Difficulties and modifications in the use of available methods for hydraulic conductivity measurements in highly clogged horizontal subsurface flow constructed wetlands

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ABSTRACT

Despite the fact that several authors consider the available measurement methods of hydraulic conductivity (k_s) suitable for a good representation of the bed condition and clogging potential in horizontal subsurface flow constructed wetlands, others have questioned their adequacy. In this work, hydraulic conductivity measurements with conventional and modified methods were undertaken in two small full-scale units, one planted with cattail (*Typha latifolia*) and the other unplanted. Both units had already been operating for seven years and showed a high degree of clogging. It was observed that the use of the falling head method, with the introduction of the tubes during the test, provided results without a clear spatial trend. On the other hand, tests done on monitoring wells inserted during construction time showed, as expected, k_s increasing with the horizontal distance from the inlet, but without reflecting actual field conditions. It was observed that, as the bed became more clogged, the use of the reported methods became more complex, suggesting the need of other methodologies. The use of planted fixed reactors (removable baskets installed in the bed) with evaluation of k_s at constant head in the laboratory showed potential for the characterization of the hydrodynamic properties of the porous medium.

Key words | clogging, constant head method, falling head method, layer-dependency, obstruction, planted fixed reactor, porosity

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INTRODUCTION

The advance of clogging in constructed wetlands (CWs) leads to a decrease of the saturated hydraulic conductivity (k_s) in the porous media, thus modifying the hydrodynamic conditions in the system (Nivala & Rousseau 2009; Babatunde 2010). Among the factors influencing k_s values in a porous medium are the porosity (ε) and the intrinsic properties of the liquid, such as specific mass and viscosity. Considering that there are no substantial changes in the characteristics of the fluid over time and space, k_s basically depends on the effective or drainable porosity (Kadlec & Wallace 2009; Xu *et al.* 2013). Thus, k_s measurement may be considered as an indirect technique to characterize a CW in terms of the accumulation of solids in the pores and hence the degree of clogging of the porous medium.

According to Ferres (2012), since the study of the clogging phenomenon in the porous media of CW is relatively recent, k_s measurement methods are still under development. Among the methods most commonly used in CWs are the constant head (CHM) and falling head methods (FHM). Comparing the two, Pedescoll *et al.* (2011, 2012) endorsed the reliability of the second, and Pedescoll *et al.* (2009) and Knowles *et al.* (2010) consider it an appropriate method to characterize, indirectly, the degree of clogging in CWs.

doi: 10.2166/wst.2017.340

However, some authors consider the available measurement methods of k_s inaccurate to characterize the hydrodynamic conditions in CWs. Suliman *et al.* (2006), for example, found no correlation between k_s and total porosity, arguing that k_s would be associated with the passing of liquid through large diameter pores, not being strongly associated with a porous medium obstruction with solids and/or biofilm.

Permeameter methods tend to lead to better results when used in vertical flow systems, because they involve a non-perforated pipe inserted in the medium (unlike the measurements done in soil) and a downward flow of the applied water. Thus, although some authors consider that flows in horizontal and vertical directions can be similar, field experience gives indications that they can be very different (Deb & Shukla 2012). Furthermore, the introduction of tubes for testing can change the bed conditions, because of compression, detachment of the attached biofilm, and vertical movement of the medium, biofilm and other retained solids.

As k_s measurement is performed near the surface of the medium, little can be concluded about the conditions of the pore spaces throughout the depth. According to Zhao *et al.* (2009) and Xie *et al.* (2010), the condition of the first layers of the substrate is of great importance in the response of k_s measurement. Knowles *et al.* (2010) obtained k_s values of 0.5 m d^{-1} near the surface, and from 100 to 1,000 m d^{-1} below the root zone.

A spatial trend of k_s values is sometimes not observed. Paoli & von Sperling (2013) found k_s values within the range 7–324 m d^{-1} without, however, observing a continuous increase along the length of a horizontal subsurface flow constructed wetland (HSSF-CW). Pedescoll *et al.* (2009) found the highest k_s values in the section of 4/5 of bed length, which were close to the measured values in a clean medium.

Knowles *et al.* (2011) and Matos (2015) made a compilation of k_s values in different systems, obtained by some authors, and found no clear relationship between k_s and a number of variables (average diameter of the medium particles, level of treatment, type of wastewater and surface loading rate), indicating that the methods using traditional measurements do not allow comparisons between the values obtained.

The objectives of this study are to evaluate the hydrodynamic conditions in planted and unplanted HSSF-CWs, based on visual field analysis, and to verify if changes in the methods of hydraulic conductivity measurements can lead to results that are consistent with the hydrodynamic conditions of the media.

