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DAMKÖHLER NUMBER DESIGN METHOD TO AVOID PLUGGING OF TIDAL FLOW CONSTRUCTED WETLANDS BY HETEROTROPHIC BIOFILMS

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ABSTRACT

Clogging of subsurface flow (SSF) treatment wetlands due to excess biofilm growth is a design problem for which only empirical guidelines exist. A method is proposed to systematically analyze this type of clogging as a design tool. In recognition of the physical reality that most SSF treatment wetland processes are a function of biofilm surface area, a Damköhler number (*Da*) definition based on specific surface area is used to investigate a method of predicting clogging induced by heterotrophic biofilms growing on treatment media. This method entails estimation of aggregate surface area and modeling of biofilm growth, and is developed in a tidal flow (flood and drain) pilot SSF wetland. The results are then applied to a horizontal flow SSF wetland. Results suggest that *Da* values can be used to predict biofilm clogging in SSF wetlands.

KEYWORDS

Biofilm; clogging; constructed wetland; Damköhler number; wastewater

INTRODUCTION

Subsurface flow (SSF) wetlands are vulnerable to clogging caused by biofilm growth in both vertical and horizontal flow configurations (US EPA, 2000; Langergraber et al., 2003). Empirical design criteria have been developed to avoid clogging based on areal mass loading rates or long-term hydraulic conductivity (US EPA, 2000), but wide variation of SSF wetland designs relegates these criteria to “rules of thumb” with limited design utility (Kadlec and Knight, 1996). Because most clogging occurs in the inlet zone, Wallace and Knight (2006) recommend limiting BOD inlet cross-sectional loading of area orthogonal to flow to 250 g $BOD_5/m^2 \cdot d$ for a horizontal flow SSF wetland, using an aggregate sieve specification of 15 mm × 25 mm. The specificity of this criterion suggests that a more broadly applicable design method can be developed.

Biofilm growth in an SSF wetland can be analyzed by means of the Damköhler number (*Da*), which is a dimensionless ratio of reaction rate to mass transport. The wetland is reaction (growth) rate limited if $Da \ll 1$ and mass transport limited if $Da \gg 1$. Most SSF wetland treatment processes are a function of biochemically active surface areas in contact with wastewater. Thus we define *Da* in terms of specific surface area (*SSA*) of biofilms growing on aggregate (or other treatment media) (Equation 1). Our study explores this formulation of *Da* as a design tool to avoid clogging from excess biofilm growth in a tidal flow (flood and drain) wetland pilot. These results are then applied to a cross-sectional loading criterion for a horizontal flow SSF wetland.

$$Da = \frac{Rate_{reaction}}{Rate_{masstransport}} = \frac{kX_a}{k_A t \cdot M_{LA}} \qquad \text{Equation 1}$$

Where: k = maximum specific substrate utilization rate, g substrate/g VS·d (M/M·T)
X_a = maximum specific concentration of active cells, g VS/m^2 medium (M/L^2)
VS = volatile solids (biofilms), g (M)
M_{LA} = specific mass loading rate, g substrate /m^2·d medium (M/L^2·T)
$k_A t$ = one-dimensional advective mass transport coefficient, $1/\tau_\theta$ (unitless)
τ_θ = normalized mean hydraulic residence time (unitless)

METHODS

Specific surface area (*SSA*)

We define the *SSA* of treatment media operationally. For a diffusion limited process, *SSA* can be measured by adsorption isotherm methods that include intragranular porosity (Tokunaga et al., 2003). In the study pilot wetland, however, advection dominates over diffusion by three to five orders of magnitude (Austin et al., 2006). Therefore, the only surfaces of interest are those in contact with moving water. These surfaces can be measured as gravitational water films on the aggregate. Water films were used to determine *SSA* and then compared to a power curve calculation for *SSA*.

Aggregate samples were submerged in clean well water for 48 hours, to saturate intragranular pores, and then drained for six hours to remove gravitational water. Drained aggregate was weighed on an analytical balance, submersed in water, immediately drained, and then weighed after ½-hour to obtain the mass of gravitational water films. Measurements were repeated until replicated on the same sample.

