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A MECHANISTIC SIMULATION MODEL OF A CONSTRUCTED WETLAND DESIGNED TO REMOVE ORGANIC MATTER FROM STORMWATER RUNOFF

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ABSTRACT

A numerical simulation model is presented for a surface-water-fed constructed wetland with a pretreatment detention pool for flow control. The model combines system hydrology with processes thought to be important in the removal and treatment of low levels of dissolved organic matter typical of stormwater runoff. A mechanistic system dynamics approach is used to explore system behavior under reasonable ranges of values of environmental conditions and potentially important design parameters. Generalized results are presented, giving insight into the importance or unimportance of such factors in influencing treatment efficiency of organic matter. Results demonstrate the importance of factors which control organic loading and available surface area for biofilm development, and the relative unimportance of factors controlling flow velocity, for example. Wetland surface area is an important design parameter with competing effects requiring optimization. Model equations are presented and can be employed in numerical simulation to study optimum design strategies for a specific location with defined environmental conditions.

INTRODUCTION

As regulatory control over industrial process discharges and publicly owned treatment works have grown increasingly comprehensive, regulatory focus has turned to stormwater discharges over the last decade. Several studies conducted by the Environmental Protection Agency (EPA) have characterized the content and runoff originating from residential, commercial, and light industrial areas [1]. Results demonstrate that such waters contain many of the contaminants found in process discharges, often in high quantities (suspended solids, metals, organic matter).

Current regulation requires stormwater discharges to evaluate best management practices (BMPs) for controlling these discharges and to implement them where possible. Criteria for evaluating BMP's generally include cost, manpower and maintenance requirements, contaminant removal efficiency, and suitable site conditions. Where site conditions allow, constructed wetlands generally compare very well in cost and maintenance requirements and can usually achieve better than 90 percent treatment efficiency if designed properly [2]. This has been demonstrated with hundreds of constructed wetlands across North America, Great Britain, and Europe which have been constructed for the purpose of treating municipal, industrial, and agricultural wastewaters [3]. Wetlands effectively treat suspended solids, nitrogen, and organic matter which produces biochemical oxygen demand (BOD) through natural processes of filtration, sedimentation, biodegradation, and absorption. They also tend to effectively sequester many metals in biological tissue and in sediments, although toxicity issues are still under investigation.

However, limited information exists on the treatment efficiency of these systems for stormwater runoff which contains these same materials at widely varying levels and intermittent discharge rates. This variability in pollutants, as well as the hydraulic fluxes during storms, creates conditions difficult to control from a design perspective. Design challenges are multiplied when the treatment processes themselves are complex natural processes whose behaviors under extreme conditions are poorly understood. Empirical design formulas typical of unit process design are limited due to lack of a good range of empirical data under well-controlled ecological conditions. Some critical design parameters that can be controlled amidst this uncertainty include surface area, depth of water, length to width ratio, inlet and outline structure for flow control, and dominant vegetation.

The purpose of this work is to present a dynamic numerical simulation model of a constructed wetland and to use the model to explore the effect of viable design parameters on treatment efficiency of organic matter. The model combines the hydrological system with the natural processes thought to be important in BOD removal. Simulation results are discussed with their implications for practical design strategies.

MODEL DEVELOPMENT

Constructed wetlands, particularly those designed for intermittent large flows, generally include a detention pond with outflow control into the primary wetland treatment area to protect against shock hydraulic loading and suspended solids deposition [4]. The pond provides some suspended solids removal and serves to dampen the storm flow amplitude through the wetland, depending on the intensity of the storm. Since a major natural treatment process for organic matter removal involves biofilms attached to submerged plant and sediment surfaces, wetland outflow control is also included to maintain a minimum water level to preserve these processes in times of low flow. For this study, a surface water fed, continuously submerged wetland with emergent vegetation is assumed. The processes critical in the fate and transport of dissolved organic matter (DOM) are bulk hydraulic flow, degradation in the dissolved phase by suspended biota, and absorption into biofilms with ensuing degradation as influenced by oxygen availability. Figure 1 conceptually presents the physical system and Figure 2 shows the various system influences affecting treatment efficiency including critical design parameters.

Within a wetland which has a very large surface to volume ratio (particularly when including plant surfaces) biofilm absorption dominates in influencing free water concentration, discharge rate, and treatment efficiency [5]. Absorption depends on biofilm porosity, diffusivity, degradation rate constants, biofilm thickness, liquid-film interface characteristics, and bulk water concentration. The mathematical formulation of absorption depends on assumptions made concerning whether the system is oxygen or substrate limited and whether microbial growth kinetics are significant in the system context and time horizon of interest.

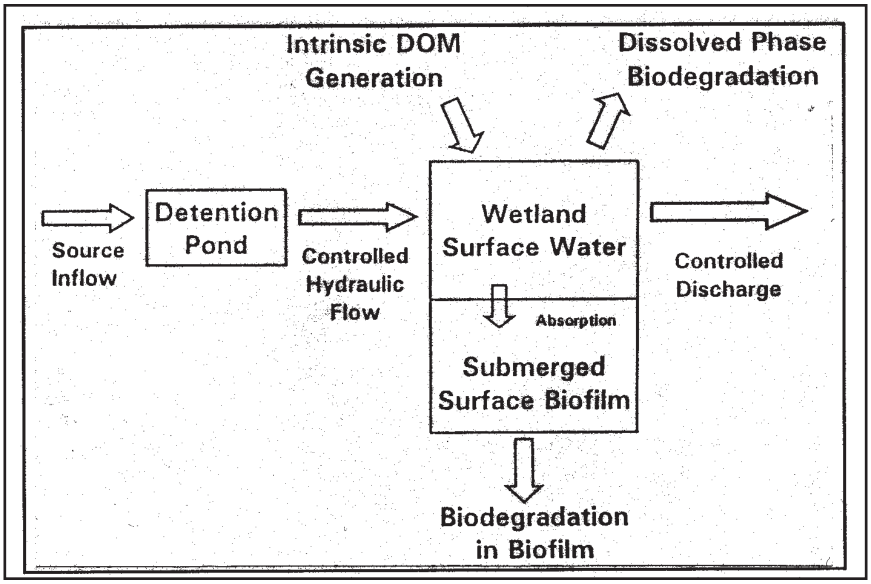

Figure 1. Modeled processes in the fate and transport of dissolved organic matter (DOM) in a submerged wetland.

