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Influence of the geometric configuration of unplanted horizontal subsurface flow constructed wetlands in the adjustment of parameters of organic matter decay models

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ABSTRACT

The aim of the present work was to evaluate the influence of the geometric configuration (aspect ratio) in unplanted horizontal subsurface flow constructed wetlands systems (HSSF-CWs), in the adjustment of reaction coefficients from different equations for estimation of organic matter decay. To that end, prototypes of unplanted HSSF-CW, of equal volumes and length-width ratios (L/W) of 1.0, 4.0 and 7.3, were utilized. The absence of plants is due to eliminate another factors of influence in reactor hydrodynamics. All HSSF-CWs were filled with gravel # 0 (D_{10} = 4.5 mm), and received pre-settled sewage during a period of 90 days, in which BOD_5 and COD were monitored in the influent and effluent from the systems. To the experimental COD and BOD_5 (total and soluble forms) data, the First-Order Kinetics Model (FOKM) and its modification (MFOKM), First-Order Kinetic Residual Concentration (RCM) and Retardation (RM) models were fitted. Higher Coefficients of Determination were obtained with the MFOKM and RM equations, with the poorer fitting being associated with the FOKM. The different geometric configurations of the HSSF-CWs did not lead to noticeable alterations in the removal of organic matter, however, the decay coefficient, that was obtained as a function of the hydraulic retention time in the systems (2,8 days), has indicated a tendency for increase with an increase of the L/W ratio (with the exception of soluble COD decay).

1. Introduction

Constructed wetlands systems (CWs) are treatment units filled with support medium, commonly finer-grained rocks, and planted with different plant species. However, it is found in the literature, variations without substrate, that could be denominated macrophytes ponds, and without plants, that would approach lagoons of stone [1,2].

Among the units, the horizontal subsurface flow wetlands systems (HSSF-CW) are the most widespread in the USA and Europe [3], and the most studied in Brazil [4]. However, there is still not a consensus about the sizing of these systems, which leads to a diversity of designs that, according to Langergraber et al. [5], are still based upon empiricism.

Some designs are based on compliance with established discharge standards for effluents coming from regional environmental legislations, others on per capita area or loading ratios. There are also those which utilize a more theoretical procedure, based upon the pollutants decay equations, many of which applicable to systems with completely different characteristics from those of the CWs [2,6]. For Kincanon and McAnally [7], Marsili-Libelli and Checchi [8] and Małoszewski et al. [9], these systems performance, which are a funtion of their physical, chemical and biological characteristics, may be predicted through mathematical models. According to Pedescoll et al. [10], in HSSF-CWs water tends to flow along the pathway of least hydraulic resistance, which is influenced by different design parameters and operational aspects, including the length-to-width ratio [11] and the inlet and outlet position [12]. Among so many variables and design possibilities, Kadlec and Wallace [2] consider the best CWs sizing strategy, those that shows greater technical-scientific basis, simplicity and good results.

According to Kadlec [13], Rousseau et al. [14] and Sezerino et al. [6], the most widely applied and recommended mathematical models for describing organic matter decay are based on First-Order Kinetics (FOKM). The first publications about this theme have suggested that the

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biological removal model should assume a first-order decay kinetics coupled with a plug-flow hydraulic model [15], as presented on the traditional Eq. (1).

$$C_e = C_0.e^{(-k_0\ .\ HRT)} \quad (1)$$

where, C_e is the effluent concentration ($mg\,L^{-1}$); C_0 the influent concentration ($mg\,L^{-1}$); k_0 the FOKM decay coefficient (d^{-1}); and *HRT* is the hydraulic retention time (d).

However, in practice, this model has not presented good fitting to experimental data, as the reactors do not have an ideal hydraulic behaviour, owing to the occurrence of anomalies in the flow, as dispersion, short circuits and dead zone presence [16]. Also, because of that and the recalcitrance of some fractions of the compounds, it is not possible to obtain a complete removal of organic matter. Another fact that influences the performance is the hydraulic retention time (*HRT*), since the biodegradability of the organic matter varies along the travelling time within the longitudinal axis. For these reasons, some adaptations to the FOKM have been proposed [17–21]. These adaptations consist, basically, in the inclusion of a term referring to the residual organic matter concentration in the system, or mathematical modifications to make the decay coefficient (k_0) variable with the *HRT*.

One possibility, when recognizing that the treatment unit does not behave as an ideal plug-flow reactor, is to use the Dispersed Flow Model [22], which requires the utilization of another coefficient (Dispersion Number *d*). Another widely-used possibility is to use the *N* Tanks-in-Series model (*N*-TIS) [2] which, in this case, aims to reproduce the hydraulic behaviour of each wetland unit as a series of *N* reactors. Kadlec and Wallace [2] further advanced this reasoning by incorporating the effect of the reduction of the biodegradability of the organic matter by assuming that the number of tanks in series is lower than *N*. In this case, they propose the concept of apparent number of tanks in series (*P*), in which $P \le N$. These approaches will not be discussed here, because the essence of the work is to propose adjustments in the traditional first order model and plug-flow equations. The adaptations proposed can be also incorporated in the Dispersed Flow and the *N*-TIS models, and do not require that *N* is modified to a lower value (*P*).

