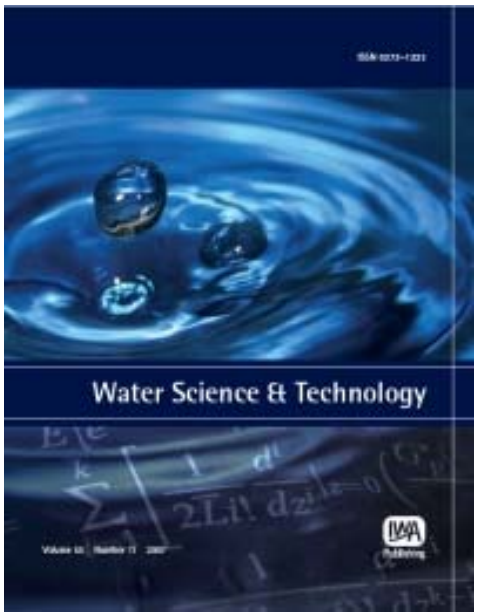

Incorporation of oxygen contribution by plant roots into classical dissolved oxygen deficit model for a subsurface flow treatment wetland

Achintya N. Bezbaruah and Tian C. Zhang

ABSTRACT

It has been long established that plants play major roles in a treatment wetland. However, the role of plants has not been incorporated into wetland models. This study tries to incorporate wetland plants into a biochemical oxygen demand (BOD) model so that the relative contributions of the aerobic and anaerobic processes to meeting BOD can be quantitatively determined. The classical dissolved oxygen (DO) deficit model has been modified to simulate the DO curve for a field subsurface flow constructed wetland (SFCW) treating municipal wastewater. Sensitivities of model parameters have been analyzed. Based on the model it is predicted that in the SFCW under study about 64% BOD are degraded through aerobic routes and 36% is degraded anaerobically. While not exhaustive, this preliminary work should serve as a pointer for further research in wetland model development and to determine the values of some of the parameters used in the modified DO deficit and associated BOD model. It should be noted that nitrogen cycle and effects of temperature have not been addressed in these models for simplicity of model formulation. This paper should be read with this caveat in mind.

Key words | BOD, constructed wetland, DO deficit, kinetic model, oxygen sag, rhizosphere

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INTRODUCTION

Traditionally, studies on constructed wetlands have focused on (i) hydraulic characteristics and their effects on wetland performance and design, and (ii) kinetics and modeling of contaminant degradation as a function of wetland forms (subsurface or free water surface flow) and operating time/conditions. Treating the wetland as a black box, BOD removal in SFCW has been modeled using various degradation models, mostly based on input/output data (Kadlec & Knight 1996; Rochfort *et al.* 1997; USEPA 1988; 2000; Wynn & Liehr 2001; Rousseau *et al.* 2004). Alternative models such as the tank-in-series model (Wynn & Liehr 2001; Liu 2002), the mixing cell method (Chen *et al.* 1999), sequential analytical models (Martin & Reddy 1997; Gerke *et al.* 2001), and multi-scale models (Marahatta 2004) have been developed for design of SFCWs. Grismer (Grismer 2005) evaluated the effects of non-uniform flow and degradation parameter uncertainty on subsurface-flow constructed wetland performance. Model-based design approaches for constructed wetlands have been reviewed by Rousseau *et al.* (Rousseau *et al.* 2004). While these are important contributions to wetland modeling, limited or no model has so far incorporated rhizosphere (plant root zone) contributions into a model.

It is well documented that wetland plants and biofilms play important roles in a constructed wetland. Biofilms have been modeled in the context of the wetland (McBride & Tanner 2000; Ragusa *et al.* 2004) but not plants. The main subsurface environmental parameters affected by roots include DO, pH, and oxidation reduction potential (ORP) (Marschner *et al.* 1987; Geelhoed *et al.* 1999; Kirk 1999; Neori *et al.* 2000; Bezbaruah & Zhang 2004, 2005). Most wetland plants transfer oxygen into the rhizosphere through

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their roots (Armstrong 1978). The plants translocate oxygen into the rhizosphere from the upper leaf area, and the oxygen is used by the root-zone microorganisms for the degradation of plant toxicants. In spite of our knowledge on rhizosphere and their microenvironments, the use of these fundamentals is essentially unknown in wetland design and modeling.

