HYDRAULIC CONDUCTIVITY VARIABILITY IN HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLANDS

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ABSTRACT: Many modifications in hydrodynamic conditions occur inside the bed of a horizontal subsurface flow constructed wetland (HSSF–CW) in operation. Studies on hydraulic conductivity measurement techniques in HSSF–CW are imperative since the monitoring of flow conditions is essential for understanding and controlling its clogging. This study aimed to assess the hydrodynamic behavior in HSSF–CW by means of saturated hydraulic conductivity (K_s) analysis. For this, six HSSF–CW were used: two non-cultivated (control), two cultivated with Tifton 85 (_Cynodon_ spp.), and two cultivated with alligator weed (_Alternanthera philoxeroides_). Application of swine wastewater (SW) in HSSF–CW started on June 15, 2011, with K_s measurement period between September 9 and November 11, 2011, in which five measurements were performed in different positions along the system length and over experimental period in order to assess the effects of vegetation, position, and time factors on this variable. K_s values ranged from 1,392 to 2,834 m d^{-1}. Plant presence led to K_s decreasing in the systems, but cultivated species had no influence on this variable. Monitoring time of HSSF–CW was no longer enough to provide a reduction in K_s, at 10% probability level.

KEYWORDS: hydrodynamic conditions, clogging, constructed wetlands, wastewater treatment.

INTRODUCTION

Wastewater treatment in horizontal subsurface flow constructed wetland (HSSF–CW) is widely used for removing pollutants from effluents worldwide. In contrast to conventional sewage treatment technologies, HSSF–CW present simple and efficient treatment mechanisms, as well as few maintenance and operation requirements (FIA et al., 2010; NIVALA et al., 2012; PRATA et al., 2013).

Over HSSF–CW operating time, removal mechanisms by filtration, sedimentation, adsorption, precipitation, and microbial degradation occur (KNOWLES et al., 2010), providing solid accumulation between particles that compose the filter bed. This phenomenon of obstructing the porous spaces is denominated clogging and it is the main HSSF–CW operational problem.

Porous medium obstruction may be associated with suspended solids in wastewater applied to the system, formed biomass, suspended mineral solid deposition, refractory organic material accumulation, and chemical precipitate formation (KNOWLES et al., 2011; PEDESCOLL et al., 2011b). Porous medium clogging of HSSF–CW by plant roots and rhizomes is still the subject of controversy since some authors consider that these plant organs promote a pumping or suspension of support material (BRASIL; MATOS, 2008) in order to create a porous volume equivalent or higher than that previously existing in the medium. A few studies have indicated root presence as the reason for surface flow problems, in some cases, being attributed to porous medium clogging (FU et al., 2013; PAOLI; VON SPERLING, 2013).

According to NIVALA et al. (2012), there are three ways of assessing the impact extent by porous medium clogging, indicating its obstruction degree. One of them consists of quantifying the amount of solids within the pores (PEDESCOLL et al., 2011a). Another is the use of tracers and monitoring of its concentration to define the hydraulic detention time (HDT) and hydrodynamic

conditions within the medium (BORGES et al., 2009; COTA et al., 2011). Finally, there is the measurement of saturated hydraulic conductivity (K_s), which varies with the operating time of a treatment unit.

Porous space obstruction of HSSF–CW modifies the medium hydrodynamic conditions, notably with respect to K_s. As the occlusion of interstitial spaces advances, an increase in load loss is observed, especially in the system's initial region, leading to a decrease in K_s and, consequently, surface flow occurrence, with possible decrease in treatment system efficiency (KNOWLES et al., 2011; PEDESCOLL et al., 2013). This possibly makes the hydraulic conductivity a variable with a strong association with porous medium clogging.

However, K_s determination in HSSF–CW bed is difficult since it undergoes the influence of out-of-control factors such as surface flow and short circuits, in addition to porosity obstruction because of growth variations and degradation of roots and/or accumulation/degradation of solid residues in HSSF–CW.