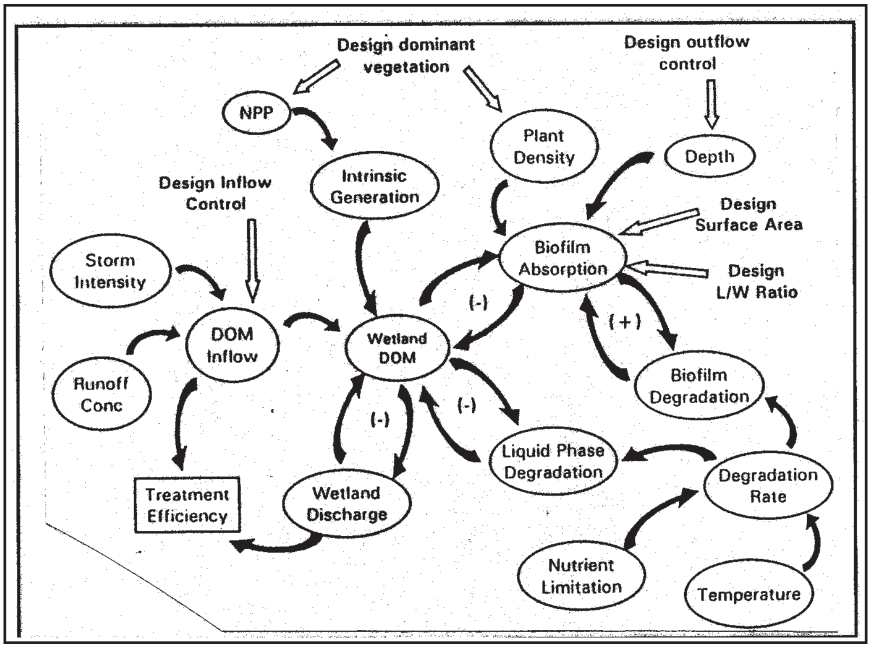

Figure 2. System influences controlling treatment efficiency of dissolved organic matter (DOM) in a submerged wetland.

Figure 3 illustrates the physical phases associated with a plant surface biofilm and an organic concentration profile resulting from absorption into and degradation within the biofilm. Polprasert and Agarwalla [6] provide a solution for the flux across the boundary layer into the biofilm in the form given below, originally provided by Lau [7].

$$J_B = \beta\, C_s \qquad \text{(equation 1)}$$

where

J_B = flux through liquid boundary layer and into biofilm (mg/hr/m^2)
C_s = substrate concentration at liquid/biofilm interface (mg/m^3)
= $\alpha\, C_w / (\alpha + \beta)$
C_w = bulk surface water concentration (mg/m^3)
α = D_w / L_s
β = $\tanh(\phi)\, K_f L_f / \phi$
ϕ = $(K_f L_f^2 / D_f)^{1/2}$
D_w = substrate diffusion coefficient in water (m^2/hr)
D_f = substrate diffusion coefficient in biofilm (m^2/hr)

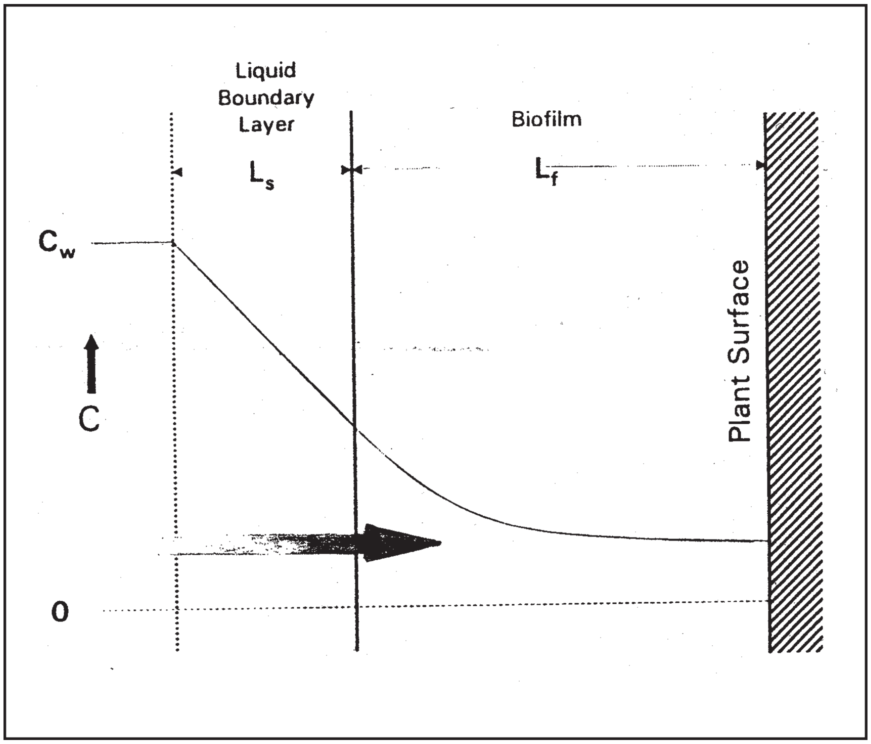

Figure 3. BOD concentration profile in biofilm and stagnant liquid boundary layer, assuming first order degradation kinetics in the film.

L_s = liquid boundary layer thickness (m)
L_s = biofilm thickness (m)
K_f = 1st order aerobic degradation rate constant in biofilm (hr^{-1})
= $K_{f,20}\,(1.1^{(T_w - 20)})$
$K_{f,20}$ = rate constant at 20°C
T_w = wetland surface water temperature (°C).

This solution assumes planar geometry (given small layer thickness compared to plant radii), first order aerobic decay throughout the biofilm, complete penetration of the biofilm by the substrate, and uniform flux across the liquid boundary layer. This flux expression, for purposes of this model, is assumed to apply over a time range in which C_w, L_s, and L_f may be considered constant. Changes in these values take place systemically on a larger time scale. The thickness of the liquid boundary layer is determined strictly by the energy dissipation rate as described by Kawashima and Suzuki [8], which is a direct function of the bulk water velocity adjacent to the surface:

$$L_s = (\varepsilon / \nu^3)^{-0.25} \qquad \text{(equation 2)}$$

where

ε = energy dissipation rate (m^2/hr^3)
= gravitational constant * bulk water velocity (when velocity > 0)
= 10^{-4} m^2/s^3 (when velocity = 0) [8]
ν = kinematic viscosity of water (m^2/hr).