To understand the wetland degradation processes it is imperative to examine the issue of oxygen availability in constructed treatment wetlands from an engineering perspective. The U.S. EPA has identified this aspect for further research (Reed *et al.* 1995; Campbell & Ogden 1999; USEPA 2000). There are some published research that reported the amount of oxygen available from plant roots in a constructed wetland. Published estimates range from 0 to 45 g O_2 m^{-2} (of wetland surface area) d^{-1} (Reed *et al.* 1995). The U.S. EPA (USEPA 2000) reported the number as 0 to 3 g O_2 m^{-2} d^{-1}. Others calculated 5–12 g O_2 m^{-2} d^{-1} (Armstrong *et al.* 1990), ~0.02 g O_2 m^{-2} d^{-1} (Brix & Schierup 1990), and ~7.2 g O_2 m^{-2} d^{-1} (Gersberg *et al.* 1991). The recent work by Bezbaruah and Zhang (Bezbaruah & Zhang 2004, 2005) suggests that plants release only ~ 0.5 to 11 mg O_2 m^{-2} (of wetland surface) d^{-1}. The large number of factors that affect the amount of oxygen release by plant roots and difficulty in quantification might have caused such disparity in values (Liehr *et al.* 2000; Stein & Hook 2005). Nevertheless there are considerable doubts about the ability of plants to effectively oxidize the rhizosphere environment to satisfy wastewater oxygen demand in constructed wetlands (USEPA 2000). Anaerobic processes also contribute towards BOD removal in a constructed wetland (Bezbaruah *et al.* 2001). So, it is important to quantify the contributions of aerobic and anaerobic processes in wetland treatment of BOD.

In this study, an effort has been made to construct a DO deficit model incorporating the plant and biomass components. The model is used to simulate the DO curve for a field SFCW. Using curve fitting techniques, the DO deficit model is used to dynamically attribute the degradation of organics (represented by BOD) to aerobic and anaerobic processes. Effects nitrogen cycle and temperature (Stein & Hook 2005) have not been modeled to keep the model simple. However, it is important to note that these factors affect the wetland and final refined model should incorporate all possible and significant parameters. This paper should be read with this caveat in mind. The paper should serve as a pointer for further refinement of the models.

MATERIALS AND METHODS

Field wetland and sampling strategy

Hanson Lakes SFCWs are designed to serve 350 households (1,750 people) in Hanson Lakes locality (Sarpy County, Nebraska, U.S.A). The wastewater (0.4 million L d^{-1} design flow; initial BOD_5 ≅ 300 mg L^{-1}; initial total nitrogen ≅ 40 mg L^{-1}; initial TSS ≅ 500 mg L^{-1}) is introduced into a 4-cell wetland (50.3 m × 30.8 m; 0.46 m pea gravel and limestone media) after passing through an equalization tank and biofilters. Cattail (*Typha spp.*, first 8.2 m), bulrush (*Scirpus validus*, 8.2 m) and reed (*Phragmites australis*, rest 32 m) are planted in the wetland cells and considered as matured (Reed *et al.* 1995).

Sampling ports were established by inserting perforated PVC pipes (~ 2-cm diameter and ~ 30-cm long) into the wetland bed. This sampling depth is assumed to be representative based on sampling experience in the wetland. A total of 19 sampling points were established along the center line of the wetland. Sampling was done during the daylight hours at random intervals. However, it was made sure that the sampling day was a sunny one and not immediately (10–15 days) after a rain event. DO and temperature were measured in-situ using a portable meters. All analyses were completed within 24 hours of collection of the samples (except for BOD analysis) as per standard methods (APHA *et al.* 1995)

DO deficit model

The model proposed is a modification of the conventional DO deficit model (Tchobaboglous & Schroeder 1987; Chapra 1997). The term for root oxygen supply $[K_R(C_s - C)]$ and attached growth biomass oxygen demand (r_{BM}) are introduced specifically to represent the subsurface flow constructed wetland environment. The introduction of the r_{BM} term took care of the oxygen demand by biomass

and biomass sorbed BOD. The biomass (attached to the wetland media and the wetland plant roots) oxygen demand rate is taken as constant. The root oxygen supply is assumed to be proportional to the DO deficit in the bulk wastewater (Bezbaruah & Zhang 2004). Rate of change of DO concentration (C) in a SFCW is represented as below.

$$\frac{dC}{dt} = -KL_{ta} + K_a(C_s - C) + K_R(C_s - C) - r_{BM} \quad (1)$$

Combining K_a and K_R into one single parameter, the following equation is obtained:

$$\frac{dC}{dt} = -KL_{ta} + K_{ar}(C_s - C) - r_{BM} \quad (2)$$

where, C, DO at any time (g O_2 m^{-3}); K, BOD rate constant (d^{-1}); L_{ta}, BOD5 to be satisfied aerobically at any time t (g BOD m^{-3}); K_a, reaeration rate constant (d^{-1}); C_s, DO saturation concentration in bulk water (g O_2 m^{-3}); K_R, root oxygen supply rate constant (d^{-1}); r_{BM}, biomass (attached growth) oxygen demand rate (g O_2 m^{-3} d^{-1}); t, time (d); K_a, Combined oxygen supply rate constant, $K_a + K_R$ (d^{-1}).

