

Improvement of wastewater treatment systems through component redesign to optimize operational efficiency

Mejora de sistemas de tratamiento de aguas residuales mediante rediseño de componentes para optimizar la eficiencia operativa

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Published

Instituto Tecnológico Superior Edwards Deming. Quito - Ecuador

Periodicity

July - September
Vol. 1, Num. 26, 2025
pp. 1-16
<http://centrosuragraria.com/index.php/revista>

Dates of receipt

Received: May 12, 2025
Approved: June 30, 2025

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Abstract: Water is a vital resource for human survival, the development of societies and the ecological balance of the planet. Its availability in adequate quality and quantity is essential for the well-being of ecosystems and for sustaining multiple human activities, such as agriculture, industry, tourism and domestic supply. However, the increasing pressure exerted on this resource, especially in urban and rural developing areas, has led to a progressive deterioration of its quality, compromising its use and natural cycle.

Key words: water, environment, nature

Resumen: El agua constituye un recurso vital para la supervivencia humana, el desarrollo de las sociedades y el equilibrio ecológico del planeta. Su disponibilidad en calidad y cantidad adecuadas es esencial para el bienestar de los ecosistemas y para el sostenimiento de múltiples actividades humanas, tales como la agricultura, la industria, el turismo y el abastecimiento doméstico. Sin embargo, la creciente presión ejercida sobre este recurso, especialmente en zonas urbanas y rurales en desarrollo, ha generado un deterioro progresivo de su calidad, comprometiendo su uso y su ciclo natural

Palabras clave: agua, medio ambiente, naturaleza

Introduction

One of the main sources of water pollution is the improper discharge of wastewater. These waters, which come from homes, commercial establishments, industries, and agricultural activities, contain a high load of organic matter, nutrients, chemical compounds, and pathogenic microorganisms that, if not properly treated, can cause severe negative impacts on receiving bodies and human health (Salazar & Cesar, 2017; Contreras et al., 2021). Globally, it is estimated that more than 80% of the wastewater generated does not receive any treatment before final disposal, especially in developing countries (UNESCO, 2020).

In Latin America, the situation is not encouraging. The region faces significant challenges in terms of sanitation and wastewater treatment. Although significant efforts have been made in regulatory and institutional terms, many existing wastewater treatment plants (WWTPs) operate below capacity or have collapsed due to lack of maintenance, design deficiencies, hydraulic overloading, or simply abandonment (Anda Sánchez, 2017; Silva et al., 2020). In Ecuador, multiple studies have revealed that a large number of WWTPs do not comply with the parameters established in current environmental regulations, which contributes to the deterioration of water quality in rivers, lagoons and subway aquifers (Núñez Collaguazo & López Ramírez, 2014; Morales et al., 2023).

These technical and structural deficiencies directly affect the ability of plants to remove key pollutants such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and nutrients (nitrogen and phosphorus). Non-compliance with environmental standards established by regulations such as the Unified Text of Secondary Legislation of the Ministry of Environment (TULSMA) in Ecuador not only represents a threat to aquatic ecosystems, but also increases the risk of waterborne diseases in nearby populations (TULSMA, 2015).

Faced with this problem, it has become imperative to adopt technical strategies that allow for the rehabilitation and modernization of existing treatment plants. In this context, the redesign of critical components of WWTPs is presented as a viable and effective solution. This strategy consists of rethinking the hydraulic sizing, functional distribution and operability of the treatment units, using updated technical criteria and technologies appropriate to the context (Allauca

Melena, 2024; Solís Chamorro, 2015; Guzmán Garrido & de la Rosa Luciano, 2015).

Several investigations have shown that the reconfiguration of elements such as grids, desander channels, Imhoff tanks, upflow anaerobic filters (AFFA), grease traps and drying beds can significantly improve system efficiency without the need to resort to complex or costly solutions (Herrera-Pérez et al., 2022; Ríos-López & Medina-Flores, 2021). In many cases, these improvements have made it possible to meet effluent quality requirements, extend the useful life of the infrastructure and reduce operating costs, especially in community or rural systems with limited budgets.