Results were used to calculate the hypothetical water film thickness per Equation 2, which assumes a spherical particle and provides estimates of water film thicknesses of 10 – 60 μm (Tokunaga et al., 2003). Equation 2 was applied to aggregate size classes (Table 1). The spherical particle assumption is not true for the highly angular LESA (lightweight expanded shale aggregate) used in the pilot, but the spherical assumption sets a reasonable theoretical maximum for water film thickness, especially considering thickening of water films (pendular rings) at granular contact points.

$$f = \frac{\rho_s d w}{6\rho_w} \qquad \text{Equation 2}$$

Where: f = water film thickness, m $\quad$ ρ_s = density of solid (particle), kg/m^3

ρ_w = density of water, kg/m^3 $\quad$ d = particle diameter, m (from Table 1)
w = measured water/solid mass ratio, unitless

Table 1. Sieve analysis for LESA. The 9.51 mm screen was 100% passing. Median diameter (d_m) of each size fraction was taken from sieve gradations within each size class, assuming even diameter distribution. Dry bulk (ρ_b) and particle density (ρ_s) were 891 and 1,800 kg/m^3, respectively.

Sieve class, mm	Granule size class, mm	Size class fraction	Fraction median diameter (d_m), mm	Uniformity coefficient, *UC*
4.75 × 9.51	$4.75 \le d \le 8.00$	0.42	6.35	8.00/2.36 = 3.4
2.36 × 4.75	$2.36 \le d \le 4.00$	0.55	3.11	
1.19 × 2.36	$1.19 \le d \le 2.00$	0.02	1.55	
< 1.19		0.01	NA	

The power curve relationship for *SSA* (Equation 3) is used by manufacturers of LECA™ (lightweight expanded clay aggregate), which is similar to LESA. It uses d_m in mm and is not dimensionally consistent.

$$SSA = 3057 d_m^{-0.9486}\text{, m}^2/\text{m}^3 \qquad \text{Equation 3}$$

Biofilm growth

Details of the 6-cell tidal flow (flood and drain) system (Figure 1) are given elsewhere (Maciolek and Austin, in press; Austin et al., 2003). For this study, it is important to know that each cell had a drainage sump with a pump. Computer controls actuated the pumps, flooding and draining all cells approximately 8 to 12 times per day during this study. Total aggregate volume and surface area were 5.4 m^3 and 10 m^2, respectively.

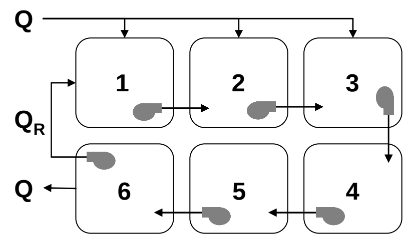

Figure 1. Tidal wetland pilot plan schematic with cell numbers.

Fifteen 1-kilogram mesh bags of aggregate were hung midway in the sump of cell 3 to subject biofilms both to average flood and drain states and the heaviest mass loading of the pilot system. One bag per week was removed from the sump. Aggregate was removed from the bag, dried at 40^{o}C for 48 hours, and then weighed. Aggregate was then ignited at 550^{o}C and volatile solids (*VS*) measured by difference from dried aggregate. Blank samples were prepared with aggregate soaked in clean well water.

Pilot wastewater was manufactured from dried cheese whey, urea fertilizer, well water and (occasionally) horse manure. The COD and BOD mass equivalents for dried cheese whey are known (Austin et al., 2003). At least 95% of COD came from cheese whey. Influent and cell 3 drainage sump grab samples were tested for BOD_5 to confirm a previously measured 96% BOD_5 removal rate in cell 3 (Austin et al., 2003).

To measure the balance between biofilm growth and decay, influent COD mass loading was varied in phases. Mass COD loading to cell 3 was approximately 300 g/d for the first nine weeks. Afterward, periods of starvation alternated with mass loadings of 150 g COD/d. Results from *VS* measurements were used to calibrate a Monod model for biofilm growth and decay (presented in the results section).

