

Analysis of Wastewater Treatment Efficiency: Environmental Consequences in a Peruvian District

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Rivers are constantly affected by domestic wastewater discharges, which, depending on their pollutant load, can cause eutrophication, loss of biodiversity, alterations in the behavior and physiology of aquatic species, as well as public health problems. This study analyzed the influence of wastewater discharges from the wastewater treatment plant (WWTP) in the Elías Soplin Vargas district on the Yuracyacu River.

Four sampling points were established, and seven parameters were monitored, following Peruvian regulations D.S. N° 003-2010-MINAM over a three-month period. The results indicated that the mixing zone of the Yuracyacu River partially dilutes the concentrations of the effluent but does not completely mitigate its environmental impact. Compliance with Peruvian regulations, such as maximum permissible limits (MPL) and environmental quality standards for water (EQS), directly determines the environmental quality of the river.

1. Introduction

Freshwater is an essential resource, but its quality is constantly threatened by human activities such as domestic wastewater discharges. The reuse of wastewater for crop irrigation can be a necessary alternative due to freshwater scarcity and groundwater depletion (Mishra, Kumar and Kumar, 2023). However, the suitability of using treated wastewater for this purpose remains a topic of debate among government authorities and policymakers.

There are different systems for wastewater treatment, which can be classified into two main treatment strategies: industrial wastewater is typically treated using physicochemical methods, while domestic or urban wastewater is treated through biological processes (Vargas *et al.*, 2022). In Peru, this issue severely affects aquatic ecosystems, particularly in regions where treatment infrastructure is inadequate. The Yuracyacu River, located in the Elías Soplin Vargas district, is an emblematic case where untreated or insufficiently treated wastewater compromises water quality, impacting downstream users and aquatic ecosystems. This study evaluates the relationship between the effluent quality of the wastewater treatment plant (WWTP), compliance with maximum permissible limits (MPL), and the environmental impact on the receiving water body.

Non-compliance with the Environmental Quality Standards (EQS) could have significant socioeconomic impacts, particularly for communities that rely on water resources for irrigation, livestock, and daily activities. Understanding these implications underscores the importance of effective wastewater treatment and regulatory compliance in regions such as the district of Elías Soplin Vargas in Peru.

2. Methodology

Four strategic sampling points were established: upstream, at the discharge point, within the mixing zone, and downstream. The monitored parameters included biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), thermotolerant coliforms, oils and fats, total suspended solids (TSS), pH, and temperature.

Monitoring was conducted over three consecutive months. The extent of the mixing zone was calculated using hydrodynamic models following the guidelines of the National Water Authority (ANA). The analyses compared the results with the maximum permissible limits (MPL) established by Peruvian regulation D.S. N° 003-2010-MINAM. The selection of monitoring points was preliminarily conducted in the office using a map of the hydrographic unit. Data collection and integration were carried out using the Google Earth Pro and ArcGIS software tools.

Once the monitoring points were identified, their locations were determined using the Global Positioning System (GPS). To ensure effective monitoring, materials and equipment were prepared in advance following the surface water sampling protocol. The collected samples were transported for analysis to an accredited testing and quality control laboratory. Water samples were stored in plastic and glass containers and preserved in a large cooler with ice packs to maintain their integrity.

2.1 Maximum Permissible Limits for Effluents from Domestic or Municipal Wastewater Treatment Plants

According to peruvian regulation supreme decree N° 003-2010-MINAM, the maximum permissible limit is the measure of the concentration or degree of elements, substances, or physical, chemical, and biological parameters that characterize an emission, which, when exceeded, causes or may cause harm to health, human well-being, and the environment (MINAM, 2010). Table 1 shows the maximum permissible limits (MPL) for effluents from the wastewater treatment plant.

Table 1. Maximum Permissible Limits for Effluents from Domestic or Municipal Wastewater Treatment Plants

Parameter	Unit	MPL for Effluents Discharged into Water Bodies
Chemical Oxygen Demand (COD)	mg/L	200
Biochemical Oxygen Demand (BOD)	mg/L	100
Thermotolerant Coliforms	NMP/100 mL	10 000
Oils and Greases	mg/L	20
Temperature	°C	< 35
Total Suspended Solids (TSS)	mL/L	150
pH	Unidad	6,5-8,5

2.2 Environmental Quality Standards for Water (EQS)

Peruvian regulation N° 28611 establishes that the environmental quality standard is the measure that sets the concentration level or degree of elements, substances, or physical, chemical, and biological parameters present in the air, water, or soil, in its condition as a receiving body, which does not pose a significant risk to human health or the environment.