The experience documented in different areas of Ecuador reinforces this perspective. In the case of the Ilapo I treatment plant, located in the parish of the same name in Guano canton, Chimborazo province, a comprehensive technical redesign was carried out with the objective of recovering its functionality and ensuring compliance with the limits established by environmental regulations. This redesign included the implementation of a FFA, substantial improvements in the septic tank, the installation of coarse and fine screens, and the reconfiguration of the desander channel to optimize the removal of settleable solids (Allauca Melena, 2024).

Other experiences, such as that of the Chiquicha Centro community, also in Chimborazo, have shown positive results. There, the rehabilitation of the WWTP included the reconstruction of the drying beds, the installation of grease traps and a new screening system, which allowed a considerable reduction in the levels of contamination in the final effluent and improved the community's perception of the sanitation service (Morales et al., 2023).

It should be noted that, in addition to the technical and environmental benefits, the redesign of components has a strong social impact. The improvement in the quality of treated water has a direct impact on public health, the quality of life of the population and the development of productive activities dependent on water resources, such as agriculture and aquaculture (). Similarly, as they are technically accessible solutions, they promote community participation, strengthen local water governance and foster social appropriation of the system (González-Vargas et al., 2021; Paredes-Herrera & Araujo-Sánchez, 2019).

At the normative level, compliance with the parameters established by the TULSMA and other international regulations such as the WHO

Guidelines on Water and Sanitation, represents an indicator of good environmental governance and institutional responsibility. Therefore, any redesign strategy must be supported by a rigorous technical evaluation, studies of current and projected flow rates, effluent characterization, and adequate hydraulic and structural sizing of each component (UN-Habitat, 2018; PAHO, 2020).

In this sense, the present article is proposed as a contribution to the technical and practical knowledge on the redesign of wastewater treatment plant components. The main objective is to evaluate the impact of the redesign on the operational efficiency of the WWTP Ilapo I, using a methodological approach based on the diagnosis of the system, the analysis of its current conditions and the proposal of solutions adapted to its operational context. The aim is to demonstrate that it is possible to significantly improve the quality of the treated effluent through accessible, sustainable and replicable technical interventions.

The research is based on a quantitative technical-applied approach, with emphasis on sanitary engineering and environmental sustainability. It also makes use of empirical evidence obtained through physicochemical analysis, direct observation and documentary review, which gives solidity to the conclusions presented. The relevance of this study lies in its applicability to other similar realities in the country and the region, where limited resources and complex geographical conditions make it difficult to implement conventional high-tech treatment systems.

In sum, the redesign of wastewater treatment plant components represents an effective, efficient and sustainable strategy to address sanitation challenges in rural and semi-urban contexts. Through well-planned and technically sound interventions, it is possible to optimize the performance of existing systems, comply with current regulations and contribute to the protection of water resources as a fundamental axis for sustainable development.

Methodology

The present research adopted a quantitative approach of a technical-applied type, with the objective of redesigning and optimizing the Ilapo I Wastewater Treatment Plant (WWTP), located in Ilapo parish,

Guano canton, Chimborazo province, Ecuador. The study was structured in three main phases: diagnosis, technical analysis and structural redesign, allowing an integral evaluation of the existing system and the proposal of specific solutions based on current environmental regulations.

Phase 1: Diagnosis of the current situation

During the first stage, a general diagnosis of the plant's operational and structural status was carried out. This process included:

On-site visual inspection, through technical visits made at different times, to evaluate the physical condition of the treatment units (grids, desander channel, septic tank, decanters and filters).

Integral cleaning of the plant, essential for the accurate collection of samples and the detection of obstructions or invisible faults under normal operating conditions.

Planimetric and topographic survey, using measuring instruments such as engineer's level, tape measure, theodolite and drone with camera, which allowed the preparation of updated plans of the existing units.

Documentary review, in which historical information available on the WWTP was analyzed, such as original plans, maintenance reports, operating records and applicable regulations (especially the TULSMA).

Phase 2: Sampling and physical-chemical analysis

The diagnosis was complemented by a process of sampling and analysis of the wastewater, both at the inlet and outlet of the system. Composite samples (24-hour weighted averages) were taken in sterile bottles, following the sampling protocol of Technical Standard INEN 2169:2013.

The parameters analyzed were:

Biochemical Oxygen Demand (BOD₅).

