Colegio de Postgraduados

Impact of Point Sources on the Water Quality of the Camalote River, Oaxaca, Mexico

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ABSTRACT
Objective: This study assesses the water quality of domestic wastewater discharges into the Camalote River, Oaxaca, Mexico, and evaluates their environmental impact. The findings aim to support the development of preventive and mitigation measures to benefit both the environment and the communities relying on this resource.
Design/methodology/approach: Seven domestic wastewater discharges into the river were analyzed following the methodology outlined in NOM-001-ECOL-1996 for water sample collection and analysis.
Results: The analysis shows that the discharges exceed the maximum permissible limits established by NOM-001-SEMARNAT-2021, particularly for total suspended solids (256.67 mg L^{-1}) and biochemical oxygen demand (392.22 mg L^{-1}) in discharge 4, as well as total coliforms (27,333,333.33 NMP 100 mL^{-1}) and fecal coliforms (10,000,000.00 NMP/100 mL) in discharge 6.
Limitations/implications: The findings indicate significant risks to public health and aquatic ecosystems. Continuous monitoring of the river is strongly recommended, particularly during drought periods when the river's dilution capacity decreases, leading to higher pollutant and organic matter concentrations and anaerobic conditions that harm aquatic biodiversity.
Findings/conclusions: The study underscores the urgent need to implement preventive and mitigation strategies, including wastewater treatment and revegetation of key areas, to reduce pollution and safeguard water quality for the benefit of the environment and the local communities dependent on this vital resource.

Keywords: Discharges, pollution, water quality indicators, monitoring.

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INTRODUCTION

The integrity of water sources refers to maintaining their structure and functionality by preserving the natural balance of their physical, chemical, and biological conditions (Qadri *et al.*, 2020). Protecting and/or restoring these water bodies requires a thorough understanding of their quality (Kroll *et al.*, 2019). Spatial and temporal variations in surface water quality are influenced by both natural factors and human activities (Chen *et al.*, 2023). Analyzing how these relationships vary across time and space, along with identifying the sources of elements that alter water properties and their behavior in rivers,

is essential for implementing effective basin-level strategies for water quality conservation and management (Hamid *et al.*, 2020). Factors affecting water quality can be categorized into two types based on their origin: point sources, such as direct discharges of domestic wastewater, and non-point sources, which transport pollutants through runoff and surface drag, contaminating water bodies (Chakraborti, 2021). Rivers possess a natural self-purification capacity that plays a critical role in enhancing water quality (Darji *et al.*, 2022). In Mexico, official data on river water quality remain limited. Nonetheless, several studies have examined these water bodies and the associated contamination processes, aiming to identify major pollution sources and generate data to support the development of management and conservation strategies (Rodriguez-Nuñez *et al.*, 2022). These studies are vital for improving water resource management and protecting both the environment and the communities that depend on these resources (Casillas-García *et al.*, 2021). Due to the above, this research evaluates the quality of domestic wastewater discharges into the Camalote River, Oaxaca, Mexico, and assesses their environmental impact. The findings may inform relevant authorities in the development of preventive and mitigation measures to safeguard the environment and the communities reliant on this vital resource.

MATERIALS AND METHODS

The Camalote River is situated in the state of Oaxaca, within the municipality of Acatlán de Pérez Figueroa, between the coordinates 18° 32' 16.48"-18° 23' 48.78" N and 96° 33' 20.69"-96° 26' 43.28" W. It forms part of the Papaloapan Basin. The region receives an average annual precipitation of 1,786.6 mm, predominantly concentrated during the wet season, which occurs from June to September. The study area is characterized by two dominant vegetation types: tropical evergreen forest, which covers 18.41% of the region, and secondary shrub vegetation of the tropical evergreen forest, accounting for 10.04% of the total area. Land use in the region is primarily divided between urban zones and agricultural activities (INEGI, 2010).

Sampling and analysis of discharges into the Camalote river

Seven water discharges were identified and mapped with the assistance of municipal authorities in Acatlán de Pérez Figueroa, who provided insights into significant sites and nearby activities relevant to the study. These discharges are located between coordinates 759638.28 E, 2048191.42 N and 760404.58 E, 2047433.41 N, at elevations ranging from 105 to 107 meters above sea level (masl). A subsequent field survey along the river was conducted to confirm the identified sampling locations.

A composite sample was collected from each wastewater discharge, comprising four grab samples taken at three-hour intervals (Figure 1). Sampling was performed in compliance with the methodology established in NOM-001-ECOL-1996, the regulation for domestic wastewater discharges. The sampling campaign was conducted during both the rainy and dry seasons of 2017.

