

## Article

# Evaluation of the Phytoremediation Capacity of a Natural Wetland Adjacent to Fluvial and Vehicular Infrastructure for Domestic Wastewater Treatment: A Case Study in Central Mexico

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**Abstract:** Untreated domestic wastewater discharged into rivers and streams severely deteriorates water quality and aquatic ecosystems, especially in regions lacking adequate treatment infrastructure. This study aimed to evaluate the effectiveness of phytoremediation of domestic wastewater by the Sector Popular natural wetland (Mexico), located adjacent to fluvial and crossing structures. The evaluation was conducted by comparing contamination levels in the influent and effluent water, based on Mexican Official Standards (NOM-001-SEMARNAT-1996, NOM-003-SEMARNAT-1997, and NOM-001-SEMARNAT-2021), as well as several water quality indicators for irrigation. The wetland reduced concentrations of five-day biochemical oxygen demand by 98%, chemical oxygen demand by 95%, total suspended solids by 96%, total nitrogen by 92%, total phosphorus by 67%, and fecal coliforms by 96%. However, the treated water did not meet reuse standards for public services due to elevated salinity and residual presence of fecal microorganisms. These findings confirm that natural wetlands can significantly improve the quality of domestic wastewater and help mitigate environmental degradation in rivers. This approach represents a feasible and complementary strategy for wastewater treatment in regions with similar hydrological and infrastructure conditions.

**Keywords:** river pollution; *Typha domingensis*; unconventional treatment methods; water management; salinity



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## 1. Introduction

A serious global issue currently exists due to the discharge of untreated wastewater into various surface and groundwater bodies. The treatment processes required to recover these waters to acceptable quality standards are either non-existent or inadequate [1]. In Mexico, an estimated 280 m<sup>3</sup>/s of wastewater is generated, with approximately 215 m<sup>3</sup>/s being collected. However, only 67% of this collected flow undergoes treatment [2]. The remaining untreated wastewater is discharged into different water bodies, such as rivers,

lakes, and aquifers [3]. This problem is largely due to insufficient and inadequate infrastructure, high acquisition and operational costs, and a lack of maintenance and trained personnel for proper operation and upkeep of treatment systems [4].

Rivers represent one of the most complex and vital aquatic systems on Earth, playing a crucial role in the circulation and transport of water while also providing a range of essential ecological functions [5,6]. The contamination of rivers and water bodies resulting from wastewater discharges is a widespread issue in Mexico and has intensified with industrial development and population growth. While complex potable water and drainage systems integrated with wastewater treatment facilities exist near major urban centers, the situation is quite different in rural municipalities and villages adjacent to these cities [7].

This is the case of towns located over the Texcoco aquifer, where most wastewater and stormwater are discharged directly into river channels that are part of the natural drainage network of micro-watersheds encompassing several communities. This results in a high level of contamination in surface water bodies, and possibly also in groundwater [8–10].

In river channels where wastewater is discharged, small ecosystems naturally emerge as a response to anthropogenic degradation. These ecosystems are primarily composed of endemic macrophytes that are tolerant to high concentrations of pollutants and can be classified as natural wetlands [11]. Such wetlands typically form in river channels with wastewater discharges due to elevated nutrient concentrations in the water, which are temporarily retained by fluvial and crossing structures such as bridges and culverts. These conditions alter the dynamics and morphology of the river channel, promoting the establishment of vegetation [6,12].

A representative example is the natural wetland known as Sector Popular, located in a section of the San Bernardino River in the municipality of Texcoco, State of Mexico. This wetland is situated immediately upstream of a road bridge that connects the Sector Popular and San Mateo Huexotla neighborhoods. The bridge acts as a dike, restricting the flow and raising the water level of the domestic wastewater discharged into the river. Only a small volume of wastewater flows through the drains located at the bottom of the bridge.

The Sector Popular natural wetland is mainly composed of the species *Typha domingensis*, commonly known as the “tule” plant, which is among the most widely used species in the phytoremediation of wastewater [13]. *Typha domingensis* is a dominant macrophyte that inhibits the establishment of other species. It is also one of the most widely distributed aquatic plants, capable of thriving under diverse environmental conditions and highly tolerant to factors such as temperature, salinity, and elevated pollutant concentrations [14].

The use of natural wetlands was a common practice among ancient civilizations worldwide, and they often discharged wastewater into areas adjacent to lakes and rivers. Although their main purpose was disposal rather than treatment, the natural purifying capacity of these wetlands helped reduce pollution levels before the wastewater reached the watercourses [15].

Several studies worldwide show that natural wetlands play a crucial role in improving water quality by reducing pollutants from agricultural runoff, residential discharges, and other sources. These ecosystems can effectively retain sediment, nutrients, and microbial contaminants through processes such as sedimentation, nutrient transformation, and uptake by plants and microorganisms [16,17]. Studies have also demonstrated significant reductions in suspended sediment, nitrate, and *Escherichia coli* loads of up to 77%, 60%, and 68%, respectively [16]. However, the effectiveness of wetlands in improving water quality can vary depending on factors such as land use, wetland morphology, and vegetation characteristics [18].