The velocity of bulk water through the wetland and past surfaces is determined by flow (as controlled by flow control devices) and the shape of the wetland expressed by the length to width ratio (another potentially important design parameter).

The value of the biofilm thickness (L_f) can be formulated differently depending on assumptions made. Kawashima and Suzuki [8] present the case where substrate degradation is oxygen limited with aerobic and anaerobic zones within the biofilm and where there is incomplete penetration of substrate due to both aerobic and anaerobic decay. For this case, a steady state value of L_f is presented as:

$$L_f = - D_f L_s / D_w + [\, (D_f L_s / D_w)^2 + 2\, (D_f C_0 / K_f)\,]^{1/2} \qquad \text{(equation 3)}$$

where

C_0 = bulk water oxygen concentration (mg/m^3).

These assumptions, arising from the context of stream beds receiving process discharge in their case, may not aptly apply to shallow wetlands with prolific vegetation and very low organic loading rates. Under very low velocities and substrate limited conditions with periodic fluctuations due to storms, biofilm thickness may be better represented with a view toward non-steady state continual biomass growth and endogenous decay, using Monod kinetics, for example. In this model, biofilm thickness is geometrically determined from total biomass, assuming uniform biomass density and thickness on all surfaces. Biomass responds to substrate availability assuming no oxygen limitation, such that a constant biomass yield coefficient applies throughout. Thus,

$$dX/dt = Y\, dS/dt - K_d\, X \qquad \text{(equation 4)}$$

where

X = total biomass (mg)
Y = biomass yield coefficient from substrate consumption
S = total substrate (mg), with the time differential referring to substrate moving into biofilm and degrading (directly related to flux into biofilm)
K_d = endogenous respiration coefficient for biomass (hr^{-1})

and

$$L_f = [\, - b + (b^2 - 4ac)^{1/2}] / 2a \qquad \text{(equation 5)}$$

where

a = π d Pop
b = π d Pop $r_p + A_w$
c = $-X / D_b$
Pop = Plant population (number of plant shoots)
d = depth of wetland surface water (m)
r_p = average radius of plant shoots (m)
A_w = design surface area of wetland (m^2)
D_b = uniform biomass density (mg/m^3).

A yield coefficient of 0.20 (reasonable) provides a stable value of biofilm thickness appropriate for natural wetlands (on the order of a few millimeters) which also dictates an endogenous decay rate constant of 1×10^{-5} hr^{-1}. Throughout simulations of the model across reasonable ranges of parameter values, L_f values do not significantly fluctuate, as might be expected in natural waters with low BOD input.

In addition to biofilm degradation of organics, some degree of free water DOM decay from suspended biomass is active, although generally much less significant. This decay is represented by a first order decay rate constant which is a function of organic loading rate as given by Polprasert and Agarwalla [6].

The model assumes a baseline stream flow with very low BOD and periodic storm flows with elevated BOD in the runoff flow. In addition to this organic loading, an intrinsic organic loading is also modeled to account for organic release from the highly productive phytoplankton, periphyton, and submerged and emergent macrophytes typical of wetland vegetation. In fact, about 5 mg/l BOD_5 is typically found in wetlands with no outside source [9]. According to Moshiri [5], dissolved organic matter release may be as much as 30 to 40 percent of the total net primary production (NPP) of the macrophytes characterizing the wetland and 10 percent of the water column NPP. Cronk [10] reports that in newly constructed wetlands, water column primary producers contributed 17 to 67 percent of the net production. This model assumes, as a baseline condition, that the wetland consists of 50 percent cattails and 50 percent reeds, together contributing 60 percent of NPP with the water column contributing the remaining 40 percent. NPP values for several wetland macrophyte species are reported by Greeson et al. [11].

Flow through the wetland during storm events is determined by the storm intensity and the runoff coefficient for the watershed, such that

$$Q_R = I_s A_{ws} R \qquad \text{(equation 6)}$$

where

Q_R = flow into detention pond during storm (m^3/hr)
I_s = storm intensity (m/hr)
A_{ws} = area of watershed feeding wetland (m^2)
R = runoff coefficient (usually 0.8 for paved industrial surfaces).

This flow is effective for the duration of the storm and enters the detention pond prior to the wetland area. The pond serves to buffer the storm inflow to the wetland and does not affect dissolved organic matter except for mixing. Excess volume capacity is assumed and flow out of the pond is controlled to a designed maximum, with actual flow approaching the maximum asymptotically in response to detention pond volume:

$$Q_{DP} = V_E \, Q_{max} \,/\, (F + V_E) \qquad \text{(equation 7)}$$

where

Q_{DP} = flow out of detention pond into wetland (m^3/hr)

Q_{max} = maximum designed flow out of detention pond (m^3/hr)

V_E = excess volume in detention pond (prevailing water volume minus the minimum volume at which no discharge occurs) (m^3)

F = flow control device parameter describing the approach to maximum flow in response to detention pond volume growth (a value of `100' used in simulations) (m^3).

Evaporation is significant in a high surface area system like a wetland and is formulated in terms of 80 percent of the class A pan evaporation rate [2]:

$$Q_h = (0.8\, E - I_s)\, A_w \qquad \text{(equation 8)}$$

where

Q_h = net flow out of wetland via atmospheric exchange (m^3/hr)

E = Class A Pan evaporation rate (m/hr).

Outflow from the wetland is set equal to the net inflow (inflow minus evaporation) until the minimum design depth is reached. Thus, with a constant baseline flow, the minimum water depth and available biofilm surface is maintained.

The complete model coupling the hydrology with organic matter removal mechanisms was formulated into a numerical simulation with STELLA (High Performance Systems, Inc.), using the Euler method of integration. The complete listing of the model's differential equations is provided in the Appendix. The model was exercised with baseline parameter values as indicated in Table 1. The range specified for each parameter represents the full range over which the parameter was varied in iterative runs while other parameters remained at their baseline value (unless otherwise indicated). Results indicate the model's sensitivity to the parameter in terms of treatment efficiency and ultimate discharge of dissolved organic matter from the wetland.