MATERIAL AND METHODS

Study area

The tests were undertaken at the Center for Research and Training in Sanitation (CePTS UFMG/Copasa), located at 19°53′42″S and 43°42′52″W, in the Arrudas Wastewater Treatment Plant (WWTP) in the city of Belo Horizonte, Brazil. Part of the sewage, after preliminary treatment (coarse and fine screens followed by grit removal) is diverted to feed the experimental units present at the CePTS, among which is one system composed of a UASB (upflow anaerobic sludge blanket) reactor and two HSSF-CWs. The wetland beds have been in operation since 2007, working in parallel, each continuously receiving around 7.5 m^3 d^{-1} of the effluent from the UASB reactor. The average surface organic load is 5.9 g m^{-2} d^{-1} of biochemical oxygen demand (BOD).

The CWs were filled with blast furnace slag as substrate, with diameter d_{10} equal to 19.1 mm and uniformity coefficient (d_{60}/d_{10}) equal to 1.2 (Dornelas *et al.* 2009), except for the inlet and outlet zones, which had larger stones (between 10 and 15 cm) to facilitate the distribution and collection of wastewater. As can be observed in Figure 1, the HSSF-CWs have an effective length of 25.0 m and a width of 3.0 m. Table 1 shows other design, construction and operational aspects of each of the CWs. One of the units (P-CW) was planted with *Typha latifolia*, popularly known as cattail, while the other remained uncultivated, acting as a control unit (C-CW).

Measurement of saturated hydraulic conductivity

In the FHM, a pipe with diameter D is inserted at a depth h' in the HSSF-CW bed. Inside the pipe, water is inserted at an initial water height h_1, then allowing infiltration/percolation to a height h_2 and measuring the corresponding time t taken (see Figure 2). The k_s value can then be estimated using the equation obtained based on the principles of conservation of mass and Darcy's Law (NAVFAC 1986):

$$k_s = \frac{D^2 . \ln(2h'/D)}{8.h'.t} . \ln\frac{h_1}{h_2} \qquad (1)$$

where k_s is given in m s^{-1}, D, h', h_1 and h_2 in meters and t in seconds. According to Ferres (2012), this method is also known as the variable descending load Hvorslev test, which is valid when the ratio $h'/D > 4.0$ (Fetter 1994). After the k_s value is obtained, it is possible to estimate the

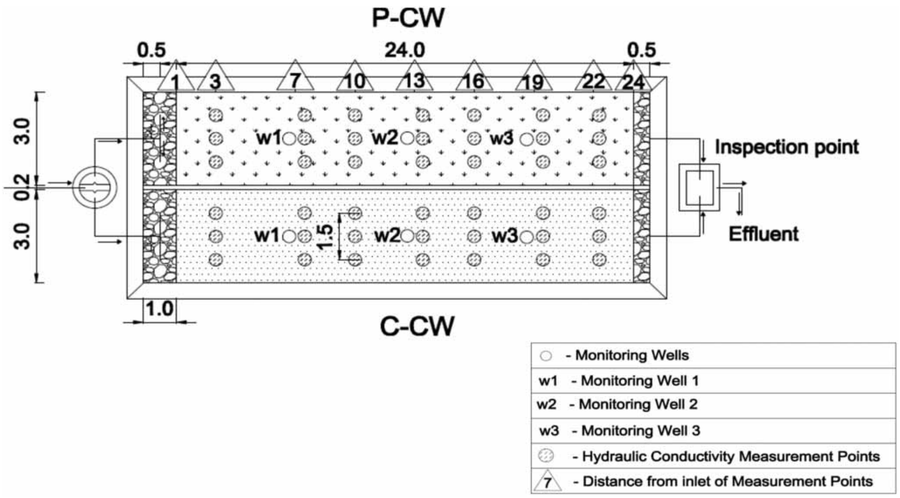


Figure 1 | Constructive details of HSSF-CW and evaluation positions of saturated hydraulic conductivity.

Table 1 | Design, construction and operational characteristics of each HSSF-CW unit

Parameter	Unit	Value
Total medium height *(h_t)*	m	0.4
Useful (liquid) height (h_u)	m	0.3
Length (top) (L)	m	25.0
Width (top) *(B)*	m	3.0
Longitudinal bottom slope (i)	%	0.5
Total bed volume (V_t)	m^3	30.0
Bed volume with liquid (V_u)	m^3	22.5
Bed surface area (top) (A_s)	m^2	72.0
Porosity of the filter medium during construction (ε)	$m^3\ m^{-3}$	0.40
Theoretical hydraulic retention time (*HRT*)	d	1.20

head loss (h_f) and the water level in the system from a relationship based on Darcy's Law:

$$Q = h_{liq}.\ b\ .\ \varepsilon\ .\ k_s\ .\frac{h_f}{L'} \tag{2}$$

where Q is the flow rate ($m^3\ d^{-1}$), h_f is the head loss (m), L' is the length of the evaluated stretch (m), h_{liq} is liquid height (m), b is the breadth of the bed (m) and ε is the porosity of the medium ($m^3\ m^{-3}$). As h_f depends on h_{liq}, which is the sum of the initial height of the liquid and head loss (h_f), it is considered that h_{liq} is equal to the wet height at the point nearest the HSSF-CW outlet, allowing h_f calculation from this position. Thus, adding the two variables, h_{liq} at any section upstream, at a distance from L' in the HSSF-CW bed, can be calculated.

