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DESIGN AND ASSESSMENT OF A DOMESTIC WASTEWATER TREATMENT SYSTEM BASED ON A CONSTRUCTED WETLAND WITH SUBSURFACE FLOW IN JARABACOA, DOMINICAN REPUBLIC[*]

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Abstract

A diagnosis, carried out as part of the conception of the National Sanitation Strategy of the Dominican Republic, states that 75% of the population does not have sewerage services, and just around 10% of the wastewater generated receive some treatment. Furthermore, the discharge of sewage from more than a million septic tanks in the country constitutes the largest source of diffuse pollution. Regarding the above mentioned, "Plan Yaque" (Plan for the Sustainable Development of the Yaque del Norte River Basin) has implemented a relatively cost-effective solution in "El Dorado," a small peri-urban settlement in Jarabacoa municipality. Nonpoint source pollution was converted into point source through a system that collects all the sewage from each septic tank and, then, brings those wastewaters into a nature-based treatment system (constructed wetland with the subsurface flow). This work shows the results obtained in the assessment of the design and exploitation of a wastewater treatment system targeting to reduce the pollution's load that is affecting the Yaque del Norte River Basin. The treatment system is based on a sewer system that brings the sewage from the houses into two septic tanks, from where they are brought to a constructed wetland. The 70 m^2 wetland was designed to treat the sewage generated by 75 inhabitants. Because of the treatment, the decrease of the pollutant's load into the inflowing sewage achieved an average removal value of 93% for COD, 95% for BOD, 98% for fecal coliforms and 44% for phosphorus as orthophosphate. The system could potentially spread out in other peri-urban settlements in developing countries.

Keywords: constructed wetland, design, domestic wastewater, subsurface wetland

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1. Introduction

The dearth of freshwater and its pollution is a global problem. The deterioration of water bodies due to the inadequate or lack of treatment for wastewater, which increasingly demands more sophisticated technologies, increases the problem. This situation is more sensitive in small urban and rural communities because most of them do not have centralized conventional treatment systems. Therefore, a solution for such cases is decentralized treatment systems, which must guarantee a low cost in their operation, be effective with compliance with discharge guidelines, and are easy to operate. In this sense, the constructed wetlands are sustainable technology to remove pollutants from wastewater (Grinberga, 2020).

The constructed wetlands (CWs) simulate the dynamics of natural systems. They base their operation on microorganisms and plants' ability to purify water and simultaneously use the advantages of inorganic supports that work as filters and adsorbent material. In that context, a simple system works based on complex physical and biochemical processes that control volatilization, adsorption, sedimentation, phytoremediation, phytoaccumulation, and microbial degradation of wastewater.

The relatively high performance of constructed wetlands is known for some of the macro parameters that define water quality, such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and the depletion of total and fecal coliforms (García-Ávila et al., 2019; Grinberga, 2020). The efficiency of CW depends on its design, the species of plants used, the nature of the substrate, the climate, the nature of the contaminants, and the operating conditions, mainly of the hydraulic retention time.

Based on their construction and flow characteristics, CWs are classified as Surface Flow (SF), Horizontal Subsurface Flow (HSSF), Vertical Subsurface Flow (VSSF), or the combination of these in Hybrid Systems (HS), which have demonstrated greater efficiency than individual wetlands.

Other advantages of CWs, versus conventional urban or rural domestic wastewater treatment facilities, are low energy consumption; the simplicity of the design, construction and operation; few maintenance requirements; the fact of providing various ecosystem services; and the ability to function stably for extended periods (Vymazal, 2019). Furthermore, they have demonstrated their capacity for secondary and tertiary treatment of wastewater and runoff and to guarantee high-quality recycling and reuse of water. However, some problems can still be solved to improve the functioning of the CW, such as the low efficiency of total nitrogen and total phosphorus removal.

The advantages and facilities to build and exploit a constructed wetland have led to a worldwide progressive increase in the use of them because they are an innovative, efficient, and more sustainable alternative to treat wastewater. These wastewater treatment technologies are used in developed countries as in developing countries, in big cities or small communities.

In the Dominican Republic, where problems with urban wastewater treatment is a big concern (De León, 2012), the first constructed wetlands was reported in the Domingo Maíz community, and some others been replicated in Jarabacoa and Vallejuelo, province of San Juan (Emmanuel and Clayton, 2019). However, to the date, there are no works that report the country's experience in the construction and analysis of constructed wetlands. The objective of this work was to design and evaluate the operation of a system for the treatment of domestic wastewater based on a subsurface flow constructed wetland in “El Dorado,” a small community in Jarabacoa, Dominican Republic. This initiative is part of the Yaque Plan's actions to reduce surface water pollution regarding domestic sewage in the Yaque del Norte River Basin (Acosta Guzmán, 2017).