RESULTS

Figures 4, 5, and 6 show the results of a single simulation run under baseline conditions with a single six hour storm event beginning at hour sixty and ending at hour sixty-six. The output in Figure 4 demonstrates steady state conditions

Table 1. Parameters Used in Model Formulation: Baseline Values, Explored Ranges, and Simulation Output Ranges

			Simulation Output Ranges	
Parameter	Baseline	Range	Peak Storm Conc (mg/l)	Peak Storm Efficiency
Wetland Design Surface Area	15,000 m^2	(5,000-30,000)	(4.58-2.18)	(0.81-0.92)
Design Depth[a]	0.5 m	(0.1-1.5)	(7.32-1.52)	(0.72-0.94)
L/W Ratio[a]	10	(0.5-30)	(2.57-2.48)	(0.90-0.90)
Normal Stream BOD Conc	2 mg/l	(not explored)	2.50	0.90
Storm Runoff BOD Conc[b]	60 mg/l	(5-180)	(0.88-6.02)	(0.76-0.92)
Normal Stream Flow Rate	15 m^3/hr	(not explored)	2.50	0.90
Storm Intensity	3 mm/hr	(0.5-12)[h]	(2.78-1.51)	(0.93-0.87)
Wetland Macrophyte NPP[c]	12 mt/ha/yr	(1-24)	(1.94-3.11)	(0.92-0.88)
Wetland Plant Porosity[d]	0.75	(0.30-0.95)	(1.58-6.91)	(0.94-0.72)
Plant Radius[e]	0.007 m	(0.001-0.025)	(1.39-6.49)	(0.95-0.74)
Class A Pan Evaporation[d]	8 mm/day	(1-16)	(2.48-2.50)	(0.90-0.91)
Biofilm 1st Order Rate Constant[f]	6.3 hr^{-1}	(2-18)	(4.84-1.52)	(0.81-0.94)
Biofilm/Water Diffusion Ratio[g]	0.35	(0.1-1.0)	(3.96-1.91)	(0.84-0.93)
Max Design DP Discharge Rate	100 m^3/hr	(60-1000)	(1.81-9.19)	(0.93-0.67)

[a] Reed and Brown [12]
[b] Field [13]
[c] Greeson et al. [11]
[d] Reed et al. [14]
[e] EPA [15]
[f] Polprasert and Agarwalla [6]
[g] Zhang and Bishop [16]
[h] Storm runoff BOD concentration also adjusted to maintain baseline organic loading.

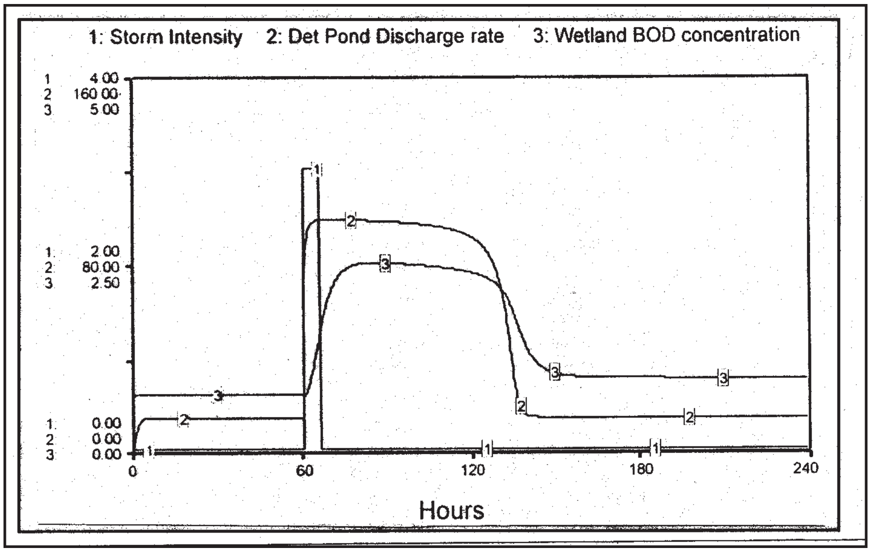

Figure 4. Single simulation run under baseline conditions with a single 6 hour storm event beginning at hour 60 and ending at hour 66: Trace 1 is storm intensity in mm/hr; Trace 2 is hydraulic inflow to wetland (outflow from detention pond) in m^3/hr; and Trace 3 is wetland BOD concentration in mg/l.

prior to the storm and a buffering of the storm shock in the system as increased flow into the wetland approaches the maximum design of 100 m^3/hr which is sustained for nearly sixty hours. Surface water BOD concentration follows a delayed pattern similar to hydraulic flow and very slowly returns to steady state after the storm flush (not having reached it by 240 hours). Extended simulations show that return to BOD steady state after a single storm is not practically reached until 2500 hours even though hydraulic steady state is achieved in seventy-five hours after the storm. Figure 5 shows the constructed wetland BOD influent rate (detention pond discharge) and the effluent rate. The early spike in the effluent BOD is the flush of intrinsic BOD in the wetland as a result of precipitation incident on the wetland itself as well as the building hydrologic discharge. In this case, the spike does not reach the level of BOD discharge eventually realized by the storm event but does demonstrate the significance of natural organic discharge when using wetlands as a treatment practice. Figure 6 views the storm event in terms of metrics of treatment efficiency. Two alternative views are presented. "Removal efficiency" speaks to the treatment of inflow BOD without regard for intrinsic BOD produced within the wetland. That is,

$$\text{Removal Efficiency} = [\text{Infl} - \text{Effl}_{\text{tot}} - \text{Effl}_{\text{Intr}})] / \text{Infl} \quad \text{(equation 9)}$$