The samples were collected and stored in glass and high-density polyethylene containers, properly labeled, preserved at 2 °C, and transported to the laboratory for analysis. The

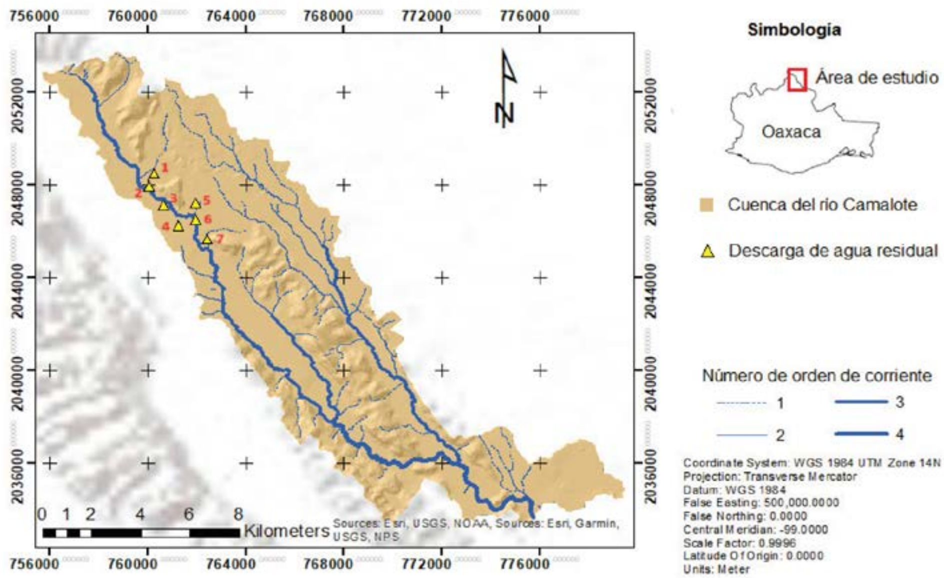

Figure 1. Camalote river basin and water discharges.

Table 1 outlines the physical, chemical, and biological parameters evaluated in the wastewater discharges, along with the corresponding analysis methods.

Data Analysis

A nested experimental design with two factors season (rainy and dry) and discharge sites as levels, each with three repetitions was employed for data analysis. Normality (Shapiro-

Table 1. Physical, chemical, and biological parameters evaluated in wastewater discharges.

Parameter	Method
1. Temperature (1)	Electrometric
2. pH (1)	Electrometric
3. Flow (1)*	Sampling port
4. Fats and oils (2) (A)	Soxhlet Extraction
5. Total suspended solids (3)	Quantitative measurement
6. 6. Sedimentable solids (2)	Imhoff
7. Biochemical oxygen demand (2)	Winkler
8. Total nitrogen (2)	Kjeldahl
9. Total phosphorus (2)	Spectrophotometric
10. Total coliforms (2) Fecal coliforms (2)	Most probable number in multiple tubes
11. Helminth eggs (2)	Microscopic observation
12. Copper, Nickel, Lead, Zinc, Cadmium, Chromium, Mercury (2)	Atomic absorption spectrophotometry

Note: (1) Data obtained in the field. (2) Data obtained in the Environmental Biotechnology Laboratory, DEIS in Soils, Universidad Autónoma Chapingo. (3) Data obtained in the laboratories of ABC Química, Investigación y Análisis, S. A. de C. V. (A) Sample adjusted in the field to pH<2 with 37% HCl.

Wilk) and homogeneity of variance (Levene) tests were performed. Upon satisfying these assumptions ($p>0.05$), an analysis of variance (ANOVA) and Tukey's mean comparison test ($p<0.05$) were conducted to identify significant differences between seasons (rainy and dry) and among discharges within each season. The statistical model used for the experimental design was as follows:

$$Y_{ijk}=\mu+p_i+P_{j(i)}+e_{ijk}$$

where: Y_{ijk}=response obtained from the determinations, μ=general mean, p_i=effect of the *i*-th season, $P_{j(i)}$=effect of the *j*-th discharge within the *i*-th season, e_{ijk}=random error associated with observation Y_{ijk}. The statistical analysis was carried out using InfoStat software, free version 2020 (Di Rienzo *et al.*, 2017).

RESULTS AND DISCUSSION

Water quality of the discharges into the Camalote river. Analysis of variance of the determinations conducted by period

The analysis of variance indicated that the variables P, As, and Cd did not show statistically significant differences between the rainy and dry seasons, nor among the discharges within each period. However, the other variables evaluated did show significant differences by period and by discharge within each period (Table 2), indicating sensitivity to temporal and spatial conditions. The observed variations suggest that water quality in the study area is influenced by rainfall and anthropogenic factors.