The Environmental Quality Standards (EQS) serve as a fundamental framework for water resource management. These EQS not only act as benchmarks for assessing water quality but also serve as points of international comparison. In developing countries like Peru, the adoption of these measures ensures alignment with global practices, promoting improved water quality management and highlighting critical areas for strengthening public policies.

Table 2 shows the environmental quality standards for water according to the parameters to be analyzed based on the MPL, describing the EQS for Category 3: Irrigation of vegetables and animal drinking water, and Category 4: Conservation of the aquatic environment, which are characteristic categories of receiving bodies of wastewater (MINAM, 2017).

Table 2: Environmental Quality Standards for Water: Category 3 and 4

Parameters	Unit of Measurement	Category 3: Irrigation of Vegetables and Animal Drinking Water			Category 4: Conservation of the Aquatic Environment
		D1: Vegetable Irrigation		D2: Animal Drinking Water	E2: Rivers
		Water for Unrestricted Irrigation	Water for Restricted Irrigation	Animal Drinking Water	Jungle
Chemical Oxygen Demand (COD)	mg/L	40	40	**	
Biochemical Oxygen Demand (BOD ₅)	mg/L	15	15	10	
Thermotolerant Coliforms	NMP/100 mL	1 000	2 000	1 000	2 000
Oils and Greases	mg/L	5	10	5	
Temperature	°C	Δ 3	Δ 3	Δ 3	
Total Suspended Solids (TSS)	mL/L	**	**	≤ 400	
pH	Unidad	6,5 – 8,5	6,5 – 8,4	6,5 a 9,0	

** Not applicable to the subcategories

3. Results and Discussion

3.1 Mixing Zone

The mixing zone is defined as the volume of water in the receiving body where dilution of discharges can occur through dispersion processes and hydrodynamic mechanisms, without considering other factors such as chemical precipitation, organic matter assimilation, sedimentation, and bacterial decay. The purpose of determining the mixing zone is to allocate a limited region for the complete mixing of the discharged effluent with the water mass of the receiving bodies and to utilize the dilutive capacity of the receiving surface water source (ANA, 2017). Figure 1 shows the mixing zone and the sampling points. This zone represents a limited water volume where parameter levels may exceed the EQS-Water standards, meaning that water from the mixing zone should not be used for any activities. The sampling population included the same locations, namely, the monitoring points located in the effluent before discharge into the surface water body (AR 1) and the sampling points located upstream (AN 1), within (AN 2), and downstream (AN 3) of the mixing zone of the receiving body. The length of the mixing zone was influenced by the river's flow characteristics and the pollutant load of the effluent. Despite its dilutive capacity, some contaminants remained at undesirable levels downstream.

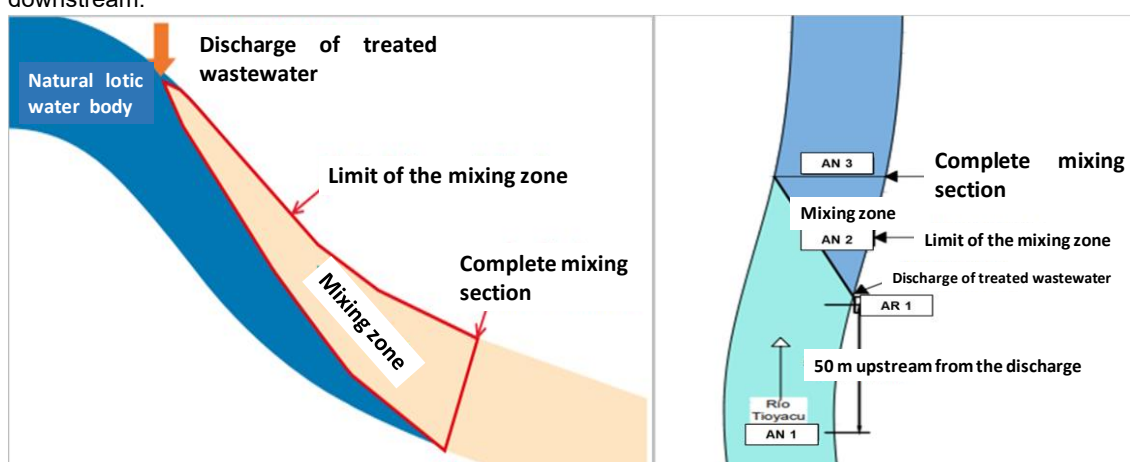


Figure 1. Mixing zone in water bodies and distribution of sampling points. The sampling points were strategically selected to represent key areas: upstream (AN 1), discharge point (AR 1), mixing zone (AN 2), and downstream (AN 3). These locations were chosen based on hydrological characteristics and effluent dispersion patterns.