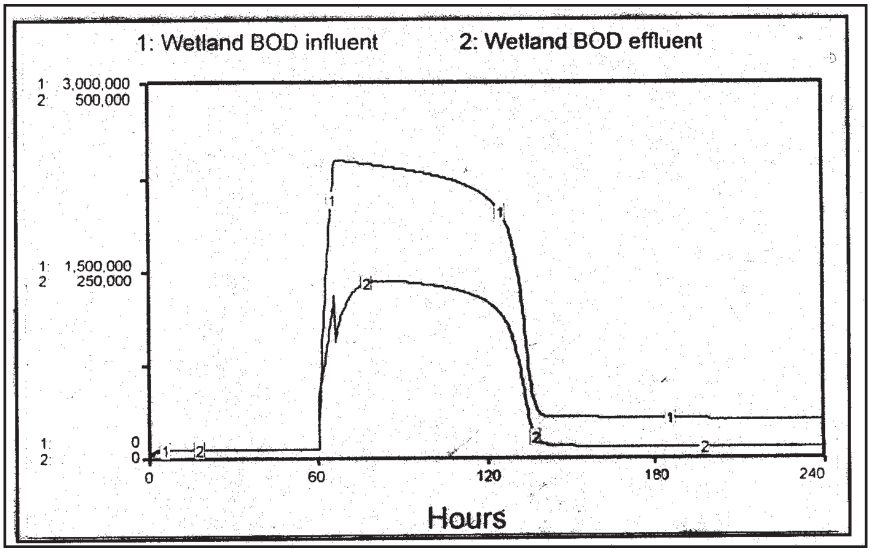

Figure 5. Single simulation run under baseline conditions with a single 6 hour storm event beginning at hour 60 and ending at hour 66: Trace 1 is total BOD inflow to wetland (discharge from detention pond) in mg/hr; and Trace 2 is total BOD outflow from wetland in mg/hr.

where

Infl = wetland BOD influent rate (detention pond effluent)

Effl_{tot} = wetland total BOD effluent rate

$\text{Effl}_{\text{Intr}}$ = wetland BOD effluent from intrinsic BOD production.

Intrinsic BOD effluent is determined for each condition simulated by running the model with no storm events and no baseline influent BOD, such that the only BOD in the system is that produced as related to primary production in the wetland itself. Several design parameters influence this steady state value. Alternatively, “total removal efficiency” refers to a straight comparison of influent to effluent regardless of source:

$$\text{Total Removal Efficiency} = (\text{Infl} - \text{Effl}_{\text{tot}}) / \text{Infl} \qquad \text{(equation 10)}$$

During steady state prior to the storm event, removal efficiency of the small BOD inflow over the intrinsic BOD discharge is essentially 100 percent while the total removal efficiency is closer to 80 percent with intrinsic BOD discharge. The difference between the two metrics disappears during the flush of the storm as intrinsic discharge is overwhelmed by the storm inflow. Both spike downward early (with total efficiency reaching near zero) with the early flush of intrinsic

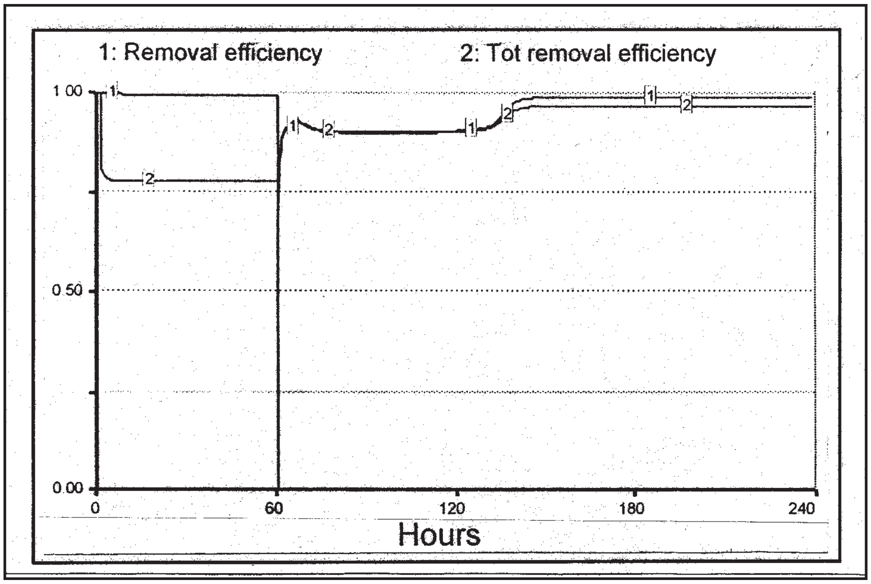

Figure 6. Single simulation run under baseline conditions with a single 6 hour storm event beginning at hour 60 and ending at hour 66: Trace 1 is BOD treatment efficiency formulated to address only the treatment of BOD flowing into the wetland in excess of intrinsic BOD production in the wetland itself; and Trace 2 is BOD treatment efficiency formulated in terms of the effluent BOD in comparison to influent BOD without correction for intrinsic BOD production.

BOD. The curves separate again once the storm flush has passed, but total efficiency is still high due to residual BOD discharge from the detention pond. Again, both curves approach the pre-storm values after 2500 hours. In evaluating performance during storm events, differences between the two metrics throughout the simulations were small and did not impact conclusions.

Table 1 also provides the range of output values of peak storm concentrations discharging from the wetland as well as the range of output treatment efficiencies from simulations exploring the range of the indicated input parameter. These results are summarized below.

Surface Area Analysis

With a constant baseline flow and no storm event, increasing the designed surface area of the wetland increases the steady state BOD concentration since there is a smaller proportionate discharge from the larger wetland volume and lower hydraulic discharge due to the higher degree of evaporation. The overall effect, even with higher surface water concentration, is lower BOD discharge with the decreased water outflow, yielding higher treatment efficiency.

During storm events when evaporation is not a factor, a larger surface area (providing a lower organic loading rate) lowers the concentration but increases overall biofilm uptake (more biofilm surface), yielding a higher efficiency with decreasing marginal improvement at higher surface areas. Increasing from 5,000 to 15,000 m^2 improves treatment efficiency from 80 to 90 percent, but a surface area of 30,000 m^2 gives only 92 percent efficiency. Figure 7 shows the difference in BOD effluent rates between a surface area of 10,000 and 20,000 m^2.

It should also be noted that increasing surface area generally tends toward increased time to return to pre-storm conditions, yielding elevated BOD discharge levels for longer periods. This effect is reversed, however, in the small surface area range where organic loading rate is high and peak storm concentrations are high. In fact, return to steady state under the baseline conditions of this model occurs at about the same time for a 5,000 m^2 and a 30,000 m^2 wetland. The optimum surface area for shortest recovery time for these conditions is between 13,000 and 15,000 m^2.