Because studies on clogging process in HSSF–CW have only been widely reported in the scientific literature in recent years (COTA et al., 2011; KNOWLES et al., 2011; XU et al., 2013), K_s in situ measurements are still developing technologies. Thus, studies that provide the improvement of K_s measurement techniques in HSSF–CW are imperative since the monitoring of hydrodynamic conditions of these systems is essential for their operational improvement.

Considering that, this study aimed to assess the hydrodynamic behavior in HSSF–CW systems used for swine wastewater (SW) treatment by means of K_s monitoring along cultivated and non-cultivated systems during wastewater application period.

MATERIAL AND METHODS

Structure and experimental conditions

The experiment was conducted at the Federal University of Viçosa (UFV), Viçosa, MG, Brazil from September 9 to November 11, 2011. The experimental structure consisted of six HSSF–CW maintained in a greenhouse to perform SW treatment.

HSSF–CW systems were composed of pilot-scale fiberglass boxes with dimensions of $0.6 \times 0.5 \times 2.0$ m in height, width, and length, respectively, installed on the ground and with no bottom slope, as presented in Figure 1. HSSF–CW systems were filled with gravel ($D_{60} = 9.1$ mm, the coefficient of uniformity Cu $D_{60}/D_{10} = 3.1$, and initial void volume of 0.398 m^3 m^{-3}), used as a support medium with a height of 0.55 m, and the water level was maintained at 0.05 m below the support medium surface. At each experimental unit outlet, we installed a drainage system composed of a 32-mm diameter PVC pipe.
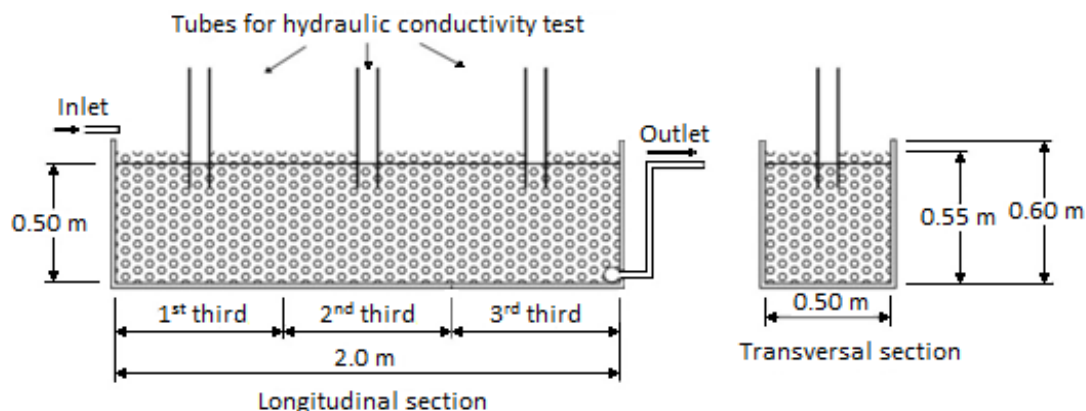

FIGURE 1. Scheme of longitudinal and transversal sections of HSSF–CW with their respective dimensions.

Wastewater used

SW used in the experiment, resulting from washing animal stall, passed through a sand trap, masonry tank, sieve, and grease trap, being subsequently collected and transferred to a hogshead-type transport tank with a capacity for 2000 L. These collections were carried out twice a week and transported to UFV, where the experiment was installed.

From the hogshead tank, SW was transferred to a temporary reservoir (2000 L), being pumped daily into polyethylene boxes with a capacity of 320 L. Subsequently, wastewater was transferred to equalization tanks and later distributed to HSSF–CW systems by metering-solenoid peristaltic pumps ProMinent® CONCEPT (flow rate in the range from 0.7 to 23 L h^{-1}) and PVC hoses.