Although wetlands can be highly effective in the short term, their long-term capacity may decline, potentially leading to the release of stored pollutants [17]. Maintaining natural

wetlands and regulating inflow rates are critical strategies for improving water quality in agricultural watersheds [16,19].

Numerous studies and publications worldwide have aimed to harness and replicate the high purification potential of natural wetlands under controlled conditions, leading to the development of artificial wetland systems [3,20]. These artificial wetlands are classified as non-conventional or extensive treatment systems. They mimic natural purification processes carried out by vegetation, soil, and microorganisms. Such systems consume less energy and are generally less expensive and complex than conventional or intensive treatment systems, while maintaining effective wastewater treatment performance [4,15,21]. They have shown promising results in experimental applications [22–24], and their effectiveness depends on both the design and the type of hydraulic infrastructure used [25].

Ideally, wastewater should not be discharged into river channels without prior treatment, in order to avoid contamination of receiving water bodies, preserve the quality of surface and groundwater, protect public health, and maintain ecosystem integrity, among other benefits [26]. In practice, however, the situation is quite different. Natural wetlands adjacent to fluvial infrastructure are commonly found in many communities and municipalities across Mexico, where untreated wastewater is directly discharged into river channels; this situation is not expected to change in the short or medium term.

This problem becomes even more complex due to river alterations caused by inadequate design, construction, and operation of fluvial and road crossing structures, which often interfere with natural vegetation and riverine processes [6]. One example is the implementation of unnecessary and environmentally harmful “channel cleaning” interventions, which represent a cyclical and unsustainable use of public resources over time [5,27]. Furthermore, the absence of integrated river management with a multidisciplinary approach—driven by a lack of information and applied research on the topic—adds to the problem [28].

Therefore, the objective of this study was to evaluate the effectiveness of phytoremediation of domestic wastewater by the Sector Popular natural wetland, which is adjacent to fluvial infrastructure, in order to provide a reference for wetlands with similar characteristics and contribute to the improvement of the design and management of fluvial and road crossing structures. The evaluation was carried out based on the current Mexican environmental regulations concerning water quality. This research was conducted under the hypothesis that natural wetlands, if properly integrated and managed alongside fluvial infrastructure, can serve as a viable solution for treating polluted water and mitigating environmental degradation in river systems.

## 2. Materials and Methods

### 2.1. Study Site

The Sector Popular natural wetland (Figure 1) is located along a section of the San Bernardino River channel in the municipality of Texcoco, State of Mexico, at coordinates 19°28′41″ N, 98°52′43″ W, and an elevation of 2269 m.a.s.l. The wetland receives direct wastewater discharges throughout the year from the Sector Popular and San Luis Huexotla neighborhoods. During the dry season, the river carries only wastewater [29], whereas in the rainy season (May through September) [30], it also receives surface runoff originating upstream of the catchment area of the micro-watershed named after the river.



**Figure 1.** Photograph of the Sector Popular natural wetland (August 2018).

The Sector Popular wetland runs parallel to the river channel, but the flow directions are opposite (Figure 2). Three key reference points are identified at the site: a road bridge (Point A), the point of wastewater discharge (Point B), and the downstream end of the wetland (Point C). The section between Points A and B—which spans approximately 30 m—represents the inflow (Influent), while Point C marks the outflow (Effluent) of the wetland. This segment was selected as the influent zone due to the site's topography and the limited access to the discharge outlet, which made it impossible to collect samples directly at that point. Additionally, this area exhibited the highest concentration of contaminants during field observations and showed consistent physical characteristics in the wastewater. The flow within the wetland moves in the opposite direction to that of the river due to the backwater effect generated upstream by the road bridge.

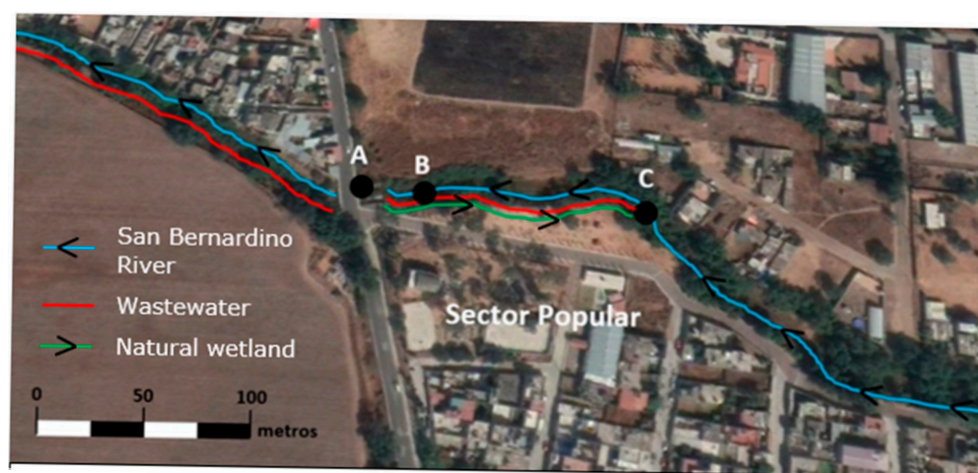


**Figure 2.** Satellite image of the Sector Popular natural wetland (January 2020). Base map: Google Earth. Image prepared by the authors.