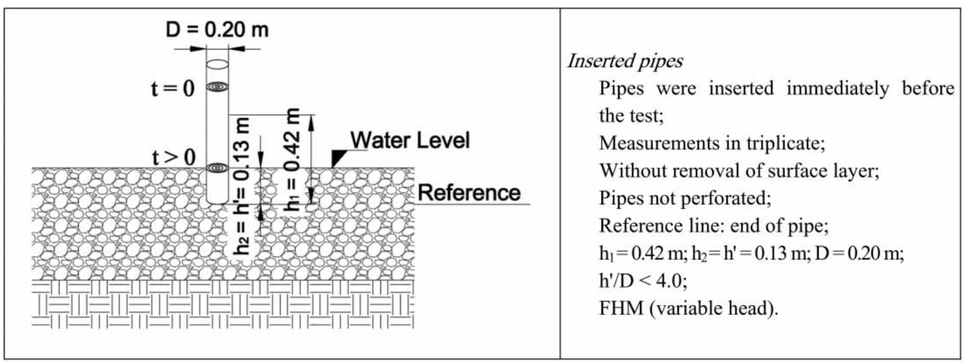


Figure 2 | Conditions for the implementation of FHM hydraulic conductivity tests on saturated medium. The pipes were inserted before testing.

The sections below describe the different methods used to obtain a characterization of the degree of clogging in the HSSF-CW investigated.

FHM in inserted pipes in bed

The first of the three methods tested consisted of the FHM. In the first trial, open-bottom permeameters were inserted in different sections along the CWs (1.0, 3.0, 7.0, 10.0, 13.0, 16.0, 19.0, 22.0 and 24.0 m from the inlet), at central, right and left points, equidistant from each other and from the embankment, as shown in Figure 1. This methodology, used in October 2013, was similar to a previous study by Paoli & von Sperling (2013), performed at the end of 2009, in the same HSSF-CWs.

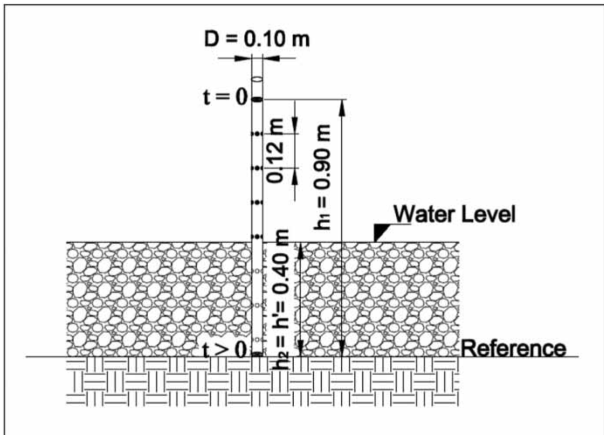
The test had h'/D ratio less than the minimum recommended by Fetter (1994), which is 4.0, a condition that would favor vertical flow rather than horizontal. The first few centimeters of the bed were not removed, in order to make the method as less invasive as possible. Another difficulty in the use of the method was to reference the dimensions from the water level, since this is variable along the HSSF-CW. Given this situation, the use of a reference at the end of the inserted pipes was evaluated, which would make the methodology more practical. Details are explained in Figure 2, where the water level coincided with the medium surface because in these wetlands there were large areas with surface flow.

FHM using monitoring well

As shown in Figure 1, there were three monitoring wells along the bed length, introduced since the initial construction in order to allow the collection of samples. Because these wells did not contain media inside them, they were not representative of the surrounding conditions, and thus, in principle, could not be used to perform measurements of k_s (Pedescoll *et al.* 2009). However, there were some advantages and limitations in their utilization: they had been present in the beds since the wetlands construction and would not cause medium disturbance; they had holes in the subsurface, allowing contact with the surrounding medium and horizontal flow; they were inserted as far as the bottom sealing layer of compacted clay; they did not have vertical flow of water. As a result, it was decided to use them for k_s measurements with some restrictions. In July 2014 the monitoring wells (with distances of 7.0, 13.0 and 19.0 m from the inlet, see Figure 1) were used to receive the permeameters. The permeameter holes positioned above the substrate level were closed, forcing the passage of the liquid only through the subsurface holes inside the bed. Figure 3 shows the installation scheme, and it can be seen that there are three rows with four holes of 0.5 cm diameter in the subsurface. Using this methodology, the obtained ratio h'/D was equal to 4.0, as recommended by Fetter (1994). However, the condition related to the reference line, as stated by Ferres (2012), could not be met.

