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Water Budget of Constructed Wetland System with Subsurface Vertical Flow in Sub-Humid Tropical Climate

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Abstract: This study evaluated, over a period of 98 days, the water budget of a constructed wetland with vertical subsurface flow for treatment of septic waste in sub-humid tropical climate. It was implanted an experimental station that consisted of two treatment cells with about 20 m² each. One was planted with Vetiver Grass (*Chrysopogon zizanioides*) and the other remained without vegetation to act as witness. Input volumes and liquid exit of each bed were measured. In a planted cell, 38.35% of the net that has entered was retained or evapotranspirated and 61.65% was drained. The control cell showed 16.30% of retention/evaporation and 83.70% of liquid drainage. The planted cell had greater reduction in the net infiltration capacity and increasing of humidity of surface sludge, while the control cell had higher sludge drying capacity. In general, the retaining and releasing water to the atmosphere in planted system was almost twice more than that found in no planted one.

Key words: roots zone, sludge dewatering, evapotranspiration

1. Introduction

Natural wetlands are widely used in the treatment and disposal of polluted water from various sources. Water flow on these environments varies depending on factors such as local climate, hydrodynamics of the system, physiology of plant species present, characteristics of the effluent to be treated, among others [1].

Water budget in natural wetlands used in the treatment of wastewater is measured by the principle of mass conservation in the system, matching the input and output volumes. As input variables: volume of liquid to be treated, rainwater drained through the soil which enters in the system, groundwater contribution and the directly precipitate volume. And as output values: treated liquid fraction, water seepage into the soil and the evapotranspirated volume [2].

As natural flooded areas, the built environment, called constructed wetlands (CW) systems and most commonly used in wastewater treatment, it has similar hydrological behavior. However, as CW aim to simulate the natural environment under controlled conditions, its water budget may have several variations.

The understanding of the hydrological behavior of CW is paramount important element to its proper sizing, deployment and operation, aimed mainly improvement and application to local characteristics [3].

One of the major differences in the design of CW compared to conventional wastewater treatment systems is the consideration of evapotranspiration in the project parameters. A significant loss of water resulting from this process should be considered in its design as it mainly changes the hydraulic behavior of

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the system, and cause changes in the concentration of pollutants in wastewater [4].

Evapotranspiration in CW depends on factors such as wind speed, humidity, temperature, atmospheric pressure, solar incidence and characteristics of vegetation used.

The water intake volumes from the rainfall and rain water drained by the soil surface should also be considered in the design of CWs calculations, since these factors can cause temporary rise in the water level in the system, changing hydraulic performance and efficiency of the treatment [5].

Several methods, direct and indirect, of measurement of the hydrological behavior in flooded areas have been proposed to take a better understanding of the phenomena involved and linking them to the best way of managing these environments [6]. However, studies are still limited, mainly because of the diversity of variables (temperature, atmospheric pressure, humidity, solar radiation, etc.) involved in the hydrologic process.

The practical application of the data obtained by the studies already developed is quite restricted to local conditions in which where conducted the experiment, especially under the weather conditions [7], which are generally different from Brazil. Thus, it is needed to research at the local level, according to the reality and needs of each region of Brazil, which produce knowledge and propitiate its practical use.

This study aimed to describe the hydrological behavior of a constructed wetland system of descending vertical subsurface flow, designed to treat septic waste in a region of sub-humid tropical climate.

2. Experimental

A septic waste (SW) experimental treatment plant was implanted, with two cells (Fig. 1). One of them was vegetated with Vetiver Grass (*Chrysopogon zizanioides*) and the other cell remained without vegetation to serve as witness.

Fig. 1 Constructed Wetland Experimental Cells for Treating SW

2.1 Configuration, Size and Substrata

Cells were dug into the ground, with waterproof PVC canvas and filled with overlapping substrate layers. From the bottom to the surface, 40 cm of gravel #0, 15 cm of gravel #1 and 10 cm of medium sand (Fig. 2) were used, totaling 65 cm of supportive environment. Above the bed surface treatment, it was allowed a free edge of 55 cm for storing SW during applications. Each cell was constructed as a truncated inverted pyramid with dimensions of 3.0 m × 4.0 m in lower base, 4.15 m × 5.15 m in high base and 1.20 m in total depth.