## 2.2. Sampling and Laboratory Analysis

The influent and effluent flows were monitored over three consecutive days (Monday to Wednesday) at various time intervals in July and early August. The highest flow rates were found to occur between 7:00 and 9:00 and 20:00 and 22:00; therefore, sampling was conducted at 8:00 a.m. on 20 August 2018, in accordance with Mexican Standard NMX-AA-003 [31]. This decision was based on the observation that higher flow rates at the study

site coincided with increased concentrations of contaminants in the wastewater, with the most critical period occurring between 7:00 and 9:00 a.m. There was no rainfall at the study site for two days prior to sampling and for four days afterward. This sampling schedule aimed to evaluate the effect of the natural wetland on wastewater treatment during the high-flow season. If the treatment results were found to be unsatisfactory during this period, monitoring during the dry season—when conditions are more unfavorable due to higher pollutant concentrations—would not be considered meaningful.

A total of 80 subsamples of 250 mL were collected from the influent and effluent, forming two composite samples of approximately 10 L each. Aliquots from these composite samples were used for laboratory analysis of selected pollutants.

In the field, pH, electrical conductivity (EC), floating solids, and temperature (average of three-point readings) were measured according to Mexican Standards NMX-AA-006, 007, 008, and 093 [31]. The following parameters were analyzed in the laboratory: settleable solids (SSs), total nitrogen (TN), total phosphorus (TP), biochemical oxygen demand (BOD<sub>5</sub>), chemical oxygen demand (COD), total solids (TSs), total suspended solids (TSSs), total coliforms (TCOs), and fecal coliforms (FCOs), as specified by Mexican Standards NMX-AA-004, 026, 028, 029, 030, 034, and 042 [31].

Total and fecal coliform bacteria, expressed as the most probable number (MPN) per 100 mL, were determined by serial dilution of the samples and inoculation in lauryl tryptose broth at four dilution levels (1:10, 1:100, 1:1000, and 1:10,000), using three tubes per dilution. Bromocresol green dye and Durham tubes were used as indicators. Tubes showing positive reactions were confirmed for fecal coliforms by inoculation in brilliant green lactose bile broth, following the method established in Mexican Standard NMX-AA-042.

An irrigation water quality analysis—focusing on salinity and sodicity—was conducted in response to the interest of residents in the Sector Popular neighborhood in using the wetland's effluent to irrigate recreational green areas. The effluent water did not show unpleasant odor or color, and its appearance suggested potential suitability for irrigation. The Mexican Official Standards addressing the use of wastewater do not include specific water quality parameters for irrigation [32,33], despite the fact that a considerable portion of wastewater in Mexico is used for irrigating agricultural fields and urban green areas [34]. The omission of key parameters—such as soluble salt and sodium content—represents a potential medium- and long-term risk in areas where wastewater is used for irrigation purposes [35].

The irrigation water quality analysis consisted of chemical evaluation, based on several water quality indicators [36] derived from the concentrations of calcium (Ca<sup>2+</sup>), sodium (Na<sup>+</sup>), magnesium (Mg<sup>2+</sup>), potassium (K<sup>+</sup>), carbonate (CO<sub>3</sub><sup>2−</sup>), bicarbonate (HCO<sub>3</sub><sup>−</sup>), chloride (Cl<sup>−</sup>), and sulfate (SO<sub>4</sub><sup>2−</sup>), following the methodology described by Colasurdo et al. [37]. The accuracy of the analytical results was verified using the following control methods: anion–cation balance, measured EC ≈ calculated EC, and measured EC ≈ sum of anions [38].

All analyses were conducted in duplicate at a Mexican laboratory certified in physical, chemical, and biological water testing.