FHM with perforated and non-perforated pipes

In this method, the objective was to investigate the hypothesis of layer-dependence and the influence of the holes in the pipe on k_s, in an attempt to approximate the actual hydrodynamic conditions of the HSSF-CW. In July 2015, k_s determination in the surface and in two layers (15 and 35 cm depth) was made, in adjacent positions to the monitoring wells, after removing the filling material relative to these depths. This evaluation used pipes with 0.5 cm diameter holes, separated by 1.0 cm from each other, and pipes without holes, as shown in Figure 4.



Well monitoring

Pipes previously inserted during construction;
Measurements in triplicate;
Without removal of surface layer;
No medium inside the pipes;
Perforated pipes;
Reference line: end of pipe;
h_1 = 0.90 m; h_2 = h' = 0.40 m; D = 0.10 m;
h'/D= 4.0;
FHM.

Figure 3 | Conditions for FHM hydraulic conductivity tests using the existing monitoring wells.

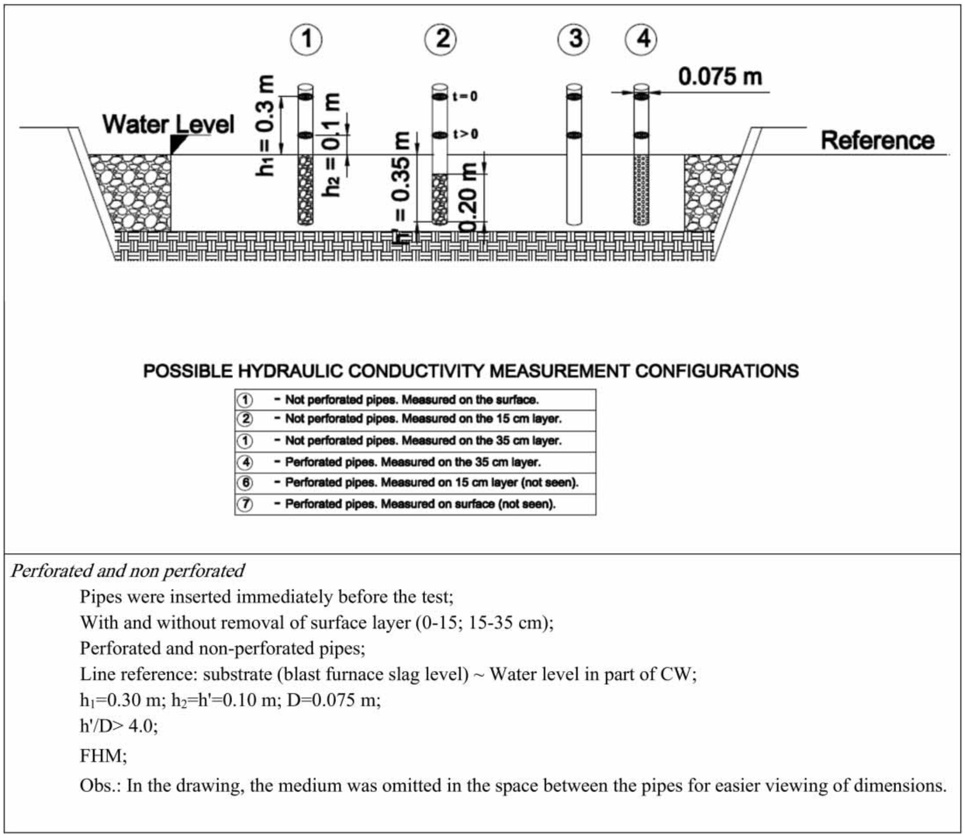


Figure 4 | Conditions for the implementation of FHM hydraulic conductivity tests by using perforated and non-perforated pipes.

K_s measurement in PFR baskets under constant head (CHM)

The planted fixed reactor (PFR) consists of a mobile basket that can be inserted into a well within a HSSF-CW, giving a good representation of the system under study (Barreto *et al.* 2015). For this reason, it was considered to be a promising method for measuring k_s. The PFRs were 0.28 m in diameter, 0.30 m in height and had laterals with openings spaced at 0.5×0.5 cm. They were filled with the same substrate and cultivated in the same way as the full-scale HSSF-CW, and remained inserted in the wetlands bed at the same height. They were positioned at 13.0 m from the inlet of the units (Figure 5(a) and 5(b)) from May 2014 (Barreto *et al.* 2015). In July 2015, the PFRs were removed from both wetlands (Figure 5(a)) and taken to the laboratory for measurement of k_s. After removal from the bed, they were placed inside external closed baskets, which had a valve on the bottom for drainage of the water added during the tests. The measurements were compared to those obtained in a clean substrate PFR, which served as a control. Water was added to saturate the entire set, with subsequent control of input and output, until these became equivalent (constant load condition). After reaching this condition, the time required to obtain a cumulative volume of 10 L was measured.