Mass transport

In a tracer study, one kilogram of sodium chloride was placed into the pump sump of cell 1. A data-logging, in-situ, electroconductivity probe with built-in conversion to total dissolved solids in the effluent sump took readings every 15 minutes thereafter.

Mass transport through porous media is treated as one dimensional. Normalized hydraulic residence time (τ_θ) tracer data was plotted as normalized time (t_i/τ) time versus normalized concentration (C_i/C_o, where C_i is the concentration at time t_i, and C_o is the initial concentration). Time to the center of mass of this curve is τ_θ (Equation 4). Normalized flushing time, $1/\tau_\theta$, is the unitless mass transport coefficient, $k_A t$.

$$\tau_\theta = \frac{1^{st}\ moment}{0^{th}\ moment} = \frac{\int \frac{C_i}{C_o}(t)t_i dt}{\int \frac{C_i}{C_o}(t)dt} \qquad \text{Equation 4}$$

RESULTS AND DISCUSSION

Specific surface area

The mass of gravitational water was 1.32 grams of water per 60.43 grams of saturated aggregate, giving w = 1.32 g/60.43 g = 0.023. Bulk density of wet, drained aggregate was 909 kg/m^3. Water temperature was 25^{o}C, thus ρ_w = 997 kg/m^3. These values are used (Equation 2) with d = 6.35, 3.11, and 1.55 × 10^{-3} m to calculate hypothetical maximum water film thicknesses of 42, 20, and 10 μm, respectively.

In draining media, water films thin over time by gravity until a zero matric potential is reached, which is the threshold at which water film thickness is affected by the capillary and adsorptive forces of aggregate particles, but not gravity. For basalt granules similar in morphology to LESA, the water film thickness at zero matric potential was observed to be 7-10 μm (Tokunaga et al., 2003). Thus 10 μm is the lower limit of water film thickness used to compute surface area by this method.

Estimation of the surface area by this method is by a three-step calculation across the 10 to 42 μm range in 1 μm increments to account for variability of water film thickness:

1. Water film area (m^2), A_w = Volume of water (1.32×10^{-6} m) ÷ water film thickness
2. Mass specific surface area (m^2/kg), $A_{ms} = A_w \div 60.426$ g × 1,000 g/kg
3. Volumetric specific surface area (m^2/m^3), $SSA = 909$ kg/$m^3 \times A_{ms}$

The averaged result of these calculations is $SSA = 810$ m^2/m^3.

By using the class fraction median diameter (d_m in Table 1) in Equation 3, a size class *SSA* can be independently calculated. The weighted sum (size class fraction × size class *SSA*) of all size classes gives an aggregate $SSA = 834$ m^2/m^3.

Close agreement (3% difference) between these results makes the simplicity of the power curve the preferred method for calculating *SSA*. If needed, a power curve relationship ($d_{granule}$ vs. *SSA*) can be developed for an aggregate sieve specification by using the water film method and changing Equation 2 so that d is a function of f.

Mass transport coefficient

The normalized mean hydraulic residence time, τ_θ, was 0.85. Thus $k_A t = 1/\tau_\theta = 1.18$.

Biofilm measurement and Monod model

With *SSA* known, kX_a is determined from data by converting g *VS*/kg aggregate to g *VS*/m^2 aggregate and then dividing by the substrate utilization rate, g COD_u/g *VS*·d (Figure 2). Because the COD utilization rate was measured from mature biofilms in cell 3, apparent kX_a in the aggregate samples was skewed by experimental methods until sample biofilms were mature. Observed kX_a used was 0.0185 g COD/m^2·d. In mature biofilms, kX_a is constant if wastewater characteristics do not change.

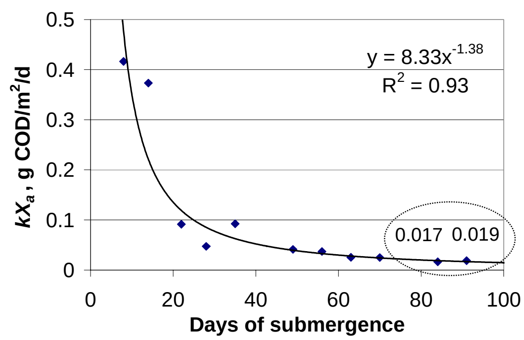

Figure 2. Direct measurement of kX_a. Final values of mature biofilm were averages for kX_a (circled values).

