Modeling of pollution removal in constructed wetlands with horizontal subsurface flow

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Abstract - Kurzfassung

This study was carried out to obtain the parameters of the kinetics equation for removal of the organic load and to evaluate the performance of four constructed wetland systems with subsurface flow (CWHSSF) measuring 24.0 x 1.0 x 0.3 m for treatment of the domestic wastewater from an anaerobic septic tank. The system was filled with a course of crushed stone that served as substrate for the macrophyte under study, which was cattail (Typha sp.). Two hydraulic retention times (t) of 1.9 and 3.8 days were used. Different volumetric organic load rates (116, 164 and 210 g m³ d⁻¹) were tested. The following variables were measured: chemical oxygen demand (COD) and total suspended solids (TSS). The parameters K_V and n of the kinetic model for organic load removal were obtained by nonlinear regression. The organic load rates had no negative influence on pollutant removal. A hydraulic retention time of 3.8 days was more effective in removing COD and TSS than a hydraulic retention time of 1.9 days. The model $(C_o/C_i = \exp(-1.6221 t^{0.2491}))$ for organic load removal, which is proposed in the present work, showed satisfactory adjustment and describes the organic load removal kinetics in the evaluated system appropriately.

Keywords: Wastewater, kinetic of degradation, treatment, constructed wetland

Modellierung der Reinigungsleistung von Pflanzenkläranlagen mit unterirdischer Horizontalbeschickung

Vier Pflanzenkläranlagen mit "subsurface flow" (24 m x 1 m x 0,3 m) wurden hinsichtlich ihrer Reinigungsleistung für vorbehandeltes häusliches Abwasser aus einer Mehrkammerabsetzgrube untersucht. Dabei wurde die Abbaukinetik für die organischen Schmutzstoffe im Abwasser ermittelt und an ein Modell angepasst. Als Substrat diente Gesteinsplitt und als Pflanze wurde Rohrkolben (Typha sp.) eingesetzt. Das Abwasser wurde mit zwei verschiedenen hydraulischen Retentionszeiten, mit 1,9 bzw. 3,8 Tagen und einer organischen Fracht von 116, 164 und 210 g m³ d⁻¹ beaufschlagt. Neben dem chemischen Sauerstoffbedarf (COD) wurden die Gesamtschwebstoffe (TSS) erfasst. Die Parameter K_V und *n* des kinetischen Modells für den Abbau der organischen Fracht wurden mit Hilfe einer linearen Regression erhalten. Die Höhe der organischen Fracht wirkte sich nicht nachteilig auf das Reinigungsverhalten aus. Bei einer hydraulischen Retention von 3,8 Tagen erfolgte ein besserer Abbau von COD und TSS als bei 1,9 Tagen. Das für den Abbau organischer Schmutzstoffe entwickelte Modell $(C_o/C_i = \exp(-1,6221 t^{0,2491})$ zeigte eine zufriedenstellende Anpassung und beschreibt näherungsweise die Abbaukinetik für organische Stoffe in dem untersuchten Abwasserreinigungssystem.

Schlüsselwörter: Abwasser, Abbaukinetik, Aufbereitung, Pflanzenkläranlage

1 Introduction

The kinetic removal of pollutants in constructed wetlands with horizontal subsurface flow (CWHSSF) is described by mathematical models, which allow dimensioning (Tchobanoglous & Burton 1991, Reed et al. 1995, Kadlec & Knight 1996 and Crites & Tchobanoglous 1998 cited in U.S. EPA 2000a). In these studies models are based on the first order kinetics, under the plug-flow conception. However, these four models do not show a good adjustment to the data already available, since the development chosen by each author and the model derivation were not obtained with the same data basis (U.S. EPA 2000a).

Wastewater treatment in constructed wetlands with subsurface flow has proved to be efficient in removing the organic load (BOD), total suspended solids (TSS), phosphorus and fecal coliforms from the primary effluent of domestic wastewater in tropical regions (Persyn et al. 1998, Nyakang'o & Van Bruggen 1999, Sousa et al. 2000, Corea 2001, Schulz & Peall 2001,

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Lim et al. 2003, Kyambadde et al. 2004, Kaseva 2004). Nevertheless, studies concerning the application of this wastewater treatment technology have been limited to evaluating the efficiency and utilization of the treatment process. Therefore only little information on the available operational and constructive parameters is available.