It is known that some variables can influence on the hydraulic behaviour of a reactor. The presence of plants influences other factors and, therefore, some authors have analysed hydrodynamic aspects in these systems without their presence. Matos et al. [23], for example, observed different values of dispersion number in unplanted and planted before and after the cut the aerial part. However, the geometric configuration (aspect ratio) was the aspect most study and associated with the hydraulic behaviour of a reactor, influencing, and, by that reason, with the adjustment of kinetic models developed to describe the removal of organic matter, when reactors were utilized in the wastewater treatment [16,24]. It is expected that the longer the reactor, with greater length-width (*L/W*), more the hydrodynamic conditions of the reactor approach the plug flow.

In this work, the objective was to evaluate the adjustment of the First-Order Kinetics, Residual Concentration, Retardation and Modified First-Order Kinetics models to the experimental data obtained in unplanted HSSF-CWs with different geometric configurations.

2. Material and methods

2.1. Study area

The experiment was conducted in the interior of a greenhouse, installed in the Agricultural Engineering Department of Federal University of Viçosa (UFV), Viçosa, Minas Gerais, Brazil, with geographic coordinates of latitude 20° 45' 12" S and longitude 42° 52' 53" W and average altitude of 650 m.

The influent used in the research was raw sewage (RS), drawn from the sewerage network of the Bosque Acamari condominium and its surroundings, whose main characteristics are shown in Table 1. The RS was pumped to a storage reservoir from where every 5 days it was re-pumped into a 1000 L reservoir, installed in the interior of the greenhouse. From this reservoir, it was distributed to the HSSF-CWs, through three ProMinet® CONCEPT peristaltic pumps, with a maximum flow of $5.3\,L\,h^{-1}$.

Table 1
Mean characteristics and standard deviation of the raw sewage used in the experiment.

Variables	Sample number	Values
total COD ($mg\,L^{-1}$)	5	494 (104)
total BOD_5 ($mg\,L^{-1}$)	5	226 (31)
TSS ($mg\,L^{-1}$)	5	246 (35)
N ($mg\,L^{-1}$)	4	48.5 (5.5)
P ($mg\,L^{-1}$)	4	8.6 (0.8)
K ($mg\,L^{-1}$)	4	7.4 (0.8)
pH	5	7.28 (0.15)
EC	5	760 (886)

COD: chemical oxygen demand; BOD_5: biochemical oxygen demand; *TSS*: total suspended solids; *N*: nitrogen; *P*: phosphorus; *K*: Potassium; *pH*: hydrogenionic potential; *EC*: electrical conductivity.

During the whole experimental period, the peristaltic pumps operated with a mean flow of $0.030\,m^3\,d^{-1}$, which provided a *HRT* in the wetland units close to 2,8 days, a period that is considered enough to evaluate the organic matter removal process in the evaluated systems. This *HRT* was defined considering that the theoretical specifications of the reactor and does not considering shortcuts or evapotranspiration in the system.

The HSSF-CWs used in the evaluations were built in a pilot scale, being made of fiberglass boxes, all with a total volume of $0.40\,m^3$. The width and length dimensions varied between the CWs, being 1.00 m × 1.00 m in CW1, 2.00 × 0.50 m on CW2 and 2.70 × 0.37 m on CW3, which provided length/width ratios (*L/W*) of 1.0, 4.0 and 7.3, respectively, as shown on Table 2.

The CWs were filled up with medium to a height of 0.25 m in relation to the bottom and the water level was kept at 0.20 m, leaving, therefore, a freeboard of 0.05 m, and were not planted. The support medium used in the filling of all CWs was constituted by gravel # 0 (diameters $D_{10} = 4.47$ mm, $D_{60} = 9.25$ mm, uniformity coefficient = 2.07 and initial void or pore volume of $0.420\,m^3\,m^{-3}$), reused from experiments conducted previously [25,26]. Before introducing in the fiberglass boxes, the gravel was passed through a 2-mm sieve, to remove the fine fraction.

The CWs operated in parallel, with the influent distribution made by a PVC tube (25 mm), with the exit placed at the half depth of the liquid column (0.10 m from the bottom), as shown on Fig. 1. At this point, a "T" connection was installed, on which a perforated tube was adjusted that performed the distribution of the RS through all the width, at the inlet of the CWs. The effluent collection was made by the bottom of the opposite end, also by a perforated tube positioned in such a way as to

Table 2
Constructive and operational characteristics of the HSSF-CWs.

Variable	CW1	CW2	CW3
Length − *L* (m)	1.00	2.00	2.70
Width − *W* (m)	1.00	0.50	0.37
L/W	1.0	4.0	7.3
Height of filter bed h_1 (m)	0.25	0.25	0.25
Height of water level h_2 (m)	0.20	0.20	0.20
Surface area (m^2)	1.00	1.00	1.00
Useful volume (m^3)	0.20	0.20	0.20
Useful void (pore) volume (m^3)	0.084	0.084	0.084
HRT (d)	2.8	2.8	2.8
Influent flow − Q_0 ($m^3\,d^{-1}$)	0.03024	0.03024	0.03024