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Research article

Understanding and managing nutrient pollution in peri-urban wetlands: The Ciénegas del Lerma, Mexico

Gloria Soto-Montes-de-Oca [a,b,*], Gustavo M. Cruz-Bello [a], Abigail Martínez-Mendoza [c], Kevin M. Hiscock [d]

[a] Department of Social Sciences, Universidad Autónoma Metropolitana Unidad Cuajimalpa, Av. Vasco de Quiroga 4871, Cuajimalpa, 05348, Mexico City, Mexico
[b] Centre for Social and Economic Research on the Global Environment, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK
[c] Department of Social Sciences, Universidad Autónoma Metropolitana Unidad Lerma, Av. Hidalgo Pte. 46, Lerma de Villada, CP. 52006, Mexico
[d] School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK

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ABSTRACT

Nutrient pollution has been broadly studied in developed countries, where the primary source is often agricultural diffuse pollution. However, more research is needed in developing countries with a predominance of low-income households, insufficient public service infrastructure, pressure from urban expansion, and scarce information. In this research, centered on the Lerma Cienega protected wetlands in a peri-urban area of Toluca city in Mexico, a socio-ecological systems framework was applied to study the nutrient pollution problem and recommend nutrient control measures. An export coefficient model was developed to estimate nutrient losses from micro-basin areas discharging to the wetlands, which range from 0 to 32 tonnes/year for nitrogen (N) and 0–4.6 tonnes/year for phosphorus (P). The highest annual N loss occurs in the case of a combination of agriculture or grassland with slow infiltration soils. In contrast, P loss is associated with agriculture or urban land use in combination with slow infiltration soils. By determining the sources and estimating the magnitude of nutrient pollution, nutrient mitigation solutions were considered for the peri-urban wetlands where low-income communities surround the immediate area and connections with urban and local communities facilitate options to conserve natural assets. In conclusion, controlling nutrient pollution can improve the protection of natural aquatic resources and the living conditions of local communities while generating other benefits for surrounding urban areas.

1. Introduction

Nutrient pollution, a form of water contamination by excessive nutrient inputs, typically of nitrogen (N) and phosphorus (P), is a global challenge that affects environmental and ecosystem health (McDowell et al., 2021; UN, 2023). The sources of nutrient pollution in freshwater and coastal areas include runoff from agriculture, livestock, aquaculture, inputs from wastewater treatment, industry and urban stormwater overflows, and atmospheric deposition of fossil fuel emissions from industrial activities and vehicles (Selman and Greenhalgh, 2009; Greenshank, 2023).

Excessive nutrients in wetlands can have severe ecological consequences. One of the most serious is eutrophication, leading to algal blooms, reduced water clarity, and depleted oxygen levels (Greiner, 2014; Kakade et al., 2021; Akinnawo, 2023). This can severely impact aquatic life, causing mass mortality of fish and invertebrates and reducing biodiversity (Amorim and Moura, 2021). Excess nutrients can also promote invasive species that outcompete native plants, disrupting ecosystems (Hong et al., 2020). Furthermore, degraded water quality diminishes the ability of wetlands to provide critical services like water filtration, flood control, and carbon sequestration (Afitiri et al., 2020). Over time, these changes weaken ecosystem resilience, making wetlands more vulnerable to further stressors and reducing their capacity to support wildlife and human communities (Mozdzer et al., 2020). The consequences extend beyond ecological impacts, with substantial economic costs for water purification, losses in fisheries and wildlife

* Corresponding author. Department of Social Sciences, Universidad Autónoma Metropolitana Unidad Cuajimalpa, Av. Vasco de Quiroga 4871, Cuajimalpa, 05348, Mexico City, Mexico.
E-mail address: gsoto@cua.uam.mx (G. Soto-Montes-de-Oca).

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production, reduced recreational value, and losses in property value (Ro et al., 2020; Mosheim and Sickles, 2021). Nutrient pollution also threatens human health, causing illnesses like rashes, digestive problems, and neurological effects (EPA, 2024). As a global challenge, nutrient pollution drives international initiatives to promote effective management and awareness among diverse stakeholders (Leach et al., 2012; UN, 2023).

Peri-urban wetlands in developing countries are vulnerable to nutrient pollution from nearby urban and industrial expansion (Lantz et al., 2013; Pérez-Belmont et al., 2019). These wetlands provide important ecosystem services like food, cultural activities, and flood control for local and urban communities (Chaikumbung et al., 2016; UN, 2023). However, they often have small farms, low-income households, limited public services, and pressure from urban growth (Pérez-Belmont et al., 2019; Mondal et al., 2022; Soto-Montes-de-Oca, 2023).

In developed countries, nutrient pollution often comes from diffuse agricultural sources such as fertiliser runoff and livestock waste entering waterways (Konrad et al., 2014; McDowell et al., 2021; Lyon et al., 2022). However, peri-urban areas in developing countries face a mix of urban pollution inputs and diffuse pollution from surrounding low-income farming communities (United Nations, 2019).

Nutrient pollution is a serious issue in developing countries, often due to inadequate urban water treatment (Nyenje et al., 2010). Reviews of wetland degradation in India and elsewhere have identified multiple pollution sources, including wastewater, sewage, and agricultural runoff (Ahmad et al., 2024). Numerous studies across developing countries have identified agriculture, urbanisation, aquaculture, tourism, and industry as key drivers of wetland degradation, with inland wetlands facing the greatest impacts (Kansiime et al., 2007; Loiselle et al., 2016; Ballut-Dajud et al., 2022; Banderas and González-Villela, 2024). These findings highlight the relevance of nutrient pollution in developing countries and the need for tailored management solutions.

Effective management is crucial for peri-urban wetlands, often designated protected areas of international importance (Ramsar, 2024). Management plans should integrate, improve, and adapt to context-specific knowledge to enhance wetland conditions. Addressing the sustainable use of wetlands requires understanding the relationships between human activities in surrounding areas and the drivers of change, including nutrient pollution (Munguía and Heinen, 2021; Kumar et al., 2023).