To determine the extent of a mixing zone located downstream of discharges, the approach can be applied to discharges at the banks or in the center of water bodies.

For discharges released at the river/streambanks, the determination of the mixing zone is obtained through:

$$L_{ZdM} = \frac{(W_{min})^2 u}{2 \pi D_y}$$

For discharges released at the center of rivers/streams, the determination of the mixing zone is obtained through:

$$L_{ZdM} = \frac{(W_{min})^2 u}{8 \pi D_y}$$

Where:

L_{ZdM} : Length of the mixing zone in meters.

W_{min} : Average width of the surface source in meters, measured over a 500 m stretch downstream of the discharge.

u : Average flow velocity (m/s) of the water at the discharge point.

D_y : Lateral dispersion coefficient in the lower section of the discharge point.

$$D_y = c \times d \times u^*$$

c : Irregularity factor of the river channel:

$c > 1.0$: For rivers with abrupt directional changes of 90° or more.

$c = 1.0$: For rivers with a natural channel exhibiting significant meandering.

$c = 0.6$: For rivers with a natural channel exhibiting moderate meandering.

$c = 0.3$: For rivers that are channeled.

$c = 0.1$: For straight rivers with a rectangular channel.

d : Average depth of the river in meters downstream from the discharge point.

u^* : Shear velocity (m/s), determined by:

$$u^* = \sqrt{g \times d \times s}$$

g : Acceleration due to gravity.

s : Slope of the river channel downstream of the discharge (m/m).

To collect samples in the receiving water body, the criteria established in the National Protocol for Monitoring the Quality of Surface Water Resources, approved by Resolution No. 010-2016-ANA, were considered (ANA, 2016). The sample was considered as the total set of parameters to be analyzed according to Supreme Decree No. 003-2010-MINAM. Parameters such as pH and temperature were evaluated in situ using a multiparameter device accredited by a laboratory. A sample of 3 liters was collected for thermotolerant coliforms (250 mL/sample), 1.2 liters for Chemical Oxygen Demand (COD) (100.0 mL/sample), and 12 liters for Biochemical Oxygen Demand (BOD₅) (1 L/sample), oils and fats (1 L/sample), and Total Suspended Solids (TSS) (1 L/sample). In total, 10.05 liters of domestic wastewater were collected from the effluent and 40.2 liters from the receiving water body.

3.2 Parameter Concentrations

In Table 3, it is observed that, with the exception of Total Suspended Solids (TSS), the average concentration of the evaluated parameters was higher in the effluent (AR 1) and lower at all sampling points located in the receiving water body. At AN 2, the concentration of all parameters significantly exceeded the values estimated at AN 1 and AN 3.

The average concentration of thermotolerant coliforms in the effluent exceeded the Maximum Permissible Limit (MPL) (10,000 MPN/100 mL) established by Supreme Decree N° 003-2010-MINAM. Similarly, the mean concentration of coliforms at AN 1, AN 2, and AN 3 surpassed the Environmental Quality Standards for Water (EQS-Water) for subcategory D1: Water for unrestricted irrigation (1,000.0 MPN/100 mL) and restricted irrigation

(2,000.0 MPN/100 mL), D2: Animal drinking water (1,000.0 MPN/100 mL), and E2: Conservation of aquatic environment in jungle rivers (2,000.0 MPN/100 mL).

It is also noted that the BOD₅ concentration downstream of the discharge point (AN 2) exceeded the quality standard for subcategory E2: Conservation of aquatic environment in jungle rivers (10.0 mg/L). Although the mixing zone partially diluted these concentrations, downstream waters still exceeded the Environmental Quality Standards for Water (EQS-Water) in several measurements.

