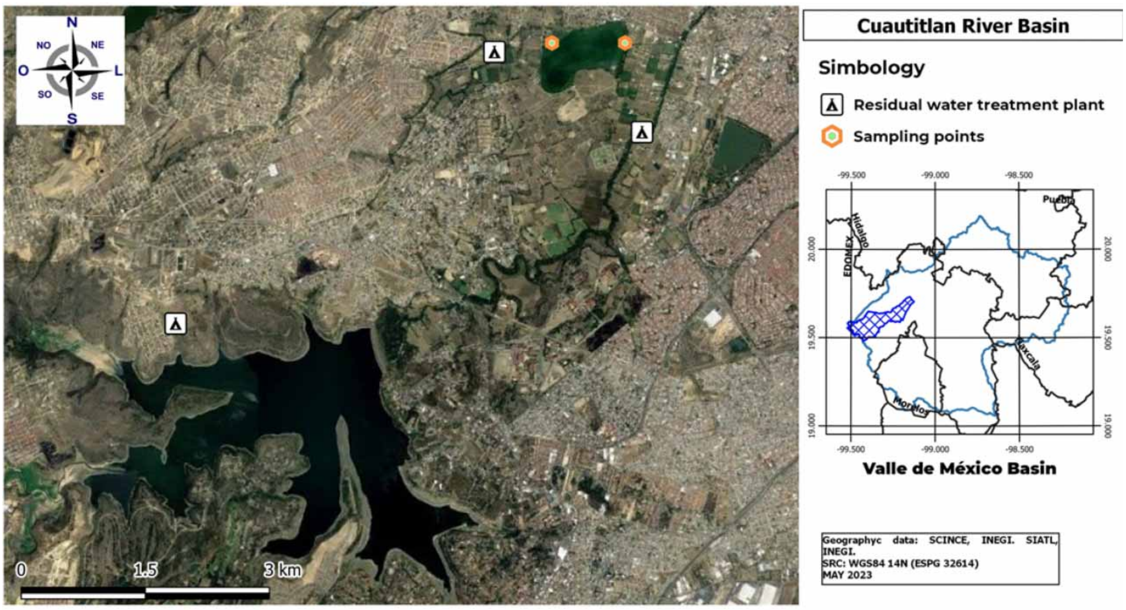


Figure 2 | WWTPs and sampling points around La Piedad Lagoon. *Sampling points are located at the entrance and gate of the Lagoon.

equipment requires replacement and maintenance. Untreated wastewater in the area is discharged into the Lagoon and the Cuautitlan River, contaminating them. As a result, the ejidatarios can no longer carry out some of the activities that generate income and food, such as fishing (Figure 2).

3.1. Water quality

The pollutants identified in La Piedad Lagoon include fats, oils, suspended solids, nitrogen, and phosphorus that have significant negative impacts on the environmental health of the system since these parameters do not comply with NOM-003-ECOL-1997 nor NOM-001-SEMARNAT-2021. The system's transparency is impacted when suspended solids exceed NOM-003-ECOL-1997 acceptable limits. Moreover, nutrient concentrations (i.e., nitrogen, phosphorus, and suspended solids surpass) record values above the limits of NOM-001-SEMARNAT-2021, suggesting a potential for eutrophication of the Lagoon. In addition, the water bodies have been found to include elements such as fats, oils, lead, zinc, cyanide, chromium, copper, and nickel, which raise more questions about the quality of the water and the origin of wastewater discharges. Reported discharges in the area comprise domestic and agriculture discharges; however, the presence of some of the pollutants mentioned provides evidence of illegal industrial discharges that must be identified and sanctioned to reduce environmental impacts on La Piedad Lagoon. This highlights the large amount of nutrients in the Lagoon, which reduces oxygen and biological diversity, causing hyper-eutrophication.

Some samples were taken at various sites in the Lagoon on April 13, 2021, to analyze the water quality in La Piedad Lagoon (Figure 2). The results are detailed in Table 3. They provide evidence of the high levels of contamination of this water body with untreated wastewater discharges, so it is to be expected that Total Suspended Solid (TSS), oils, total nitrogen and Chemical Oxygen Demand (COD) are outside the maximum permissible limits established by the NOM-001-SEMARNAT-2021.

Improving the quality of the water is critical since it is considered that the Lagoon can be an alternative water source for human consumption in Mexico City, so it should present low levels or absence of microorganisms such as phytoplankton and bacteria, among others (Arcos Pulido *et al.* 2005). A high nutrient load, mainly P and N, as well as excess organic matter, results in a low level of dissolved oxygen, which negatively impacts the environmental health of the soil system.

In aquatic systems such as La Piedad Lagoon, eutrophication is recorded from oligotrophic (Olvera-Viascán *et al.* 1998) to eutrophic (Merino-Ibarra *et al.* 2008). The presence and persistence of these algal blooms are attributed to high levels of nitrogen–phosphorus ratio (O'Farrell *et al.* 2012). These cyanobacterial blooms increase the pH values, which verify the high contamination levels in the Lagoon.

3.2. Biodiversity

The Lagoon has a high diversity of plants and animals species. The vegetation in La Piedad Lagoon includes an induced forest made up of species of the grass family (*Poaceae*), Nopal Blanco (*Opuntia megacantha*), and rainfed crops, among which corn (*Zea mays*) stands out. Other species present are oats (*Avena sativa and Avena byzantina*), grass (*Bouteloua hirsuta*), zoapatle (*Montanoa tomentosa*), acacias (*Acacia farnesiana*), and hydrophilic vegetation such as American hat (*Hydrootyle verticillata*), corn cob (*Phytolacca icosandra*), Santa Maria (*Polygonum sp.*), and romaza (*Rumex sp*). There are also species such as Pirul (*Schinus molle*), White Cedar (*Cupressus lindleyi*), and Eucaplito (*Eucalyptus camaldulensis*), and species linked to water bodies such as Fresno (*Fraxinusudhei*), Willow (*Salíx sp.*), Weeping Willow (*Salíx babylónica*), Tejocote (*Crataegus pubescens*), and Capulin (*Prunus serotina var capuli*) (Adame Villamil 2022).