At the bottom of the two cells, tubes to drainage leachate and gases ventilation were installed.

Planted cell received twenty seedlings, spaced about 60 cm apart.

Considering the average diameter of 25 cm from each clump and the area of the CW, the planted surface density was 1 plant/m².

On the outside of each drainage system it was installed a hydrometer to measure the effluent volume, a sample collector for sampling the treated liquid, a vertical pipe, to control the internal liquid level in cells and a flow control for emptying the cells (Fig. 3). The liquid level was maintained at about 10 cm below the surface of the substrate in order to maintain the subsurface flow, avoiding direct contact of the liquid with the atmosphere.

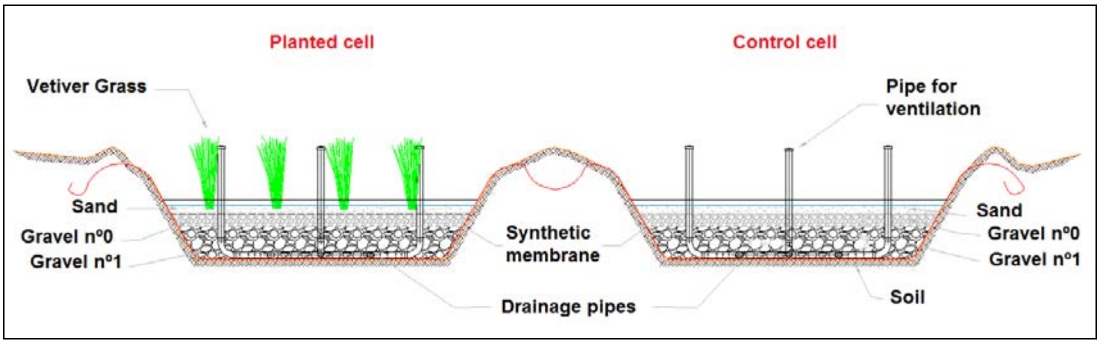

Fig. 2 Cross Section of the Implanted Representative Experimental Station

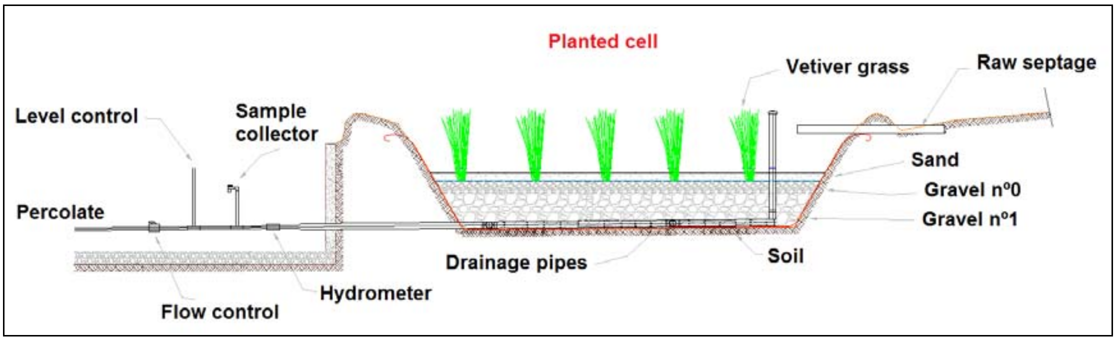

Fig. 3 Representative Longitudinal Section of the Hydraulic System of the Experimental Treatment Plant of SW

During application of SW in both cells of treatment, the atmosphere (through substrate) was deemed unsaturated, because the introduction of air and then oxygen, favoring the aerobic reactions and faster treatment of waste. Also during the filling period of the cells to the control level, the environment can be considered unsaturated. Only after reaching the control level and the liquid fill all the spaces, once occupied by the air, the waste treatment environment became under saturated conditions.

2.2 Application of SW

Feeding cells occurs in batches, applying an average of 3.3 m³ of SW per cell weekly by the depletion of trucks "clean drains". The average application rate of solids was 34.36 kg TS.m^{-2}.$year^{-1}$. The average volumetric rate was 0.165 m³.m^{-2}. $week^{-1}$.