2. Material and methods

2.1. Study area

The domestic wastewater treatment system based on a CW is located in the periurban settlement “El Dorado,” in the municipality of Jarabacoa, Dominican Republic. The location coordinates are 19.123306° north latitude and –70.633472° west longitude at 541 meters above sea level.

2.2. Conceptual bases for wetland design and operating conditions

In order to guarantee an efficient treatment of the domestic wastewater in the study area, it was decided to design a system based on a CW. The system consists of a sewage line, two septic tanks, and a horizontal subsurface flow wetland. The HSSF-CW, since they do not have exposed water in their surface, do not release odors; do not create favorable biotopes for the spread of mosquitoes or other vectors; and avoid risks of accidents to the child population or others who visit the systems or the project area.

When designing a wetland, there are several important elements to consider: a) the feasibility (financing, level of slope, population, available land, community integration); b) the type of wastewater to be treated; c) the methodology for design calculations (flow rates, pollutant loads, hydraulic retention times, volume of septic tanks, area and volume of the wetland); d) species of plant selection (macrophytes, are chosen based on their adaptation capacity to the project area and the development of their root system; generally native species, already existing in the area); e) the selection and placement of the substrate, on which the sustainability of the operation of the system depends, so as to guarantee non-clogging due to obstruction of flow; f) the adequate leveling of the base of the wetland, guaranteeing a homogeneous water level throughout the hydraulic gradient; g) the waterproofing of the land, in this case a 300 micron thick polyethylene geomembrane was used, and, finally, h) the inlet and outlet structures of the water flow to the wetland, which guarantee uniform flow conditions to achieve the expected yields (all were selected from PVC). The design took into account ground conditions and the CW was designed for full gravity flow to achieve low operating costs.

For the CW design, it was taken into account that the system had to guarantee the treatment of 100 liters of wastewater per day per inhabitant, for a community of 75 people. Since it is a peri-urban community, the area for the construction of the system was limited. The CW was built in the land donated by one of the community's residents.

In order to calculate the design and operation parameters, a working algorithm was followed that took into account the principles described by other authors in the literature (Brix et al., 2000; Li et al., 2018; Reed et al., 1995). The daily flow (Q_d) of wastewater was determined by Equation (1):

$$Q_d = P \cdot D \tag{1}$$

Where P is the population served, and D is the per capita water supply. The average flow (Q_m) or hourly flow was calculated from the daily flow according to Equation (2).

$$Q_m = Q_d/24 \tag{2}$$

On the other hand, the peak flow (Q_p) allows the evaluation of the volume of water generated in the time of highest water consumption and is used for the sizing of the conduction lines and the slope degree of the pipes’ line. It is determined from the average flow rate – Equation (3).

$$Q_p = Q_m \cdot \left(1.5 + \frac{2.5}{\sqrt{Q_m}}\right) \tag{3}$$

The peak coefficient is determined as the ratio of the peak flow to the mean flow rate – Equation (4).

$$C_p = \frac{Q_p}{Q_m} \tag{4}$$

In order to take into account the effects of rainfall and runoff, the rainfall peak flow (Q_r) is finally determined, expressed as three times the average flow, according to (Reed et al., 1995), Equation (5).

$$Q_r = 3 \cdot Q_m \tag{5}$$

The pollutant load was determined from the estimated value of COD (Brix et al., 2000; Reed et al., 1995) by Equation (6).

$$COD = \frac{C_e \cdot P}{Q_d} \tag{6}$$

Where C_e is the contaminant load, represented by the results of one or more BOD samples from the flow to be served in the treatment system, usually expressed in mg/L. In order to ensure safe operation of the wetland, the maximum pollutant load was estimated, taking into account the peak coefficient, by Equation (7).

$$CDO_{max} = CDO \cdot C_p \tag{7}$$

Subsequently, the wetland was sized. Initially, the surface area coefficient was calculated – A_s, Equation (8).

$$A_s = \frac{Q_d \cdot \log\left(\frac{C_s}{C_p}\right)}{K_t \cdot h \cdot N} \tag{8}$$

Where C_s is the pollutant load at the outlet of the wetland, which is chosen to meet the standards for discharge of treated water to rivers (ESWC, 2003), h is the height of the wetland, N is the particle size of the porous medium, and K_t is the temperature coefficient which is calculated according to Equation (9).