In La Piedad Lagoon, there is also a great variety of birds, which accounts for 102 species of both permanent and migratory; some of these species are under a risk category based on the NOM-059-Semarnat-2010, such as the lesser grebe (*Tachybaptus dominicus*) and the Mexican duck (*Anas platyrhynchos diazi*) (Naturalista 2023). The Lagoon has a high diversity of zooplankton species, such as rotifers and cladocerans (water fleas); this confirms the levels of pollution in the Lagoon, which also constitute a food source for some filter-feeding bird species, such as the northern shoveler (*Spatula clypeata*). The presence of this great variety of species in the Lagoon, despite its levels of contamination, shows the environmental relevance of the area and the contribution that its recovery would have on the regional ecological functions. Table 2 lists some of the most important species in the area.

Table 2 | Biodiversity in La Piedad Lagoon, Cuautitlan Izcalli

Birds	Reptiles
• Mexican Duck (*Anas diazi*)	• Mesquite Spiny Lizard (*Sceloporus grammicus*)
• White Heron (*Ardea alba*)	• Alicante (*Pituophis deppei*)
• American Coot (*Fulica americana*)	• Mexican Nomadic Water Snake (*Thamnophis eques*)
• Golden Toed Heron (*Egretta thula*)	
Amphibians	Invertebrates
• Spurred Mountain Toad (*Spea multiplicata*)	• Cabbage White Butterfly (*Leptophobia aripa*)
• Mountain Tree Frog (*Hyla eximia*)	• Asian Ladybug (*Harmonia axyridis*)
• Cannon Frog (*Hyla arenicolor*)	• Mealybug Hunting Spider (*Dysdera crocata*)

Source: Naturalista (2023).

3.3. Climate change and future water availability

La Piedad Lagoon registers the effects of climate change, such as hotter springs, summers, and winters, and changes in the rainy season since precipitation is concentrated in just 3 months instead of four. These effects are expected to have severe repercussions on the availability and quality of water, as there are potential increases in temperature close to 2.0°C and reductions in precipitation of 2.17% in the short-term scenario (2015–2039), based on the GFDL CM3 RCP 8.5 model. These variations could reduce water availability by close to 30% in the short term (Figure 3).

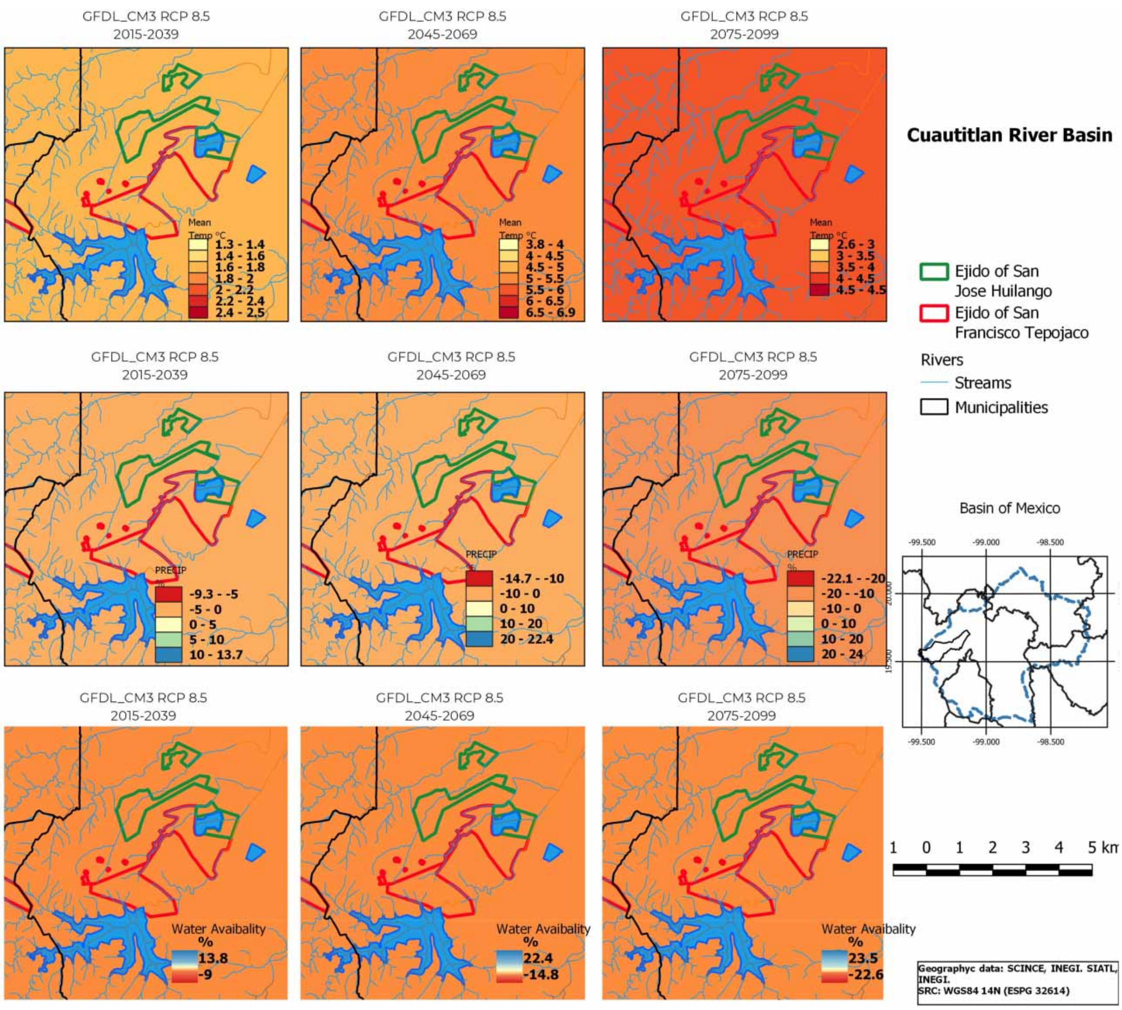


Figure 3 | Temperature, precipitation, and water availability scenarios in the sub-basin of Cuautitlan. The map was created using the Free and Open Source QGIS.