Given the high rate of water infiltration/percolation, it was opted to evaluate the effect of changing the water outlet position to 3.7 cm below the substrate level of PFRs, in order to facilitate the horizontal flow, to the detriment of vertical descent, in the porous medium. In both variants, four replicates were made.

As the form of radial flow is not included in the solution given by Darcy's Law's traditional equation for k_s calculation, which assumes parallel flow lines in the flow section, an attempt was made, in the literature, to find a solution to this type of flow. Bedient *et al.* (1994) showed a k_s estimation equation referring to unconfined aquifers submitted to pumping, that adapted to the measurement conditions, as:

$$k_s = \frac{Q_b \cdot \ln\left(\frac{R_0}{r_{dr}}\right) . 864000}{\pi .(h_{dr}^2 - h_w^2)} \tag{3}$$

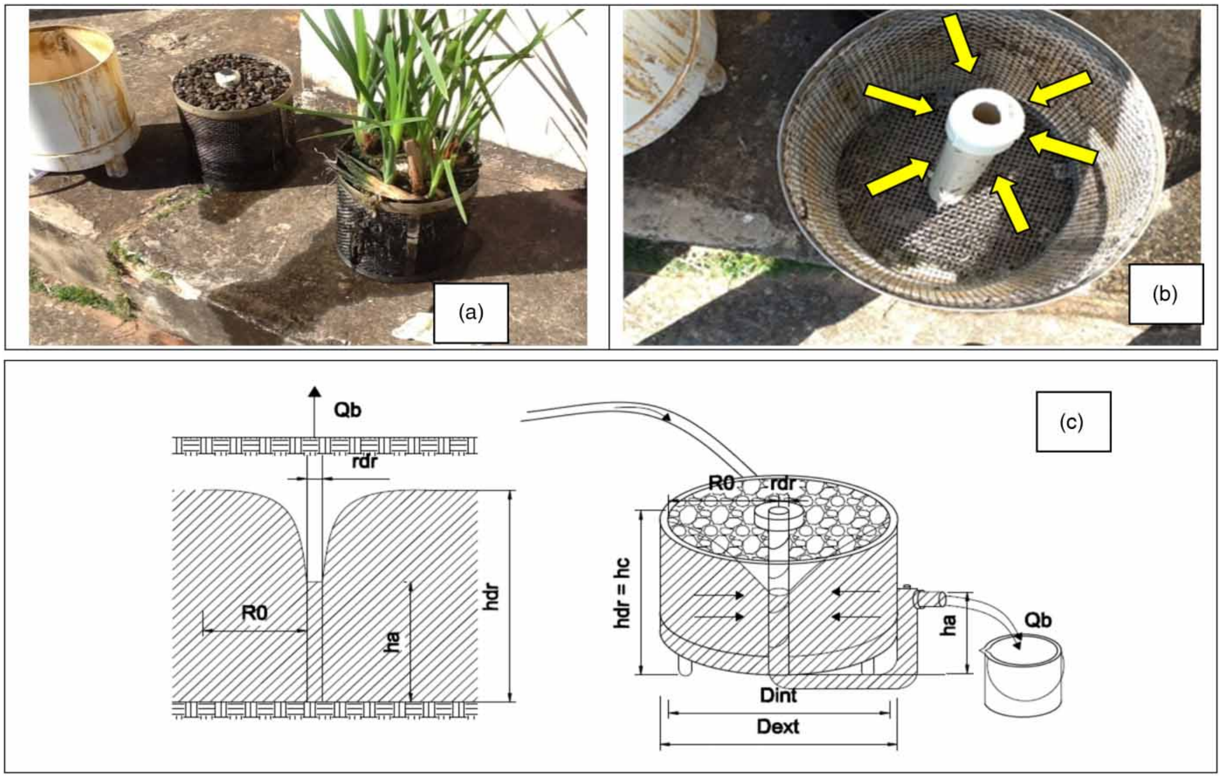


Figure 5 | (a) Detail of PFR removed from the baskets from the unplanted and planted units; (b) the water flow direction inside the PFR baskets; (c) analogy between the hydraulic conditions in the experimental apparatus used to determine the hydraulic conductivity of saturated medium (right) and pumping wells in an unconfined aquifer (left).

where k_s is given in m d^{-1}; Q_b is the flow rate (L s^{-1}); R_0 is the radial distance of the remote location referenced, the external border of PFR basket, in relation to the well (drain) (28 cm); r_{dr}, drain radius (2.5 cm); h_{dr} is the height of water in the PFR basket (30.0 cm), which is equal to the total height above the bottom drain; h_w and the level of water inside the drain (26.3 cm). The value of 86,400 is used to convert the time in seconds to days. The analogy between the experimental apparatus set and pumping wells is shown in Figure 5(c).