In managing nutrient pollution, evaluating point and non-point sources is relevant. In urban settings, nutrient loads are often multiple-point source releases from septic tanks, sewer overflows, or unregulated industrial and commercial activities. Non-point runoff from agriculture originates in the application of manure and inorganic fertiliser, cropland drainage, and livestock grazing (Lintern et al., 2020). Whereas reducing nutrient loads from point sources such as municipal or industrial wastewater can often be managed with engineering or structural solutions, loads from non-point or diffuse sources such as agriculture or livestock require changes to catchment management and land use decisions. These changes and decisions need finer spatial scale information to assess reduction alternatives (McDowell et al., 2021; Hiscock et al., 2023).

Mitigation options to reduce nutrient pollution assessed in different studies include nature-based solutions (NbS) such as wetlands and riparian management (Hey et al., 2005; Raffensperger et al., 2017; Jabłońska et al., 2020; Kakade et al., 2021), land management strategies such as crop conversion (Hiscock et al., 2023), and technology options such as biogas digestors (Dahlin et al., 2015). As there are several options to reduce nutrient pollution (UNEP, 2022), it is also essential to consider cost-effective mitigation to guide the choices of stakeholders in the allocation of resources (Konrad et al., 2014).

Recognising catchments as socio-ecological systems allows transparency in who takes ownership of the potential nutrient mitigation strategies (Luna Juncal et al., 2023). The socio-ecological systems framework defines the hydrological spaces of land in which water is stored and released through streams and associates the water quality of wetlands with human activity (Adger et al., 2021; Lyon et al., 2022). An important consideration is that decisions made by urban and peri-urban residents and stakeholders, including farmers, and at different levels of governance, can affect catchment conditions and where interaction, not being linear, is seen as complex and interdependent (Ostrom, 2009; Morrison et al., 2019).

The purpose of this study is to understand the relationship between human activities and nutrient pollution in peri-urban wetlands and to suggest management strategies in a developing country context. Using a socio-ecological systems framework, the study identifies N and P pollution sources, estimates their magnitude through export coefficient modelling, and proposes context-specific nutrient management strategies. The research aims to recommend solutions to improve water quality in peri-urban wetlands, support ecosystem health, and enhance the living conditions of surrounding low-income communities while addressing the challenges of limited data availability.

2. Materials and methods

2.1. Study area

The Ciénegas del Lerma wetlands are located between 19°05' and 19°25' N and 99°25' and 99°34' W, east of the Toluca Metropolitan Area, the capital of the State of Mexico (CONAPO, 2020; Orozco-Hernández et al., 2020). The Cienega is part and origin of the Lerma River basin, one of two external water sources for nearby Mexico City (CONAGUA, 2018a). The Ciénegas del Lerma comprises three spatially separated wetlands: Almoloya, Lerma and San Bartolo (Fig. 1). The federally protected areas of these wetlands cover an extent of 16 km^2. Specifically, the area has been a Ramsar site since 2003 (Ramsar, 2003, cited in INEGI, 2019a).

The Ciénegas del Lerma, initially formed by a large lake, has diminished to only 11% of the original area due to land conversion and urban expansion (Orozco-Hernández et al., 2020). The wetlands are located at an altitude of 2580 m above sea level, with a mean temperature of 11.8 °C and a mean annual precipitation of 911.2 mm (INEGI, 2019a). The rainfall regime determines the extent of the floodable areas of the lakes, with periods of flooding between 6 and 8 months. The wetlands include deep water (up to 5 m), areas with emergent vegetation, and flooded and riparian vegetation. The soils are mainly of the gleysol, swamp-type found in areas where water accumulates and stagnates up to 50 cm deep for most of the year. There are also deep clay vertisols. To a lesser extent, phaeozem-type soils have a dark, thick surface layer rich in organic matter and nutrients (INEGI, 2019a).

The protected wetlands are adjacent to diversely polluted water courses that flow through urban and peri-urban areas. The Lerma River runs parallel to the wetlands and is highly polluted with untreated municipal and industrial discharges after its origins in the Almoloya wetland. The locations of overflows are poorly known, but an indication of the associated nutrient pollution is the growth of water lilies concentrated mainly on wetland banks (CONANP, 2017).

The federal Protected Areas authority monitors biological oxygen demand (BOD), an indirect indicator of nutrient pollution. Of the nine sampled areas, only one was considered 'good quality', five were rated as 'acceptable' and three as 'contaminated' (CONANP, 2018).

Records of N and P for the three wetlands exist from two decades ago (Pérez, 2005), but conditions have changed considerably in the region. Information from 2016 is available only for the Lerma wetland as shown in Table 1.

Subsistence farming practices are present (Albores, 2002), while the peri-urban communities are small and medium localities. Local families near the wetlands consume wild food from the Cienega and collect material to produce handicrafts (CONANP, 2017). Indigenous families in the area, mainly Otomi people, have a long-term attachment to the natural environment (Albores, 2002; Martínez et al., 2023). Records of