### 2.3. Irrigation Water Quality Indicators

Based on the recommendations of Puñales and Aguilar [36], the irrigation water quality of both influent and effluent samples was evaluated using the following indicators: electrical conductivity (EC), sodium adsorption ratio (SAR), residual sodium carbonate

(RSC), permeability index (PI), potential salinity (PS), and effective salinity (ES). These indicators were calculated using the following equations [39]:

$$\text{SAR} = \frac{\text{Na}^+}{\left(\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}\right)^{\frac{1}{2}}} \quad (1)$$

$$\text{RSC} = \left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right) - \left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) \quad (2)$$

$$\text{PI} = \frac{\left(\text{Na}^+ + \left(\text{HCO}_3^{-}\right)^{\frac{1}{2}}\right)}{\left(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+\right)} * 100 \quad (3)$$

$$\text{PS} = \text{Cl}^{-} + \frac{1}{2}\left(\text{SO}_4^{2-}\right) \quad (4)$$

There are four options for ES, depending on the case:

$$\text{(A) ES} = \left(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+\right) - \left(\text{CO}_3^{2-} + \text{HCO}_3^{-} + \text{SO}_4^{2-}\right) \quad (5)$$

$$\text{If } \text{Ca}^{2+} > \left(\text{CO}_3^{2-} + \text{HCO}_3^{-} + \text{SO}_4^{2-}\right)$$

$$\text{(B) ES} = \left(\text{Mg}^{2+} + \text{Na}^+ + \text{K}^+\right) \quad (6)$$

$$\text{If } \text{Ca}^{2+} < \left(\text{CO}_3^{2-} + \text{HCO}_3^{-} + \text{SO}_4^{2-}\right)$$

$$\text{and } \text{Ca}^{2+} > \left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right)$$

$$\text{(C) ES} = \left(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+\right) - \left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right) \quad (7)$$

$$\text{If } \text{Ca}^{2+} < \left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right)$$

$$\text{and } \left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) > \left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right)$$

$$\text{(D) ES} = \left(\text{Na}^+ + \text{K}^+\right) \quad (8)$$

$$\text{If } \left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) < \left(\text{CO}_3^{2-} + \text{HCO}_3^{-}\right)$$

where  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^{-}$ ,  $\text{Cl}^{-}$ , and  $\text{SO}_4^{2-}$  represent the concentrations of calcium, sodium, magnesium, potassium, carbonate, bicarbonate, chloride, and sulfate ions, respectively, expressed in  $\text{meq L}^{-1}$ .

## 2.4. Analysis and Classification

Water quality classification was based on the Maximum Permissible Limits (MPLs) established by the Mexican Official Standards NOM-001-SEMARNAT-1996 [40], NOM-001-SEMARNAT-2021 [41], and NOM-003-SEMARNAT-1997 [42].

- The 1996 standard defines MPLs for pollutants in wastewater discharged into national waters and public properties.
- The 2021 standard defines MPLs for discharges into receiving water bodies owned by the nation.
- The 1997 standard specifies MPLs for treated wastewater intended for public (non-potable) reuse.

The MPL values used correspond to the following categories: Rivers—Urban Public Use (NOM-001-SEMARNAT-1996), Rivers, Streams, Canals, and Drains (NOM-001-SEMARNAT-2021), and Public Services with Direct Contact (NOM-003-SEMARNAT-1997).

The average value of each parameter was used for classification. Criteria proposed by various authors were also considered for irrigation water classification (Table A1 in Appendix A).

Although NOM-001-SEMARNAT-2021 replaced NOM-001-SEMARNAT-1996, both standards were applied in this study. The current version imposes stricter MPLs for certain parameters but omits others, such as fecal coliforms, that were included in the previous version and are crucial due to their potential impact on human health.

Based on the water quality results for the wetland effluent, a general proposal was developed for the design and management of natural wetlands with similar characteristics.

### 3. Results and Discussion

#### 3.1. Removal of Physical, Chemical, and Biological Contaminants Based on Mexican Official Standards

Table 1 shows that the effluent water is completely different from the influent water. The water treated by the Sector Popular natural wetland complies with the maximum permissible limits (MPLs) established by the Mexican Official Standards NOM-001-SEMARNAT-1996 and NOM-001-SEMARNAT-2021, while the influent water, with the exception of pH, does not meet the minimum requirements. This demonstrates the phytoremediation capacity of the Sector Popular natural wetland and confirms that NOM-001-SEMARNAT-2021 is stricter in its MPLs compared with the previous regulation.

**Table 1.** Average values of water quality parameters in influent and effluent water samples from the natural wetland, and the MPLs of the Mexican Official Standards.