In the trucks running out, the residue was arranged in a receiving box that was grating (mesh 2 cm × 2 cm) and drained equally to the treatment cells by gravity.

Inside the cells, the residue fell on a concrete block, dissipating its energy, spread by surface and percolating slowly. The solid material was filtered off and accumulated on the surface of the bed after each application. The liquid fraction percolated filling the voids of the substrate to reach the control level. The surplus was drained by control level pipe.

After six days of application, the emptying of treatment beds upon opening the records was proceeded. Thus, the hydraulic retention time (HRT) was 6 days. The liquids were completely drained and their volumes measured by hydrometers. In the next day, further application was performed. This cycle was repeated for a period of 98 days (May, April and June) consecutively, totaling 14 applications.

A barrier of bags filled with soil was built around the beds of treatment, in order to prevent the entry of rainwater runoff in the system.

Application rate of SW showed highest variability (4.49 to 100.17 kg TS.m^{-2}.$year^{-1}$) of total solids content, as characteristic of this type of residue.

Also as an input value, the accumulated rainfall during the week was added. Output volumes consisted of treated effluent and evapotranspirated and evaporated volumes, in planted and control cells, respectively.

2.3 Water Budget Calculation

To evaluate the water balance associated with each cell, procedures for measuring the input and output fluid volumes were carried out.

SW input volumes were estimated by weighing the trucks before and after discharge process. Thus, there was obtained the value of the mass exhausted. Residue samples were collected to determine their specific mass and subsequent calculation of the input volume of SW in cells.

Rainfall was measured by a rain gauge, installed next to the experimental station. Precipitated volumes were measured for each cycle of the operation.

Based on precipitation data and surface areas, the rainwater contribution volumes for each treatment bed were calculated. Evaporation (EP) or evapotranspiration (EPT) volumes of the systems (control and planted, respectively) were calculated using water balance (input volume equal to the volume of output), according Equation (1).

$$\text{EPT } or \text{ EP} = R + I - O - SU \quad (1)$$

EPT (m^3) = Evapotranspirated volume;
EP (m^3) = Evaporated volume;
R (m^3) = Rain volume;
I (m^3) = Inflow septic waste liquid volume;
O (m^3) = Outflow septic waste liquid volume;
SU (m^3) = Liquid volume in accumulated sludge.

Effluent volumes of the systems were measured by hydrometers (Fig. 4). Water meter standard were used. The records remained open until the flow was insufficient to rotate the pointer meter. At this time the records were closed.

Water retained in the surface layer of the substrate was calculated by analyzing the moisture content of the accumulated sludge. Each sample, taken to the laboratory, consisted of 5 sub-samples collected at random in each cell. Retained water volume was calculated by multiplying the accumulated sludge volume (layer thickness x surface area of the treatment cell) by the percentage of humidity.

Fig. 4 Water Meters Used for Measuring the Net Volume of the Cells Output

Thickness of the accumulated sludge layer before each application was measured using a graduated scale. An arithmetic mean of 10 measurements was carried out at random in each bed.

Accumulated sludge moisture and thickness of slime layer on the substrate surface were monitored during SW application period and four weeks after the last one.

3. Results and Discussion

Unlike natural systems, water behavior in CW is partly controlled by human interests. In the present experiment, the input streams and underground water flows from the system does not exist, since both treatment beds were sealed.

Waterproofing of CW is important because it eliminates the exchange of water between the system and the external environment; prevent environmental contamination or alteration of the hydraulic behavior and system efficiency

In this sense, the water balance has been given only to the volumes of applied SW and rainfall, as input values, and the volumes of treated effluent, water accumulated in sludge surface and evapotranspired water (in planted cell), as output values.

Influence of local climatic conditions is fundamental to the hydrological behavior and efficiency in pollutants removing in the CW [8]. Warmer climates while favoring evaporation of rainfall values contribute to increasing the input volume.

During the experiment rainfall was recorded at weeks 1, 2, 3, 8, 9 and 10 values with 38 mm, 22 mm, 72 mm, 13 mm, 0.5 mm and 37 mm, respectively. In the other weeks there was no rain. Temperatures remained with averages ranging between 16°C and 30°C, characteristics of sub-humid tropical climate.

The water balance of the treatment beds are shown in Table 1 (planted and control bed).