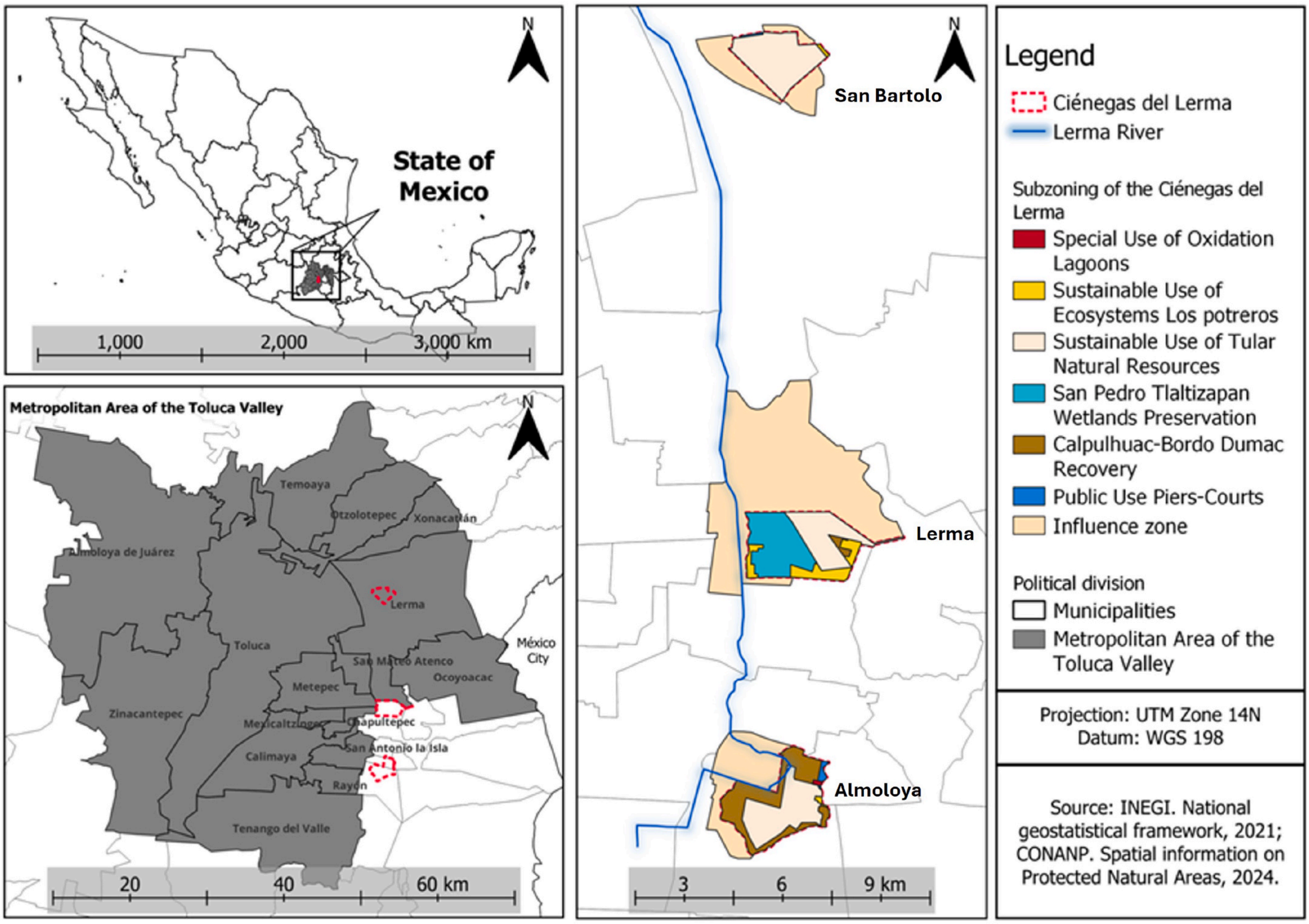

Fig. 1. Location of the Lerma Cienega wetlands showing the Toluca Valley Metropolitan Area and municipal divisions in the State of Mexico (left-hand panels) and sub-zoning of the Natural Protected Areas (central panel).

Table 1
Measured N and P loadings during the dry and rainy seasons in 2016 for the Lerma wetland based on Guzman (2017).

Location	Dry season		Rainy season	
	N (kg/day)	P (kg/day)	N (kg/day)	P (kg/day)
Eastern area	57.0	71.7	135.6	103.7
Western area	13.8	33.7	38.9	38.9

economic interests in the area exist from the 16th century and, from 1857, projects were initiated to drain the wetlands that now give the region its lake identity (Albores, 1995; Sugiura et al., 2016; Martínez and Mendoza, 2022; Martínez et al., 2023).

2.2. Research design

To define the physiographic and socioeconomic characteristics of the study area, this research adopted a socio-ecological systems framework as applied to catchments (Lyon et al., 2022), using official data produced at the national level as well as information generated by federal authorities for the specific protected areas (Table 2). The information aimed to observe both the ecological dimension through hydro-ecological and land use indicators, and the social dimension through socio-demographic and economic indicators. The analysis followed four stages. The first stage delineated the sub-basins and micro-basins affecting the water quality of each wetland as these define

Table 2
Data used to characterise hydro-ecological and socio-demographic indicators of nutrient pollution in the Lerma Cienega wetlands.

Data type	Scale/units	Source
Hydro-ecological and land use indicators:		
Hydrographic network	1:150,000	INEGI (2010)
National Geostatistical Framework		INEGI (2021)
Spatial information on Protected Natural Areas		CONANP (2024)
Land use	1:250,000	INEGI (2019b)
Crop area cultivated	ha	CONANP (2017)
Livestock area and number of head	ha and head	CONANP (2017)
Socio-demographic and economic indicators:		
Locality population	Number of inhabitants and households	INEGI (2020)
Sewage connection	Households without connections	INEGI (2020)
Marginality index	Municipal level	CONEVAL (2023)
Ejido land tenure		Registro Agrario Nacional, 2023b
River and stream overflows	Point	Google Earth Pro & J. Doe, pers. comm., July 2024
Economic units	Number	INEGI (2024a)

the hydrological flows for nutrient transport (Fitz, 2008). Micro-basin areas were delineated using the SWAT model (Neitsch et al., 2011), a digital elevation model (INEGI, 2021), and a 1:50,000 scale water flow layer (INEGI, 2010). Micro-basins draining towards the protected areas were then selected.

The second stage characterised the socio-economic context of each catchment. The localities, population and households established in the micro-basin areas influencing each wetland, the municipality boundaries, and socio-demographic indicators were incorporated. The number of households that lack sewage infrastructure was included as an indicator of point source pollution (INEGI, 2020). River and stream overflows were located through Google Earth Pro and verified with the CONANP authorities. The percentage of income poverty as a measure of social deprivation was considered, though this is only available at the municipal level (CONEVAL, 2023). The number of economic units (commercial activities) was included to observe the potential impact of point source pollution from urban and industrial activities. We included data on the number of ejidos in each catchment (Registro Agrario Nacional, 2023a) to detect potential conflicts over communally owned and managed land due to property rights disputes (Ávila-Sánchez, 2011) (Supplementary Material, Table S1).