The main variables of the mathematical models describing the organic matter removal kinetics in CWHSSF are the removal constant *K* and the hydraulic residence time *t*. According to Reed et al. (1995) and Badkoubi et al. (1998), the temperature variations can affect the *K* constant in CWHSSF. Vymazal (1998) evaluated several experimental results obtained in CWHSSF set up in the Czech Republic and found the BOD₅ removal was not dependent on temperature. However, research accomplished with data from unique system showed 5 % variation in the average removal efficiencies (BOD₅ inclusive) as a function of the temperature (Tunçsiper et al. 2004).

Average values from the literature used for the variables mentioned should be better adjusted, as some equations for modeling the CWHSSF were obtained at limited system numbers (Tchobanoglous & Burton 1991) and for temperate climate regions.

Besides the first order model with the plug-flow conception, other relations have been examined as models for the pollutant removal in CWHSSF. These comprised the conception of the dispersed-flow hydraulic model (Batchelor & Loots 1997), the saturated reaction kinetics (Mitchell & McNevin 2001), and kinetics for serial tank arrangements (Kadlec 2003), although none of those relations has reasonably adjusted to all data already available (U.S. EPA 2000b).

Therefore, one objective of this study was to assess the treatment efficiency for domestic wastewater along a gradient within a constructed wetland system. Another objective was to define the variables of a mathematical model that describes the organic load removal kinetics and the effect of temperature under subtropical conditions in Brazil.

2 Material and methods

The experiment was carried out in the Experimental Area for Residue Treatment belonging to the Agricultural Engineering Department, Universidade Federal de Viçosa - DEA/UFV, in Viçosa, Minas Gerais State, Brazil (20° 45' S, 42° 55' W). The study area is located at a mean altitude of 690 m. Mean temperature during the study period from 24.8.2004 to 22.1.2005 was 19.4 °C. Four CWHSSF systems were built in parallel for secondary treatment of domestic wastewater as presented in Fig. 1. The design of the constructed wetland was 24.0 m x 1.0 m x 0.3 m. The bed had a depth of only 0.3 m, because Typha sp. was cropped in the CWHSSF, a macrophyte with a maximum root depth of 0.3 m. This condition is suggested to support an efficient nitrogen removal. The substrate of the CWHSSF consisted of crushed stone with a diameter $D_{60} = 7.0$ mm, a degree of non-uniformity $D_{60}/D_{10} =$ 1.6, a pore volume of 48.4 % and saturated hydraulic conductivity of $K_{s20} = 7.97 \text{ m d}^{-1}$.

Along the CWHSSF, five 40 mm-diameter PVC tubes were installed longitudinally every 4 m to collect the samples of wastewater, as shown in Fig. 1. All four



Fig. 1: Cross-section of a CWHSSF (1) influent distribution device, (2) inflow area, (3) impermeable geomembrane, (4) outflow area, (5) sump, (6) discharge device and level control, (7) treated domestic wastewater, (8) substrate, (9) internal stations of the resident liquid

CWHSSF (1, 2, 3 and 4) were fed with domestic wastewater from an anaerobic septic tank, under different organic load rates (OLR) that were presented in Tables 1 and 2 and applied with increasing values at three successive phases (Phase 1: 24.8.2004 to 7.10.2004 with low OLR; Phase 2: 8.10.2004 to 17.11.2004 with intermediate OLR; Phase 3: 18.11.04 to 22.1.2005 with high OLR) and a constant hydraulic application rate of 68, 53, 29 and 44 liter m⁻² d⁻¹ in the CWHSSF 1, 2, 3 and 4, respectively. At each phase, three samplings were accomplished to evaluate the kinetics of the organic material degradation and the efficiency of the system.

