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Constructed Wetland Pilot System in Semi-arid Northeast Brazil Used in the Post-Treatment of Anaerobic Effluents.

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Abstract. This study was conducted in Nova Redenção, Bahia State, northeast Brazil. This city, as well as others in Brazil, has serious environmental sanitation problems. One factor that complicates the resolution of the sanitation problem is a lack of financial and human resources. Studies and improvements in technologies for the simplified treatment of domestic effluents are in line with the peculiarities of these locations are also important topics for current research. The objective of this study was to evaluate the start of the system of treatment of domestic sewage which was composed of a septic tank with a coupled anaerobic filter followed by constructed wetlands. After eleven weeks of monitoring there was 85% COD removal, 86% BOD_5 removal and 90% TSS removal. In addition, the amounts removed of ammoniacal nitrogen, of total phosphorus and of soluble phosphorus were 25%, 36 % and 40%, respectively. The removal of *E. coli* was recorded at 2.1 logarithmic units. The sand used--of very fine particle size--particularly affected the hydrodynamics of the constructed wetlands, creating a sheet of water on the support material. It reduced the hydraulic detention time of the constructed wetlands, which may be associated with low efficiency.

Keywords. constructed wetlands, post-treatment of anaerobic effluents, septic tank

INTRODUCTION

In poor locations, it is impractical to install sophisticated systems for collecting and treating effluents. A simplified technology for sanitation should be included in the technical, academic and political-administrative agendas of countries like Brazil. CHERNICHARO (1997) reported that with a sanitation deficit in developing countries, there is a need for simplified systems of collecting and treating effluents. According to ANDRADE NETO and CAMPOS (1999), given the environmental, cultural and economic conditions in developing countries, solutions that are fundamentally simple are those that use "more natural" procedures and reactors that are less mechanized and easier to construct and operate.

Among the simplified technologies, septic tanks are an attractive option. Studies regarding the use of these units demonstrate the need for post-treatment of the effluent, since it usually does not meet standards of release into bodies of water (KOOTTATEP, 2004; ANDRADE NETO et al., 1999). This implicates the need for another simplified post-treatment system. Constructed wetlands are attractive options for the post-treatment of effluent from anaerobic septic tanks. These advantages include the low cost of installation and easy operation (UNEP, 2004); however, they require large areas (BRIX, 1993).

This study aimed to design constructed wetland systems for use in post-treatment with septic tanks followed by coupled anaerobic filtering. The system was evaluated in terms of the removal of organic matter, solids, nutrients (N and P) and *E. coli* over a period of eleven weeks.

METHODOLOGY

Nova Redenção, the city in which a pilot plant was constructed, is located in the state of Bahia, in region of the Chapada Diamantina in the Paraguaçu River Watershed. The city has the 69th worst Human Development Index (HDI) of Bahia, a state that already has a low HDI. It is situated in the Poligono das Secas (an area that suffers from frequent droughts). It is located at 12^0 46' S and 41^0 22' W and its elevation reaches 580 m. It is characterized by a transitional climate that exists between tropical-humid and semi-arid, with minimal precipitation, low humidity and considerable evaporation. The annual precipitation is around 500 mm. The annual average temperature is 23.6 ºC according to Silva and Azevedo (2000). The latter paper obtained the hydric index for the municipality (Hi = -10.9, for an available water capacity of 125 mm) and observed that this town is located in areas associated with extended periods of drought.

General description of the studied units

The pilot system of domestic effluent treatment comprised a septic tank coupled with a filter executed in masonry with an impermeable internal coating. After the septic tank, two constructed wetland zones of sub-superficial series flow were installed (CW1 and CW2). The wetland tanks were excavated and coated with PVC geo-membranes with a nominal thickness of 1.00 mm and a weight of 1,300 g.m^{-2}. The macrophyte used was Tifton 85 (*Cynodon spp*.). The planting density was approximately fifteen plants per square meter. We used washed sand, the only material available in the district that was reasonably affordable. The treatment units in the pilot plant were installed as shown in Figure 1. The system was fed by PVC (100 mm) pipes from the collecting network.

Table 1 shows the main characteristics of the sand that was used as a substrate for the constructed wetlands.

Figure 1: Schematic of the pilot unit

Table 1: Characteristics of the sand

Particle size	0.074 to 2.000 mm
Specific diameter (D_{10})	0.150 mm
Coefficient of uniformity (D_{60}/D_{10})	2.66
Porosity	51%

Evaluation of Control Parameters

The system was monitored based on the following control variables: electrical conductivity, sodium, calcium and magnesium content, the temperature, pH, the presence of solids, COD, BOD_5, nitrogen series, the total and soluble amounts of phosphorus and finally, concentrations of *Escherichia coli*. Monitoring of the physiochemical and bacterial variables followed the directions in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005). All laboratory analyses were performed by the National Service of Industrial Learning (SENAI) and the Industrial Technology Center Pedro Ribeiro (CETIND), in the city of Lauro de Freitas, in Bahia, Salvador, about 430 km from Redenção-BA.