The third stage involved the development of an export coefficient model to estimate the nutrient loading to the wetlands based on the methodology originally presented by Johnes (1996). Export coefficient modelling is a widely used empirical modelling approach that estimates the total amount of N and P exported by agricultural and rural non-point sources (Chen et al., 2018) through the equation:

$$L = \sum_{i=1}^{n} E_i[A_i(I_i)] + P$$

where L is the annual loss of nutrients (kg); E is the export coefficient for nutrient source i (kg/ha/year); A is the area of the catchment occupied by land-use type i (ha), or number of livestock type i, or rural population; I_i is the input of nutrients to source i (kg); and P is the input of nutrients from precipitation (kg/ha/year).

Due to the scarcity of data on nutrient inputs to the Lerma Cienega wetlands, the method described by Osmolovsky (2013) was used to estimate the most probable value of nutrient export (in kg/ha/year) for each land use category (agriculture, urban, grassland, forest, wetland and bare land). To reduce uncertainty, the method is based on the relationship between land use (obtained from CONABIO, 2015) and the range of N and P inputs reported in the literature, modified to account for field soil drainage characteristics derived from INEGI (2024b) (Supplementary Material, Table S2–S4).

Although the nutrient input from precipitation is a relatively minor source compared to N and P loads from land use, estimates of nutrient loading from precipitation were made based on export coefficient values determined using data on the composition of rainfall in the region (Supplementary Material, Table S5).

For septic sources associated with the population and livestock in the protected areas the export coefficient values given by Ding et al. (2010) and Tong et al. (2022) were adopted (Supplementary Material, Table S6). Households with sewage connections discharge ultimately to the Lerma River, which is unconnected to the wetlands. Hence, only the fraction of households without sewage connections is assumed to drain to the wetlands (Supplementary Material, Table S7).

2.3. Nutrient management options

The final stage of the methodology was to draw upon the literature and the results of the socio-ecological systems approach to recommend management options to reduce nutrient pollution in the peri-urban wetland catchments. Strategies applicable to practices in both urban and agricultural sectors within a developing country context were considered.

3. Results

3.1. Wetland catchment and land use characteristics

Distinguishing between micro-basins helps define the land use types that contribute to the water quality of each wetland. Five micro-basins flow directly to the Almoloya wetland, and 21 indirect tributary basins are further upstream (Fig. 2a). Four micro-basins flow directly to the Lerma wetland, and 12 are further upstream. Only three micro-basins flow directly into the San Bartolo wetland.

The 26 micro-basins that discharge directly or indirectly to the Almoloya wetland, in the headwaters of the Lerma River, cover an area of 210 km^2 and correspond to 14 municipalities (Almoloya del Río, Calimaya, Capulhuac, Joquicingo, Lerma, Ocoyoacac, Ocuilan, Rayón, San Antonio la Isla, Tenengo del Valle, Texcalyacac, Tianguistengo, Toluca and Xalatlaco). The five micro-basins draining to the Lerma wetland belong to six municipalities (Atizapán, Capulhuac, Chapultepec, Lerma, Ocoyoacac Tinaguistenco and Jalatlaco) and cover an area of 194 km^2. The three micro-basins that discharge directly to the San Bartolo Wetland cover an area of 53 km^2 and are all within the Lerma municipality. The distribution of land use in the micro-basins that discharge directly or indirectly to the wetlands occupies mostly agricultural land (56.5%), forestry (29.7%) and urban land (7.9%), as shown in Fig. 2b.

The designated protected area of the Almoloya wetland occupies an area of 596 ha, the Lerma wetland 656 ha and the San Bartolo wetland 346 ha. Table 3 shows the land use in the protected areas, including vegetation, agriculture, and livestock production.

3.2. Socio-demographic characteristics

The Almoloya wetland catchment comprises 13 localities, with a total population of 117,502 inhabitants living in 32,265 households, of which 166 have no sewage connection (Supplementary Material, Table S7). These localities are in seven municipalities (Almoloya del Río, Calimaya, Rayón, Texcalyacac, San Antonio de la Isla, Tenango del Valle and Joquingo) with only one communal property (ejido). Regarding the point sources, there is an oxidation lagoon in the vicinity of the wetland, which might overflow into the wetland, and there is also an aquaculture farm, but information from local sources needs to confirm whether there is any associated contamination. The catchment has three overflows from streams with polluted water, but only one impacts the wetland (see Fig. 2a for locations).

The Lerma wetland catchment has 13 localities, with 161,331 inhabitants in 42,805 households, of which 188 are without a sewage connection. The localities are in five municipalities (Capulhuac, Ocoyoacac, Lerma, Tiangistenco and Xalatlaco). One overflow from the Lerma River and three overflows from streams with polluted water are registered in this wetland, with the first appearing to occur during the rainy season when water is drained towards the wetland to avoid flooding of the adjacent land (Fig. 2a). Another overflow receives the disposal of residues from sheep meat sold in restaurants at localities in the Capulhuac municipality, which pollute the wetland through canals. In this catchment, there are three registered ejidos.

The San Bartolo wetland has five localities in its catchment area, with 33,339 inhabitants living in 9135 households, 89 of which do not have sewer connections. Six registered ejidos border its entire perimeter, which may explain why the San Bartolo wetland is the smallest water body because ejidos use water for agricultural activities (Orozco-Hernández et al., 2020). Six overflows from streams with polluted water are registered in this wetland, probably linked to urban localities, but more information is required (Fig. 2a).