Chemical Oxygen Demand (COD)

Total Suspended Solids (TSS)

Fecal coliforms

pH

The tests were performed in certified laboratory, using standardized techniques according to the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). The results obtained were

contrasted with the maximum permissible limits established by the Unified Text of Secondary Legislation of the Ministry of Environment (TULSMA, 2015) for freshwater bodies.

Phase 3: Hydraulic analysis and sizing

With the data collected, the hydraulic and structural analysis of the existing units was carried out, considering:

Current and projected population: INEC population growth rates were applied to determine the future population load.

Average daily flow and peak flow: Estimated based on average per capita consumption (200 L/inhab/day) and the daily coefficient of variation (1.5 for rural areas).

Hydraulic retention time (HRT), surface load, flow velocities, and theoretical efficiency of each treatment unit.

The units with evident deficiencies were selected for structural intervention. Among these, priority was given to the desander channel, the septic tank, the grate system, and an upflow anaerobic filter (AFAF) was incorporated as a secondary treatment technology adaptable to rural contexts without electricity consumption.

Phase 4: Technical and structural redesign

The redesign was based on the application of sanitary engineering principles and national and international standards. Drawings were prepared in AutoCAD Civil 3D and design calculations in Excel sheets with hydraulic and treatment formulas.

Structural improvements included:

New system of coarse and fine grids in cascade, to improve the retention of coarse solids from the inlet of the system.

Reconfiguration of the desander channel, increasing the slope and hydraulic width to optimize sedimentation of heavy particles.

Redesigned septic tank, with differentiated compartments, improved ventilation, grease traps and volume adapted to the new estimated flow.

FAFA installation, which uses existing biomass for biological treatment without requiring energy inputs.

Inspection chambers and 20-series PVC piping to facilitate maintenance and operational monitoring.

Phase 5: Operational validation and preparation of the manual

Following the redesign, an operation and maintenance (O&M) manual was developed with clear instructions for local personnel, including inspection frequencies, cleaning procedures, sampling methods, and preventive routines.

In addition, a community training program was developed, focusing on operators and community leaders, in order to guarantee social ownership of the system and ensure its long-term sustainability.

Results

Figure 1 shows the schematic diagram of the main components of the wastewater treatment system of the PTAR Ilapo I plant. The influent flow initially enters the overflow box, where a preliminary separation is performed, followed by a desander channel that removes heavy solids. Subsequently, the wastewater is directed to the Imhoff tank, which performs sedimentation and primary digestion, and then passes to the overflow box, which allows flow monitoring. Finally, the treated water exits as effluent. The diagram also contemplates a bypass that connects the overflow box directly to the review box and the effluent, allowing for an emergency bypass if necessary.

Figure 1: Diagram of components of the current PTAR Ilapo I system.