For the medium and long term, an increase in the average annual temperature of 3.67°C is estimated for the period 2045–2069 and of 5.58°C for the period 2075–2099, according to the GFDL_CM3 RCP 8.5 model. For precipitation, its reduction is estimated at 8.81% in 2045–2069 and at 11.28% in 2075–2099 for the same model. As a result of this variability, it is estimated that in the medium and long term, surface water availability could decrease by more than 40%. This situation can lead to a water crisis in the sub-basin of Cuautitlan and La Piedad Lagoon (Figure 3).

Based on the climate normals (1971–2001, 1981–2011, and 1991–2021), the expected temperature and precipitation were estimated for the short (2015–2039), medium (2045–2069), and long (2075–2099) term, taking into account the increases in temperature (°C) and the reductions in precipitation (%) projected by the GFDL_CM3 RCP 8.5 model. After calculating the precipitation and temperature, potential evapotranspiration and soil moisture were projected to build a water availability scenario considering the effects of climate change. The GFDL_CM3 RCP 8.5 model has proven to reproduce historical climate variability with the least bias, for which its scenarios were selected to estimate surface water availability.

The water balance was estimated by using the Thornthwaite & Mather (1957) model, which continues to be widely used to estimate the water balance in basins where detailed information is lacking. In this model, water inputs to the system are precipitation, while the outputs are runoff and evapotranspiration. The difference between the inputs and the outputs measures surface water availability.

The air temperature (maximum, minimum, and daily average) and precipitation data were obtained from the National Meteorological Service (NMS) climatic stations. In the case of the daily precipitation records, the information was weighted with Thiessen polygons using ArcGIS 10.8, as recommended by the NOM-011-CNA-2000 with the direct method based on hydrometric records (Government of Mexico 2000). The precipitation values in mm were transformed to millions of m^3.

Potential evapotranspiration was estimated using the Thornthwaite (1948) formula, whose results presented the lowest sum of squared errors for evapotranspiration reported by CONAGUA hydrometric records. The results were contrasted using the Thornthwaite (1948), Turc (1961), Dunne & Leopold (1978), and Hargreaves & Samani (1985) formulas. Each month's soil moisture changes were calculated from the potential water loss using the Thornthwaite & Mather (1957) model.

Evidence shows that increases in the frequency and intensity of storms and droughts increase the anthropogenic impacts associated with the presence of nutrients and the outbreak of cyanobacteria in water bodies. The above is because the quality of water in bodies of water can be modified due to climate change, which can favor an increase in water temperature, reduce oxygen solubility, and change the processes of nitrification and eutrophication (Hamilton *et al.* 2016).

Temperature increases can affect physical, chemical, and biological properties in aquatic systems and, therefore, modify the solubility of compounds, including essential gases such as oxygen, which are less soluble at higher water temperatures (Zhu *et al.* 2006). Higher water temperatures cause a lack of dissolved oxygen, which makes aquatic life more sensitive to toxic waste, parasites, and diseases (Koycheva & Karney 2009). An increase in nitrification, toxicity, and eutrophication can also be expected.

Other factors that affect water quality are evaporation and transpiration, which are necessary for the hydrological balance that affects climate, plant growth, distribution, and water demand and use. The increase in temperature increases the evaporation potential; however, the evaporation rate is restricted by water availability on vegetated surfaces and in soils (Milly *et al.* 2005; Stefanova *et al.* 2019).

These alterations in water bodies represent significant challenges for those responsible for supplying water to the population. As a result of the climate change scenarios expected for Laguna La Piedad, the previously mentioned impacts will increase the pollution levels of the Laguna, and with it also the environmental, social, and economic impacts, which are already high in the area, due to bad management practices and the lack of territorial planning.

4. INTERVENTION PROPOSAL FOR LA PIEDAD LAGOON

Community participation is crucial for changing water management paradigms; this must be accompanied by a detailed understanding of the environmental conditions in which the water bodies are to be intervened. The intervention of the Laguna La Piedad has been based on the following steps to guarantee a successful ecological recovery.

1. Community participation in conservation.
2. Diagnosis and ecological monitoring.
3. Interventions with green infrastructures.
4. Inclusion of traditional agroecological practices such as terraces and chinampas.
5. Reestablishment of riparian and aquatic biological connectivity.
6. Development of alternative economic activities.
7. Setting up a demonstration site for training in wetland restoration.

The lessons learned from these can be replicated in other interventions.

4.1. Community participation

Participatory science is promoted so the community actively diagnoses riparian and aquatic ecosystems and monitors relevant environmental indicators such as water quality, macroinvertebrates, amphibians, and reptiles. Another activity considered is the development of environmental education centers to raise awareness in the community about riverside ecosystems, their benefits, and the activities to be carried out to maintain constructed wetlands, in addition to disseminating the variety of species of plants and animals for their conservation.

4.2. Diagnosis and ecological monitoring

The physical structure and the ecological function of constructed wetlands will be evaluated before, during, and after the intervention. The objective is to track hydrology, geomorphology, and environmental behavior improvements. To do this, living organisms such as macroinvertebrates and other species in the study area will be analyzed. Likewise, the presence and concentration of contaminants have been studied, and the physicochemical treatments to remove them will be identified.

As part of the ecological monitoring, the persistence of recalcitrant pollutants (i.e., drugs, dyes, pesticides) will be evaluated before and after treatment with constructed wetlands to determine their purification capacity. A diversity of chemical products used in daily life are discarded in wastewater, and due to their characteristics, WWTPs cannot eliminate them (Palomares-Reyna *et al.* 2022). Additionally, this diagnosis seeks to create plant and animal inventories. So far, 240 species of aquatic plants have been documented: 227 are native, and 13 have been introduced (Mora-Olivo *et al.* 2013). Finally, the ecological baseline will be documented with drones to evaluate improvements resulting from the intervention.