During the experimental period, six simple samples of SW affluent to the HSSF–CW systems (SW$_A$) were collected and characterized according to the Standard Methods for the Examination of Water and Wastewater (APHA et al., 2012). Table 1 shows the value ranges of the main variables analyzed in SW affluent to the HSSF–CW systems throughout the experimental period.

TABLE 1. Average values and standard deviation of the main variables in six samples of swine wastewater affluent (SW$_A$) to the HSSF–CW systems.

pH	EC	COD	BOD	TSS	TN	P	K	Na
	dS m^{-1}	-------------------------------------- mg L^{-1} --------------------------------------						
8.0 ± 0.2	3.81 ± 0.38	1.188 ± 572	818 ± 570	198 ± 64	437 ± 73	50 ± 5	79 ± 12	81 ± 27

EC – electric conductivity; COD – chemical oxygen demand; BOD – biochemical oxygen demand; TSS – total suspended solids; TN – total nitrogen.

Experiment conduction

Cultivated plant species were Tifton 85 (*Cynodon* spp.) (HSSF–CW 2 and 5) and alligator weed (*Alternanthera philoxeroides*) (HSSF–CW 3 and 6), planted at a density of 20 planting holes m^{-2} and arranged in triangular spacing. At each planting hole, we planted four propagules of Tifton 85 and only one of alligator weed. No plant species was cultivated in HSSF–CW 1 and 4. Table 2 displays the operational characteristics of HSSF–CW based on SW$_A$ characteristics.

TABLE 2. Operational characteristics of HSSF–CW.

	Q$_A$	HDT	OLR$_S$	OLR$_T$	SLR$_T$
	(m³ d^{-1})	(d)	-------------------- (g m^{-2} d^{-1}) --------------------		
Average values	0.069 ± 0.014	2.9 ± 0.6	56.4 ± 11.4	3,272	792

Q$_A$ – affluent flow; HDT – hydraulic detention time; OLR$_S$ – surface organic loading rate (BOD$_5$); OLR$_T$ – organic loading rate (BOD$_5$) in relation to HSSF–CW transversal section; SLR$_T$ – total suspended solids loading rate in relation to HSSF–CW transversal section.

Between the reservoir and metering pump outlets, there was a reduction in SW suspended solids concentration for two main reasons: deposition of a large part of solids at the storage reservoir bottom and filtration in a device coupled to the metering pump inlet valve (indispensable to avoid its obstruction). To accelerate HSSF–CW clogging process, part of the amount of solids retained in the storage/feeding system was applied weekly, thus enabling the recovery of part of the real load of solids contained in the raw SW. A volume of 1 L of solids deposited at the SW reservoir bottom was added weekly in each HSSF–CW. Solids collected at the reservoir bottom presented an average concentration of 21,611 ± 4,070 mg L^{-1} in total suspended solids (TSS). Thus, the average weekly load of solids in each HSSF–CW was 117.245 g, resulting in an average daily application of 16.749 g m^{-2} d^{-1}.

SW application in HSSF–CW started on June 15, 2011. At the end of the experiment, on November 11, 2011, we harvested the plants determined dry matter productivity. For this, we

collected plant shoot separately from each third of each HSSF–CW, and let it dry at 65 °C in a forced air circulation oven until reaching the constant mass.

Determination of hydraulic conductivity (K$_s$)

K_s value in support medium of cultivated and non-cultivated HSSF–CW was determined in a punctual way along the system length and over the experimental period in order to assess the effects of vegetation, position, and time factors on this hydrodynamic property. During the experimental period (63 days), we performed five measurements.

The K_s was measured in each HSSF–CW third by means of the installation of PVC pipes with 75 mm in diameter and 0.50 m in length, which worked as piezometers. These tubes were placed at the center of each HSSF–CW third, at a wet depth of 10 cm. Measurements were carried out at distances of 0.33, 1.00 and 1.67 m from the system beginning. The variable load test (falling head test) was used with a downward water level similar to that used by PAOLI & VON SPERLING (2013), but with a different geometry piezometer. The mathematical solution used was in accordance with HVORSLEV (1951). The K_s values obtained represent vertical hydraulic conductivity, which is associated with the way the piezometer was installed.