$$K_t = K_{20} \cdot 1.107^{T-20} \tag{9}$$

Where T is the historical minimum temperature value in degrees Celsius. The characteristic dimensions of the wetland and the hydraulic retention time were then calculated by Equations (10)-(13).

$$w = \sqrt{\frac{A_s}{0.7}} \tag{10}$$

$$L = C_{l/w} \cdot w \tag{11}$$

$$S = l \cdot w \tag{12}$$

$$t_{HR} = \frac{S \cdot h \cdot N}{Q_m} \tag{13}$$

Where w is the width of the wetland, l is the length of the wetland, $C_{l/w}$ is the length/width ratio, determined by the type of wetland to be constructed, S is the surface area of the wetland, and t_{HR} is the hydraulic retention time.

For subsurface wetlands with the horizontal flow, the recommended depth is 0.6 m (Brix et al., 2000; Li et al., 2018; Reed et al., 1995). Wetlands deeper than 0.6 m favor anoxic environments, which are undesirable for wetland functioning (Brix et al., 2000; Reed et al., 1995).

2.3. Sampling and chemical and microbiological analysis

Eight samples were taken at the entrance and exit of wetland, in the period between April 2018 and January 2020. Two liters of each sample were conserved in polyethylene plastic bottles, which were kept at 4°C in the absence of light until analysis. Four parameters were measured: BOD, COD, phosphorus as orthophosphate, and fecal coliforms according to standard methods for water and wastewater analysis.

From the experimental data, the process efficiency was calculated by Equation (14).

$$E = \frac{X_{inlet} - X_{outlet}}{X_{inlet}} \cdot 100 \tag{14}$$

Where E is the efficiency in percent, and X_{inlet} and X_{outlet} are the values of the parameter evaluated at the entrance and exit of the wetland, respectively.

3. Results and discussion

3.1. Characteristics of the domestic wastewater treatment system

Table 1 shows the main characteristics of the "El Dorado" domestic wastewater treatment system. For the design, the maximum value of organic load expressed as COD of 740 mg/L was estimated – Equations (6) and (7).

Table 1. Main characteristics of the "El Dorado" wetland

Parameter	*Description*
1- Population served	75 inhabitants
2- Waste water flow	7.5 m^3/d
3- Number of septic tanks	2 (6 m^3 and 4.84 m^3)
4- Wetland dimensions	l=10 m; w=7 m; h= 0.6 m
5- Wetland area	70 m^2
6- Wetland waterproofing	Geomembrane, 300 µm thick
7- Support	Gravel, 2.2 cm
8- Water/medium ratio	60-40 %
9- Type of macrophyte	Vetiver (Vetiveria zizanioides L.); Average size of roots: 30 cm; Average foliage size: 70 cm

10- Wetland operating time	18 months

Fig. 1 shows the treatment system's conceptual scheme and a photo of the wetland after 18 months of operation. It is important to note that the wetland cost 267 USD per inhabitant, which is higher than this indicator for constructed wetlands and other wastewater treatment systems (2.14-120 USD per inhabitant; (Su et al., 2019)), which can be explained by the small number of inhabitants in the community where the CW was constructed. Nevertheless, at the same time, it demonstrates the willingness of both the inhabitants and the local government to improve the quality of the water discharged into the Yaque del Norte River. On the other hand, the wetland occupies an area of 3.7 m^2/inhabitant, an indicator in the range reported at the international level (0.05-50 m^2/inhabitant; (Su et al., 2019)).

Fig. 1. "El Dorado" wetland. On the left, the conceptual plan of the treatment system and on the right, a photo of the wetland after 18 months of operation

3.2. Efficiency in the removal of organic matter

In order to determine the degradation efficiency of organic matter, BOD5 and COD's behaviors were evaluated. Fig. 2-A shows the variation of BOD5 at the exit of the wetland as a function of BOD5 at the entrance. The dashed line represents 90% BOD5 removal efficiency. As can be seen from the five available values, only one is below that efficiency (85.15%). The mean BOD5 removal efficiency value was 93 ± 5%. This value is in the range of the best reported in the literature (Grinberga, 2020; Vymazal, 2019) and above other works that report yields between 66 and 88% (García-Ávila et al., 2019; Khalifa et al., 2020). It is essential to highlight that, in all cases, the final value of BOD5 is below the limit established in the Dominican Republic for the discharge of used water to rivers (below the red line in figure 2; (ESWC, 2003). As is known, in CWs, the biodegradation is mainly due to the action of the communities of microorganisms present on the filter support or in the rhizosphere of the macrophytes.