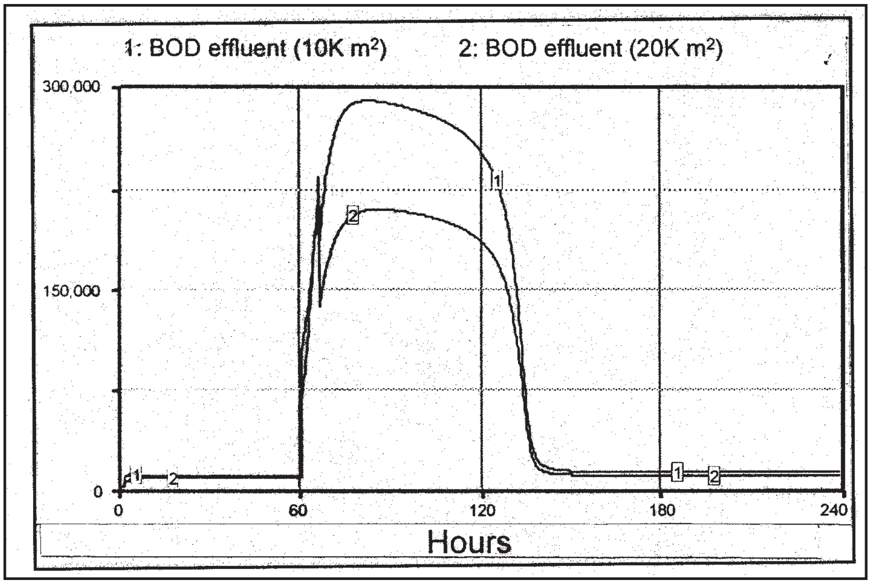

Figure 7. Two simulation runs under baseline conditions showing the effect of designed wetland surface area on wetland BOD discharge (mg/hr): Trace 1 is BOD discharge for a surface area of 10,000 m^2 and Trace 2 is BOD discharge for a surface area of 20,000 m^2.

Length to Width Ratio Analysis

The only relevant effect of this parameter is to vary the velocity of bulk water moving through the wetland. A higher L/W ratio increases velocity, decreases the diffusion barrier of the liquid boundary layer adjacent to biofilms, increases biofilm uptake, lowers bulk water concentration, and increases treatment efficiency. However, this effect, although visible, is insignificant even when the ratio is varied from 0.5 to 30. Boundary layer diffusion does not appear to affect system performance, and no strategy to control flow velocity through the wetland appears to be important, except to prevent excess velocities which would compromise the structural integrity of biofilms (not likely in typical wetlands).

Runoff BOD Concentration Analysis

Increasing influent concentration yields (as expected) a proportionate increase in peak wetland concentration and discharge. Treatment efficiency rises from a low of 75 percent at low influent of about 5 mg/l to 90 percent at 60 mg/l due to increased biofilm uptake. Incremental increases in efficiency above 60 mg/l influent are small, reaching 92 percent at 180 mg/l. This is, of course, inherent in the formulation of efficiency, and attention should be given to actual discharge levels. For 5 mg/l stormwater influent, maximum discharge concentration was less than 1 mg/l but was over 6 mg/l with an influent of 180 mg/l. As expected, time to return to pre-storm concentrations is extended with higher influent concentration, but not significantly (still between 2500 and 3000 hours for all cases simulated).

Storm Intensity Analysis

In simulating ranges of storm intensity, the influent storm BOD concentration was adjusted to achieve the same total organic loading during the storm. With flow control out of the detention pond limiting wetland influent to a maximum of 100 m^3/hr, increased storm intensity lowered the organic loading rate (even though total loading did not change), lowering the peak wetland concentrations and lowering treatment efficiency. Varying intensity from 0.5 to 12 mm/hr changed peak concentrations from 2.78 to 1.51 mg/l and efficiency from 93 percent to 87 percent.

Wetland Vegetation Analysis

Constructed wetland design may involve some control over the dominant vegetation through seeding with organic soils from similar wetlands or direct planting. Depending on the environment and the ability of invading species to eventually dominate, controlled initial dominance of desired species in early wetland development may be sufficient to sustain the desired species mix, particularly in larger wetlands. Control of the dominant species allows control over system parameters such as net primary productivity (determining intrinsic BOD production), plant density (determining water flow cross section and available biofilm surface area), and plant radius (also determining available biofilm surface area).

A change in NPP gives a proportionate change in baseline wetland concentration as expected (from intrinsic BOD input) but also yields moderate changes in peak storm concentration and treatment efficiency (less intuitive). An increase in NPP from 6 to 21 mt/ha/hr increases wetland peak storm concentration from 2.20 to 2.96 mg/l and decreases efficiency from 91 percent to 89 percent. It should be noted that reasonable ranges of intrinsic BOD production can contribute approximately half the organic loading of a typical storm event. Therefore, intrinsic BOD sources can have significant effect on a treatment wetland's performance.

Increasing plant porosity (decreasing density) has three primary system effects: 1) lower velocity, yielding decrease in DOM flux into biofilm and lower treatment (this is an insignificant effect as previously discussed), 2) lower biofilm surface area yielding lower biofilm uptake and lower treatment (an intuitively significant effect), and 3) higher hydraulic retention time yielding higher treatment (also intuitively significant). Increasing plant porosity from 0.75 to 0.95 increases peak wetland storm concentration from 2.49 to 6.91 mg/l and decreases efficiency from 90 percent to 72 percent, indicating dominance of the effect of lower biofilm surface area. However, at a lower porosity range (0.3 to 0.6) peak concentrations and efficiencies range from 1.58 to 1.92 mg/l and 94 percent to 93 percent, respectively, indicating that higher retention times are effectively countering the lower biofilm surface area effect.

Increasing plant radius alone without changing plant density has the major effect of reducing biofilm surface area by reducing the plant population. The effect is fairly linear across practical ranges. An increase in radius from 0.005 to 0.02 m yields an increase in peak concentration from 2.02 to 5.54 mg/l and a decrease in efficiency from 92 percent to 78 percent.