Measurement procedure consisted of applying a hydraulic load of 0.40 m as a pulse by using a piezometer, observing the time required for water to infiltrate into HSSF–CW porous medium. To measure the water level decay over time, a hydrostatic level transmitter HYTRONIC®, model TSH/100M/P/02 (0 to 1 m.c.a.), was used connected to converter modules 7520 and A/D 7018 and subsequently to a computer. Every second water level was recorded. For data collection and storage, the software Sistema de Aquisição de Dados, developed by BATALHA (2011), was used. The liquid used for measurements was HSSF–CW effluent (SW$_E$).

Clean gravel K_s (without SW) was estimated by means of an HSSF–CW with the same dimensions as the other experimental units. At the center of each third of this HSSF–CW, piezometers with 75 mm in diameter and 0.50 m in length were also installed at a wet depth of 10 cm. K_s were measured at each third using clean water. The resulting average value corresponded to K_s in a clean bed, without the presence of biofilm, solids, roots, stolons, and plant residues.

In the mathematical procedure proposed by HVORSLEV (1951), parameters from piezometer and from the curve h/h_0 versus time (t) are used on a semi-logarithmic scale. According to this solution, K_s can be obtained using [eq. (1)]:

$$K_s = \frac{\pi\, d + 11\, H}{11\, t_{37}} \times 100$$

(1)

where,

K_s is the saturated hydraulic conductivity (m s^{-1}),

d is the inner tube diameter (m),

H is the submerged tube height (m),

t is the time corresponding to water level height h (s),

t_{37} is the basic delay time (s) correspondent to the time elapsed until the water level reaches 37% of initial level, i.e. $h/h_0 = 0.37$,

h_0 is the initial water height inside the tube (m), and

h is the water level height inside the tube at time t (m).

The K_s measures were corrected to the reference temperature (20 °C) by using [eq. (2)]. The liquid temperature inside each HSSF–CW was obtained from the reading on a mercury thermometer. Viscosity values used in the calculations were those referring to clean water obtained in tables available in the technical literature.

$$K_{s20} = K_{es}\left(\frac{\mu_e}{\mu_{20}}\right)$$

(2)

where,

K_{s20} is the saturated hydraulic conductivity of liquid at a standard temperature of 20 °C (m d^{-1}),

K_{es} is the experimental saturated hydraulic conductivity (m d^{-1}),

μ_e is the dynamic viscosity of water at ambient temperature (kg m^{-1} s^{-1}), and

μ_{20} is the dynamic viscosity of water at 20 °C (kg m^{-1} s^{-1}).

Experimental design

The experiment consisted of three different treatments: non-cultivated HSSF–CW (SP), HSSF–CW cultivated with Tifton 85 (*Cynodon* spp.) (P1) and HSSF–CW cultivated with alligator weed (*Alternanthera philoxeroides*) (P2), installed in a split-split-plot design with treatments in the plots, each HSSF–CW third in the subplots, and assessment times in the sub-subplots. The experimental design was completely randomized design with two replications. Data were analyzed by means of analysis of variance and regression. For qualitative factor, averages were compared by using the Tukey's test at 10% probability level.

RESULTS AND DISCUSSION

Based on the analysis of variance of K_s data, vegetation factor (absence of plants, Tifton 85, and alligator weed) and the interaction of position and vegetation effects were significant at 10 and 5% probability, respectively. Position and time factors did not present an independent significant effect. No significant effect was also observed in the interactions between time and vegetation, time and position, and time and position and vegetation (Table 3).

TABLE 3. Summary of relative analysis of variance of K_s in HSSF–CW non-cultivated (SP) and cultivated with Tifton 85 (P1) and alligator weed (P2).