Primarily small commercial activities are registered in the sub-basins of the three wetlands (Supplementary Material, Table S7). Of the 4578 economic units registered, 93% are very small units (less than five employees), while only 19 establishments (mostly government offices)

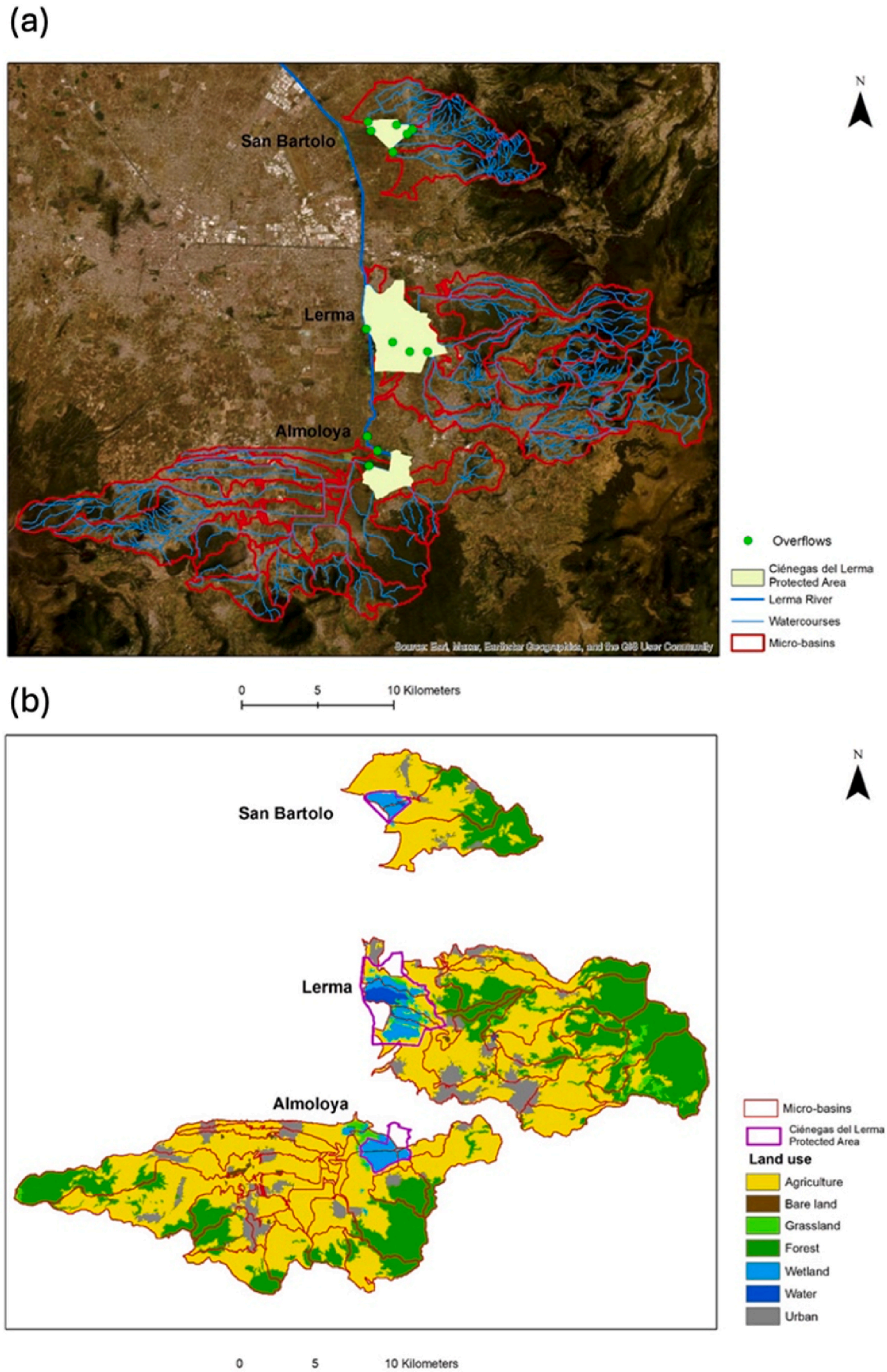

Fig. 2. (a) Delineation of micro-basins flowing to the Lerma Cienega wetlands and showing the location of wastewater overflows. (b) Land use distribution in the micro-basins discharging to the Lerma Cienega wetlands based on data from CONABIO (2015).

Table 3
Land use in the protected areas of the Lerma Cienega wetlands.

Polygon (ha/number)	Almoloya (596 ha)	Lerma (656 ha)	San Bartolo (346 ha)
Moisture agriculture (ha)	196.72	312.95	59.04
Non-irrigated agriculture (ha)	10.68	5.45	3.88
Human settlements (ha)	0.59	0.04	–
Waterbody (ha)	119.19	–	–
Cultivated grassland (ha)	–	235.57	–
Tular (sedge) vegetation (ha)	269.42	102.58	283.85
Total	596.60	656.59	346.77
Corn (maize) (ha)	8.77	67.79	7.8
Broad beans (ha)	1.87	5.32	–
Livestock area (ha)	194.3	90.5	44.1
Sheep (number)	150	200	20
Cattle (number)	50	–	15
Horse (number)	20	–	–
Ejidos in adjacent areas (number)	1	3	6

Source: https://www.inegi.org.mx/temas/usosuelo/#descargas; CONANP, 2017; Registro Agrario Nacional (2023b).

have more than 50 employees. In the Lerma sub-basin, the predominant economic activity is sheep-processed food restaurants (586 units) (INEGI, 2024a). A general characteristic of the three wetland areas is household poverty across the municipalities, with 57–75% of households classified as living in income poverty (CONEVAL, 2023).

3.3. Export coefficient modelling

Based on the land use types and hydrologic characteristics of the soils present, the estimated export coefficient values ranged from 0 to 30.0 kg/ha/year for N and 0–4.4 kg/ha/year for P across the three wetland catchments (Supplementary Material, Fig. S1). Given the spatial distribution of export coefficient values, the losses per micro-basin ranged from 0 to 32.0 tonnes/year for N and 0–4.6 tonnes/year for P (Fig. 3). Some micro-basins that drain directly into protected watersheds have the highest losses. The estimated inputs to the Almoloya wetland are 231 tonnes/year for N and 34 tonnes/year for P (Table 4). To the Lerma wetland, inputs are 163 tonnes/year for N and 24 tonnes/year for P, and to the San Bartolo wetland, 85 tonnes/year for N and 12 tonnes/year for P. The highest annual N loss occurs in the case of a combination of agriculture or grassland with slow infiltration soils (hydrologic soil groups C and D; Supplementary Material, Table S2). The highest annual loss for P is associated with agriculture or urban land use in combination with slow infiltration soils.