Modeling of biofilm film growth uses an incremental addition of growth to the existing biofilm mass (Equation 5). The net biomass growth, r_g, (Equation 6) can be directly calibrated to *VS* measurements to produce a Monod model fit to *VS* data. The model is built with the observed yield, $Y = 0.068$ g *VS*/g COD, and COD loading data, S. Other values, $k = 3.30$, $K_s = 25$, and $k_r = 0.020$, were established from literature and visual model fitting (Figure 3). The large error bars are taken from blank standard errors. Sample drying time was insufficient to remove all water retained in intragranular pore spaces. We recommend a longer drying time, perhaps seven days, at 40°C to remove water prior to ignition of *VS*.

$$X_t = X_{t-i} + t_i r_g \qquad \text{Equation 5}$$

Where: X_t = biomass at time *t*, g/m^3 $\quad$ r_g = growth rate, g/m^3·d $\quad$ t_i = time, d.

$$r_g = \frac{YkXS}{K_s + S} - k_r ln(X)X \qquad \text{Equation 6}$$

Where: Y = yield, g *VS* / g COD$_u$
k = substrate utilization rate, 1/d
X = biomass concentration, g/m^3
k_r = endogenous respiration coefficient, 1/d
ln(X) = density dependent decay cofactor for k$_r$, unitless
COD$_u$ = COD utilized, g/m^3·d
S = utilized substrate, g COD$_u$/m^3
K_s = half-velocity constant, g/m^3

The biomass decay cofactor *ln(X)* in Equation 6 merits attention. Biofilms encounter lateral spatial limitations growing on aggregate surfaces. The extremely long mean cell residence time of mature biofilms also provides a stable environment for biofilm grazing organisms. The cofactor *ln(X)* is used to represent these spatial density and age dependent phenomena. The Monod model can not fit data without it.

The close fit of Equations 5 and 6 to data (Figure 3) demonstrate the utility of Monod kinetics to modeling system behavior. Terms in this spreadsheet biofilm growth and decay model can be reformulated in terms of *SSA* to model kX_a over time to obtain a result similar to direct measurement (Figure 2). By "growing" virtual biofilms and extracting kX_a, this model and *Da* calculation of can be extended to other SSF wetland systems.

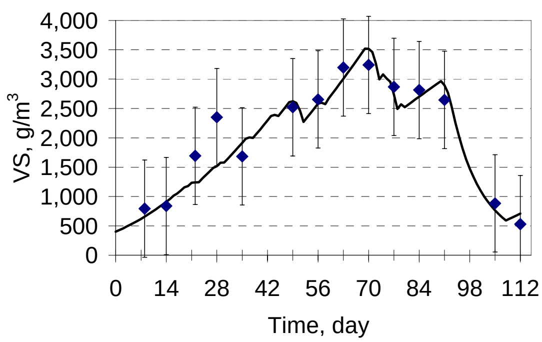

Figure 3. Biofilm growth and decay (*VS*, g/m^3) vs. time: Data, diamonds; Monod model, solid line. Error bars are control blank mean standard error.

Damköhler number

There is a transition value *Da* between tendencies to clog from excess biofilm growth or be free from clogging. The Damköhler number must be correlated to observed clogging at a given COD or BOD mass loading. Over nearly three years of pilot operations, a mass loading of 150 g COD/m^3 aggregate·d (approximately 100 g BOD$_5$/m^3·d) induced clogging, which was reversible at lower loadings. This loading rate corresponded to a specific surface area mass loading rate, M_{LA}, of 0.18 g COD/m^2·d. With kX_a = 0.0185 g

COD/m^2·d and $k_A t$ = 1.18, *Da* = 0.09 per Equation 1. At *Da* > 0.09 there is little to no tendency to clog, while *Da* < 0.09 induces clogging; *Da* = 0.09 is a transition value

In the study system, at *Da* > 0.09 the dynamic balance between biofilm growth and decay (Figure 3, Equation 6) kept biofilms from clogging the system (Figure 4). Because of this dynamic balance, the transition *Da* is theoretically sensitive to system factors upon which both *k*, the substrate utilization rate, and k_r, the endogenous respiration (or decay) rate (Equation 6), are functionally dependent. Some of these factors are temperature, pH, salinity, toxic compounds, and the system redox state.