During the dry season, an increase in Biochemical Oxygen Demand (BOD_5), total suspended solids, and fats and oils was observed, reflecting an accumulation of pollutants due to the river's reduced dilution capacity. BOD_5 reached 239.32 mg L^{-1} during the dry season, nearly doubling the value recorded during the rainy season (119.55 mg L^{-1}). Total coliforms (6,823,238 MPN/100 mL) and fecal coliforms showed a considerable increase during the dry season, posing a higher risk to public health. Additionally, there was an increase in the presence of helminth eggs (1.48 eggs L^{-1}) and in the concentrations of heavy metals such as chromium, mercury, and lead, which were significantly higher during the dry season. These results suggest that drought conditions exacerbate pollution risks in the Camalote river, highlighting the need to consider both temporal and spatial factors when assessing water quality, as corroborated by previous studies like that of Taher *et al.* (2021).

Average daily flow, ph, settleable solids, total suspended solids, fats and oils

During the rainy season (Table 3), discharge six recorded the highest flow rate (20.56 L s^{-1}), making it the most significant source of water discharged into the river by volume. Discharge three showed the highest amount of settleable solids (2.02 mL L^{-1}), indicating an increased accumulation of material on the riverbed. Discharge four exhibited the highest total suspended solids concentration (256.67 mg L^{-1}), exceeding the daily maximum permissible limit (MPL) of 72 mg L^{-1} (NOM-001-SEMARNAT-2021) by 3.5 times. High turbidity levels, as noted by Kowe *et al.* (2023), can reduce light

Table 2. Analysis of variance of the determinations conducted in the discharges.

Parameter	P value		Period average	
	Period	Discharge	Rain	Dry
Average Daily Flow (L/s)	0.0001	0.0001	7.13 a	3.58 b
Average Daily Temperature (°C)	0.0001	0.0420	26.44 b	29.40 a
pH	0.0001	0.0001	7.48 a	7.18 b
Total Coliforms (MPN 100 mL^{-1})	0.0001	0.0001	3972523.81 b	6823238.10 a
Fecal Coliforms (MPN 100 mL^{-1})	0.0001	0.0001	3733952.38 a	3038142.86 b
Helminth Eggs (Eggs L^{-1})	0.0080	0.0001	1.14 b	1.48 a
Settleable Solids (mL L^{-1})	0.0001	0.0001	1.61 a	0.40 b
Total Suspended Solids (mg L^{-1})	0.0001	0.0001	159.33 a	86.14 b
Fats and Oils (mg L^{-1})	0.0001	0.0001	3.18 b	6.36 a
BOD_5 (mg L^{-1})	0.0001	0.0001	119.55 b	239.32 a
N total (mg L^{-1})	0.0001	0.0001	4.45 b	9.20 a
Fósforo (mg L^{-1})	0.2873	0.4652	1.00 a	1.00 a
As (mg L^{-1})	0.2921	0.2001	1.2E-03 a	1.3E-03 a
Cd (mg L^{-1})	0.3343	0.3476	0.00015 a	0.00015 a
Cu (mg L^{-1})	0.0001	0.0001	2.5E-03 b	0.06 a
Cr (mg L^{-1})	0.0001	0.0001	3.1E-04 b	0.03 a
Hg (mg L^{-1})	0.0001	0.0001	2.7E-05 b	2.0E-04 a
Ni (mg L^{-1})	0.0001	0.0001	0.01 b	0.02 a
Pb (mg L^{-1})	0.0001	0.0001	0.01 b	0.05 a
Zn (mg L^{-1})	0.0001	0.0001	0.35 b	0.73 a

* Different letters per row indicate significant differences ($p<0.05$). Tukey's Mean.

penetration and harm aquatic ecosystems. Discharge six recorded the highest fats and oils concentration (17.79 mg L^{-1}), just below the MPL of 18 mg L^{-1} (NOM-001-SEMARNAT-2021). These contaminants, as highlighted by Adetunji and Olaniran (2021), can inhibit water oxygenation and negatively affect aquatic flora and fauna. During the dry season (Table 3), discharge 6 again showed the highest flow rate (10.13 L/s), which was less than half the volume observed in the rainy season. According to Vione *et al.* (2023), lower flow during dry periods reduces the river's dilution capacity, resulting in elevated pollutant concentrations. Discharge four continued to exhibit the highest total suspended solids concentration (183.00 mg L^{-1}), exceeding the MPL by 2.5 times (NOM-001-SEMARNAT-2021), indicating persistent turbidity. Discharge 3 recorded the highest settleable solids concentration (0.94 mL L^{-1}), reflecting the diminished transport capacity of particles during the reduced flow. Discharge 6 maintained the highest fats and oils concentration (34.25 mg L^{-1}), surpassing the MPL by 1.8 times (NOM-001-SEMARNAT-2021), signaling an ongoing source of contamination.