Writing DO deficit at any time t as D ($= C_s - C$), the differential Equation (Equation 2) can be solved as:

$$D = \frac{KL_{oa}}{K_{ar} - K}[\exp(-Kt) - \exp(-K_{ar}t)] + D_o{}^{*}\exp(-K_{ar}t) + \frac{r_{BM}}{K_{ar}}[1 - \exp(-K_{ar}t)] \quad (3)$$

where, L_{oa}, Initial BOD_5 to be degraded aerobically (g BOD m^{-3}); D_o, Initial DO deficit (g O_2 m^{-3}).

To use the model, the wetland is divided into a number of small imaginary wetlands of hydraulic retention time (HRT) Δt. Each of the wetland cell is imagined to consist of many (j = 1 to n) continuously stirred tank reactors (CSTR) in series. As in Equation 3, the DO deficit, D_i in $CSTR_j$ at time t_i is calculated based on, among other parameters, L_{oa} (the effluent BOD of $CSTR_{j-1}$ at t_i that would be aerobically degraded within $CSTR_j$). A distribution between 100–0 (i.e., 100% aerobic and 0% anaerobic degradation) and 0-100 can be used to dynamically distribute the BOD into aerobic and anaerobic degradation. The accuracy of the distribution, together with other parameters, then can be checked by comparing the DO data collected from the field (e.g., Hanson Lakes SFCWs as in this study) with simulation curves obtained from Equation 3.

The aerobic and anaerobic distribution obtained from the DO deficit model then can be used to simulate a BOD curve over fractional distance (or time). Assuming both the aerobic and anaerobic degradation of BOD to be first order reactions, the BOD remaining at any time can be expressed with Equation 4. The aerobic and anaerobic degradation rate constants may vary along the length of the wetland (Shepherd *et al.* 2001). Accordingly, it would be wiser to try to fit the BOD curve with a retarded rate expression (Crites & Tchobanoglous 1998). With the incorporation of the retardation factor, the new expression for calculating BOD at any instant can be written as Equation 5.

$$L_t = L_o f_a \operatorname{Exp}(-Kt) + L_o f_{an} \operatorname{Exp}(-K_{an} t) \quad (4)$$

$$L_t = L_o f_a \operatorname{Exp}\left[-\frac{K}{R}\ln(1 + Rt)\right] + L_o f_{an} \operatorname{Exp}\left[-\frac{K_{an}}{R}(1 + Rt)\right] \quad (5)$$

where, L_t, BOD at any time t (g BOD m^{-3}); L_o, Ultimate BOD (g BOD m^{-3}); f_a, Percent fraction of BOD treated aerobically; K, BOD rate constant (d^{-1}); K_{an}, Anaerobic degradation rate constant (d^{-1}); f_{an}, Percent fraction of BOD treated anaerobically $= (1 - f_a)$; T, Time (d).

MODEL INPUTS AND RESULTS

Results from the Hanson Lake SFCWs (not shown) indicate that the wetland worked very efficiently for BOD removal (77%); however, ammonia removal is very limited (~23%). DO increased from the inlet (0.07 mg L^{-1}) to the outlet (1.01 mg L^{-1}), and ORP from −350 to +38 mV. Results of the authors' earlier studies on constructed wetlands (Bezbaruah & Zhang 2003, 2004, and 2005) cannot be used to explain why there is enough oxygen in the wetland outlet and a different approach is needed.