Table 1 Evapotranspirated (EPT), Evaporated (EP) and Liquid Output Volumes in Both Cell Treatment

	Planted cell			Control cell		
Week	**EPT (m^3)**	**EPT (%)**	**Outflow (%)**	**EP (m^3)**	**EP (%)**	**Outflow (%)**
1[a]	0.02	0.40	99.60	0.01	0.20	99.80
2[a]	2.11	40.73	59.27	0.94	18.15	81.85
3[a]	0.23	8.06	91.94	0.02	0.67	99.33
4[a]	0.51	33.00	67.00	0.18	11.33	88.67
5[a]	0.96	30.34	69.66	0.08	2.47	97.53
6[a]	1.25	30.54	69.46	0.61	14.94	85.06
7[a]	2.02	45.51	54.49	0.40	9.00	91.00
8[a]	1.87	57.83	42.17	0.86	26.43	73.57
9[a]	1.12	42.91	57.09	0.74	28.35	71.65
10[a]	2.10	67.10	32.90	1.15	36.69	63.31
11[a]	2.93	63.89	36.11	0.83	18.10	81.90
12[a]	1.05	39.77	60.23	0.85	32.09	67.91
13[a]	1.97	52.29	47.71	0.70	18.52	81.48
14[a]	0.41	24.55	75.45	0.19	11.32	88.68
Media	1.32	38.35	61.65	0.54	16.30	83.70

Input volumes were the same for both treatment beds. However, the output values of the effluent, measured by hydrometer, were always higher in the control than in the planted cell. This fact is justified mainly by the ability the vegetation has to transfer system water to the atmosphere through the process of transpiration. Planted bed releases into the atmosphere much more water than no planted cell kept under the same weather conditions. In addition, another important factor to be noted is the planted system’s ability to retain moisture, evidenced by the increase of moisture content and thickness of the slugde surface layer.

Evapotranspirated volumes in planted cell were higher than evaporated in control, reaching a maximum of 67.10% of the input volume compared to the peak of 36.69% of the volume in cell without plants. On average, the bed with plants released into the atmosphere or retained in their environment approximately 38.35% of the liquid entering in the system. But the tank without plants had an averaged evaporation of 16.30%, almost half of planted cell.

The increased water retention capacity of the planted tank was evidenced by increased humidity of the sludge retained on the tank surface. Table 2 shows the temporal variation of moisture accumulated sludge in both tanks.

After two applications, sludge layer increased in surface of both tanks, as the solids contained in the residue were filling the voids of the substrate surface. Thereafter, the thickness of the surface layer of mud varied depending on the applied rate and the sludge moisture, reaching a maximum value of 36 mm for the planted tank and 29 mm for the controlled one.

Ceased the residue applications, after the 14th week, the thicknesses of the layers of slime decreased both tanks, as a function of moisture loss and lack of rains in place and stabilized average values of 32 mm in planted tank and 27 mm for the control.

The increased evaporation rate in control cell directly influences the drying (and consequent reduction in the thickness) of the accumulated layer of sludge in the system [9].

Whereas the surface area of the two cells, the thicknesses and moisture contents of the accumulated sludge layer were increasing more in planted cell. It was estimated that the water retention capacity of the system planted increased considerably in relation to no planted environmental (Table 3).

Table 2 Temporal Variation of Moisture Accumulated in Sludge on the Surface of the Cells

Week	Planted (%)	Control (%)
3ª	75.45	69.31
6ª	72.11	63.21
9ª	79.59	64.20
12ª	82.35	65.30
14ª	88.05	62.37
17ª	8.65	3.75

Table 3 Liquid Volume Retained in the Accumulated Sludge Layer on the Surface of the Treatment Beds

Week	Planted (m^3)	Control (m^3)
3ª	0.136	0.097
6ª	0.245	0.164
9ª	0.430	0.244
12ª	0.511	0.339
14ª	0.616	0.362

Along the time and the application of new wastes, the thickness of sludge layer on the surface of both tanks increased, becoming increasingly slow infiltration of the liquid into the substrate. Fig. 5 shows the variation of the thickness of the layer of sludge accumulated on the surface of each tank.

These values suffered significantly influence of precipitation and previous applications since the moisture content increased in both tanks and the liquid infiltration capacity decreased considerably, especially in the planted system.