The CWHSSF were operated with six hydraulic retention times t that were different and simultaneous, as a function of the distances 0, 4, 8, 12, 16, 20 and 24 m of the CWHSSF extension, and with two fixed final times, i.e. 1.9 days in CWHSSF 1, 2 and 4; and 3.8 days in CWHSSF 3. The retention time t was obtained from the average flow values, which were determined between two subsequent collection points set up along the CWHSSF by applying the principles of Darcy's law. The fluid retention time t in porous saturated medium is defined as

$$t = \left[d/(q_i/\mu_p) \right] \tag{1}$$

with

d = distance between two collection points (m)

 $q_i = \text{flow} (\text{m}^3 \text{m}^{-2} \text{d}^{-1})$

 μ_p = macroporosity of substrate (m³ m⁻³)

All four CWHSSF were constructed with the following longitudinal slopes at the bottom and at the surface: CWHSSF 1 = 0.5 %, CWHSSF 2 and 3 = 1.0 % and CWHSSF 4 = 1.5 %.

The sampling for evaluation of the organic matter degradation kinetics began four months after operation of the system started and was finished six months later, after 10 complete months in operation. During the evaluation period, the stand of *Typha sp.* was dense, according to the values shown in Table 3, and the biomass was removed by a shallow cut (10 cm height) three months from the beginning of the evaluation.

The laboratory analyses consisted of quantifying the chemical oxygen demand (COD) measured on the bulk sample, soluble COD measured on the filtered sample, and total suspended solids (TSS) measured by gravimetric determination of the dry weight. Methods for both parameters were in accordance with recommendations of the Standard Methods for the Examination of Water and Wastewater (APHA 1995).

The average temperature of the liquid retained inside the CWHSSF was estimated, by using the average of the maximum and minimum temperature of the previous day and the temperature at 9 a.m. For example, average temperature = (maximum temperature + minimum temperature + actual temperature)/3 and the temperature value used for comparing the *K* constant of each sampling was the average value obtained over the period corresponding to both retention days of the liquid in CWHSSF 1, 2 and 4, whereas for CWHSSF 3 it corresponded to the relative average value at four days of its hydraulic retention time.

Table 1: Mean volumetric organic load rates OLR_V (g $\text{m}^{\text{-3}}\ \text{d}^{\text{-1}})$ of COD and BOD_5 with standard deviations

CWHSSF	Phase 1		Phase 2	2	Phase 3		
	COD	BOD_5	COD	BOD_5	COD	BOD ₅	
1	118 ± 7	51 ± 3	163 ± 12	85 ± 6	210 ± 6	97 ± 3	
2	110 ± 5	52 ± 2	162 ± 9	76 ± 3	211 ± 7	107 ± 3	
3	60 ± 6	31 ± 2	87 ± 10	47 ± 4	108 ± 7	58 ± 3	
4	107 ± 9	51 ± 2	167 ± 17	86 ± 5	208 ± 12	110 ± 4	

Table 2: Mean area organic load rates ${\rm OLR}_A$ (kg $ha^{\text{-1}}\,d^{\text{-1}})$ of COD and BOD5 with standard deviations

CWHSSF	Phase 1		Phase 2	!	Phase	Phase 3		
	COD	BOD ₅	COD	BOD ₅	COD	BOD ₅		
1	132 ± 3	58 ± 3	183 ± 6	93 ± 7	236 ± 3	118 ± 3		
2	98 ± 3	45 ± 2	144 ± 4	72 ± 4	187 ± 3	93 ± 3		
3	52 ± 3	26 ± 3	75 ± 6	39 ± 5	93 ± 4	48 ± 4		
4	71 ± 4	37 ± 3	110 ± 9	57 ± 6	137 ± 6	71 ± 4		

Table 3: Average density of plants in four CWHSSF during three study phases, based on the superficial area (m^2) and the effective pore volume of the substrate (m^3)

Dariad	CWHCCE	Plant density				
renou	Сүүпээг	(plants m ⁻²)	(plants m ⁻³)			
Phase 1	1	47.3	421.1			
	2	30.3	341.5			
	3	34.2	394.2			
	4	43.1	655.2			
Phase 2	1	58.6	522.5			
	2	36.0	405.8			
	3	40.3	463.8			
	4	51.1	776.4			
Phase 3	1	52.4	467.1			
	2	32.9	370.6			
	3	37.6	432.6			
	4	47.5	721.5			

The kinetic model was adjusted by using the values of the relative COD concentration in the wastewater along the extension of the CWHSSF as a function of the time t at three operating phases of the system. The model parameters were estimated by the Least Square Method, using Quasi-Newton's Iterative Method as well as the software Statistica 6.0. As proposed by Regazzi (2003), results were interpreted according to the parametric statistical analysis method (identity of nonlinear models).