This study confirms that domestic discharges degrade water quality, consistent with Boyd (2019), who asserts that anthropogenic pollution, particularly via runoff, increases turbidity and sedimentation, thereby adversely affecting aquatic ecosystems.

Table 3. Average flow rate, daily average temperature, pH, settleable solids, and fats and oils for the different discharges.

Discharge	Average daily flow rate ($L\ s^{-1}$)	Average daily temperature (°C)	pH	SS ($mL\ L^{-1}$)	SST ($mg\ L^{-1}$)	Fats and oils ($mg\ L^{-1}$)
Rainy season						
1	1.87 f	26.27 a	7.5 b	1.16 e	122.33 d	0.24 d
2	5.43 cd	25.93 a	7.3 b	1.22 de	127.00 d	1.70 b
3	4.53 cd	26.50 a	8.0 a	2.02 a	208.67 b	0.04 h
4	7.49 b	26.40 a	7.3 b	1.70 c	256.67 a	1.60 b
5	3.76 e	25.70 a	7.5 b	1.33 d	143.33 c	0.04 d
6	20.56 a	27.60 a	7.4 b	1.86 b	203.67 b	17.79 a
7	6.68 bc	26.67 a	7.3 b	1.99 a	53.67 e	0.88 c
Dry season						
1	0.98 c	27.87 c	7.13 b	0.05 e	7.67 d	0.66 c
2	3.57 b	28.70 bc	7.13ab	0.10 e	65.33 c	3.51 b
3	1.15 c	29.43 ab	7.83 a	0.94 a	101.33 b	0.24 c
4	3.63 b	29.93 ab	7.23ab	0.20 d	183.00 a	2.63 b
5	0.97 c	29.93 ab	7.00 b	0.65 c	61.00 c	0.34 c
6	10.13 c	30.90 a	7.00 b	0.80 b	167.00 a	34.25 a
7	4.66 b	29.07 bc	6.83 b	0.10 e	17.67 d	2.86 b

BOD_5, total nitrogen, coliforms, and helminth eggs

During the rainy season, BOD_5 varied significantly among discharges. Discharge 7 showed the highest concentration, at 189.76 mg L^{-1} (Table 4), exceeding the MPL (180 mg L^{-1} daily average) set by NOM-001-SEMARNAT-2021. Total suspended solids exceeded the MPL by up to 3.5 times, highlighting the need to minimize them to prevent further increases in BOD_5 after their release (Donald *et al.*, 2022). Discharge 6 exhibited the highest concentration of total coliforms (14,000,000 MPN/100 mL) and fecal coliforms (18,666,666.67 MPN/100 mL), far exceeding the MPL (500 MPN/100 mL) established by NOM-001-SEMARNAT-2021.

During the dry season, BOD_5 increased across all discharges (Table 4), with the highest value recorded in discharge 4 (392.22 mg L^{-1}), exceeding the MPL of 180 mg L^{-1} daily average (NOM-001-SEMARNAT-2021). This indicates a higher organic load associated with domestic wastewater, a concerning situation as the presence of organic matter promotes oxygen consumption by bacteria during oxidation, leading to anaerobic conditions that hinder the survival of aquatic organisms (Yoon *et al.*, 2024). Muñoz-Nava *et al.* (2012) noted that settlements near rivers contribute to increased BOD_5 levels. Discharge 6 (Table 4) maintained high levels of contamination by total coliforms (27,333,333.33 MPN/100 mL) and fecal coliforms (10,000,000.00 MPN/100 mL), far exceeding the MPL of 500 MPN 100 mL^{-1} (NOM-001-SEMARNAT-2021). This fecal contamination, attributed to untreated wastewater discharges, poses risks to both aquatic life and human health (Bhatt *et al.*, 2024). Regarding the number of

Table 4. Biochemical oxygen demand, total nitrogen, coliforms, and helminth eggs in the different discharges.