Samples were collected at 9 am, 12 pm, 3 pm and 5 pm, at the points indicated in Figure 1. The sampling frequency was weekly. The samples for our microbiological analyses were collected at 6 pm., this time was established according to the sample validity. On the days of sampling, the pH profile, temperature (pH meter model 206 by Lutron) and turbidity (Turbidimeters Plus Alfakit) were also measured in the affluents and effluents of the treatment units. The flow was measured regularly at the entrance and exit points of the units throughout the day, every fifteen days. The monitoring period spanned May to August 2008.

Hydrodynamic testing

Hydrodynamic testing used sodium chloride (NaCl) as a tracer under a pulse testing paradigm. NaCl was chosen primarily because it is easily obtained in the municipality. The tracer was prepared by dissolving 12 kg of NaCl in 24 liters of water. A single pulse was released in the system affluent.

However, our tracer dilution protocol was ineffective because the product was of poor quality and contained large NaCl crystals that could not be diluted. The non-diluted material was collected and its dry weight (2,102 km) was discounted from the expected dilution. Thus, the final tracer dilution was 412 g L^{-1}. DANTAS *et al.* (2000) utilized a tracer solution with a concentration of 320 g L^{-1} for an anaerobic filter with a volume of 3.36 m^3. The approximate volume of the septic tanks was 36.0 m^3.

After the tracer solution had been injected, effluent samples were collected from each unit at regular intervals of one hour over a period of six days. Electrical conductivity (EC) readings were taken using a condutivimeter Marconi brand MACA150P monitoring system. The NaCl concentration was obtained from the equation for the resulting conductivity calibration curve. From the NaCl concentration curve, the axial dispersion number, the hydraulic detention time and the variance were calculated. Equations from LEVENSPIEL (1974) were used.

RESULTS AND DISCUSSION

Quantitative characterization of the gross inflow

The average inflow was 7.0 m^3 day^{-1}. This is very low compared to the expected system inflow (8.22 m^3 day^{-1}). To achieve the latter flow rate, effluent was collected from 57 residences, housing about 213 individuals. The system inflow features three peaks during the day. One is in the early morning, another at midday and the third during the late afternoon. The higher median is in the morning and the variation of the values around them is also more evident during this period.

Given this flow data, we calculated the average daily hydraulic load on the constructed wetlands, and we found that it ranged from 35 to 74 mm d^{-1}. These hydraulic load values are less than data from MBULIGWE (2004), where a hydraulic load of 149 mm d^{-1} was used in treating similar effluent. The loads applied to the constructed wetlands in our study are higher than those of COOPER et al. (1996 and 2001) and KADLEC et al. (2000), whose studies were conducted in more temperate climates.

The average outflow was 4.6 m^3 d^{-1}. Approximately 34% of the entrance volume was lost due to evapotranspiration.

Qualitative characterization of the gross inflow

The domestic sewage affluent in the pilot STS featured the characteristics listed in Table 1.

The average values of BOD_5, COD, ammoniacal and organic nitrogen and the total and soluble phosphorus were elevated, indicating a concentrated sewage which typical of small communities. It is a suspected that the elevated values of the nitrogen forms are due to clandestine butcheries located among the residences in the network. Table 3 shows the superficial loads applied on the wetlands.

To calculate the superficial loads applied to the second wetland, the average concentrations of the chemical variables in the effluent of CW1 were considered; concerning the flow, a water loss of 17% of the septic tank inflow was considered. On the wetlands, there was a water loss of 34% (see item 3.1) due to evapotranspiration.

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Table 2: Characterization of domestic sewage tributary in the pilot STS

Parameter	**Unit**	**Number of samples**	**Gross Effluent (average)**	**Standard Deviation**
pH	-	6	7.61	± 0,14
Temperature	ºC	11	27.19	± 0,68
Total alkalinity	mg $CaCO_3$ L^{-1}	11	528	± 203
COD	mg L^{-1}	11	966	± 416
BOD_5	mg L^{-1}	11	389	± 170
Sodium (Na)	mg L^{-1}	11	170	± 24
Calcium (Ca)	mg L^{-1}	11	52	± 34
Magnesium (Mg)	mg L^{-1}	11	13	± 2
Total Solids	mg L^{-1}	11	1087	± 195
Suspended Solids	mg L^{-1}	11	126	± 129
Sedimentables Solids	mL L^{-1}	11	1.0	± 3
Total Phosphorus	mg L^{-1}	11	16	± 4
Total Soluble Phosphorus	mg L^{-1}	11	13	± 5
Escherichia coli	UFC $100^{-1}mL^{-1}$	10	$3.7x10^7$	± 2.4×10^7
Ammoniacal Nitrogen	mg L^{-1}	11	94	± 36
Organic Nitrogen	mg L^{-1}	11	22	± 17
Electrical conductivity	µS/cm	11	1832	± 293