4.3. Interventions with green infrastructures

Green infrastructure is an ecological approach to water management that focuses on restoring the ecological functions of rivers and wetlands, such as their purification capacity; among the benefits of this type of intervention are recreational opportunities for communities, improvement of air and water quality, control of wetland flow, passive irrigation, aquifer recharge, and carbon sequestration. The economic benefits are reduced implementation costs and low maintenance, long-term duration, flood risk reduction, and increased added value of intervened areas. Other benefits include developing alternative economic activities such as tourism, fishing, traditional agriculture, and bird watching.

4.4. Inclusion of traditional agroecological practices

The improvement and rehabilitation of wetlands allow the introduction of traditional agroecological practices through terraces, metepantlis, slats, ponds, chinampas, and calales, used by the pre-Hispanic cultures of the Basin of Mexico. Promoting these practices would generate high-value agroecological products, and La Piedad Lagoon can become a learning and training site.

4.5. Restoration of riparian and aquatic biological connectivity

Another objective of the intervention is re-establishing the ecological connectivity of the riparian and aquatic ecosystems. Given that the landscape is currently highly fragmented, this will be achieved through reforestation with terrestrial and aquatic species. Restoring the wetlands will also increase ecosystem services in the area.

4.6. Alternative economic activities

The intervention aims to promote a broad portfolio of green activities such as greenhouses for aquatic and terrestrial plant propagation, monitoring and bird watching, high-added value crops, commercial and recreational fishing, tourist activities, and handcrafts with wetland materials. In Mexico, there is a lack of greenhouses focused on aquatic plant reproduction, representing a relevant obstacle to the intervention. The community is building a greenhouse to supply aquatic plants to the constructed wetland. In addition, several cooperatives have been created to conduct environmental projects such as sustainable waste management, organic agriculture, and environmental education. These cooperatives are expected to promote Lagoon conservation since their incomes will depend on it. Therefore, linking the community's economic activities with the conservation of the Lagoon is vital for the intervention to be successful in the long term.

The intervention polygon comprises 60.0 km^2, representing a unique opportunity for developing a Water Recovery and Climate Buffer Park since it is not urbanized. The use of wetlands will support not only the improvement in water quality but also attenuate the occurrence of floods and increase the biodiversity and biological connectivity of the area. Some advances in analyzing the most propitious species for the constructed wetland system are explained below.

5. CONSTRUCTED WETLANDS

The epicontinental freshwater systems are currently scarce resources, highly disturbed by anthropogenic activities (Beltrán-López *et al.* 2023); given the growing water demands due to the increase in the population of the MAMC, reservoirs are needed, such as La Piedad Lagoon, to store water during the rainy season and distribute it later, during the dry season.

La Piedad Lagoon responds differently to the intervention strategies depending on the physicochemical, geological, and ecological conditions present, which vary throughout the year; these conditions are also influenced by the anthropogenic activities carried out, such as agriculture, livestock, tourism, aquaculture, and housing among others. This Lagoon is a central element of the basin since, being in the lower basin, it functions as a regulating vessel for storing runoff in the area. However, anthropogenic activities modified the physicochemical and biological characteristics of the Lagoon, affecting the water quality (Naveen *et al.* 2017), evidenced by the presence of microorganisms such as cyanobacterial blooms for the dominant genus in the phytoplankton.

The strategies to improve the Lagoon's water quality depend on the use the water will be put to. For example, if the water from the Lagoon is to be used for human consumption, it must not contain microorganisms such as phytoplankton. The presence of green algae in the phytoplankton in La Piedad Lagoon can help predict and manage the effects of pollutants. The Lagoon has a high nutrient load; thus, significant levels of P, N, and excess organic matter are identified. As a result, low levels of dissolved oxygen are observed in the sample results, with variations of other parameters such as pH or conductivity, which negatively impacted the environmental health of the Lagoon (Gradilla-Hernández *et al.* 2020) (Table 3).

Currently, research that explains what factors influence seasonal dynamics and the spatial distribution of phytoplankton in aquatic systems often focuses on photosynthetic and growth responses (Pineda-Mendoza *et al.* 2020); however, the amounts of nutrients that are discharged into the systems must be taken into account, as in the case of this study, where the presence of nutrients with water quality are related, as well as their absorption by aquatic plants, which function as biofilters.

In the constructed wetlands installed in La Piedad Lagoon, engineering elements are considered to improve water quality by removing organic matter and emulating the purification mechanisms of natural systems (Vymazal & Kröpfelová 2008). These contaminants will degrade due to the interaction of their components, which include the bed or support medium, aquatic plants, and purifying organisms, which carry out filtration, adsorption, fixation, biochemical assimilation, and sedimentation processes (Aburto 2011). Various nutrient-focused methodologies that limit primary productivity (i.e., phosphates and nitrates) have been investigated (Maberly *et al.* 2020); however, few have been applied to the remediation of eutrophic waters in lakes (Pereira & Mulligan 2023). Therefore, implementing bioremediation systems by using aquatic plants has proven to be a helpful strategy.

Several laboratory tests were conducted to determine the aquatic plant species in the area with the most significant capacity to remove contaminants from wastewater discharges. For this, a mesocosm consisting of three water containers with a capacity of 3 l was used, in which four repetitions were made per treatment test. These containers used the water from La Piedad Lagoon, and a small wetland was built on it with the species *Eichhornia crassipes* and *Lemna minor*. One plant was used per experimental unit to treat the water of La Piedad Lagoon with *E. crassipes*, which were weighed before being placed into the container. In the case of *L. minor*, 24.2 g was weighed and placed in each container. At the end of the experiment, they were dried in