Further application of the export coefficient model to the specific region of the wetland protected areas (16 km^2) allows comparison of the relative contributions of land use, septic sources (population without sewage connection and livestock) and precipitation. As shown in Table 5, land use dominates the nutrient sources in the Lerma wetland, accounting for 78% of N inputs and 87% of P inputs. In contrast, the Almoloya and San Bartolo wetlands show greater nutrient pressure from septic sources that account for at least 40% of N inputs and 27% of P inputs. Nutrient inputs to the wetlands from precipitation are $<14\%$ for N and $<4\%$ for P.

4. Discussion

4.1. Nutrient inputs

The results provide evidence of the nutrient pollution pressures in each wetland, with many localities and municipalities involved in each catchment area. There are different proportions of land use, with a predominance of agricultural land (57%), forestry (30%) and urban areas (8%) in a context of marginality and urban growth (Orozco-Hernández and Sánchez-Salazar, 2004). As previously noted, official (2016) data confirm pollution levels in the Lerma wetland (Table 1), but there are no data for the Almoloya and San Bartolo wetlands. Total nutrient inputs to the Lerma wetland based on export coefficient modelling (163 tonnes/year for N and 24 tonnes/year for P) compared with the 2016 data (ranges of 5.0–49.5 tonnes/year for N and 12.3–37.9 tonnes/year for P) appear to show no improvement in P inputs and a deteriorating condition in N inputs.

Average nutrient inputs to the Lerma Cienega wetlands based on land use type range from 8.4 to 16.1 kg/ha/year for N and 1.24–2.27 kg/ha/year for P (Table 4), and for the specific region of the wetland protected areas range from 5.4 to 14.3 kg/ha/year for N and 0.74–2.08 kg/ha/year for P (Table 5). These ranges are similar to published values for export coefficient modelling studies that encompass various nutrient inputs (crop land, grassland, livestock, residential, forestry, orchards, bare land, atmospheric deposition) that range from 6.3 to 19.6 kg/ha/year for N and 0.35–1.94 kg/ha/year for P (Ding et al., 2010; Wu et al., 2015; Chen et al., 2018; Tong et al., 2022). Compared to these studies, the rate of P input for the San Bartolo wetland is higher (>2.08 kg/ha/year) and reflects the fact that the micro-watersheds that discharge into this wetland have mostly soils with low and very low infiltration rates, which cause greater runoff and nutrient loss.

The export coefficient model provides a simple and widely adopted approach to estimating nutrient loading in a data poor context (Chen et al., 2018; Liu et al., 2022). The results presented in this study are a first approximation of likely N and P discharges to the wetlands and the findings should be evaluated considering the sources of uncertainty. Using export coefficients derived from bibliographic values may not accurately reflect local or temporal conditions, although this is mitigated by using the most likely estimate of nutrient export for each land use category (Osmolovsky, 2013). To limit uncertainties, further research should validate the model results against available field data. Due to its simplicity, the model structure does not consider the complex hydrological interactions that influence pollutant transport (Ding et al., 2010; Guzmán et al., 2015; Moreno-Rodenas et al., 2019). Process-based models that describe the hydrological dynamics (e.g., runoff, sediment transport, nutrient attenuation) and the complex interactions between pollutants and ecosystem processes (e.g., nutrient cycling and vegetation uptake) can be developed where data availability allows (Xin et al., 2019).

The pollution sources identified in this study are associated with small-scale farming, livestock, and specific point sources from domestic and commercial activities, with no apparent evidence of industrial discharges. However, official information mentions that industrial wastewater and effluents from more than 700 industries from five industrial parks discharge into the Lerma River, near the wetlands (CONAGUA, 2018b). Official documents also mention discharges of domestic wastewater in the Almoloya and Lerma wetlands (Gobierno del Estado de México, 2011; INEGI, 2019a), as confirmed by the detected overflow points found through Google Earth (Fig. 2a), but fieldwork is necessary to confirm the inputs of N and P to reduce this source of uncertainty.

4.2. Nutrient management options

Despite the scarcity of information about water quality conditions, the combination of methods allowed an estimation of pollution levels of non-point sources and the identification of point pollution practices typical of developing countries that impact water quality, such as small-scale livestock farming, specific peri-urban commercial activities, and polluted water courses generated in urban areas.

Several runoff mitigation strategies have been proposed and assessed (Collins et al., 2016; Luna Juncal et al., 2023; Hiscock et al., 2023; UN, 2023), with several strategies relevant to the Lerma Cienega wetlands. Application of the export coefficient model to the protected areas (Table 5) showed that land use dominates the nutrient sources in the Lerma wetland, in contrast to the Almoloya and San Bartolo wetlands