Evaporation Rate Analysis

Evaporation is a significant hydrologic outflow in large surface area wetlands and can quickly disrupt the mechanisms of DOM treatment through loss of water volume and available biofilm surface area in conditions where no baseline stream flow exists between storm events. In this model (which maintains minimum volume through flow control and a small baseline stream flow) concentrations and treatment efficiency are unaffected by evaporation rate in long simulation runs with no storm events. Increased evaporation would tend to raise wetland concentration and lower discharge at the outfall (raising concentration even more). But the combined effects are not significant and tend to be countered by increased biofilm uptake associated with increased concentration. Concentrations and efficiencies are essentially insensitive to wide variations in ambient evaporation rate (1 to 16 mm/day, Class A Pan rate).

Design Wetland Depth Analysis

An increase in depth alone increases total volume which proportionately decreases the fractional discharge rate (tending to increase concentration). This is countered (and dominated) by a proportionate increase in both hydraulic retention time and in biofilm surface area, assuming all species are emergent at the selected depth, so that increases in design depth ultimately decrease peak concentration and increase efficiency. Increasing depth from 0.1 to 1.5 m decreases peak storm concentration from 7.32 to 1.52 mg/l and increases efficiency from 72 percent to 94 percent. This effect flattens out quickly, however, with a depth of 0.75 m yielding an efficiency of 92 percent.

Biofilm Analysis

The characteristics of the biofilm which are of interest here are those which affect the substrate degradation rate and the diffusion resistance. Different dominant strains of microorganisms (with characteristic density and metabolic rates) are determined by environmental factors such as temperature, pH, and type of substrate. Temperature and pH can also directly affect substrate utilization rates within the same strain. The model does not attempt to mechanistically represent the comprehensive effects of these factors, but model sensitivity to substrate degradation rate and diffusion resistance within the film can be studied.

The first order biodegradation rate within the biofilm directly addresses the primary DOM removal mechanism and, thus, significantly affects performance. An increase from 2 to 18 hr^{-1} yields a decrease in peak concentration from 4.84 to 1.52 mg/l and an increase in efficiency from 81 percent to 94 percent (92% at 9 hr^{-1}). The response is fairly linear until the rate rises above 10 hr^{-1} where diffusion limitation appears to limit the further effect of enhanced substrate utilization rate.

Diffusion resistance is represented in the model by the ratio of the diffusion coefficient in the biofilm to the coefficient in water. Biofilm flux is quite sensitive to this parameter at low values (below 0.3), representing diffusion limited conditions, but much less sensitive at higher values where the limitation becomes the degradation rate. Increasing the ratio from 0.1 to 0.3 decreases peak concentration from 3.96 to 2.62 mg/l and increases efficiency from 84 percent to 90 percent. In the less sensitive range from 0.4 to 1.0, the change is from 2.39 to 1.91 mg/l and from 91 percent to 93 percent, respectively.

Detention Pond Flow Control Analysis

A decrease in the designed allowable maximum discharge rate from the detention pond proportionately decreases the organic loading rate and increases hydraulic retention time in the wetland, yielding lower wetland concentration and higher treatment efficiency. At a storm intensity of 3 mm/hr, a runoff coefficient of 0.8, and a watershed area of 100 acres, 1000 m^2/hr maximum flow is essentially uncontrolled flow. The effect of reducing the maximum allowed flow to 100 m^3/hr is dramatic, decreasing peak concentration from 9.19 to 2.49 mg/l and increasing treatment efficiency from 67 percent to 90 percent (reaching 93% at a maximum designed flow of 60 m^3/hr).

Multiple Storm Event Analysis

The observation that pre-storm steady state concentrations are not restored in the system until approximately 2500 hours after a storm event, suggests that one should be concerned about compounding effects of multiple storms in succession. This is partially explored by way of two example scenarios: 1) three-hour storm events occurring one week apart, and 2) six-hour storm events occurring two weeks apart.

In the first case, Figure 8 demonstrates that the oscillating conditions approach amplitude steady state by about week eight with peak storm concentrations in the wetland growing by about 30 percent over the eight-week period. Treatment efficiencies during peak storm conditions do not change, however, apparently due to the building detention pond concentration, yielding increasing wetland influent for succeeding identical storms. Comparing conditions during the first storm with those of the eighth storm, the peak concentration rose from 1.8 to 3.3 mg/l while the treatment efficiency remained at 91 percent for all storms. The second case yielded approximately the same results except that amplitude steady state was reached by week five.

CONCLUSIONS

With regard to the treatment of low levels of organic matter from stormwater runoff, it must be realized that a constructed wetland produces a relatively significant source of dissolved organic matter itself. Thus, a constructed wetland with continual baseline flow creates a new BOD discharge. Increased surface area, allowing a higher percentage evaporation, can lower the total discharge of intrinsic BOD during periods of no storm events. The initial flush of this organic buildup at the beginning of a storm can produce BOD discharges which rival that produced by the storm runoff itself. This is influenced primarily by the dominant vegetation characterizing the wetland, which the designer may be able to influence. This influence also affects plant density which influences hydraulic

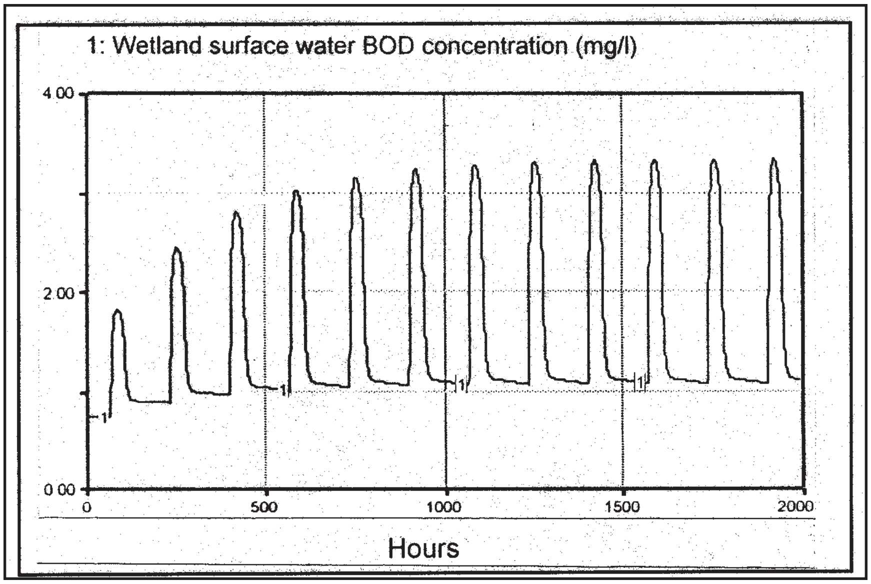

Figure 8. Multiple 3 hour storm events occurring one week apart. Trace shows wetland surface water BOD concentration (mg/l) with higher successive peaks due to the influence of previous storms until a quasi dynamic steady state is reached.

retention time and available surface area for biofilm growth (opposing influences on treatment efficiency which must be optimized for the design problem).