Table 3: Concentrations of Physicochemical and Microbiological Parameters in the Effluent

Parameters	Units of Measurement	AR 1	AN 1	AN 2	AN 3
Thermotolerant Coliforms	NMP/100 mL	224 000,0*	15 366,7**	44 133,3**	24 500,0**
Chemical Oxygen Demand (COD)	mg/L	76,0	<5,0	31,8	17,1
Biochemical Oxygen Demand (BOD ₅)	mg/L	28,9	<2,0	11,8***	6,4
Oils and Fats	mg/L	<5,0	<0,5	<0,5	<0,5
Temperature	°C	24,1	20,9	21,0	20,1
Total Suspended Solids (TSS)	mg/L	7,4	8,2	8,5	6,7
pH	pH Unit	8,1	7,3	7,9	7,7

Note: The average concentrations of the parameters were calculated based on monitoring data collected at each sampling point, following the procedures established in the National Protocol for Monitoring the Quality of Surface Water Resources (ANA, 2016).

*Exceeds MPL for effluents from domestic WWTPs.

**Exceeds EQS for water: subcategories D1, D2, and E2.

***Exceeds EQS for water: subcategory E2.

The MPL for effluents from WWTPs determined the water quality of the Yuracyacu River. The average concentration of COD, BOD₅, oils and fats, temperature, TSS, and pH did not exceed the MPL nor the EQS-Water in the receiving body downstream of the discharge point (AN 2). However, thermotolerant coliforms exceeded the MPL and contributed to exceeding the standards at both AN 2 and AN 3. This can be attributed to the inefficient treatment of thermotolerant coliforms at the WWTP in the district of Elias Soplin Vargas. Proper treatment of wastewater before discharge is required to mitigate these impacts.

It has been determined that, according to seasonality, there are differences in the concentrations of parameters in the receiving water body, with values capable of exceeding the water quality standards for subcategories D1, D2, and E2. The highest values can be attributed to low-flow periods. This aligns with what has been reported by (Rodríguez and Silva, 2015; Villanueva *et al.*, 2023) who indicate that the highest pollution levels are detected during low-flow periods. Domestic wastewater effluents produce social impacts, potentially affecting crops adjacent to rivers and altering public health. As direct users of water resources, local communities can provide a deeper understanding of the socio-ecological context and contribute valuable lived experiences related to water quality, expectations for water resources, and water usability (Rangecroft *et al.*, 2023). The discharge of non-domestic wastewater from the WWTP in the district of Elias Soplin Vargas influences the environmental quality of the Yuracyacu River, and the higher the pollutant load in the effluent, the greater the effects on the aquatic environment.

El río Yuracyacu arrastra una elevada carga microbiológica desde aguas arriba del punto de vertimiento, posiblemente por el vertimiento de otros efluentes y desarrollo de otro tipo de actividades, al llegar a la zona de mezcla y posterior a esta se incrementa la carga del contaminante debido al aporte de elevadas concentraciones del efluente. Las concentraciones de DQO, DBO₅, aceites y grasas, temperatura y pH son significativamente menores aguas arriba del punto de vertimiento y se incrementan en la zona de mezcla debido a la elevada carga contaminante que se descarga de la PTAR, que, de acuerdo a la temporalidad, longitud de zona de mezcla y características hidrológicas del río las concentraciones pueden exceder los estándares de calidad para agua y ocasionar efectos ambientales más relevantes en el cuerpo receptor.

4. Conclusions

The Yuracyacu River carries a high microbiological load from upstream of the discharge point, possibly due to the discharge of other effluents and the development of various activities. Upon reaching the mixing zone and beyond, the pollutant load increases due to the contribution of elevated effluent concentrations.

The concentrations of COD, BOD₅, oils and fats, temperature, and pH are significantly lower upstream of the discharge point but increase within the mixing zone due to the high pollutant load discharged from the WWTP. Depending on the seasonality, mixing zone length, and hydrological characteristics of the river, these concentrations can exceed water quality standards and cause more significant environmental effects on the receiving water body.

It is recommended that the wastewater treatment plant in the district of Elías Soplin Vargas, Peru, implement more advanced treatment technologies to enhance efficiency in the removal of thermotolerant coliforms and other contaminants. Additionally, continuous monitoring and stricter enforcement of national environmental regulations are essential to ensure compliance and mitigate long-term impacts on the Yuracyacu River.

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