Source of variation	DF	Mean square
Vegetation (V)	2	4,952,972.0°
Error (a)	3	1,285,998.0
Position (P)	2	31,908.2^{ns}
P × V	4	2,515,700.0*
Error (b)	6	960,356.8
Time (T)	4	57,817.1^{ns}
T × V	8	40,653.0^{ns}
T × P	8	41,066.5^{ns}
T × P × V	16	38,625.2^{ns}
Residual	36	39,069.2
CV plot	53.93%	
CV subplot	46.61%	
CV sub-subplot	9.40%	

^{ns}, *, and °: not significant and significant at 5 and 10% probability level, respectively, by the F test.
DF – degrees of freedom; CV – coefficient of variation.

Even if the vegetation factor was significant, statistical analysis effect depended on position. For this reason, Table 4 displays the breakdown of this interaction.

TABLE 4. Average values of K_s (m d^{-1}) for combinations between vegetation (Tifton 85 – P1, and alligator weed – P2) and position in HSSF–CW.

Treatment	Position		
	1st third	2nd third	3rd third
SP	2,123 aA	2,682 aA	2,834 aA
P1	2,390 aA	2,257 aAB	1,392 aB
P2	1,824 aA	1,449 aB	1,973 aAB

Means followed by the same letter do not differ significantly from each other at 10% significance level by the Tukey's test. Lowercase letters refer to lines and uppercase letters refer to columns.

According to the data presented in Table 4, no significant differences was observed between K_s values obtained in different measurement positions, within the same HSSF–CW, i.e. no differences can be attributed between inlet, central, and outlet zones for any of the treatments applied. This is due, at least in part, to the relatively small dimensions of HSSF–CW used, which may have provided a rapid solid distribution throughout the porous medium, and to a possible effect of tank walls on the applied water flow during K_s measurements. In addition, the hydrodynamic conditions of porous medium downstream of measuring point may possibly have influenced.

Although there were no differences in K_s considering the measurement position in the systems, comparative studies of values found in HSSF–CW inlet and outlet zones have shown significant differences of this variable in relation to position. In a review on clogging, KNOWLES et al. (2011) reported 21 cases of distinct HSSF–CW, in which differences were identified between K_s values measured in inlet and outlet regions, with an average reduction of 60%. The authors attributed the porous medium obstruction to operational factors related to wastewater solids applied and chemical precipitates, introduction and accumulation of solid materials from the substrate, the growth of plant roots and biofilm, and plant residues presence in a porous medium.

In the study developed by PAOLI & VON SPERLING (2013), longitudinal and transversal variations were observed in K_s for both cultivated and non-cultivated systems. However, the authors obtained very low hydraulic conductivities when compared to those obtained in this study. In the inlet zones, cultivated HSSF–CW presented values from 7 to 11 m d^{-1} and from 67 to 70 m d^{-1} for those non-cultivated. In the outlet zones, cultivated systems presented K_s values from 30 to 107 m d^{-1} and non-cultivated HSSF–CW presented a range from 198 to 324 m d^{-1}. These results can be associated with a longer operating time of assessed systems (about two years), which allows a greater porous space occupation with solids from the applied wastewater, detached from the substrate, precipitated, and from the biofilm developed in the system. In other studies, K_s heterogeneity has also been reported, as in PEDESCOLL et al. (2012) and RANIERI & YOUNG (2012).

The substrate surface layer removal, a procedure inherent to the measurement method used, could also have been one of the factors responsible for non-detection of the position effect in K_s. Surface bed clogging has a great influence on hydraulic conductivity since it exerts a strong resistance to water infiltration in the medium (XIE et al., 2010). By removing the surface layer and introducing the measuring tube into the substrate, the resistance offered by this layer to wastewater flow is eliminated, providing only the measurement of a part of the subsurface hydraulic conductivity and not of the entire porous medium layer.