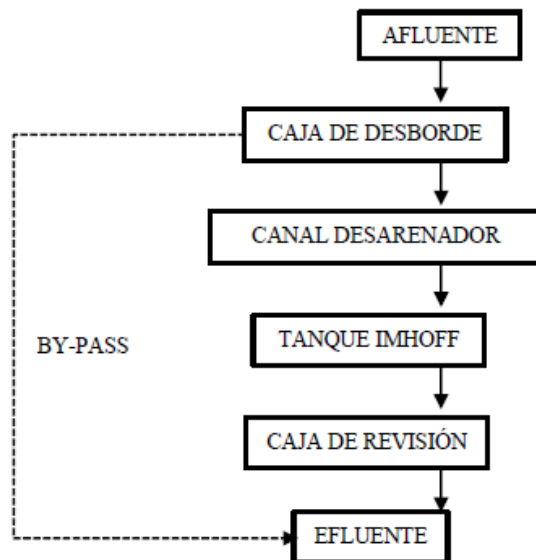
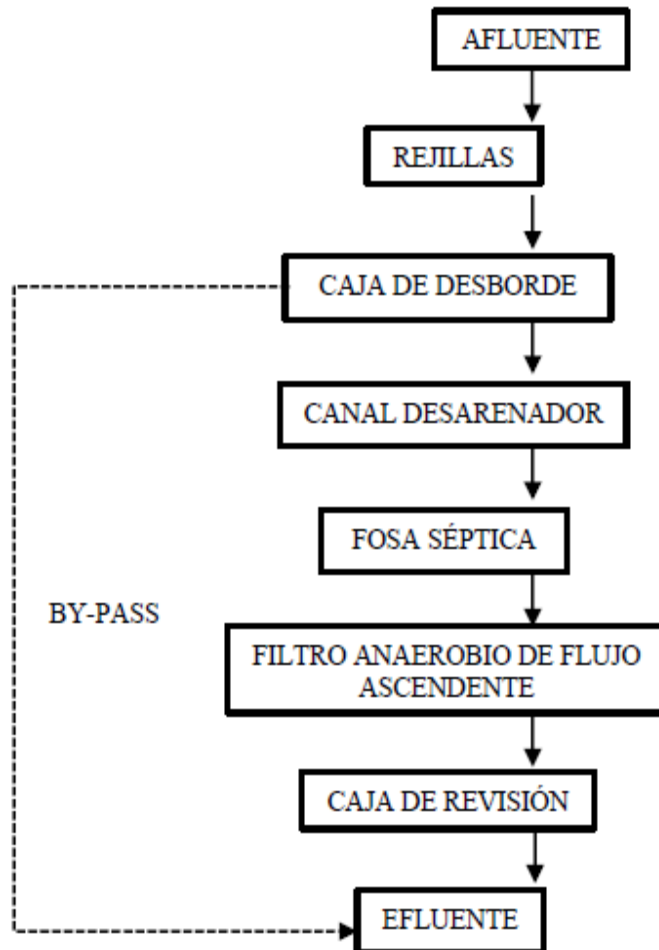


Figure 2 presents the diagram of the proposed redesign of the wastewater treatment system at PTAR Ilapo I, which incorporates new stages to optimize the purification process. In this proposal, the influent flow first enters a screen that retains coarse solids, then passes to the overflow box and continues to the desander channel, where heavy particles are removed. The wastewater then enters a septic tank, which performs primary sedimentation and part of the anaerobic treatment. The flow is then conveyed to an upflow anaerobic filter, which enhances the reduction of the organic load. Finally, it passes to the overflow box and exits as effluent. The scheme also contemplates an emergency by-pass, which connects the overflow box directly to the overflow box and the effluent, allowing the flow to be diverted in case of need. This redesign seeks to improve treatment efficiency and treated water quality.

Figure 2: Diagram of the redesign of the Ilapo I WWTP.



The results derived from the technical redesign of the Ilapo I Wastewater Treatment Plant (WWTP) show substantial improvements in all key operational efficiency indicators. This progress was made possible by a comprehensive intervention that addressed both structural and functional aspects of the system. Evaluations following the implementation of the redesign show that the plant has not only improved the quality of the treated effluent, but also reduced its environmental impact and optimized its operational sustainability.

Prior to the redesign, the contamination levels present in the treated water far exceeded the limits established by the Unified Text of Secondary Legislation of the Ministry of the Environment

(TULSMA). In particular, the BOD₅, COD and TSS values evidenced that the system did not meet the minimum treatment requirements.

Another relevant aspect was the pH behavior. Although this parameter did not represent a critical problem before the redesign (7.2), the intervention allowed stabilizing it even closer to neutrality, with a post-redesign value of 7.0. This is important because it ensures that no corrosive or toxic conditions are generated for the receiving aquatic ecosystems, which complements the benefits achieved in terms of organic matter and solids removal.

Beyond the numbers, the results obtained have a concrete impact on the quality of the environment and public health. The improvement in BOD₅ removal efficiency translates into a decrease in the organic load discharged to water bodies, which in turn implies a lower demand for dissolved oxygen by degrading microorganisms in the environment. This is crucial to avoid anoxic conditions affecting aquatic fauna.

Reducing TSS also has obvious benefits, as it limits water turbidity and reduces sedimentation of organic and inorganic materials in riverbeds or canals. This helps maintain water transparency and improves conditions for aquatic life. pH stabilization, on the other hand, minimizes the risks of physiological stress in sensitive species, especially in reproductive stages.