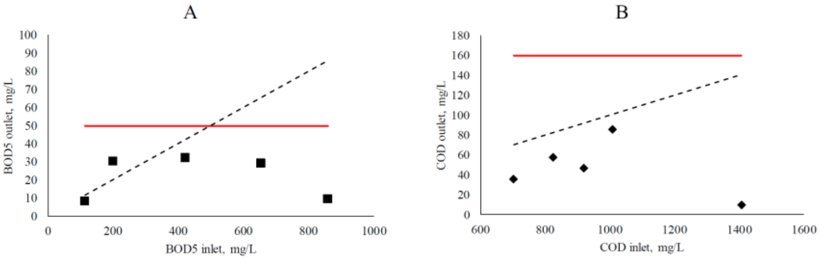

Fig. 2. BOD5 (A) and COD (B) behavior in the "El Dorado" wetland. The dashed lines represent 90% removal efficiency; the values below these lines have efficiency higher than 90%. The solid red lines represent the river discharge standard approved in Dominican norms

As for the BOD5, the organic carbon removal efficiency can vary between 40% and more than 90% depending on the climatic conditions, the stage of plant growth, and fluctuations in the quality of the wastewater at the facility entrance. As shown in Figure 2-B, in all cases, more than 90% yield is observed for an average value of 95 ± 3%. These values are also in the range of the highest reported, both for horizontal subsurface flow wetlands and for hybrid wetlands and above of other reported (71-88%) by several authors (García-Ávila et al., 2019; Khalifa et al., 2020; Vymazal, 2019). The standards established by the regulatory authorities for the discharge of water into rivers are met (ESWC, 2003). An important aspect to note is that, although the constructed wetland was designed for a maximum COD load of 740 mg/L, the system was able to respond efficiently and effectively to higher loads between 824 and 1408 mg/L. Therefore, we can conclude that the designed system responds efficiently to the removal of organic matter.

3.3. Efficiency in phosphorus removal

The phosphorus is one of the macronutrients present in wastewaters. In the form of phosphate, it is crucial for the growth of plants, but its levels in the waters must be controlled to avoid eutrophication. Phosphate removal in CWs is carried out mainly by absorption with plants and transformation by microorganisms (Khalifa et al., 2020). The effectiveness of this process varies between 30 and 70%, depending on the characteristics of the wastewater and the media used (García-Ávila et al., 2019; Khalifa et al., 2020), and it can reach very high efficiencies of over 90% in hybrid wetlands. In this case, the phosphate removal efficiency was between 11-70%, with an average of 44 ± 23%. As Fig. 3 shows, in all cases, the phosphate concentration is higher than the value established in the Dominican regulations for the discharge of effluents into rivers (the eight points studied are above the red line: 2 mg/L). The CWs do not have efficient mechanisms for phosphorus removal, except the macrophytes, which use small amounts of this nutrient for their biological functions. A solution to increase the elimination of phosphorus is in the choice of an adsorbent substrate such as zeolite, dolomite, limestone, and apatite or the combination of wetlands with biochar filters (Li et al., 2018).

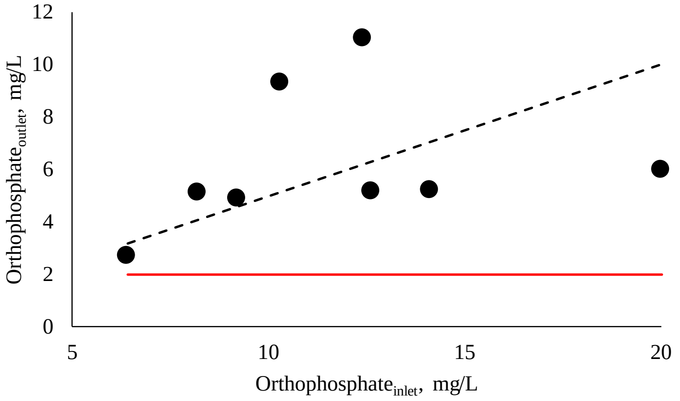

Fig. 3. Phosphorus concentration of orthophosphate in the "El Dorado" wetland. The dashed line represents 50% efficiency; the values below that line have efficiency values higher than 50%. The solid red line represents the river discharge standard approved in Dominican norms

3.4. Efficiency in the removal of pathogens

One of the objectives of wastewater treatment is to achieve a quality effluent that allows the reuse of water. For this, it is essential to guarantee the elimination of the microbial load present in the wastewater. In constructed wetlands, pathogen elimination is accomplished through the combination of physical, chemical, and biological processes. Among them, we can cite the filtration and adsorption of microorganisms in the roots of the plants and the filter support; the oxidation, thanks to dissolved oxygen or exposure to biocides excreted by some plants (Khalifa et al., 2020). Fig. 4 shows that despite the high initial load of pathogens in the incoming wastewater, removal efficiencies greater than 90% were achieved in all cases (all points are below the continuous line with a mean of 98 ± 2%).