Table 3: Surface loads applied in the system of constructed wetlands

	gCOD m^{-2} d^{-1}	$gBOD_5$ m^{-2} d^{-1}	gN-Amon m^{-2} d^{-1}	gN-Org m^{-2} d^{-1}	gTP m^{-2} d^{-1}	gTSP m^{-2} d^{-1}
CW 1	31.4	12.5	8.9	2.0	1.4	1.2
CW 2	9.7	3.7	6.2	1.8	1.0	0.9

The superficial organic loads applied on the first, as well as on the second wetland, in terms of COD and BOD_5, shown in Table 2, are within the range that was used successfully by VALENTIM (2003). Yet SOUZA et al. (2004) used lower values, ranging from 5.01 to 9.45 gCOD m^{-2} d^{-1}. All these authors treated anaerobic effluent.

Performance of the system in the treatment of domestic effluent

Temperature and pH

The gross sewage had an average temperature of 27.19 ± 0.68 °C and the septic tank effluent had a temperature of 27.20 ± 0.87 °C. CW1 and CW2 showed average effluent temperatures of 26.81 ± 1.99 °C and 25.54 ± 2.19 °C, respectively. The average pH of the gross effluent was 7.6 ± 0.1 and the effluent from the septic tank was lower (7.0 ± 0.1), probably because of the production of organic acids in the process of anaerobic digestion. The pH of the constructed wetlands effluent was higher: 8.1 ± 0.2 for CW1 and 8.6 ± 0.1 for CW2. The higher pH for the constructed wetlands effluent can be explained in terms of CO_2 consumption by algae that were in the small water sheet that formed alongside the two units. Generally, the pH of the effluents was stable; the chemical reactions and the biological processes offered stability for the removal of pollutants.

Organic matter and total suspended solids

The organic matter was removed from the septic tank, which had a removal efficiency that averaged 68% in terms of COD and BOD_5. After the first week of monitoring, there was a rapid stabilization of organic matter removal in the septic tank and in CW1. Until the eighth week of monitoring, the CW2 had BOD and COD_5 effluent values that were higher than its affluent, due to operating failures. The overall efficiency in terms of the removal of organic matter was 86 ± 8% for COD and 85 ± 11% for BOD_5. The septic tank had a removal efficiency of 57% of TSS. The first constructed wetland had an additional removal of TSS that reached 68% and the second constructed wetland had an additional TSS removal of 29%. The overall efficiency of the system for TSS was 90%.

Ammoniacal Nitrogen and Phosphorus

N-Amon removal efficiency was 25%, a disappointing result. Other papers, such as CALIJURI et al. (2007) have showed more satisfactory data for the removal of N-Amon. The overall efficiency of phosphorus removal was 36% for total phosphorus and 40% for soluble phosphorus.

E. coli

During the monitoring period, both constructed wetlands exhibited low efficiency in terms of *E. coli* removal. Their efficiency was even weaker than the efficiency of the septic tank. Low efficiency can be attributed to the incomplete establishment of the macrophyte colony. For example, CALIJURI et al. (2007) and SOUZA et al. (2003) reported that constructed wetlands with macrophytes tend to have greater efficiency in the removal of fecal contamination. VALENTIM (2003) found low values of *E. coli* removal, even with well-established macrophytes. VALENTIM (2003) concluded there is a limitation on the efficiency of *E. coli* removal in these systems with hydraulic detention times that lasted less than six days. Depending on the final destination of the effluent, a post-treatment protocol such as disinfection may be necessary.

Table 4 summarizes the efficiency for each unit as well as for the overall system.

Table 4: Summary of the efficiency for each unit and for the overall system.

Parameter	Efficiency of the ST**	Efficiency of CW1	Efficiency of CW2	Overall Efficiency
Total alkalinity	-21%	6%	10%	-2%
COD	68%	63%	-17%	86%
BOD_5	68%	64%	-30%	85%
Suspended solids	57%	68%	29%	90%
Total phosphorus	10%	13%	18%	36%
Total soluble phosphorus	10%	9%	27%	40%
Escherichia coli	1.4*	0.4*	0.3*	2.1
Ammoniacal nitrogen	5%	16%	5%	25%
Electrical conductivity	-2%	4%	7%	9%

* removal in logarithmic units.