The key to these improvements lies in the redesign of critical plant components. Elements such as the desander channel, which was resized and its slope increased to improve the settling of heavy solids, and the septic tank, which was rebuilt with a new operating volume and an improved sealing and ventilation system; the upflow anaerobic filter (FAFA), which was designed and implemented to increase biological efficiency without the need for additional energy inputs; and finally, the screen system, which was replaced with a cascading set of coarse and fine screens, improving the retention of solids from the system inlet.

Each of these improvements not only contributed individually, but worked synergistically with the rest of the system. For example, the FAFA allowed for more effective reduction of BOD₅, but its efficiency depended on adequate solids removal previously achieved in the desander channel and grates. Also, the improved septic tank facilitated a more uniform and stable process, which in turn optimized the operation of the downstream units.

In addition, the operational stability of the system was improved. The redesign reduced the frequency of corrective maintenance, while simplifying daily operational tasks. This translates into lower long-term costs and greater financial sustainability for the system. In social terms, the redesigned system generates greater confidence in the local community, which now perceives water treatment as an effective and tangible action to improve the quality of the environment.

As shown in Table 1, biochemical oxygen demand (BOD₅) was 150 mg/L, chemical oxygen demand (COD) reached 280 mg/L, and total suspended solids (TSS) were as high as 200 mg/L. These figures were alarming, considering that the permissible limits established by environmental regulations are 50 mg/L for BOD₅, 150 mg/L for COD and 100 mg/L for TSS.

After the redesign, the figures changed drastically. BOD₅ was reduced to 40 mg/L, COD dropped to 90 mg/L and TSS stood at 60 mg/L. These values are not only below legal limits, but also reflect an optimized system that has recovered its functionality and pollutant removal capacity. The efficiency of the system can be seen in the reduction percentages: BOD₅ was reduced by 73.3%, COD by 67.9% and TSS by 70%. These removal rates place the plant in an optimal operating range, comparable to modern treatment systems.

Table 1. Comparison of water quality parameters before and after the redesign of the Ilapo I WWTP.

Parameter	Before redesign	After redesign	Allowable (TULSMA)	limit
BOD₅ (mg/L)	150	40	50	
COD (mg/L)	280	90	150	
TSS (mg/L)	200	60	100	
pH	7.2	7.0	6.5-8.5	

As can be seen, the redesign made it possible to reduce BOD₅ by 73.3%, going from 150 mg/L to 40 mg/L, thus complying with current regulations. Likewise, COD was reduced from 280 mg/L to 90 mg/L, representing an improvement of 67.9%. Total suspended solids decreased by 70%, reaching an average value of 60 mg/L after the

intervention. The pH remained stable within the permitted range, reflecting good regulation of the treatment system.

Figure 1. Graphical comparison of BOD₅, COD and TSS parameters before and after the redesign of the Ilapo I WWTP.