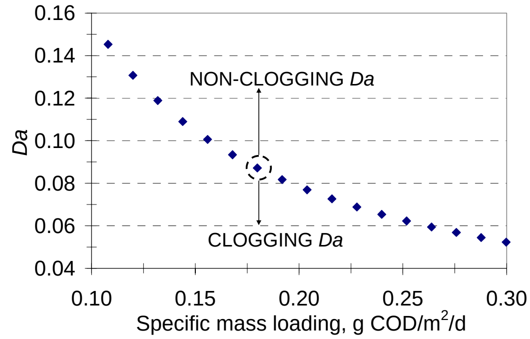

Figure 4. Specific mass loading vs. *Da*. *Da* = 0.09 is transition between non-clogging tendencies.

We apply this Damköhler analysis to a hypothetical horizontal flow SSF system using the following assumptions:

1. Inlet cross sectional loading is 250 BOD_5 g/m^2
2. Flow, Q = 100 m^3/d; influent BOD_5 = 150 mg/L
3. BOD_5 removal follows 1st order kinetics
4. Aggregate specifications: d_m = 15 mm, $UC \leq 4$, and SSA = 234 m^2/m^3 (Equation 3)
5. kX_a = 0.0185 g COD/m^2·d

Per Equation 7 and assumed parameter values, system HRT, τ, is 4.5 days.

$$\tau = -\ln\left[\frac{C_e}{C_o}\right] \div \eta k_v \qquad \text{Equation 7}$$

Where: C_o = influent concentration, 150 mg/L C_e = effluent concentration, 20 mg/L
η = mean pore fraction, 0.3 k_v = volumetric rate coefficient, 1.5/d

Mass flux is 15,000 g BOD_5/d, requiring an inlet cross sectional area of 60 m^2. With aggregate depth, *h*, of 1 meter, the inlet zone is 60 meters wide. The wetland area, A_w = $\tau Q/\eta h$ = 1,500 m^2, and length is 25 meters. Specific mass loading, M_{LA}, in the first meter of the inlet zone is 1.07 g BOD_5/m^2·d (15,000 g/d ÷ [234 m^2/m^3 × 60 m^3]).

The wetland was modeled as four reactors in series, using normalized concentration and time to obtain $k_A t = 1/\tau_\theta$ = 1.59 per Equation 4. The inlet zone occupies 1/25 (4.0%) of system length, but is assumed to have twice the flow velocity because of reduction of pore diameters by growth of biofilm. Thus the effective hydraulic length of the inlet zone is 8.0% of system length, giving $k_A t_{inlet} = 0.08 k_A t = 0.13$. Per Equation 1, $Da = 0.10$. Close agreement to the pilot transition Da (0.09) suggests that this method of clogging analysis can be applied across SSF wetland systems. More research is needed to understand further application of this methodology.

CONCLUSION

Results from the methods of this paper suggest that Damköhler numbers may be used to predict clogging in SSF wetland systems. These methods include determination of aggregate specific surface area, and direct measurement of both aggregate biomass and specific substrate utilization rate. A unitless mass transport coefficient, $k_A t$, can be obtained from tanks in series (TIS) models, provided that a characteristic TIS model for a design system is known. Monod kinetics with a modified decay term allows spreadsheet modeling of biofilm growth and decay in an SSF wetland. By combining this model with specific surface area calculations, kX_a can be extracted and, with $k_A t$, used to calculate Da. There is a Da for mass loadings that induces clogging. In sizing a wetland, process kinetics may not be sufficient if clogging kinetics are left unquantified. Thus, significant potential exists for these methods to be useful tools in design to avoid biofilm clogging of SSF treatment wetlands or unnecessary sizing conservatism.

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