Table 3 | Results of the quality of water in La Piedad Lagoon

Parameters	Units	Maximum Permissible Limits (MPL) NOM-001-SEMARNAT-2021 reservoirs, lakes, lagoons	Lagoon entrance	Lagoon gate
Physicochemical parameters				
Fats and oils	mg/L	21	32	46
pH	-	6–9.0	8.63	8.52
TSS	mg/L	28	49	81
COD	mg/L	140	239	164
Nitrogen total	mg/L	30	34.63	43.81
Total phosphorus	mg/L	15	5.7	4.2
Heavy metals				
Arsenic	mg/L	0.2	2.985	2.457
Cadmium	mg/L	0.2	1.035	0.789
Cyanides	mg/L	2	<0.002	<0.002
Total chromium	mg/L	1.0	0.005	0.003
Mercury	mg/L	0.01	0.0003	0.257
Nickel	mg/L	4	0.066	0.057
Lead	mg/L	0.4	5.267	4.485
Zinc	mg/L	20	0.08	0.044

an oven and then weighed. Every seven days, the physicochemical parameters of the water were measured, including temperature, dissolved oxygen, and saturation percentage, using a Hach probe; the concentrations of nutrients, ammonium, nitrites, and phosphates were analyzed with Hanna field colorimeters. In Figures 4 and 5, the nutrient absorption process of each aquatic plant species can be observed, and therefore, their ability to reverse the eutrophication process of La Piedad Lagoon.

Nitrites are a natural ionic species that are part of the nitrogen cycle in soil and water and are generally stable in the environment (Wakejo *et al.* 2022). According to the Ecological Criteria, the permissible limit of nitrites for water bodies used as a drinking source is 5 mg/L. In the results of the aquatic species analyzed, it can be observed that nitrites exceed the established limit. Due to the present values, nitrites stimulate algae growth, which proves that La Piedad Lagoon presents a eutrophic condition (Ma *et al.* 2021). This situation is consistent with the great abundance of phytoplankton in the Lagoon. However, nitrites decreased due to the purification capacities of both analyzed species: *E. crassipes* and *L. minor*.

The phosphate ion (PO4) is formed from the inorganic phosphorus that exists as a mineral and can serve as a nutrient for algae development. It can come from natural sources (phosphoric deposits and rocks that release phosphorus) and anthropogenic sources such as domestic and industrial sewage and runoff from agricultural and domestic areas (Malairajan & Namasivayam 2021). The Ecological Criteria establish a maximum permissible limit of 0.1 mg/L of phosphates for drinking water supply sources; in the La Piedad Lagoon samples results, values found are above this limit. However, nitrites decreased due to the purification capacities of both analyzed species: *E. crassipes* and *L. minor*. However, the purification capacities of the aquatic plants analyzed reduced the concentration of phosphates in the samples analyzed. These concentration levels depend primarily on fertilizers used on the farmlands around Laguna La Piedad, which run off into the Lagoon during irrigation and the rainy season (Ayele & Atlabachew 2021).

6. CONCLUSIONS

The Basin of Mexico, and especially La Laguna de La Piedad, is very vulnerable to climate change and is expected to face notable modifications in its hydrological cycle, which will affect the availability, demand for, and quality of water, and increase the challenges for the management of water sources. Unfortunately, due to poor management practices, La Piedad Lagoon has received large volumes of wastewater discharge, severely contaminating it and losing a relevant alternative source of drinking water for the population of Mexico City.

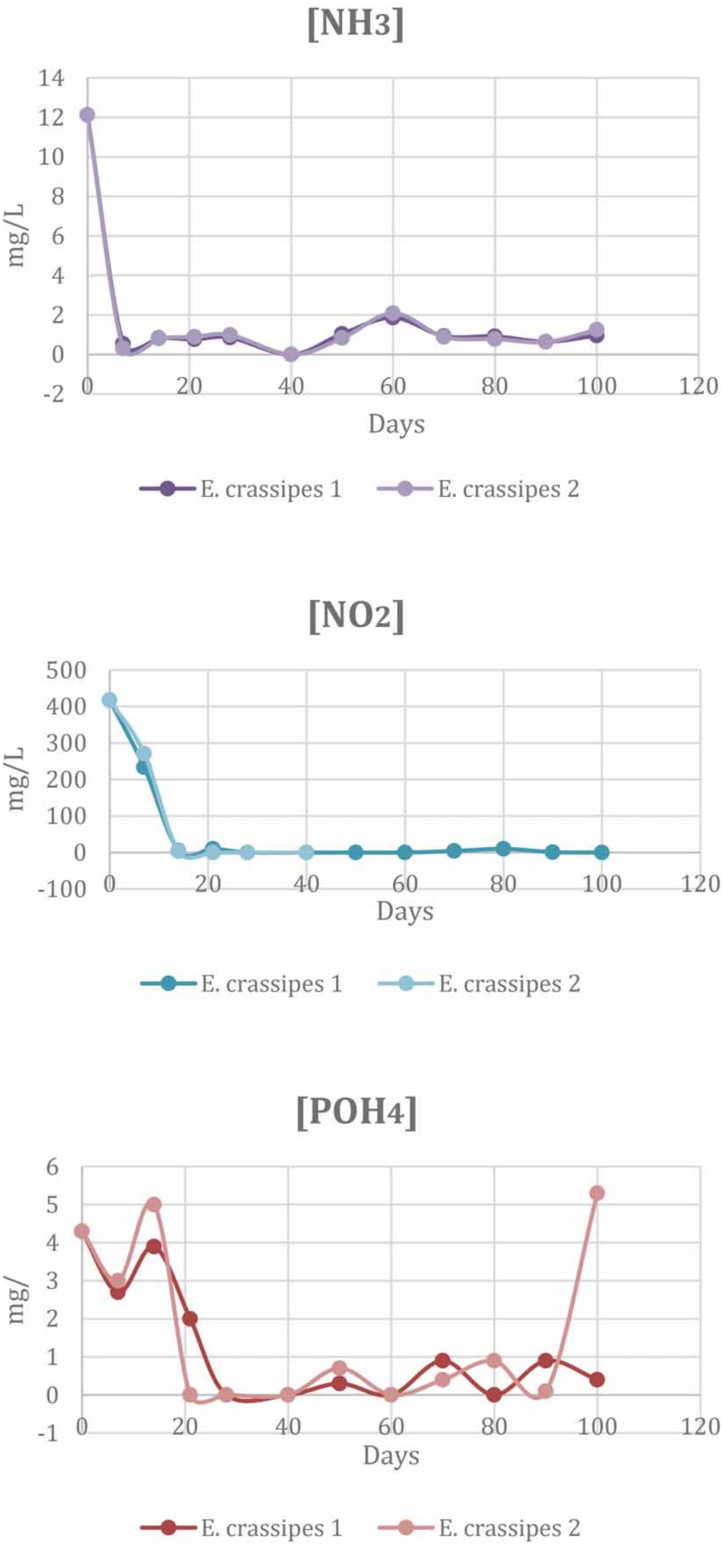


Figure 4 | Nutrient absorption process of the species *E. crassipes.*

Recovering this body of water requires a comprehensive vision beyond the ecological rescue of the Lagoon; this must include institutional and legal strengthening, the consolidation of governance, and the development of economic activities based on the excellent quality of the water, so that the communities and beneficiaries of the rescue of the Lagoon can become guardians for the conservation of this water.