| Parameter         | Unit                  | Influent   | Effluent  | NOM-001 (1996) | NOM-001 (2021) | NOM-003 (1997) |
|-------------------|-----------------------|------------|-----------|----------------|----------------|----------------|
| pH                |                       | 8.08       | 7.69      | 5.00–10.00     | 6.00–9.00      | N.A.           |
| EC                | $\mu\text{S cm}^{-1}$ | 1727.00    | 1280.00   | N.A.           | N.A.           | N.A.           |
| Floating Matter   |                       | Present    | Absent    | Absent         | N.A.           | Absent         |
| Settleable Solids | $\text{mL L}^{-1}$    | 15.00      | 0.30      | 2.00           | N.A.           | N.A.           |
| Total Nitrogen    | $\text{mg L}^{-1}$    | 241.30     | 19.40     | 60.00          | 30.00          | N.A.           |
| Total Phosphorus  | $\text{mg L}^{-1}$    | 19.90      | 6.48      | 30.00          | 18.00          | N.A.           |
| BOD <sub>5</sub>  | $\text{mg L}^{-1}$    | 881.45     | 18.23     | 150.00         | N.A.           | 20.00          |
| COD               | $\text{mg L}^{-1}$    | 2745.05    | 130.13    | N.A.           | 180.00         | N.A.           |
| Total Solids      | $\text{mg L}^{-1}$    | 1650.00    | 848.60    | N.A.           | N.A.           | N.A.           |
| TSSs              | $\text{mg L}^{-1}$    | 442.00     | 19.65     | 125.00         | 72.00          | 20.00          |
| Total Coliforms   | MPN/100 mL            | 122,480.00 | 29,543.00 | N.A.           | N.A.           | N.A.           |
| Fecal Coliforms   | MPN/100 mL            | 9370.00    | 360.00    | 2000.00        | N.A.           | 240.00         |

Notes: pH = hydrogen potential; EC = electrical conductivity; BOD<sub>5</sub> = biochemical oxygen demand over 5 days; COD = chemical oxygen demand; TSSs = total suspended solids; MPN = most probable number; N.A. = not applicable.

According to NOM-003-SEMARNAT-1997, the effluent water is not recommended for reuse in public services without additional purification and disinfection treatment, as it exceeds the MPL for fecal coliforms, although its concentration was considerably reduced compared with the influent. It is also important to highlight that BOD<sub>5</sub> and TSS values in the effluent were slightly below the MPLs, whereas the influent values were significantly higher.

Contaminant removal from domestic wastewater is attributed to the simultaneous and complex physical, chemical, and biological processes that occur in natural wetlands [43,44],

including sedimentation, filtration, plant and microbial assimilation, volatilization, precipitation, microbial degradation, and predation [15,45]. Additionally, a hydraulic factor contributes to treatment effectiveness since the direction of water flow in the Sector Popular wetland is opposite to the river's slope, favoring physical purification mechanisms.

Regarding total nitrogen and total phosphorus, effluent water complied with the MPLs of both the former and current regulations, while the influent failed to meet the current standards. The wetland demonstrated higher removal efficiency for nitrogen than for phosphorus, similar to what was reported by Vera et al. [46]. The percentage of phosphorus removed was also comparable to that obtained by Villanueva and López [47] when treating domestic wastewater using *Typha* species in July in Mexico.

Nitrogen removal mechanisms depend on the chemical form of the element—organic nitrogen, ammoniacal nitrogen, or oxidized nitrogen. Most nitrogen is eliminated by microbial activity through nitrification–denitrification [48]. Other processes include volatilization, adsorption, anaerobic ammonium oxidation (anammox), mineralization of organic nitrogen, and plant assimilation [43].

Phosphorus is removed through both biotic and abiotic processes. Biotic mechanisms include plant and microbial assimilation, while abiotic mechanisms involve soil adsorption, precipitation, filtration, and sedimentation [49]. The majority of phosphorus is removed by adsorption, a complex process due to the low mobility of phosphorus-containing compounds [43].

Regarding parameters associated with organic matter—BOD<sub>5</sub>, COD, and TSS—the effluent met the MPLs. Results were consistent with previous studies in both natural and constructed wetlands. COD levels were similar to those found by Romero-Aguilar et al. [4] in a pilot system using *Typha dominguensis* and *Phragmites australis*. BOD<sub>5</sub> values aligned with those reported by Morales et al. [43] for surface wetlands, and TSS values were comparable to those reported by Vera et al. [46] in a constructed wetland with *Typha dominguensis*.

Dissolved organic matter is degraded via aerobic and anaerobic pathways. Aerobic degradation occurs via aerobic heterotrophic bacteria, particularly near plant roots, where oxygen is supplied by plants. Anaerobic degradation involves facultative fermentative bacteria, which produce substrates that are subsequently broken down by sulfate-reducing and methanogenic microorganisms [43,44]. Plant uptake of organic matter is minimal compared with microbial degradation [4].

Suspended solids are removed primarily through physical processes, such as filtration by plant roots and rhizomes, sedimentation of particulate matter, and flocculation via particle aggregation, enhanced by low water flow velocity in the wetland [44].

For fecal coliforms, the effluent complies with NOM-001-SEMARNAT-1996 but not with NOM-003-SEMARNAT-1997. The fecal coliform count in the influent was lower than that reported by Rivera-Vázquez et al. [29] in the San Bernardino River, likely because their study was conducted during the dry season, while this one was conducted in August, during the rainy season. Protozoan concentrations also tend to increase in summer (June 21 to September 22 in the Northern Hemisphere) due to higher temperatures [44].