To evaluate the capacity of the methods employed to assess the current condition of the CWs, measurements of surface overland flow extension and of the water level above the substrate were made. The measurements presented in this work date from the end of July 2014.

RESULTS

Visual field analysis

Figure 6 shows a 'surface flow map', that is used to assist the discussion of the results obtained in k_s measurement by the different methods. It is observed that there is less surface flow in the planted wetland (P-CW), but this unit had the worst initial conditions (with highest water level), while the zone of the unplanted control (C-CW) with the most critical situation is close to its center. Both beds were not levelled at the surface because of factors such as medium 'swelling' (volume expansion due to penetration of roots in the pore spaces), removal of weeds (which carry part of the substrate of the bed), and removal of samples for analysis. For this reason, the water level varies in the same cross section. Even so, this visual characterization was useful to better identify the most affected regions and to evaluate the degree of clogging in the units.

FHM using pipes inserted in the bed

The k_s values measured in the C-CW and P-CW are shown, respectively, in Figures 7 and 8. Analysing the figures, prepared with measurements made at the end of 2013, it appears that, in general, k_s was higher in the unplanted control unit, when compared with the value measured in the equivalent position in the planted unit, especially in positions more distant from the inlet end, where there is

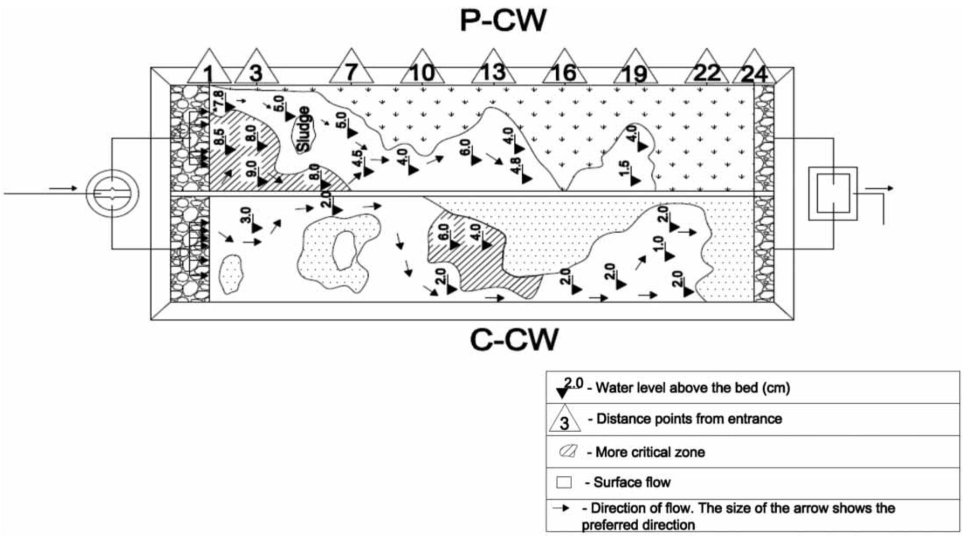


Figure 6 | Visual analysis of the wetland conditions, with indication of visible surface flow and the presence of a water level above the bed surface.