When comparing the treatment effect on K_s values measured at same positions in HSSF–CW, the value measured at the second third of HSSF–CW cultivated with alligator weed was lower than that obtained at the second third of non-cultivated HSSF–CW. For HSSF–CW cultivated with Tifton 85, K_s value measured at the system's central part did not differ from any of those measured in the other systems. At the third, HSSF–CW cultivated with Tifton 85 presented lower K_s in relation to non-cultivated HSSF–CW, which may be associated with pore occupation by plant roots.

Based on the results presented in Table 4, differences can be observed between K_s values when considering the same measurement positions in HSSF–CW, with no significant differences

between plant species. However, K_s value found at the second third in HSSF–CW cultivated with alligator weed and that found at the third cultivated with Tifton 85 differed from those obtained in non-cultivated HSSF–CW, which is an indication that the cultivated plant species may influence the porous medium hydrodynamic characteristics.

Plants can maintain hydraulic conductivity over time by means of two main mechanisms: a) creation of preferential paths for water flow as a result of root growth and, particularly, rhizome penetration in the bed; and b) appearance of annular holes, or even cracks, at plant insertion points in the bed due to stem and leaf movement, resulting from wind action. This corroborates the results obtained by MATOS et al. (2010), who observed lesser pore obstruction of support medium in cultivated HSSF–CW than in those non-cultivated. Similarly, BRASIL & MATOS (2008) observed an increase in K_s value in HSSF–CW at the first 4 months of the experimental period in relation to the K_s measured in clean gravel (without wastewater) due to support medium material uplift occurrence after vegetation establishment.

Regarding the influence of measuring position in bed on K_s value, at the first third was observed that vegetation presence did not promote significant differences. This may be related to lower plant development at the inlet region and superficial layer removal, as recommended when using the method chosen to measure K_s. During the experimental period, plants of inlet region had lower density and height when compared to those cultivated at other HSSF–CW positions. This can be evidenced by the difference in dry matter productivity obtained for each third (Table 5). This impaired growth may be associated with lower root presence, which may mean a lower reduction in medium macroporosity.

A non-uniformity in root and biomass distribution along the bed length is related to a non-uniformity in K_s distribution. In addition to roots, plant senescence can produce large amounts of plant residues, which will be deposited unevenly on the bed. Thus, where there is a higher plant incidence, there will be a greater contribution of plant-origin solids, and vice versa, which will influence the clogging process and, consequently, K_s value measured.

TABLE 5. Dry matter productivity (t ha^{-1}) for each third of cultivated HSSF–CW after 60-day cultivation.

Plant	Dry matter productivity (t ha^{-1})		
	1st third	2nd third	3rd third
Tifton 85	8.2	9.8	8.9
Alligator weed	6.0	7.4	6.7

Although K_s had no significant differences during the experimental period (63 days), it does not imply that the measurement method is not sensitive to these variations. In this sense, two main reasons can explain this fact. One is because the measurement method clearly alters substrate (support medium) conditions at the test site, as previously mentioned. Another might be due to an insufficient experimental time, leading to changes in K_s in a porous medium which were perceptible by the method used. Figure 2 shows a graph with K_s average values obtained over HSSF–CW operating time.
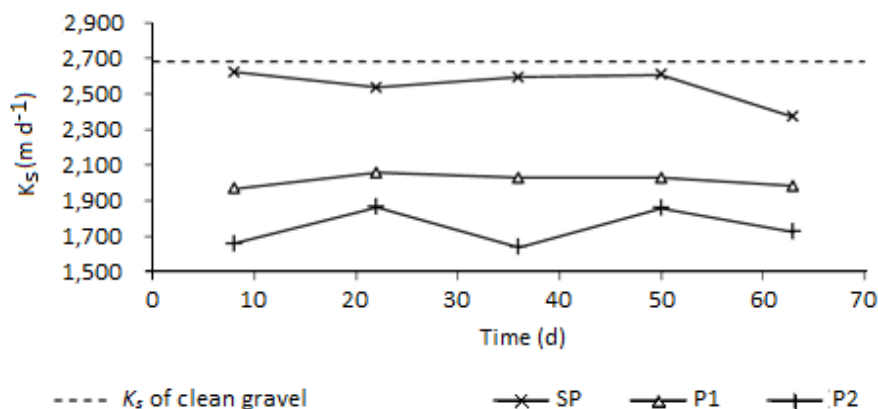
FIGURE 2. K_s values obtained for clean gravel and non-cultivated HSSF–CW (SP) and cultivated with Tifton 85 (P1) and alligator weed (P2).