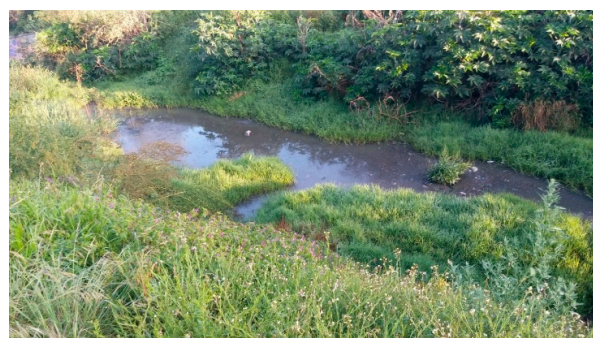
Valdez and Vázquez [50] indicated that during the self-purification process in rivers, pathogenic organisms decrease due to unfavorable environmental conditions and predation by bacteriophages and protozoa. However, some pathogens may persist in clear water zones. Therefore, once contaminated, water is not safe for reuse unless it undergoes proper treatment, similar to what was observed in the effluent from the Sector Popular wetland. Pathogen removal mechanisms in wetlands include exposure to biocides secreted by macrophyte roots, adsorption, natural die-off, predation, sedimentation due to flow reduction, and competition for nutrients [44].

The Sector Popular wetland contains the four zones of contamination and recovery defined by Valdez and Vázquez [50]:

- Degradation zone—Located between the vehicular bridge and the wastewater discharge point (Figure 3a). This zone is established immediately downstream of the discharge outlet. The water is dark and turbid, anaerobic decomposition processes dominate, and a progressive reduction in dissolved oxygen is observed.
- Active decomposition zone—Extending from the discharge point to approximately one-third of the remaining distance to the wetland’s outlet (Figure 3b). This section exhibits severe contamination, characterized by the absence of dissolved oxygen and intense anaerobic decomposition. As a result, gas bubbles emerge, forming black foam on the surface. The water appears gray to black and emits a strong fetid odor.
- Recovery zone—Found between the end of the active decomposition zone and near the end of the wetland (Figure 3c), where larger patches of *Typha dominguensis* are present. A large portion of the organic matter settles in the previous two zones, which allows for an increase in dissolved oxygen in this area. The water appears lighter in color, aerobic decomposition becomes predominant, and aquatic macrophytes begin to play a more active role in the purification process.
- Clear water zone—Located at the terminal section of the wetland (Figure 3d). Here, the water regains characteristics similar to natural water bodies. It appears clear, has no foul odor, and presents favorable conditions due to the combined effects of previous purification processes.



(a)



(b)



(c)



(d)

**Figure 3.** Photographs of four zones of the Sector Popular natural wetland (August 2018): (a) the degradation zone, (b) the active decomposition zone, (c) the recovery zone, and (d) the clear water zone.

### 3.2. Removal of Soluble Salts with Reference to Water Quality Indicators for Irrigation

Effluent water had lower concentrations of all analyzed ions and water quality indicators associated with salinity risk (EC, PS, and ES) compared with influent water. However,

indicators associated with sodicity risk (SAR, RSC, and PI) were slightly higher in the effluent (Table 2). This can be attributed to the lower sodium removal efficiency of the wetland, which is expected due to the high solubility of sodium and the low uptake capacity of this element by certain aquatic macrophytes [51].

**Table 2.** Average concentrations of ions and irrigation water quality indicators in influent and effluent samples from the natural wetland.

| Parameter                          | Unit                  | Influent | Effluent |
|------------------------------------|-----------------------|----------|----------|
| Calcium ( $\text{Ca}^{2+}$ )       | $\text{me L}^{-1}$    | 9.90     | 6.80     |
| Magnesium ( $\text{Mg}^{2+}$ )     | $\text{me L}^{-1}$    | 2.10     | 1.60     |
| Sodium ( $\text{Na}^{+}$ )         | $\text{me L}^{-1}$    | 3.50     | 3.16     |
| Potassium ( $\text{K}^{+}$ )       | $\text{me L}^{-1}$    | 2.00     | 0.82     |
| Carbonate ( $\text{CO}_3^{2-}$ )   | $\text{me L}^{-1}$    | 0.00     | 0.00     |
| Bicarbonate ( $\text{HCO}_3^{-}$ ) | $\text{me L}^{-1}$    | 14.40    | 11.00    |
| Chlorite ( $\text{Cl}^{-}$ )       | $\text{me L}^{-1}$    | 2.50     | 1.50     |
| Sulfate ( $\text{SO}_4^{2-}$ )     | $\text{me L}^{-1}$    | 1.30     | 0.60     |
| EC                                 | $\mu\text{S cm}^{-1}$ | 1727.00  | 1280.00  |
| PS                                 |                       | 3.15     | 1.80     |
| ES                                 |                       | 5.50     | 3.98     |
| SAR                                |                       | 1.43     | 1.54     |
| RSC                                |                       | 2.40     | 2.60     |
| PI                                 |                       | 47.06    | 56.03    |

Notes: EC = electrical conductivity; PS = potential salinity; ES = effective salinity; SAR = sodium adsorption ratio; RSC = residual sodium carbonate; PI = permeability index.