Discharge	BOD_5 (mg L^{-1})	Total N (mg L^{-1})	Total coliforms (NMP 100 mL^{-1})	Coliformsf Fecal (NMP 100 mL^{-1})	Helminth eggs (eggs L^{-1})
			Rainy season		
1	28.14 g	0.13 d	100000.00 e	8333.33 d	1.00 b
2	154.78c	1.73 c	180000.00 e	186666.67 d	1.33 b
3	135.26d	1.64 c	1933333.33 d	1966666.67 c	1.00 b
4	180.64b	2.59 c	8333333.33 b	866666.67 dc	1.00 b
5	98.16 e	6.73 b	3333333.33 c	4400000.00 b	1.67 a
6	50.10 f	6.43 b	14000000.00 a	18666666.67 a	1.00 b
7	189.76a	11.88 a	17666.67 e	42666.67 d	1.00 b
			Dry season		
1	91.44 e	0.57 f	22666.67 d	21000.00 d	1.33 bc
2	299.91b	3.58 de	206666.67 d	2433333.33 c	1.67 abc
3	223.47c	2.73 e	3066666.67 cd	2300000.00 c	1.00 bc
4	392.22a	4.33 d	10333333.33 b	2066666.67 c	2.00 ab
5	182.58d	16.02 b	4366666.67 c	4400000.00 b	2.67 a
6	121.77e	14.44 c	27333333.33 a	10000000.00 a	0.67 c
7	392.22a	22.73 a	2433333.33 cd	46000.00 d	1.00 bc

helminth eggs, discharge five recorded the highest concentration (2.67 No. H/5L). Although Mexican regulations do not specify MPLs for these pathogens in river waters, their presence poses a health risk for residents who use the water directly. Helminth eggs are considered indicators of microbiological contamination (Téllez *et al.*, 2023).

Heavy metal concentration

During the rainy season, Zn was the only metal that showed significant differences among the seven discharges ($p<0.05$), with the highest concentrations found in discharges 6 (0.56 mg L^{-1}) and 4 (0.55 mg L^{-1}), without exceeding the MPLs established by NOM-001-SEMARNAT-2021 (Table 5). During the dry season, significant differences ($p<0.05$) were observed in all heavy metals evaluated in the river water, although none exceeded the MPLs according to NOM-001-SEMARNAT-2021. Discharge 1 recorded the highest concentrations of Hg (5.6E-04 mg L^{-1}) and Ni (0.07 mg L^{-1}), while discharge 7 had the highest concentrations of Cu (0.28 mg L^{-1}), Pb (0.17 mg L^{-1}), and Zn (0.93 mg L^{-1}).

Although heavy metals did not exceed the MPLs, continuous monitoring of water quality in the Camalote river is recommended, particularly during the dry season, as Cr, Hg, and Zn have toxic effects and can bioaccumulate in aquatic food chains (Liu *et al.*, 2021). Additionally, Ni and Zn negatively affect the growth and reproduction of aquatic organisms, such as macroinvertebrates (Mancilla-Villa *et al.*, 2023).

Table 5. Heavy metal concentrations in the different discharges.

Discharge	Cu	Cr	Hg	Ni	Pb	Zn
	mg L^{-1}					
Rainy season						
1	2.5E-03 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.38 c
2	2.5E-03 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.05 d
3	2.5E-03 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.37 c
4	2.5E-03 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.55 a
5	2.5E-03 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.09 d
6	2.5E-03 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.56 a
7	2.5E-06 a	3.1E-04 a	2.7E-05 a	0.01 a	0.01 a	0.47 b
Dry season						
1	2.5E-03 c	3.1E-04 e	5.6E-04 a	0.07 a	0.01 b	0.90 a
2	2.5E-03 c	3.1E-04 e	5.7E-04 a	0.01 d	0.01 b	0.48 c
3	0.10 b	0.01 d	2.7E-05 b	0.03 b	0.13 a	0.74 b
4	0.04 bc	0.08 a	6.6E-05 b	0.01 d	0.01 b	0.98 a
5	2.5E-03 c	0.04 c	6.6E-05 b	0.01 d	0.01 b	0.30 d
6	2.5E-03 c	0.05 b	9.5E-05 b	0.02 c	0.01 b	0.76 b
7	0.28 a	3.1E-04 e	2.7E-05 b	0.01 d	0.17 a	0.93 a

CONCLUSIONS

The water quality of domestic discharges entering the CamaloterRiver during both the rainy and dry seasons exceeds the maximum permissible limits (MPLs) for settleable solids, total suspended solids, BOD_5, and total and fecal coliforms as established by NOM-001-SEMARNAT-2021. These exceedances pose significant risks to public health and aquatic ecosystems. Although heavy metal concentrations remained below the MPLs, continuous monitoring is essential due to their potential for bioaccumulation and adverse effects on the food chain. This study underscores the urgent need for mitigation and prevention measures, such as enhancing wastewater treatment systems and implementing revegetation in strategic areas, to reduce pollution and safeguard water quality for the benefit of the environment and the communities that rely on the river.

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