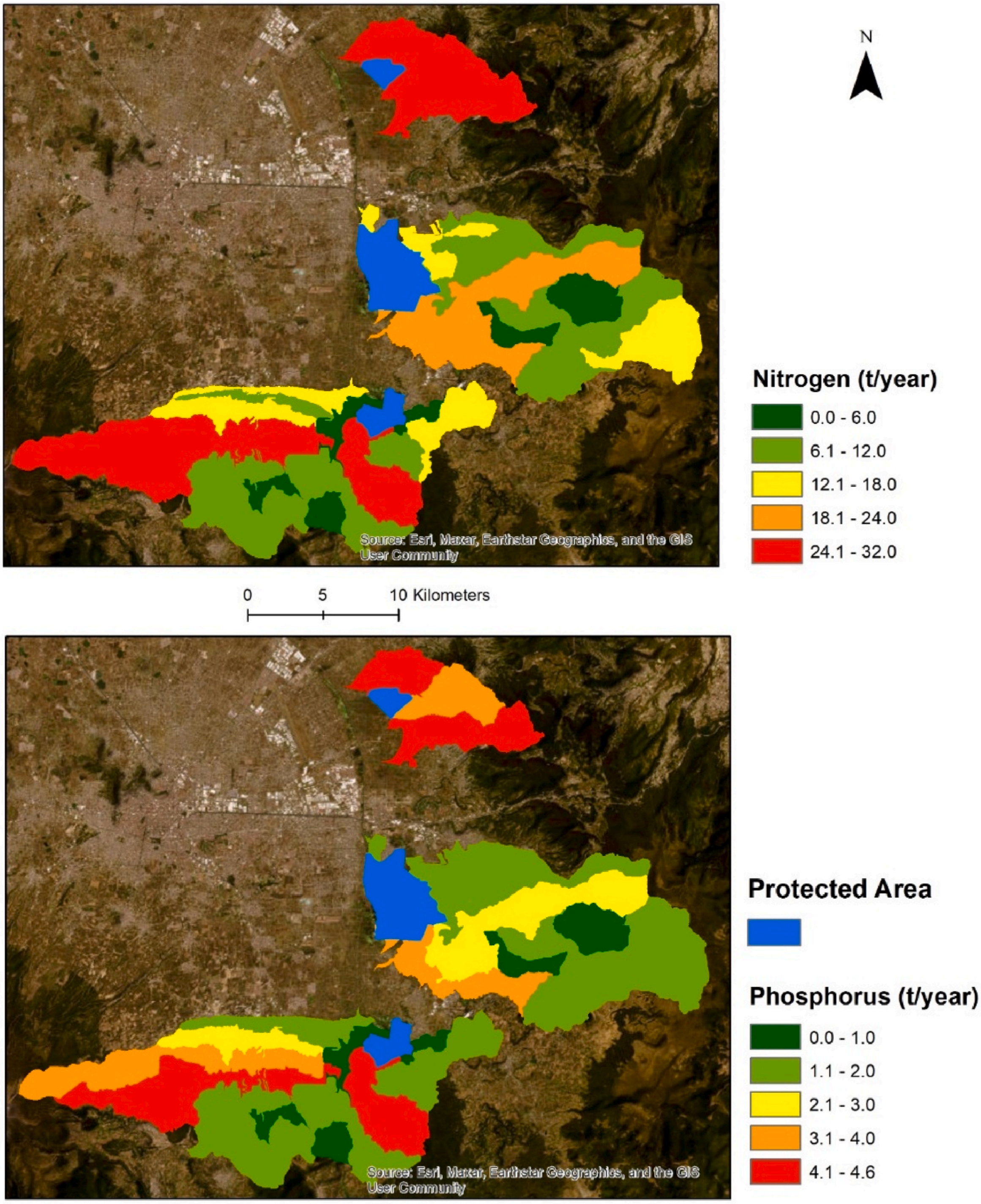

Fig. 3. Nutrient losses per micro-basin in tonnes/year in the Lerma Cienega wetlands.

Table 4
Estimated nutrient losses to the Lerma Cienega wetlands based on export coefficient modelling of land use types.

Wetland	Area	N input		P input	
	(km^2)	(tonnes/year)	(kg/ha/year)	(tonnes/year)	(kg/ha/year)
Almoloya	210	231	11.0	34	1.62
Lerma	194	163	8.4	24	1.24
San Bartolo	53	85	16.1	12	2.27

that show greater nutrient pressure from septic sources. Considering these pollution sources, the recommendations listed in Table 6 are intended for sectors associated with (i) agricultural practices scalable to small farmers and (ii) small-scale technologies to address pollution from localised household sewage discharges and commercial activities.

While some options are relevant for the three protected wetlands and their catchment areas, particularly agricultural, nature-based solutions and overflow options, others are case-specific (Table 6). Animal confinement and waste management systems are relevant options for the Lerma and Almoloya wetlands because of the number of livestock in the immediate area. Bio-digestors are a likely solution to manage meat

Table 5
Comparison of nutrient source inputs to the Lerma Cienega wetland protected areas based on export coefficient modelling.

Source	N input (kg/ha/year)			P input (kg/ha/year)		
	Almoloya	Lerma	San Bartolo	Almoloya	Lerma	San Bartolo
Land use	1.50	11.10	2.50	0.51	1.81	0.52
Population	1.90	2.02	1.76	0.15	0.23	0.20
Cattle and horse	0.86	0.00	0.32	0.04	0.00	0.01
Sheep	0.35	0.43	0.08	0.01	0.01	0.00
Precipitation	0.74	0.74	0.74	0.03	0.03	0.03
Total	5.35	14.29	5.40	0.74	2.08	0.76
Land use/Total	0.28	0.78	0.46	0.69	0.87	0.68
Septic sources/Total	0.58	0.17	0.40	0.27	0.12	0.28
Precipitation/Total	0.14	0.05	0.14	0.04	0.01	0.04

Table 6
Management options to control nutrient pollution in the Lerma Cienega wetland catchments.

Wetland catchment	Sector	Management option	Party responsible for implementation
Almoloya, Lerma, San Bartolo	Agriculture	Conservation tillage and prevention of soil erosion Controlled-release fertiliser Crop rotation Drip irrigation[a] Vegetated streams Organic production	Ejidos, landowners, agriculture authority, CONANP (protected areas), NGOs.
Almoloya, Lerma	Livestock	Animal confinement Fencing around streams Animal waste management systems (biodigestors) Silvopasture	Ejido, landowners, agriculture authority, CONANP (protected areas), CONAFOR, NGOs.
Almoloya, Lerma, San Bartolo	Nature-based solutions	Riparian forest buffers Riparian grass buffers Silvopasture Vegetation recovery (land use change)	Ejido, landowners, CONANP (protected areas), CONAFOR and/or state or municipal government, NGOs.
Almoloya, Lerma, San Bartolo	Sewage	Connection to sewage system Artificial wetlands Bio-digestors	Municipal governments, state government.
Almoloya	Aquaculture	Removing aquaculture waste and use in agriculture Bio-digestors	Ejido, agriculture authorities, CONANP, NGOs.
Lerma	Food commercial activities	Artificial wetlands Bio-digestors Engineered logjams	Commercial sector, municipal and/or state government
Almoloya, Lerma, San Bartolo	Overflows	Improved drainage ditches and maintenance Engineered logjams	CONAGUA, CONANP, ejido, landowners.