The advantages of constructed wetlands include their low costs of operation and maintenance compared to conventional systems. They contribute to beautifying the landscape and being a habitat and refuge for wildlife.

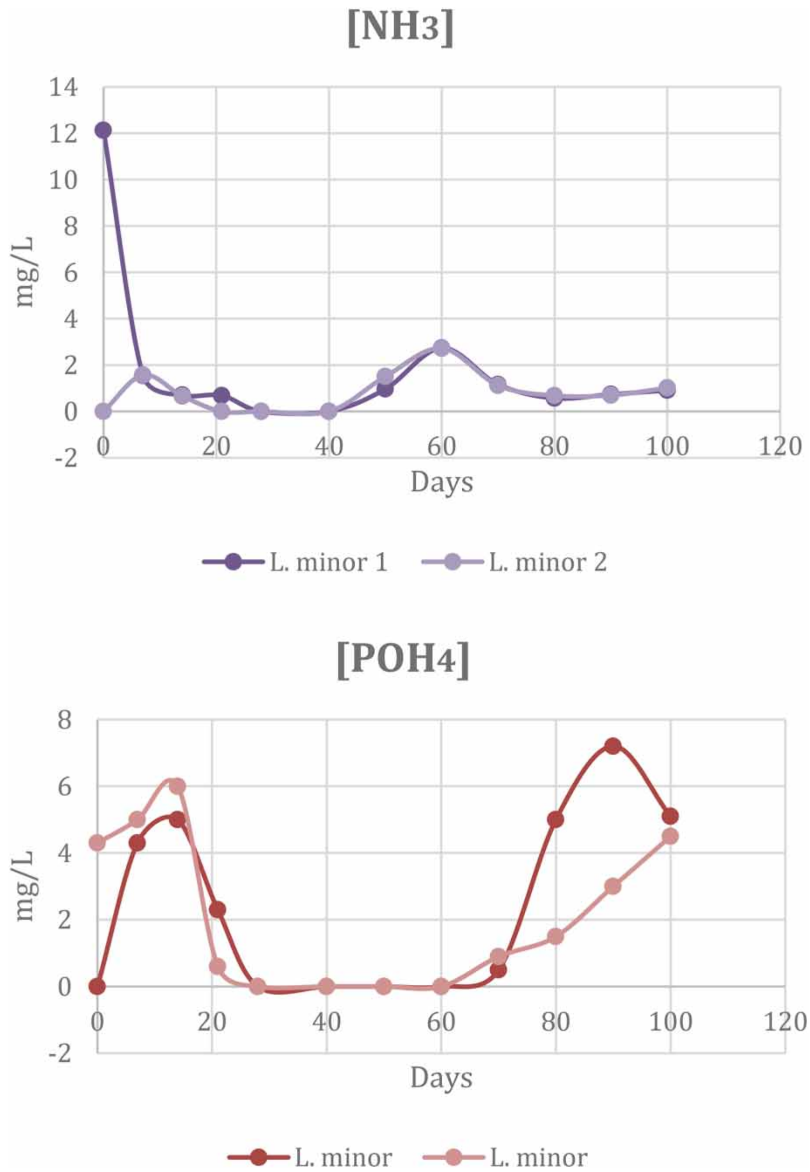


Figure 5 | Nutrient absorption process of the species *L. minor.*

These ecosystems can also create opportunities for developing new economic activities such as cultivating ornamental flowers, organic agriculture, tourism, bird watching, and fishing. Moreover, they imply low energy costs and low generation by-products. Nevertheless, constructed wetlands also have disadvantages, such as high hydraulic retention times and requiring large intervention areas. In the case of La Piedad Lagoon, one of the most relevant disadvantages is its requirement for a significant intervention area for improving its water quality with constructed wetlands. For this reason, it is vital to have the operation of WWTPs in place to complement the wastewater treatment processes.

The recovery of the Lagoon and its wetlands will improve its water quality. Still, it will also provide numerous benefits through its ecosystem services by becoming a water reservoir that can prevent floods and scarcity. It can also become a water source for different uses, such as agricultural, industrial, and environmental, in times of scarcity due to more frequent and intense droughts.

The Lagoon can provide food, medicinal plants, materials (i.e., tules), and recreational opportunities. Its recovery can also reduce methane emissions generated by the wastewater discharge in this water body. For this reason, it is crucial to address the causes of wetlands degradation and disappearance. Among these causes stand out: untreated wastewater discharges and wetlands removal in favor of agricultural, urban, industrial, and real estate sector activities. Addressing these problems requires coordinated work between the community, authorities, academia, and the private sector.

The study provides evidence of changes in the composition of the nutrients in the La Piedad Lagoon. It was possible to corroborate the function of macrophytes to improve water quality and their allelopathic potential. Although percentages of elimination of physicochemical parameters will not be obtained as those reported by other authors, several parameters such as turbidity, phosphates (PO4), total solids (ST), suspended (SS), and dissolved (SD) did improve.

Based on the study, aquatic plants positively affect water quality by reducing the values of specific physicochemical parameters. These results are influenced by free-living phytoplankton species that eutrophicate aquatic systems such as the La Piedad Lagoon since it is a prior treatment, achieving a better purification process and improved water quality in this reservoir.