The moisture from the sludge in the planted cell was higher than in control tank, especially by the influence of shading caused by foliar system of plants. With the reduction of rain in local, sludge retained in the control tank showed higher drying capacity and lower moisture retention, mainly due to the direct exposure to sunlight and high temperatures.

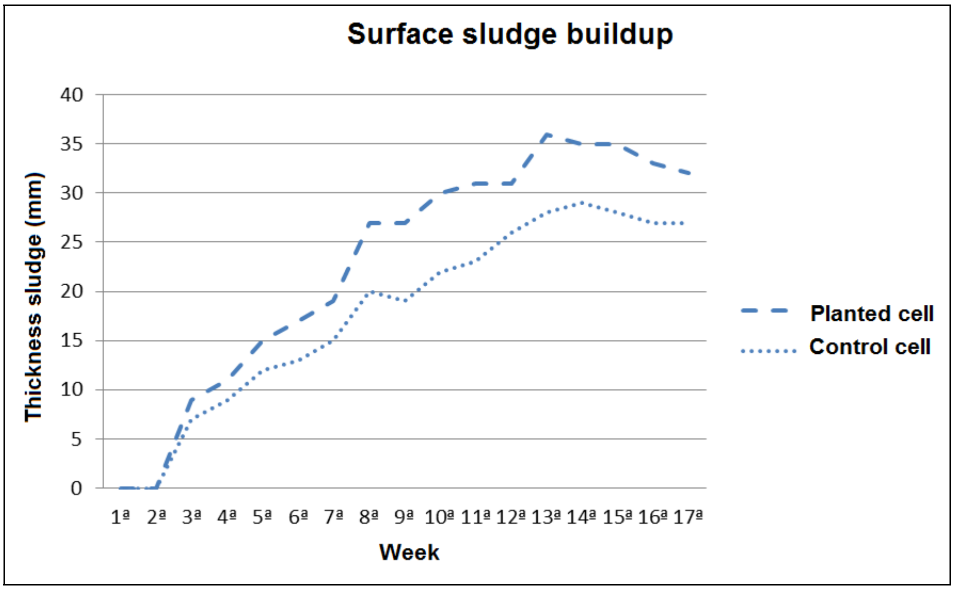

Fig. 5 Variation of the Thickness of the Surface Layer of Sludge Accumulated over Applications

In most cases, solar radiation is responsible for over 75% of the transpiration in plants, while the humidity and temperature are responsible for the remaining. Transpiration rates are significantly different for different seasons. However, the sweating phenomenon presents a complex connection with other variables such as the type of vegetation and its physiology [6].

It is also noteworthy that moisture from the sludge retained on the surface was influenced by rainfall. It is evident that the analysis carried out in the 3rd week, in which there were rains, there were higher moisture contents than in the three weeks later, when there was no precipitation.

The evapotranspiration and evaporation values in both systems were quite variable depending on local weather conditions.

In other researches, evapotranspiration rates ranging between 11% and 27% of the inflow in a horizontal subsurface flow system [4].

In a tropical climate region, the measure evapotranspiration rate around 50% of the influent volume [11]. Ranging from 20% to 50%, depending on the season of the year in Central Europe [12].

The evapotranspiration values vary not only depending on local climatic conditions, but also the type of system used. Subsurface flow CWs have a lower evapotranspiration rate than free surface systems, which are in direct contact with the atmosphere [1].

In contrast to evapotranspiration and evaporation, control tank always presented greater effluent volume discharge. On average, the planted bed discharged 61.65% of influent volume and no planted cell 83.70%.

The high evapotranspiration rate and fluid retention in wetlands constructed (planted system) in downward vertical subsurface flow system must be taken into consideration in system design, especially in project parameters as the hydraulic retention time (HRT), the accumulation and disposal of sludge system output concentration of the treated effluent will be more concentrated and may not meet the launch of legal parameters in water bodies, among other factors.

Just as important is the evapotranspiration for CW project parameters, and the efficiency calculation should be taken into account in such phenomenon [13].

With regard to water meters, it was observed that its operation has always behaved in a normal way after opening the records to depletion of tanks and only after hours of flowing is the flow measurement not possible because the pointers stopped spinning and yet small amount of liquid drained. It was found that lower flows that 0.0039 $L.s^{-1}$ were not measured by water meters.