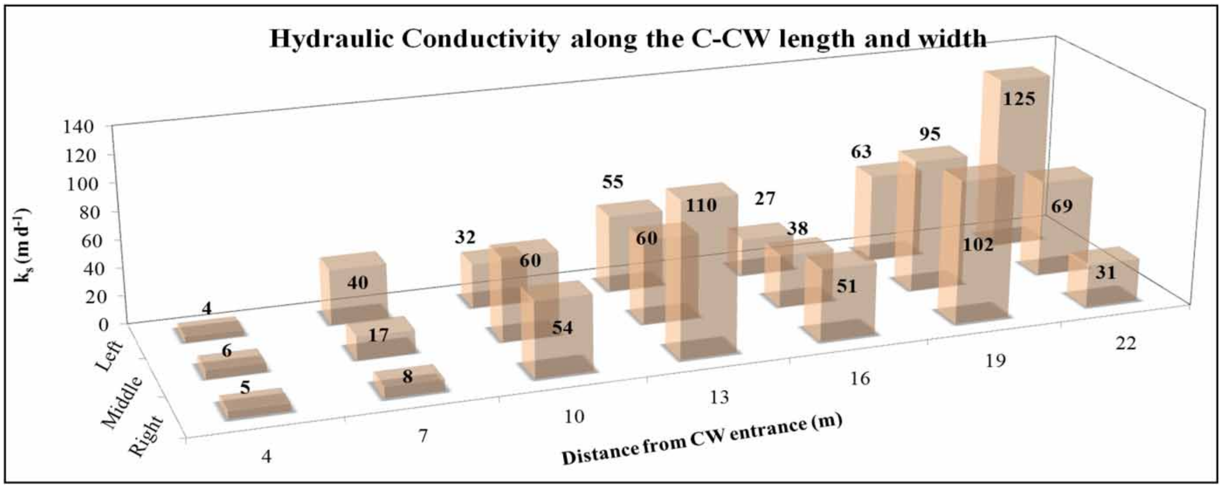


Figure 7 | Saturated hydraulic conductivity using FHM, at several points in the unplanted control wetland.

lower surface overland flow extension. Close to the entrance of the beds, the P-CW showed higher k_s values, but field observations indicated a different situation, with the presence of a higher water level at the entrance of the planted unit. In some zones closer to the end of the beds, k_s was greater than the one measured in the vicinity of the entrance areas, revealing a certain variable fluctuation along the length of these systems. These results contradict the expectation of continued growth of k_s with the distance from the inlet to the outlet of the HSSF-CWs, due to the accumulation of organic matter in the porous medium.

Measurements made by Paoli & von Sperling (2013) in the same HSSF-CWs, about four years before, also indicated, in general, lower k_s values in the planted unit, with hydraulic conductivities of 7 and 107 m d^{-1}, respectively, at points 3.0 and 18.0 m from the inlet. In the unplanted unit, the values at the same distances were 67 and 324 m d^{-1}. On the other hand, Turon *et al.* (2009) and Seeger *et al.* (2013), among others, mentioned that roots and rhizomes attenuate clogging in HSSF-CWs. Therefore, it is believed that the k_s measurement, in the way it was made, could not adequately characterize the hydrodynamic conditions in these systems.

Another way to verify the suitability of the obtained results to characterize the degree of clogging of the CWs is related to the head loss and the estimation of the

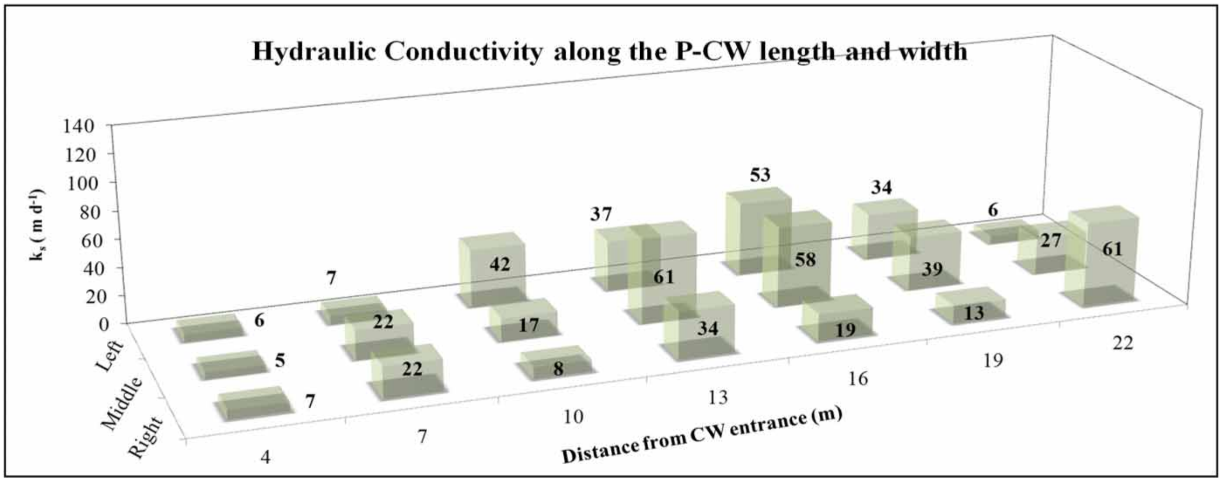


Figure 8 | Saturated hydraulic conductivity using FHM, at several points in the planted wetland.

water level in the units. Considering k_s values that were obtained using Equation (2), there should have been surface flow over all the bed, which was not observed in the field. Even with the change in the reference level, as recommended by Ferres (2012), this unreal condition was maintained.