Finally, climate change is expected to affect the water quality of aquatic ecosystems due to the increase in water temperature, which favors the reduction of oxygen solubility and the processes of nitrification and eutrophication. Climate change scenarios for the Basin of Mexico, particularly in the region where La Piedad Lagoon is located, estimate increases in the average temperature of more than 2°C and reductions in the precipitation of more than 20% of the annual volume in the long term. This situation highlights the water emergency the region will face due to the potential reduction in water availability, which will intensify the reduction in the quantity and quality of water sources. These problems, combined with the expected demographic increase and the greater demand for water for human and industrial consumption, represent enormous challenges for those responsible for providing water and sanitation services in an increasingly uncertain context. Therefore, the recovery of bodies of water and the wetland system in lagoon ecosystems is crucial to facing the impacts of climate change on the availability and quantity of water. These efforts must be urgently integrated into public policy strategies at all levels of government, in addition to creating the conditions that allow social support and political will to make interventions of this nature a reality.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Aburto, C. S. 2011 *Análisis y modelación del proceso de nitrificación en sistemas experimentales que simulan humedales artificiales (Analysis and Modeling of the Nitrification Process in Experimental Systems That Simulate Artificial Wetlands)*. UNAM, Mexico, pp. 31–250.

Adame Villamil. 2022 *Estrategia para la selección del scenario conceptual más viable para el mejoramiento y aprovechamiento del agua de la Laguna La Piedad, en Cuautitlán Izcalli, Estado de México.* II-UNAM, Mexico.

Arcos Pulido, M. D. P., Avila de Navia, S. L., Estupiñan Torres, S. M. & Gómez Prieto, A. C. 2005 *Indicadores microbiológicos de contaminación de las fuentes de agua (Microbiological Indicators of Contamination of Water Sources)*. NOVA Publ. Cient. pp. 69–79.

Arreguin-Cortes, F. I., Saavedra-Horita, J. R., Rodriguez-Varela, J. M., Tzatchk, V. G., Cortez-Mejia, P. E., Llaguno-Guilberto, O. J. & Sainos-Candelario, A. 2020 State level water security indices in Mexico. *Sustainable Earth* **3** (1), 1–14.

Ayele, H. S. & Atlabachew, M. 2021 Review of characterization, factors, impacts, and solutions of Lake eutrophication: Lesson for lake Tana, Ethiopia. *Environmental Science and Pollution Research* **28** (12), 14233–14252.

Beltrán-López, R. G., García-Andrade, A. B. & Ornelas-García, C. P. 2023 Mexican freshwater fishes in the anthropocene. In: *Mexican Fauna in the Anthropocene* (Jones, R. W., Ornelas-García, C. P., Pineda-López, R. & Álvarez, F., eds.). Springer International Publishing, Heidelberg, pp. 129–152.

Chen, Y. & Bilton, A. M. 2022 Water stress, peri-urbanization, and community-based water systems: A reflective commentary on the metropolitan area of Mexico City. *Frontiers in Sustainable Cities* **4**, 790633.

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (National Commission for the Knowledge and Use of Biodiversity) (CONABIO), Secretaría del Medio Ambiente del Distrito Federal (Federal District Secretariat of