3 Results and discussion

3.1 Temperature effect

The COD removal volumetric constant K_V dependent on the temperature was calculated, by using a first order relationship between the removal and the hydraulic retention time *t*, considering a plug-flow hydraulic model as shown in equation (2)

$$K_{V} = -\frac{\left[\ln\left(\frac{C_{o}}{C_{i}}\right)\right]}{t} \tag{2}$$

with

- C_o = effluent concentration (mg L⁻¹)
- C_i = influent concentration (mg L⁻¹)
- K_V = volumetric removal constant, dependent on the temperature (d⁻¹)

t = hydraulic retention time (d)

The effect of the temperature on K_V was considered, using the modified Arrhenius equation

$$K_V = K_{20} \theta^{\mathrm{T}} \tag{3}$$

with

 K_{20} = volumetric removal constant under temperature 20 °C (d⁻¹)

 θ = temperature coefficient

T = water temperature (°C)

A second order polynomial regression was established for the relationship between log (K_V) and *T*, thus obtaining the adjustment coefficient R² for the experimental data.

Table 4 and Fig. 2 show the effect of temperature on the COD removal volumetric constant K_V . No relationship occurred between these two variables either in CWHSSF 1, 2 and 4 that operated with a retention time *t* of 1.9 days, or in CWHSSF 3 that operated with a retention time of 3.8 days. These results are in accordance with those obtained by Vymazal (1998) for BOD₅ removal in a CWHSSF operated in the Czech Republic, but contrast with those found by Badkoubi et al. (1998) and Tunçsiper et al. (2004), who observed positive effects of the temperature on the organic load removal.

As no temperature effect on the removal of the organic load was observed in the present study, a volumetric constant K_V that is independent of the temperature will be used, as in the work reported by Laber et al. (1999) and Valentim (2003).

		Phase 1			Phase 2			Phase 3		
Hydraulic retent	tion = $1.9 days$									
Temperature (°C)		19.2	19.5	19.9	21.6	21.9	24.9	25.0	25.4	25.6
$K_V(d^{-1})$ C	CWHSSF 1	0.8994	1.0949	1.1712	1.2362	0.9661	1.1233	1.0811	1.1930	0.9702
$K_V(d^{-1})$ C	CWHSSF 2	1.0323	0.8264	1.0936	1.2589	1.0479	1.1999	1.0496	1.0856	1.0158
$K_V(d^{-1})$ C	CWHSSF 4	1.1705	0.7927	1.0189	1.1672	1.4426	1.1772	1.2910	1.0850	1.1400
Hydraulic retent	tion = $3.8 days$									
Temperature	(°C)	19.5	19.8	20.3	21.4	22.0	24.2	24.2	24.5	25.2
$K_V(d^{-1})$ C	CWHSSF 3	0.6205	0.5030	0.5701	0.7292	0.6065	0.7023	0.5756	0.6957	0.6548



Fig. 2: Plotting the values of the Log K_V (COD) as a function of temperature and data polynomial regression

3.2 Adjusting the organic load removal model

Reed et al. (1995) presented the kinetic model assuming the first order reaction

$$C_o/C_i = e^{(-Kt)} \tag{4}$$

If this model is adjusted to the experimental data of this study, the removal constant K was not constant along the CWHSSF and decreased from the beginning to the end of the treatment bed (Fig. 3). Decreasing K_V values are probably due to the increase of the recalcitrant organic material that persisted and were degraded only at the most downstream positions in the CWHSSF.

The prediction of the organic matter removal in CWHSSF, using the plug-flow first order model, might overestimate the results, as shown in Fig. 4, where the adjustment curve of this model to the COD removal data by Valentim (2003) is presented. The coefficient $R^2 = 0.808$ was obtained.