This model demonstrates that attempts to design toward a particular velocity (such as adjusting the length to width ratio) in order to reduce diffusion resistance into surface biofilms have no significant effect on either discharge levels or treatment efficiency.

Assuming that surface biofilm thickness is not artificially enhanced through addition of substrate, this model suggests that natural wetland environments (including periodic storm events) do not cause significant variations in biofilm thickness, and the only effective design strategies for enhancing biofilm uptake are those which increase total available surface area for biofilm development.

Design surface area is a major consideration in constructed wetland development. In general, larger surface area lowers discharge rate and improves treatment efficiency, both during storm events and between events. However, large surface area also tends toward longer period of elevated BOD discharge after storm events, which may be a significant factor in areas which experience frequent sequential storms. (This effect becomes smaller and even reverses at low surface area ranges.) Simulations in this work demonstrated a 30 percent increase in discharge levels in subsequent storms compared to those of an initial storm. Depending on the available area and the meteorology of the region, design surface area may be an important and complicated optimization parameter.

Controlled depth within the wetland controls hydraulic retention time but must preserve the primary treatment processes which remove organic matter. Simulations in this work assumed a constant density of emergent vegetation at all depths simulated. Thus, depth should be designed to optimize available surface area for biofilm development in consideration of optimal conditions for the dominant vegetation selected or dictated by the environment.

The level of flow control provided at the discharge to the detention pool before entry into the wetland is a primary design feature, and significantly influences ultimate discharge and treatment efficiency by controlling the organic loading rate and hydraulic retention time in the wetland.

The model presented here has proven useful in exploring the concept of a constructed wetland system designed for removal of dissolved organic matter from stormwater runoff. The mechanistic dynamic systems approach allows investigation into a number of potentially important design parameters as well as the system’s sensitivity to important environmental parameters. Optimization among all parameters requires simulation under the constrained condition dictated by a specific location and specific treatment objectives. The generalizations offered here serve as an excellent starting point for expectations as an optimal set of design parameters is pursued.

APPENDIX:
Model Equations

$$V_w\, dC_w/dt = Q_{DP}\, C_{DP} - Q_w\, C_w + P_{Intr} - V_w\, C_w\, K_{sw} - J_B\, A_B$$

$$V_{DP}\, dC_{DP}/dt = Q_R\, C_R - Q_{DP}\, C_{DP}$$

$$dV_w/dt = Q_{DP} - Q_w - Q_{w,evap}$$

$$dV_{DP}/dt = Q_R - Q_{DP} - Q_{DP,evap}$$

$$dM_B/dt = J_B\, A_B\, Y - M_B\, K_d$$

where

C_w = wetland surface water BOD concentration
C_{DP} = detention pond BOD concentration
V_w = wetland surface water volume
V_{DP} = detention pond water volume
M_B = total biomass comprising biofilms on submerged surfaces in contact with wetland surface water
Q_{DP} = flow from detention pond into wetland
= as formulated in Equation 7, if $V_{DP} >$ ‘no outflow’ volume
= 0, otherwise

Q_w = flow at wetland outfall (controlled outflow from constructed wetland assumed in order to maintain minimum volume)
= $Q_{DP} - Q_{w,evap}$, if $(Q_{DP} - Q_{w,evap}) > 0$ and $V_w >$ `no outflow' volume
= 0, otherwise
$Q_{w,evap}$ = net flow from wetland to atmosphere
= $(0.8\ E - I_s)\ A_w$
E = Class A Pan evaporation rate
I_s = storm intensity
A_w = wetland surface area
P_{Intr} = wetland intrinsic BOD production rate
= $P_m + P_{wc}$
P_m = intrinsic BOD production from macrophytes (30% of their net primary productivity)
= $0.3\ NPP_m\ A_w$
P_{wc} = intrinsic BOD production from water column producers (10% of their net primary production)
= $0.1\ NPP_{wc}\ A_w$
NPP_{wc} = $0.67\ NPP_m$ (total NPP assumed to be 60% from macrophytes and 40% from water column)
K_{sw} = first order degradation rate constant in bulk liquid phase in wetland
= $K_{sw,20}\ (1.1^{(Tw - 20)})$ (EPA [15])
$K_{sw,20}$ = rate constant at 20⊃C
= $K_{STD}\ \{1 - 0.083\ \mathrm{Log}(67.2/TOL)\ /\ K_{STD}\ \}$ (Polprasert and Agarwalla [6]
K_{STD} = standard first order rate constant ($0.056\ \mathrm{day}^{-1}$)
TOL = total organic loading rate on wetland
= $(P_{Intr} + Q_{DP}\ C_{DP})\ /\ A_w$
T_w = wetland surface water temperature (⊃C)
J_B = BOD flux into biofilm from wetland surface water (Equations 1, 2, and 5)
A_B = total surface area of biofilm exposed to surface water (on plant surfaces and bottom and sides of wetland basin)
= $2\pi\ (L_f + r_p)\ d\ Pop + A_w + 2d\ [(L/W)\ A_w]^{1/2} + 2d\ \{A_w\ /\ [(L/W)\ A_w]^{1/2}\}$
L_f = biofilm thickness (Equation 5)
r_p = average radius of plant shoots
d = depth of wetland surface water ($V_w\ /A_w$)
Pop = number of plant shoots in wetland
L/W = length to width ratio of wetland
Q_R = stream inflow to detention pond (baseline stream flow + storm runoff)
$Q_{DP,evap}$ = net flow from detention pond to atmosphere
= $(0.7\ E - I_s)\ A_{DP}$

A_{DP} = detention pond surface area
Y = biomass yield coefficient from substrate utilization (BOD degradation)
K_d = biomass intrinsic death rate constant (a minimum substrate utilization rate is required for maintenance before biomass growth is realized)

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