The results in Table 2, in conjunction with the quality criteria in Table A1 (Appendix A), indicate that both influent and effluent water are only conditionally suitable for irrigation due to salinity and sodicity risks. Similar results were obtained by Bautista et al. [32] when analyzing treated wastewater discharged into a section of the Cantarranas River in Puebla, Mexico. They observed reductions in ion concentrations attributed to physical, chemical, and biological purification mechanisms, along with nutrient uptake by aquatic plants. However, these reductions were not sufficient to classify the treated water as fully acceptable for irrigation based on EC, PS, ES, SAR, and RSC.

Salt removal through phytoremediation in the Sector Popular wetland is noticeable, but remains limited when compared with conventional methods such as reverse osmosis, electrodialysis, nanofiltration, multi-stage distillation, and solar distillation [52]. Salinity is a key design factor in constructed wetlands [24]. This highlights the importance of selecting salt-tolerant plant species for effective wastewater treatment—Typha, for example, has demonstrated notable resistance to saline conditions [14].

Based on the study results, residents and local authorities of the Sector Popular neighborhood were informed that the effluent is not recommended for irrigating green areas unless it undergoes additional treatment for purification and disinfection, along with further management to mitigate salinity and sodicity risks. It was also clarified that the objective of this research was to assess the phytoremediation potential of the Sector Popular natural wetland, not to issue a recommendation on the reuse of treated wastewater. A broader and longer-term study, with the involvement and validation of competent government agencies, would be necessary for that purpose.

### 3.3. Phytoremediation Proposal in Natural Wetlands

Currently, most rivers in Mexico have significant anthropogenic contamination, posing major challenges for achieving sustainable wastewater management. Addressing these challenges requires integrated solutions that encompass social, environmental, technolog-

ical, economic, legal, and political dimensions [53]. This issue is not unique to Mexico; it is similar in many other countries, particularly in developing nations [54–56]. Thus, it is urgent to implement new, responsible policies to ensure proper wastewater management [8,53,55], while also promoting short- and medium-term alternatives that are easy to implement and can help mitigate environmental damage in rivers as long-term strategies are developed and enacted.

Phytoremediation in natural wetlands is characterized by a complex interaction of physical, chemical, and biological processes occurring simultaneously. For this reason, it is not recommended to deliberately use natural wetlands for large-scale wastewater treatment [24,57], as their conditions are difficult to stabilize and predict. However, natural wetlands adjacent to fluvial and vehicular crossing infrastructures could be considered a viable option for mitigating environmental damage in rivers receiving domestic wastewater discharges.

This proposal arises from the results obtained in the Sector Popular natural wetland, where the phytoremediation capacity of natural wetlands adjacent to fluvial and crossing structures is evident. Even better results could be achieved with proper management and optimization of the wetland and the associated fluvial and vehicular crossing infrastructure; additionally, secondary benefits such as resource savings and landscape enhancement could be realized [5].

Numerous studies and authors support the initiative to move away from traditional, unidisciplinary approaches to river and infrastructure management. Notable examples include Conesa-García and Pérez-Cutillas [12], Fazeli-Tello and Moral-Ituarte [5], García et al. [28] (2021), Pérez et al. [6], Ojeda et al. [58], and Salinas-Díaz [59]. Traditional management tends to suppress the natural morphology and dynamics of rivers, often resulting in negative outcomes in many respects.

It is important to note that applying a multidisciplinary approach to the management of wastewater, rivers, and fluvial and vehicular crossing infrastructures involves greater methodological complexity [57]. However, the benefits obtained would justify the additional effort, helping to avoid complications that, in the long term, may lead to more work and unnecessary resource expenditure.

One example is highlighted by Ollero-Ojeda [27] and Salinas-Díaz [59], who discuss traditional vegetation management in riverbeds, where cleaning and dredging activities indiscriminately remove sediments and vegetation instead of targeting anthropogenic waste, which should be the primary focus. Such interventions significantly alter natural river processes, promote erosion and sediment transport, and are costly, environmentally harmful, and often counterproductive over time.

Figure 4 illustrates sediment and debris deposition on the vehicular bridge located downstream and adjacent to the Sector Popular natural wetland following a rainfall event. A few weeks before the photo was taken, cleaning and dredging works had been conducted in the upstream section of the river channel. These actions contributed to erosion and sediment transport, eventually causing blockage of the bridge drains with sediment, anthropogenic waste, and dry plant remains from the cleanup. This supports the earlier assertion that traditional unidisciplinary management can generate new problems due to the lack of consideration for the full consequences of the interventions, which then require additional corrective efforts.



**Figure 4.** Photograph of sediment and material deposition on the vehicular bridge located downstream of the Sector Popular natural wetland as a consequence of traditional management (March 2023).