The overestimation of the organic matter removal in the adjustment curve occurs due to the fact that in the case of adjustment of the first order model, an average-valued K_V is obtained, relative to those obtained along the CWHSSF. So, at the end of time t of treatment, the removal constant K_V has a lower value because of the higher resistance to degradation of the recalcitrant material that prevails at the end of the treatment bed. This confirms that the determination of K_V based just on the input and output data of CWHSSF, as has usually been adopted, cannot be representative of several values of times t, but instead only of the time t in which it was determined.

In order to correct these inadequacies of the model presented by Reed et al. (1995), it is suggested that a new coefficient should be inserted into the empirical model, making it more representative of the kinetics of organic matter degradation in CWHSSF, by using the differential equation (5).

$$\frac{dC_o}{dt} = -nKt^{n-1}C_o \tag{5}$$

n is the coefficient representing the increased resistance of the remainder of the organic material and the reduced hydraulic retention time due to the effects of the hydraulic retention time distribution in the system. Therefore, the magnitude of n is a function of either



Fig. 3: Average values of K_{ν} in distance function and of time *t* along CWHSSF



Fig. 4: Adjustment curves for the COD removal data, selected by Valentim (2003), to both the first order model (dotted line) and the modified model proposed in the present study (solid line)

the variations in the recalcitrance the organic material or the hydraulic dispersion degree in the system. The magnitude of n was inversely proportional to the dispersion degree of the system.

By integrating equation (5) and making $C_o = C_i$, at t = 0, with constant C_i , the following function is obtained:

$$C_o/C_i = e^{\left(-K_v t^n\right)} \tag{6}$$

where n is a coefficient related to the increased recalcitrance of the organic matter and to the reduction of the retention time t (dimensionless).

In Table 5, the results are presented for the hypothesis formulated in the statistical test applied in analyzing the identity of the model at the significance levels of 1 % and 5 %, thus confirming that the parameters determined in the proposed model are identical for the CWHSSF 1, 2 and 3. It is observed that the *n* values on which the estimate was based in the results of this research were 0.2491 for CWHSSF 1, 2 and 3, and 0.2037 for CWHSSF 4, which are inferior to the value of 0.356 estimated for Valentim's data (2003).

In Fig. 5, 6 and 7 two curves are plotted using two different first order plug-flow removal models: the model $C_o/C_i = e^{(-K_v t)}$ presented by Reed et al. (1995) and the the model proposed here $C_o/C_i = e^{(-K_v t^n)}$.

In Fig. 5, the organic load removal curves are plotted and expressed in terms of COD in CWHSSF 1, 2 and 3, for which common parameters were obtained and analyzed by the Model Identity Test. In Fig. 6, the removal curves are plotted for CWHSSF 4 that presented no parameters in common with the other CWHSSF. Fig. 7 shows the curves for the TSS removal in CWHSSF 1, 2 and 3.

Although this semi-empirical model has been adjusted to subtropical climate conditions, it is expected that it can be useful for predicting the removal of organic matter under temperate climates also, as the organic degradation in CWHSSF obeys the same kinetics under both climates. In other words, the organic substrate flows through the porous system medium in the hydraulic model that is predominantly of the plugflow type. Therefore a more recalcitrant material remains to be degraded in the fine portions of the beds and consequently reduces the magnitude of K. The only difference for temperate climate will theoretically be the effect of the temperature on constant degradation K, which must be adjusted.

3.3 Efficiency of the organic load removal

The results of the organic load removal are presented in Table 6. It is generally observed that even at low hydraulic retention times CWHSSF have remarkable removal efficiencies for organic load:

Table 5: Hypothesis appraised for the proposed model parameters, statistical values of the qui-square (χ^2) test and number of freedom degrees. Asterisks mark the significance of tabulated χ^2

CWHSSF	Hypothesis	Model	K_V (d ⁻¹)	Ν	Calculated χ^2	Freedom degree	Tabula 1 %	tted χ^2 5 %
1, 2, 3, and 4	Ho (1): k1= k2= k3= k4=k	$C_o/C_i = e^{\left(-K_V t^n\right)}$	1.6752	0.2041	27.47	8-2 = 6	16.81*	12.59*
1, 2, 3	and n1 = n2 = n3 = n4 = n		1.6221	0.2491	5.24	6-2 = 4	13.27	9.48