** ST – septic tank.

Hydrodynamic testing in our constructed wetlands

The real HDT estimated from the test was 2.4 days and 2.5 days for constructed wetlands one and two, respectively. Those times were higher than predicted (1.2 days for each constructed wetland).

The effluent electrical conductivity for the constructed wetlands did not return to the initial hydrodynamic testing levels, even after 150 hours of monitoring. It only reached the lower and more stable levels, as shown in figures 4 and 5. The actual residence time of the tracer in the constructed wetland was greater than the monitoring time. The calculated hydraulic detention times (2.4 and 2.5 days) are lower than the real values.

The high values of variance (1687.7 and 1682.2 for constructed wetlands one and two, respectively) represent a strong dispersion in the concentration values. This was caused by concentration increases during the day and reductions at night.

Figures 4 and 5 show the EC curves from hydrodynamic testing. There was a rise and a fall in EC during the day and at night. These figures also show that, on the third day of monitoring, at around 53 hours after the start of our test, a storm caused a sudden dilution of the effluent from both of the constructed wetlands. After the rain, the EC values increased again during the day, and at night, there was another reduction.

The shaded areas in the graph demarcate the nighttime periods. The first two areas are wider; they refer to the EC monitoring periods at measurement intervals of one hour. After 56 hours of monitoring, the measuring intervals passed to two hours and the following areas were narrower in Figures 4 and 5.

A layer of sewage approximately 2 cm deep flowed over the substrates in both constructed wetlands. The support material is sand with a low index of emptiness and a high uniformity coefficient. In the future, a layer of gravel should be added to better distribute the fluid to the constructed wetlands. In fact, a layer was placed just around the pipes where the effluent was distributed and collected. This did not generate a suitable flow distribution, and instead created paths of least resistance. SHUT (2001) stated that, in such systems, the overload leads to superficial flow over the support material, which can reduce system efficiency.

The constructed wetlands operated in the context of daytime soil runoff. At night, the inflow decreased substantially, and the wetlands started to unload the flow that was "saved" during the day into the substrate. Therefore, the EC decayed in the evening. The water sheet generally increases over time as the substrate saturates. This is due to the particle dimensions of the sand used.

This test allowed us to verify what we already observed in the constructed wetlands. It was not possible to calculate the variance and axial dispersion due to the peculiarities of our constructed wetlands. The small diameter of the sand caused the formation of a water sheet above the support material at times of greatest inflow. Also, precipitation during hydrodynamic testing made the calculation of those parameters inviable.

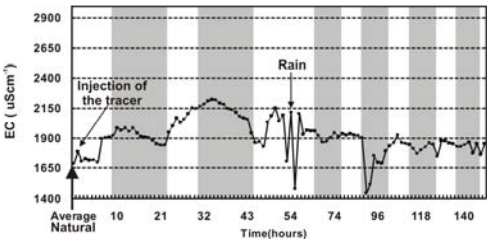

Figure 4: Electrical conductivity curve generated during hydrodynamic testing in CW1.

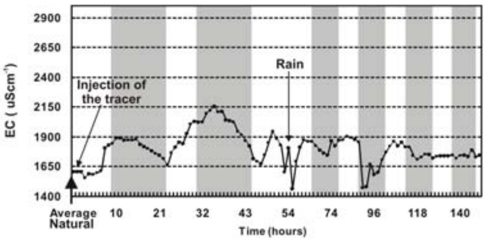

Figure 5: Electrical conductivity curve generated during hydrodynamic testing in CW2

Costs

Our system had a total installation cost of approximately US$10,440.00. This corresponds to a cost of US$41.70 per capita. Operating costs include at least two workers who perform general maintenance of the system.

CONCLUSIONS

Constructed wetland systems are appropriate for the post-treatment of anaerobic effluent from septic tanks. For communities with characteristics similar to those presented in this study, it is remarkable that the constructed wetlands can still be easily constructed and operated.

The treatment system study exhibited the following results for an eleven-week trial: 85% average removal of COD, 86% average removal of BOD_5 and 90% TSS removal. The removal of ammoniacal nitrogen, and the total and soluble phosphorus measured 25%, 36 % and 40%, respectively. The removal of *E. coli* was 2.1 logarithmic units.

The sand used exhibited a very fine particle size - this may have affected the hydrodynamics of the constructed wetlands by causing a water sheet to form over the support material. This reduced the hydraulic detention time of the constructed wetlands and may have negatively impacted system efficiency.

Acknowledgments

The authors acknowledge the financial assistance provided by the National Council for Scientific and Technological Development, CNPq (process N^0 500075/2006-9).

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