Proper management of wastewater, fluvial infrastructure, and natural wetlands requires consideration of multiple aspects and factors. Those responsible for such projects must adopt a multidisciplinary perspective or seek support from experts in different fields, integrating social, environmental, technological, economic, legal, and political aspects in a comprehensive manner. Furthermore, the limitations and potential of each site and situation must be considered [57]. These complexities make it difficult to formulate a broad, universal recommendation applicable to all cases involving natural wetlands adjacent to fluvial and vehicular crossing structures.

Therefore, it is crucial to expand and deepen research on natural wetlands located adjacent to fluvial and crossing structures where wastewater is discharged. Following the recommendations of Cristóbal-Muñoz et al. [60], it is essential to isolate factors that cause disturbances to the real conditions of the systems or phenomena under study. When dealing with research that involves multiple, complex, and simultaneous processes, it is vital to obtain results that are representative of real-world conditions and to report methodological details accurately.

Finally, in the case of existing fluvial works with design and operational issues, it is advisable to adjust the design and incorporate complementary hydraulic structures, taking the natural hydromorphological system as a reference, as recommended by García et al. [28]. Similarly, wherever feasible, river systems should be restored to their natural state [27]. For new fluvial projects, design should recognize and respect the natural processes of rivers and their vegetation. If the situation allows, these natural processes should be harnessed, because continuing with the traditional approach of trying to control—or even combat—natural dynamics will inevitably lead to failure in the medium or long term.

All of this must be done with consideration for the limitations and specific context of each site and case. It is common to manage and design fluvial infrastructure based on experiences from other locations with similar environmental and technological conditions, while overlooking the social, economic, and political differences that can jeopardize the success of a project due to such omissions.

#### 4. Conclusions

Based on the case study of the Sector Popular natural wetland located in central Mexico, this research confirms the potential of natural wetlands adjacent to fluvial and vehicular infrastructure as a complementary strategy for the phytoremediation of domestic wastewater. The evaluated wetland demonstrated effective capacity to reduce physical,

chemical, and biological contaminants, supporting its role in mitigating environmental degradation in river systems impacted by wastewater discharges.

To optimize the performance, replicability, and long-term sustainability of these systems, it is essential to promote planning and management with a multidisciplinary approach. This approach should integrate natural hydrological and ecological processes with social, technical, environmental, economic, legal, and political dimensions. Moreover, it must be tailored to the specific conditions of each site and, whenever possible, aligned with efforts aimed at preserving or restoring the natural dynamics of fluvial ecosystems.

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## Appendix A

**Table A1.** Classification of irrigation water quality by various authors.

| Quality Index | Reference            | Ranges                         | Interpretation                      |
|---------------|----------------------|--------------------------------|-------------------------------------|
| EC            | Richards (1954) [61] | C1: $EC < 250 \mu S/cm$        | Low-salinity water                  |
|               |                      | C2: $250 < EC < 750 \mu S/cm$  | Medium-salinity water               |
|               |                      | C3: $750 < EC < 2250 \mu S/cm$ | High-salinity water                 |
|               |                      | C4: $2250 \mu S/cm < EC$       | Very-high-salinity water            |
| SAR           | Richards (1954) [61] | S1: $SAR < 10$                 | Low-sodium water                    |
|               |                      | S2: $10 < SAR < 18$            | Water with medium sodium content    |
|               |                      | S3: $18 < SAR < 26$            | Water with high sodium content      |
|               |                      | S4: $26 < SAR$                 | Water with very high sodium content |

Table A1. Cont.

| Quality Index | Reference                       | Ranges                                                   | Interpretation                    |
|---------------|---------------------------------|----------------------------------------------------------|-----------------------------------|
| RSC           | Wilcox et al. (1954) [62]       | RSC < 1.25                                               | Acceptable water for irrigation   |
|               |                                 | 1.25 < RSC < 2.50                                        | Conditioned water for irrigation  |
|               |                                 | 2.50 < RSC                                               | Unacceptable water for irrigation |
| PI            | Doneen (1964) [63]              | Class I: 100% of maximum permeability (Doneen diagram).  | Excellent water for irrigation    |
|               |                                 | Class II: 75% of maximum permeability (Doneen diagram).  | Good water for irrigation         |
|               |                                 | Class III: 25% of maximum permeability (Doneen diagram). | Unacceptable water for irrigation |
| PS            | Palacios and Aceves (1970) [64] | PS < 3                                                   | Acceptable water for irrigation   |
|               |                                 | 3 < PS < 15                                              | Conditioned water for irrigation  |
|               |                                 | 15 < PS                                                  | Unacceptable water for irrigation |
| ES            | Palacios and Aceves (1970) [64] | ES < 3                                                   | Acceptable water for irrigation   |
|               |                                 | 3 < ES < 15                                              | Conditioned water for irrigation  |
|               |                                 | 15 < ES                                                  | Unacceptable water for irrigation |

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