Figure 1 shows the difference caused by modifications provided in K_s as the systems started operating. Comparing K_s values obtained for clean gravel with K_s average values of non-cultivated HSSF–CW, those cultivated with Tifton 85, and alligator weed, an average reduction of 5, 25, and 35% was observed, respectively.

Studies on K_s modifications over time have been performed during longer periods of HSSF–CW operation. BRASIL & MATOS (2008) observed an increase in K_s from 7,970 to 15,423 m d^{-1} after planting southern cattail in HSSF–CW filled with gravel #0 ($D_{60} = 7.0$ mm, Cu $D_{60}/D_{10} = 1.6$, and void volume of 48.4%) as medium support. After 6.5 months of system operation for treating primary wastewater from domestic sewage, a decrease in K_s to 9,144 m d^{-1} was observed, which is higher than that measured in clean gravel.

Solid introduction into the substrate from both SW and vegetation, as well as biofilm growth, led to a reduction in Ks for both cultivated and non-cultivated systems, as reported in the literature. According to LA VARGA et al. (2013), multiple local factors and conditions can influence solid accumulation and thus K_s values. Therefore, each system presents a distinct response due to a set of factors, such as the applied TSS load, cultivated plant species, system operating time, wastewater characteristics, climatic conditions, etc.

TSS load applied in the studied HSSF–CW was higher than that usually reported in the literature. All systems received the same TSS load and each of them presented a distinct K_s reduction (Figure 1). Thus, apparently, no direct relationship exists between a single factor, such as TSS rate, and K_s variation. Similarly, not necessarily higher TSS loads imply in higher K_s reductions, which is evidenced in several studies found in the literature. In this sense, in a study carried out by LA VARGA et al. (2013), whose systems were cultivated with *Juncus effusus*, K_s presented average values of 56.4 and 67.5 m d^{-1} for HSSF–CW inlet and outlet, respectively. These systems were used for 4.7 years for domestic sewage treatment at a TSS application rate of less than 9.98 g m^{-2} d^{-1}. When applying a TSS rate of 1.5 g m^{-2} d^{-1} of the effluent from wastewater treatment generated in wine production, after 2.2 years of system operation, the values found were 137.1 and 131.1 m d^{-1} for HSSF–CW inlet and outlet, respectively. PEDESCOLL et al. (2013) assessed HSSF–CW systems cultivated with *Phragmites australis* in domestic sewage treatment. After 2.6 years, theses authors observed that K_s value decreased from 484 m d^{-1} (PEDESCOLL et al., 2011a) to 28.3 m d^{-1} in an HSSF–CW that received an average TSS load of 9.0 m^{-2} d^{-1}, and to 25.2 m d^{-1}, in the initial parts of HSSF–CW systems that received double the SST load. Thus, K_s variability is due to a set of factors, which interfere in a concomitant and integrated way. Moreover, the composition of accumulated material, responsible for clogging, is as important as its quantity (KNOWLES et al., 2011; POZZO-MORALES et al., 2013) regarding K_s reduction.

CONCLUSIONS

Based on the results, no difference was observed in K_s values obtained in cultivated and non-cultivated HSSF–CW, over the experimental period. However, a K_s reduction was observed in relation to the value obtained in the HSSF–CW that did not receive swine wastewater. Similarly, no spatial variation was observed in K_s along the length of HSSF–CW systems. Conditions established in K_s measurement method, HSSF–CW size, and short-period experiment conduction may have influenced the results.

ACKNOWLEDGEMENTS

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