[a] Option recommended for the protected area but not the catchment area.

discharges in the Lerma wetland. Alternatives to reduce the effects of aquaculture and the oxidation lagoon should be considered for the Almoloya wetland. Some options might be helpful in the protected areas but less efficient for the wider catchment area, such as drip irrigation because this practice might increase the agricultural intensity or extension.

Recommended nature-based solutions (NbS) in the three wetlands are riparian buffers and vegetation recovery, most likely through land use change, particularly in protected areas. Engineered logjams are another solution by building ditches with natural material in water courses to trap sediments and attenuate nutrients from upstream runoff canals (Lloyd et al., 2024). An option for the overflows of contaminated water from the Lerma River to the Lerma wetland is to improve drainage ditches and maintenance. However, a constraint on this option is that authorities allow overflows during the rainy season to prevent flooding. Hence, actions are also necessary to reduce the risk of flooding in the surrounding areas to minimise this practice.

The efficiency of specific nature-based solutions in reducing N and P has been assessed in some cases. For instance, riparian grass buffers can reduce N losses by 13–46% and P by 30–45% (BMPD, 2016), depending on their width (10−30 m) (Lloyd et al., 2024). Engineered logjams present benefits to removing N because of the vegetation behind dams, but more evidence is required to estimate the actual reduction (Lloyd et al., 2024). Silvopasture can reduce N and P losses because trees inhibit leaching and reduce wind erosion. A tree density of 100/ha provides these environmental benefits, but more monitoring is required to estimate the specific N and P reduction (Lloyd et al., 2024).

The mitigation strategies proposed here should be undertaken by specific actors depending on the driving force (Table 6). Ejidos and landowners could implement actions associated with agriculture, livestock and nature-based solutions, supported by the agriculture and forestry authorities (CONAFOR); specific municipalities could install lacking sewerage connections; small commercial businesses could associate to build biodigesters in the Lerma and Almoloya wetlands, supported by municipal or state governments; the federal water authorities (CONAGUA) could undertake actions to avoid overflows from streams and the Lerma River with polluted water, and also produce information about water pollution. At the same time, the National Commission of Natural Protected Areas could use nature-based solutions to reduce N and P pollution in the three wetland areas.

The protected wetlands are managed with rules determined by the National Commission of Natural Protected Areas and the Ramsar Convention. In general, the Commission should work with stakeholders to incorporate management options towards reducing nutrient pollution. Wetland-protected areas depend on the collaboration between different actors and the ability of authorities to produce context-specific information and alternatives for sustainable management (Kumar et al., 2023). In addition, Ramsar Convention administrators sometimes have inadequate instruments to maintain ecological conditions (Munguía and Heinen, 2021) and, therefore, generating specific guidelines addressing nutrient pollution should become a valuable input.

The Mexico City Government is a further stakeholder because the Lerma system provides an external water source. Here, the New York City's experience is an example of how the city government is involved in maintaining and enhancing the high quality of surface water sources through its Watershed Protection and Watershed Agricultural Programs, which develop projects with farm and forest landowners in the relevant watersheds to protect water quality (NASEM, 2020).

Despite some alternatives that might seem rational from an ecological perspective, the socio-economic context could reduce the possibility of success, such as a negative preference for buffer zones in agricultural catchments in small field systems (Buckley et al., 2012). A collaborative approach is recommended, as observed in some peri-urban communities that are willing to try new practices based on their awareness of an environmental problem, and where local knowledge and traditional practices help to define adaptation strategies based on the specific conditions of communities (Soto-Montes-de-Oca and Alfie-Cohen, 2019).

Reducing nutrient pollution problems in peri-urban wetlands in Mexico requires the recognition of the three levels of government and the importance of consulting local communities. The goal is to establish strategies, finance commitments and timelines. This means that the planning, regulation and finance instruments should be harmonised to reflect congruency with local conditions and long-term sustainability.

Future research should investigate the perceptions, attitudes and preferences of people and other stakeholders to observe whether they are concerned with nutrient pollution and their willingness to try new practices (Imdad et al., 2023). To advance this approach, a better understanding of the factors affecting pollution needs to be supported by monitoring, reporting and verification processes of the point and non-point pollution sources to assess N and P losses to water bodies.

5. Conclusions

This study, focusing on the Ciénegas del Lerma in Mexico, demonstrated the utility of a socio-ecological systems approach to address nutrient pollution in peri-urban wetlands and to propose suitable mitigation strategies scalable for other regions facing similar socio-ecological challenges. Socio-demographic data emphasised the challenges of addressing pollution in low-income communities with limited resources. The study proposed a suite of context-specific management strategies that integrate agricultural practices, nature-based solutions, improved sewage systems and small-scale technological options and provide actionable insights for stakeholders to address nutrient pollution and enhance wetland conservation. Overall, the choice of nutrient pollution management options is oriented towards implementation by low-income communities engaged in agriculture, livestock and commercial activities, as long as the competent authorities support the solutions. In this approach, fieldwork with local communities is recommended to understand their perspectives concerning possible options and to corroborate actions with nutrient pollution monitoring results. Ideally, management practices should become a package of nutrient mitigation measures to inform Ramsar Convention administrators of the alternatives to address nutrient pollution problems in protected, peri-urban wetlands.

CRediT authorship contribution statement

Gloria Soto-Montes-de-Oca: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Gustavo M. Cruz-Bello:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abigail Martínez-Mendoza:** Writing – review & editing, Investigation, Conceptualization, Validation. **Kevin M. Hiscock:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Data curation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124042.

Data availability

Data will be made available on request.

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