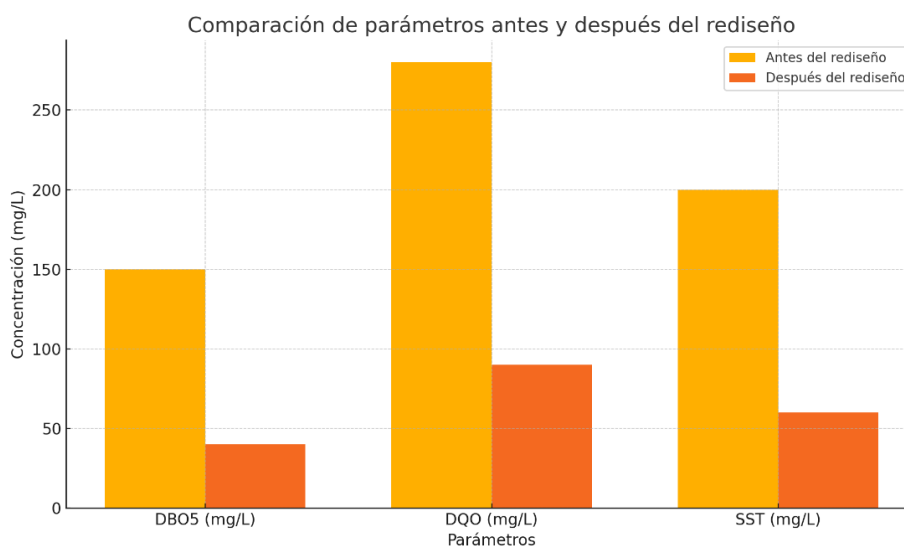


Figure 1 presents a graphical comparison of BOD₅, COD and total suspended solids (TSS) values measured before and after the redesign of the Ilapo I WWTP. A significant reduction is observed in all three parameters, evidencing a substantial improvement in the quality of the treated effluent. In the case of BOD₅, the value decreased from 150 mg/L to 40 mg/L; COD went from 280 mg/L to 90 mg/L; and TSS decreased from 200 mg/L to 60 mg/L. These results reflect considerable efficiency in the removal of organic matter and solids, far exceeding compliance with the limits established by environmental regulations. The graph visually demonstrates the positive impact of the technical redesign on the operational optimization of the plant.

Therefore, the redesign of the Ilapo I WWTP demonstrates the effectiveness of this strategy to improve deteriorated treatment systems. Not only was it possible to comply with current environmental standards, but the operational capacity was improved, the ecological impact was reduced and the sustainability of the system was strengthened. This experience is a replicable example for other communities with similar conditions, where technical and economic

limitations make it difficult to implement higher-cost conventional solutions.

The results obtained after the redesign of the Ilapo I wastewater treatment plant show a significant improvement in the efficiency of the system. The reduction of key parameters such as BOD₅ (73.3%), COD (67.9%) and total suspended solids (70%) not only reflects the correct hydraulic sizing of the new components, but also the effectiveness of the structural redesign in the purification process.

These findings are consistent with previous studies conducted in Ecuador and other Latin American countries, where the redesign of deteriorated WWTPs has proven to be an effective strategy to recover operational capacity and comply with regulatory requirements (Morales et al., 2023; Solís Chamorro, 2015). In particular, the incorporation of appropriate technologies such as the upflow anaerobic filter (AFAF), the redesign of the desander and the implementation of an improved grid system allowed optimizing the physical and biological processes without resorting to high-cost or technically complex solutions.

It should be noted that the pH stability within the permissible range (7.0) confirms that the redesigned system does not generate extreme conditions in the effluent, which is fundamental to prevent adverse impacts on the receiving bodies. In addition, the comparison of the results obtained with the limits established by TULSMA shows that the new design complies with national environmental quality standards, which validates its applicability in rural and semi-urban contexts with limited resources.

On the other hand, it is important to point out that the success of this intervention does not depend only on the technical redesign, but also on the correct operation and maintenance of the system. In this sense, the preparation of a specific operating manual for the Ilapo I WWTP is a crucial contribution to ensure its long-term sustainability. The continuous monitoring, the training of local personnel and the institutionalization of control routines should be considered strategic factors to avoid the progressive deterioration of the plant.

Conclusions

The redesign of the Ilapo I Wastewater Treatment Plant (WWTP) proved to be an effective technical strategy to optimize the operational efficiency of the system and ensure compliance with current

environmental regulations. From the analysis of the results obtained, the following conclusions can be drawn:

Significant improvement in effluent quality: The intervention allowed reducing the levels of BOD₅, COD and total suspended solids by more than 65%, reaching values that are below the limits established by the TULSMA, which evidences an efficient wastewater treatment.

Efficiency of component redesign: The resizing of the desander channel, the redesign of the septic tank, the installation of an upflow anaerobic filter (FAFA) and the implementation of improved grids were decisive in improving the performance of the system. These structural elements made it possible to optimize the solids, grease and organic matter separation process.

Adaptability of the design to rural contexts: The technical proposal was characterized by its operational simplicity and economic viability, making it a replicable solution in other communities with similar conditions, where access to advanced technologies is limited.

Importance of maintenance and operational management: The success of the system depends not only on the physical redesign, but also on technical follow-up, periodic maintenance and training of the personnel in charge. The development of an operation and maintenance manual is a key tool for the sustainability of the system.

Positive environmental and social impact: The redesign of the WWTP contributes to the protection of the receiving water sources, reduces the risk of waterborne diseases and improves the quality of life of the local population, promoting access to a healthier and safer environment.

Based on the above, it is recommended to promote the evaluation and redesign of other deteriorated treatment plants at the national level, prioritizing technical approaches adapted to the context and sustainable in the long term.

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