4. Conclusions

The planting system always retained or released more water to the atmosphere than the witness system.

Of all the liquid that entered the system planted, an average of 38.35% was retained in the environment or evapotranspirated and 61.65% exhausted by drain pipe. In the not planted system there was an average of 16.30% retention/evaporation and 83.70% of drained liquid.

The system planted show greater reduction in the liquid infiltration capacity and increased moisture on the surface layer of sludge accumulated over time due to the characteristics of the waste used, since it has a high solids content and under surface of the shading tank caused by foliar system of plants, in contrast to the direct sun exposure in tank without plants.

Built planted cell system showed a most double retention and evapotranspiration capacity to release water into the atmosphere. These values must be considered for a dimensioning of new systems, especially in the design of CWs parameters for downward vertical subsurface flow to treat septage.

The hydrometers have operated satisfactorily in measuring volumes drained of treatment beds and can be used in similar studies with relative degree of confidence, to nearby flows to 0.0039 L.s-1.

References

[1] R. H. Kadlec and S. D. Wallace, Treatment Wetlands (2nd ed.), Taylor & Francis Group, 2009.

[2] Usepa – United States Environmental Protection Agency, Manual: Constructed Wetlands Treatment of Municipal Wastewater, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, 2000.

[3] M. Borin, M. Milani, M. Salvato and A. Toscano, Evaluation of Phragmites australis (Cav.) Trin. evapotranspiration in Northern and Southern Italy, Ecological Engineering 37 (2011) (5) 721-728.

[4] M. S. Brasil and A. T. Matos, Avaliação de aspectos hidráulicos e hidrológicos de sistemas alagados construídos de fluxo subsuperficial, Engenharia Sanitária e Ambiental 13 (2008) (3) 323-328.

[5] T. R. Headley, L. Davison, D. O. Huett and R. Muller, Evapotranspiration from subsurface horizontal flow wetlands planted with Phragmites australis in sub-tropical Australia, Water Research 46 (2012) (2) 345-354.

[6] S. Sánchez-Carrillo, M. Álvarez-Cobelas and M. Benítez, A simple method for estimating water loss by transpiration in wetlands, Hydrological Sciences-Journal-des Hydrologiques 46 (2001) (4) 537-552.

[7] M. Milani and A. Toscano, Evapotranspiration from pilot-scale constructed wetlands planted with Phragmites australis in a Mediterranean environment, Journal of Environmental Science and Health 48 (2013) (5) 568-580.

[8] M. Garfi, A. Pedescoll, E. Bécares, M. Hijosa-Valsero, R. Sidrach-Cardona and J. García, Effect of climatic conditions, season and wastewater quality on contaminant removal efficiency of two experimental constructed wetlands in different regions of Spain, Science of the Total Environment 437 (2012) 61-67.

[9] E. Uggetti, I. Ferrer, A. Argilaga and J. García, Dewatering model for optimal operation of sludge treatment wetlands, Water Research 46 (2012) (2) 335-344.

[10] T. Koottatep, N. Surinkul, A. S. M. Kamal, C. Polprasert, A. Montangero, K. Doulaye and M. Strauss, Material fluxes in constructed wetlands treating septage and their polishing systems, in: 9th International IWA Specialist Group Conference on Wetlands Systems for Water Pollution Control, 2004, Anais… Avignon: IWA.

[11] J. T. Sousa, A. V. Haandel, E. P. C. Lima and I. N. Henrique, Utilização de wetland construído no pós-tratamento de esgotos domésticos pré-tratados em reatores UASB, Engenharia Sanitária e Ambiental 9 (2004) (4) 285-290.

[12] U. Stottmeister, A. Wiebner, P. Kuschk, U. Kappelmeyer, M. Kästner, O. Bederski, R. A. Müller and H. Moormann, Effects of plants and microorganisms in constructed wetlands for wastewater treatment, Biotechnology Advances 22 (2003) 93-117.

[13] R. A. Almeida and F. E. Ucker, Considerando a evapotranspiração no cálculo de eficiência de estações de tratamento de esgoto com planta, Engenharia Ambiental 8 (2011) 39-45.