Fig. 5: COD removal curves of both the first order removal (dotted line) and that adapted and proposed, adjusted to the experimental data for CWHSSF 1, 2, 3 (solid line)

Fig. 6: COD removal curves of both the first order removal (dotted line) and that adapted and proposed, adjusted to the experimental data for CWHSSF 4 (solid line)

Fig. 7: TSS removal curves of both the first order removal (dotted line) and that adapted and proposed, adjusted to the experimental data for CWHSSF 1, 2, 3 (solid line)

Total COD

The effluent concentrations were 35 mg L^{-1} in the CWHSSF 1, 2 and 4 operating under a hydraulic retention time of 1.9 days (87 % removal) and 25 mg L^{-1} in CWHSSF 3 operating under a hydraulic retention time of 3.8 days (90 % removal). These results for the efficiency of organic matter removal can be considered satisfactory, because the organic load rates on the

basis of superficial area (OLR_A) of the CWHSSF and expressed in terms of BOD₅ varied from 26 to 118 kg ha⁻¹ d⁻¹, therefore partially surpassing the load recommended by U.S. EPA (2000b) and ITRC (2003) for treatment of septic tank effluents in CWHSSF, which is only 60 kg ha⁻¹. The results for COD removal efficiency were superior to those 57 %, which were estimated and obtained by Valentim (2003), when treating

	CWHSS	F 1, 2, 4	CWHSSF 3		
Pollutant	Effluent concentration	Removal (%)	Effluent concentration	Removal (%)	
Total COD (mg L ⁻¹)	35 ± 12	87 ± 3	25 ± 9	90 ± 3	
Soluble COD (mg L ⁻¹)	26 ± 11	81 ± 7	19 ± 7	85 ± 6	
TSS (mg L ⁻¹)	7 ± 3	91 ± 6	7 ± 6	91 ± 10	

Table 6: Pollutant concentrations in effluent and the removals (average \pm standard deviation) obtained during evaluation of the CWHSSF

septic tank effluent in CWHSSF cropped with *Typha* sp. at a hydraulic retention time t of 2 days, but similar to those obtained by Rivera et al. (1997), who reported an average removal of 87.4 % at t corresponding to 1.7 days.

Soluble COD

The average removal efficiencies were 81 % in CWHSSF 1, 2 and 4, but 85 % in CWHSSF 3. However, an isolated comparison of the averages for each CWHSSF shows that CWHSSF 4 reached an average removal efficiency equal to that of CWHSSF 3, which operated with twice the time t. The efficiency of soluble COD removal was not as high as for total COD. It is important to consider that the CWHSSF received high loads of particulate organic material. The liquid phase was flowing through the substrate, while most of the particulate organic material was retained in the substrate, undergoing slow but efficient degradation.

Total suspended solids

The value of both TSS effluent concentration and its removal efficiency obtained in CWHSSF 1, 2, and 4 was inferior to that obtained in CHWHSSF 3 that operated with twice the value for t. The values for removal efficiency were superior to the 79 % obtained by Valentim (2003) under t of 1.9 and 3.8 days, but similar to those obtained in small CWHSSF used for domestic wastewater both in Australia (Davison et al. 2004) and in the Czech Republic (Vymazal 2004).

4 Conclusions

On the basis of the results obtained and for the experimental conditions, the following conclusions may be drawn:

 The first order plug-flow model for organic load removal in CWHSSF was not adjusted well to the data observed. Therefore we proposed the removal model

 $[C_o/C_i = e^{(-K_v t^n)}]$, which is much better adjusted. The proposed model seems to be well fitted to the kinetics of the organic load removal in the evaluated system. Nevertheless, this model should be gauged in other CWHSSF, where the magnitude of the dispersion with tracers and associated to the *n* coefficient might be studied in order to enable identification of a more representative value for the organic matter degradation coefficient;

- The hydraulic retention time of 3.8 days provided higher efficiency in removing COD, although the time of 1.9 days has been efficient for producing an effluent that satisfies the patterns for discharging into receiving water bodies, according to the environmental legislation in Minas Gerais State, Brazil;
- The temperature did not affect the degradation constant K;
- The design of the CWHSSF studied proved to be adequate for the treatment of pretreated wastewater from septic tanks.

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