Environment) (SMADF). 2016 *La biodiversidad en la Ciudad de México (Biodiversity in Mexico City)*. CONABIO-SMADF, Mexico.
CONAGUA. 1971 *Plan and Delimitation of La Piedad Lagoon*. No. VM-AH-0826. Historical Water Archive. CONAGUA, Mexico.
CONAGUA. 2022 *General Sub-Directorate of Drinking Water, Drainage and Sanitation*. Basic Water Services Information System (SISBA), CONAGUA, Mexico.
Cuautitlan Irrigation Unit (CIU) 2023 *Volumes Managed by the Cuautitlan Irrigation Unit*. CIU, Mexico City, Mexico.
Dunne, T. & Leopold, L. B. 1978 *Water in Environmental Planning*. W. H. Freeman Co., San Francisco, CA.
García-Sánchez, M. & Güereca, L. P. 2019 Environmental and social life cycle assessment of urban water systems: The case of Mexico City. *Science of the Total Environment* **693**, 133464.
Government of Cuautitlan Izcalli. 2019 *Cuautitlan Izcalli Urban Development Plan*. Cuautitlan Izcalli, Mexico.
Government of Mexico. 2000 *Conservation of Water Resources- That Establishes the Specifications and the Method to Determine the Average Annual Availability of National Waters*. NOM-011-CNA-2000. Official Gazette of the Federation, Mexico.
Government of the State of Mexico. 1959 *State Protected Natural Area Called State Park for the Protection and Promotion of the Zumpango Lagoon Water Sanctuary*. State Decree No. ANPE-0651. Government of the State of Mexico, Mexico.
Gradilla-Hernández, M. S., de Anda, J., Garcia-Gonzalez, A., Meza-Rodríguez, D., Yebra Montes, C. & Perfecto-Avalos, Y. 2020 Multivariate water quality analysis of Lake Cajititlán, Mexico. *Environmental Monitoring and Assessment* **192** (1), 5.
Hamilton, D. P., Salmaso, N. & Paerl, H. W. 2016 Mitigating harmful cyanobacterial blooms: Strategies for control of nitrogen and phosphorus loads. *Aquatic Ecology* **50**, 351–366.
Hargreaves, G. H. & Samani, Z. A. 1985 Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* **1**, 96–99.
Koycheva, J. & Karney, B. 2009 *Stream Water Temperature and Climate Change. An Ecological Perspective*. International Symposium on Water management and Hydraulic Engineering, Skopie, Macedonia, 1–5 September 2009, pp. 771–777.
Ma, S. N., Wang, H. J., Wang, H. Z., Zhang, M., Li, Y., Bian, S. J., Liang, X. M., Søndergaard, M. & Jeppesen, E. 2021 Effects of nitrate on phosphorus release from lake sediments. *Water Research* **194**, 116894.
Maberly, S. C., Pitt, J. A., Davies, P. S. & Carvalho, L. 2020 Nitrogen and phosphorus limitation and the management of small productive lakes. *Inland Waters* **10** (2), 159–172.
Malairajan, S. & Namasivayam, V. 2021 Management of phosphate in domestic wastewater treatment plants. *Environmental Biotechnology* **4**, 69–100.
Merino-Ibarra, M., Monroy-Rios, E., Vilaclara, G., Castillo, F. S., Gallegos, M. E. & Ramírez-Zierold, J. 2008 Physical and chemical limnology of a wind-swept tropical highland reservoir. *Aquatic Ecology* **42**, 335–345.
Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. 2005 Global pattern of trends in streamflow and water availability in a changing climate. *Nature*. **438**, 347–350.
Ministry of Agriculture and Hydraulic Resources (MAHR). 1978 *Official Letter No. R-16.11.3/2419 and 204.3.1.-681*. SARH, Mexico.
Mora-Olivo, A., Villaseñor, J. L. & Martínez, M. 2013 Las plantas vasculares acuáticas estrictas y su conservación en México (Strict aquatic vascular plants and their conservation in Mexico). *Acta botánica mexicana [Mexican Botanical Act]* **103**, 27–63.
National Meteorological Service (NMS). 2023 *Climate Databases*. CONAGUA, Mexico.
Naturalista. 2023 *Biodiversity Database*. Naturalista, CONABIO, Mexico.
Naveen, B. P., Mahapatra, D. M., Sitharam, T. G., Sivapullaiah, P. V. & Ramachandra, T. V. 2017 Physico-chemical and biological characterization of urban municipal landfill leachate. *Environmental Pollution* **220**, 1–12.
O'Farrell, I., Bordet, F. & Chaparro, G. 2012 Bloom forming cyanobacterial complexes co-occurring in a subtropical large reservoir: Validation of dominant eco-strategies. In: *Phytoplankton Responses to Human Impacts at Different Scales* (Salmaso, N., Naselli-Flores, L., Cerasino, L. & Flaim, G., Tolotti, M.). Springer, Dordrecht, pp. 175–190.
Olvera-Viascán, V., Bravo-Inclán, L. & Sánchez-Chávez, J. 1998 Aquatic ecology and management assessment in Valle de Bravo reservoir and its watershed. *Aquatic Ecosystem Health & Management* **1** (3–4), 277–290.
Palomares-Reyna, D., Sosa-Rodriguez, F. S., Palma Goyes, R. E., Fuentes-Camargo, I., Elizalde, I., Ramirez-Lopez, M., Lartundo-Rojas, L. & Vazquez-Arenas, J. 2022 Concomitant abatement of ciprofloxacin, sulfamethoxazole and cefadroxil in synthetic wastewater using hybrid photoelectrochemical ozonation driven on TiO_2 containing C, N and P species. *Journal of Hazardous Materials Advances* **8**, 100179.
Pereira, A. C. & Mulligan, C. N. 2023 Practices for eutrophic shallow lake water remediation and restoration: A critical literature review. *Water* **15** (12), 2270.
Pineda-Mendoza, R. M., Briones-Roblero, C. I., Gonzalez-Escobedo, R., Rivera-Orduña, F. N., Martínez-Jerónimo, F. & Zúñiga, G. 2020 Seasonal changes in the bacterial community structure of three eutrophicated urban lakes in Mexico City, with emphasis on Microcystis spp. *Toxicon* **179**, 8–20.
Sosa Rodríguez, F. S., 2019 Limitando el calentamiento global a 1.5 C° y sus beneficios en la disponibilidad del agua: La necesidad de una reflexión a nivel local (Limiting global warming to 1.5 C° and its benefits on water availability: The need for reflection at the local level). In: *¿Aún estamos a tiempo para el 1.5 °C? (Are We Still in Time for 1.5 °C?)* (Rueda Abad, J. C. eds). UNAM, Mexico.

Sosa Rodríguez, F. S., Vázquez Arenas, J., Galindo Leal, C., Alva Martínez Alejandro, F., Herbiet, A., Dultzin, D. & Nava Arias, A. 2022 The water forest and its benefits for the rescue of Laguna la Piedad, Cuautitlán Izcalli. In: *Scientists and Society in Action for Biodiversity and Sustainability of the Water Forest of the Megalopolis of Mexico* (Avila Åkerberg, V. & González Martínez, T. M., eds.). Editorial ICAR-UAEMex, Mexico, pp. 21–28.

Stefanova, A., Hesse, C., Krysanova, V. & Volk, M. 2019 Assessment of socio-economic and climate change impacts on water resources in four European Lagoon Catchments. *Environmental Management* **64**, 701–720.

Thornthwaite, C. W. 1948 An approach toward a rational classification of climate. *Geographical Review* **38**, 55–94.

Thornthwaite, C. W. & Mather, R. J. 1957 *Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance.* Laboratory of Climatology, Centertown, NJ.

Turc, L. 1961 Évaluation des besoins en eau d'irrigation, evapotranspiration potentielle. *Formule climatique simplifiée et mise a jour. Ann. Agron* **12**, 13–49.

US-EPA. 2002 *Ground Water Contamination. US EPA Seminar Publication. Wellhead Protection: A Guide for Small Communities*. Chapter 3. EPA/625/R-93/002.

Vymazal, J. & Kröpfelová, L. 2008 Types of constructed wetlands for wastewater treatment. In: *Wastewater Treatment in Constructed Wetlands with Horizontal Sub-Surface Flow* (Vymazal, J. & Kröpfelová, L, eds.). Springer, Dordrecht, pp. 121–202.

Wakejo, W. K., Meshesha, B. T., Habtu, N. G. & Mekonnen, Y. G. 2022 Anthropogenic nitrate contamination of water resources in Ethiopia: An overview. *Water Supply* **22** (11), 8157–8172.

Zhu, T., Jenkins, M. W. & Lund, J. R. 2006 *PIER Project Report Number 2006-003*. California Energy Commission. PIER Energy-Related Environmental Research Program & California Ocean Protection Council.

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