FHM using monitoring wells

In 2014, k_s was measured using the monitoring wells, leading to the results presented in Figure 9. It can be noted that, unlike the results using the pipes that were inserted specifically for the tests, there was a clear tendency of k_s increase from inlet to outlet, with higher values in the unplanted control unit. These tests observed the restriction related to the h'/D ratio (that should be greater than 4.0), but probably the best responses were caused by not having disturbances to the bed, since there was no introduction of a pipe directly in the medium. But, even so, k_s was lower in the planted unit, contrary to the expectation of having better hydrodynamic conditions from the bed center, as suggested by the visual analysis.

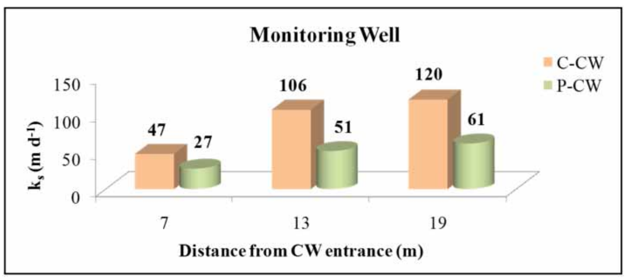


Figure 9 | Saturated hydraulic conductivity measured in monitoring wells located at different points in the HSSF-CW.

FHM with perforated and non-perforated pipes

This method did not provide results close to reality, because it was not possible to measure k_s values, either by 'leakage' of water to holes near the bed surface or the inability to have infiltration/percolation in the original tube (without holes). Also, the removal of a 15 cm layer from the substrate inside the pipe did not result in improvement in this scenario. For this reason and because of the difficulty of introducing the tube into the porous media in an advanced clogging state, it is believed that the method, in the way it is proposed, does not characterize the hydrodynamic system conditions well (Pauly 1990) and is not applicable in any condition. It is believed that the FHM could be used up to a certain degree of clogging of the HSSF-CWs porous media, under the condition of a low rate of water infiltration/percolation, until the occurrence of more severe conditions in the bed, wherein vertical flow virtually ceases.

K_s measurement in PFR baskets under constant head

The k_s and Q_b results obtained in the tests in which the PFR baskets were used are shown in Table 2. Using the Mann-Whitney test (data presented a non-normal distribution) at 5% level, to compare independent data (two different outlet positions), it was found that the water outlet position had a significant influence, with flow being reduced by more than a half when the water outlet was positioned below the

Table 2 | Mean and standard deviation values of hydraulic conductivity with two different outlet conditions in the PFR baskets filled with clean substrate or after removal from the wetland units

	Flow ($m^3 d^{-1}$)		Hydraulic conductivity ($m d^{-1}$)
Baskets	**Configuration I (outlet in the lower level)**	**Configuration II (outlet near the top of the substrate level)**	**Configuration II (outlet near the top of the substrate level)**
Clean substrate	10.8 (0.20) AB	4.9 (0.15) A	182 (5.59) A
Planted CW	11.0 (0.12) A	4.4 (0.20) B	161 (7.29) B
Control CW	9.5 (0.48) B	4.7 (0.12) AB	173 (4.31) AB

k_s values followed by the same letter in each column do not differ significantly, by the Kruskal–Wallis test at the 5% significance level.
Four repetitions were made for each test.

top level of the medium in the PFR, due to the reduction of the hydrostatic pressure associated with the lower head. This effect appears to be more pronounced in the planted unit, since it provided a higher flow than in the unplanted unit, at the first hydraulic configuration, and less flow, thought not significant, in the second one. Apparently, the greater hydrostatic pressure seems to have favored the water flow through the pore space provided by the roots and rhizomes. At the second hydraulic configuration, the PFR baskets were placed at 13.0 m from the inlet (mid wetland length), a position in which there is no substantial difference between the two units in terms of the degree of clogging and water level above the bed. This was reflected in the k_s results, which showed no significant differences between them, by the Kruskal–Wallis test, used to compare grouping (clean substrate, planted CW and control CW). From the results and practical aspects, it appears that the use of PFR baskets may be a suitable possibility for measuring k_s and a useful tool for assessing the degree of clogging in an HSSF-CW.

CONCLUSIONS

In conclusion, it can be said that:

- the measurement of hydraulic conductivity, in the way it is usually carried out, did not provide consistent results that matched the visual field analysis;
- the adaptations made in the methods (presence of holes in tubes and k_s quantification in pipes previously inserted in porous media or in different layers) also did not guarantee the undertaking of more reliable measurements;
- some emerging methodologies, such as the PFR baskets, were shown to be promising, because they could simulate better the conditions in beds with horizontal flow without causing disturbance in the medium.

ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian agencies CAPES, CNPq and FAPEMIG for their support to the research, Copasa for providing the site for the experimental units, CAPES for the scholarship of the first author and Federal University of Minas Gerais.

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First received 14 November 2016; accepted in revised form 23 May 2017. Available online 7 June 2017