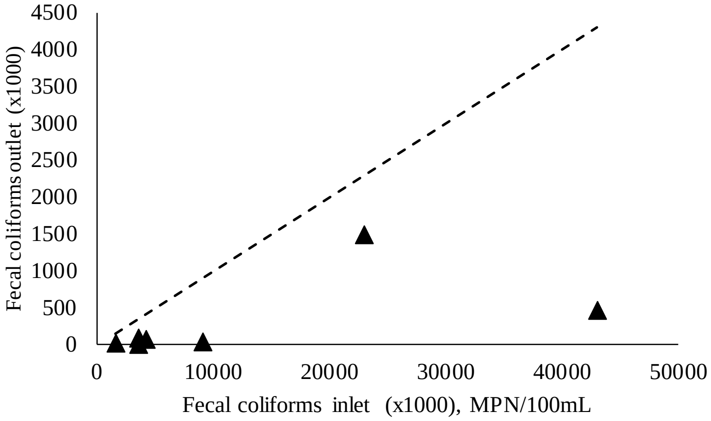

Fig. 4. Behavior of total coliforms in the "El Dorado" wetland. The dashed line represents 90% efficiency; the values below that line have efficiency values higher than 90%

These are high values compared to those reported by other authors (Khalifa et al., 2020). However, despite the high efficiency, it was not possible to comply with the value established in national regulations (ESWC, 2003) for the discharge of effluents into rivers. As with phosphorus, CWs do not have an efficient mechanism for removing pathogens (fecal and total coliforms). Fecal and total coliforms are removed by chlorination and UV radiation, systems that require a high cost of installation, maintenance, and operation. Although, another alternative would be filtration through infiltration systems or incorporation to the biofilter system.

3.5. Other considerations on the operation of the horizontal subsurface flow wetland in "El Dorado"

The meteorological conditions at wetland site, during the studied weeks, behaved very stable, around 23ºC and 84% relative humidity, with minimal variation between the daily minimum and maximum temperature, and a variation of just 4 ºC, approximately, between the weekly temperature averages of the week with the lowest and highest average temperatures. On the other hand, there was not practically rainfall those weeks (only the first week of sampling was rainy). Therefore, we can conclude that the possible influence of the variation of meteorological conditions on the results of the measurements made is negligible.

It is important to highlight other benefits derived from the installation of the domestic wastewater treatment system in the periurban area "El Dorado." The system was successfully incorporated into the local environment where it was built, improving its aesthetics. In its 18 months of operation, local population has not reported no emission of harmful odors or the presence of mosquitoes or other vectors.

Taking into account the international experience and our own experience, we will refer to some lessons learned in this work. The filler material should be chosen with care and always opt for washed gravel without contamination (silt, clay, or other geological or artificial contaminants) or other adsorbent materials that aid in the removal of phosphorous. The support granulometry must be greater than 1.5 cm to guarantee adequate hydraulic flow. In our case, we use a 2.2 cm grave, and there was not any difficulty with the flow in the system. The height of the wetland should be between 0.6 and 0.8 to guarantee proper operation and facilitate maintenance. On the other hand, it is necessary to underline the importance of trained personnel responsible for monitoring the operation of the waste treatment system. Finally, to solve the pathogen elimination efficiency, it should try to bring the outflow to an infiltration system after CW.

4. Concluding remarks

The construction of the domestic wastewater treatment system based on a horizontal subsurface flow wetland in the periurban zone “El Dorado,” Jarabacoa, Dominican Republic, guaranteed an efficient elimination of COD, BOD, and fecal coliforms, with average removal of 93, 95 and 98%, respectively. Regarding the elimination of phosphates, 44% elimination was reached. Although this value is in the range reported in the literature, it can be considered a low one. The system proved to respond to its design capabilities by achieving efficient and effective removal of loads higher than designed for COD. Regarding the quality indicators, the effluent water complied with the established Dominican standards for BOD and COD, but not for phosphate and fecal coliforms. Therefore, we have to do some efforts to solve these problems, probably through adjustment of retention time, evaluation of other species of macrophytes, or combining CW with other secondary and tertiary treatment processes.

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