The constructed wetland experiments done with and without artificial aeration clearly indicate that anaerobic processes also contribute towards BOD removal in a constructed wetland (Bezbaruah *et al.* 2001). Therefore, it

is necessary to distribute the BOD among the aerobic and anaerobic processes to estimate the remaining aerobically-degradable BOD (L_{oa}) at a particular time (t_i). To do so, it is necessary to know the percentages BOD that are treated aerobically and anaerobically. However, anaerobic processes that exist in a constructed wetland have not been fully investigated, and as such the anaerobic BOD removal rate constant is not known. The presence of a large amount of biomass attached to the wetland media makes the anaerobic contribution to BOD removal in a SFCW similar to those in conventional fixed-bed attached growth processes for wastewater treatment. Therefore, on the basis of results obtained from other wastewater treatment processes, a value of $5\,d^{-1}$ (Rittman & McCarty 2001) is used for this analysis. Selecting a high value would add additional factor of safety to the model.

The DO data collected from the Hanson Lakes SFCWs are used in this study. For the purpose of simulating the DO sag, the field wetland is imagined to be divided into small CSTRs with each having an HRT, $\Delta t = 0.05\,d$. Using a spreadsheet (MS Excel) for Equation 3, DO deficit along the wetland is simulated and DO remaining ($C = C_s - D$) is calculated. K, K_{an}, and K_{ar} are manipulated to replicate the DO curve obtained from the field measurements. The initial K and K_{an} values are taken as $0.21\,d^{-1}$ and $5\,d^{-1}$, respectively, and BOD decrease is assumed to be a retarded first order reaction (Equation 5) with a retardation factor of 0.5.

It is found that changing K and K_{an} from their initial values do not help in getting a simulation curve approximately close to the curve obtained from the field data. However, when K_{ar} is gradually reduced from the initial value of $1.00\,d^{-1}$ at inlet to $0.11\,d^{-1}$ at outlet, the stimulated curve more or less follows the 'field curve'. Based on this analysis it is identified that the possible distribution will be within 60-40 and 70-30. While it is easy to interpret some aerobic and anaerobic distribution curves as poor fits, the distributions in the mid range are difficult to be visually interpreted. The best fit is determined based on root mean square (RMS) analysis for the field and the simulated data. The RMS values for various aerobic decomposition percentages indicate that the best fit is 64-36, meaning that 64% organics (BOD) are degraded aerobically and rest 36% anaerobically (Figure 1).

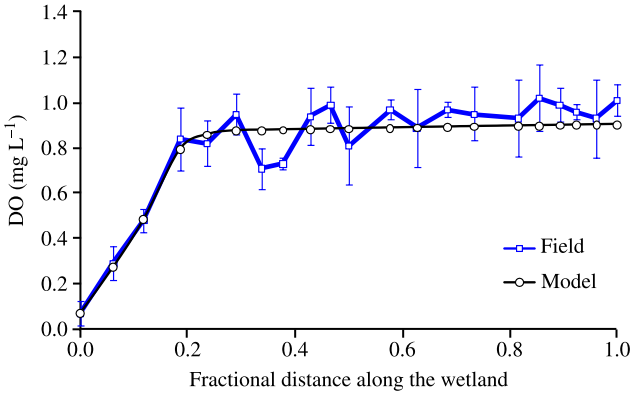

Figure 1 | Field and model generated DO curves. 64% aerobic and 36% anaerobic degradation curve fits the field data the best. Error bars are the standard deviations (±).

The aerobic and anaerobic distributions obtained from the DO deficit model are then used to simulate a BOD curve over fractional distance (or time). Using Equation 5, the BOD curves are plotted with $f_a = 64\%$ and $f_{an} = 36\%$ with and without a retarded rate constant (Figure 2). Various retardation factors are also tried along with various f_a and f_{an}.

It is observed that with a low retardation factor the simulated curve mimics the field situation much better. Therefore, it is checked whether Equation 4 (rate constants without retardation factors) would be a better choice and found that Equation 4 is a better choice for the present wetland.

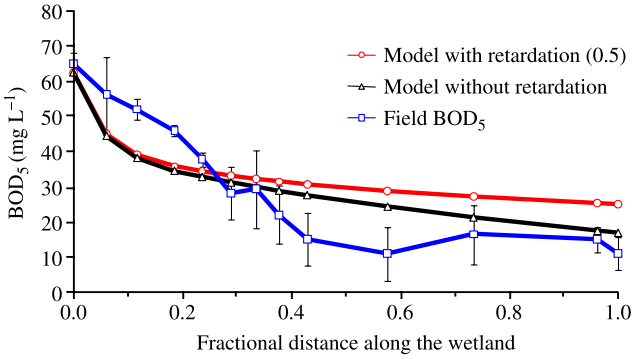

Figure 2 | Model generated (64% aerobic and 36% anaerobic) and field BOD_5 curves. A retardation factor of 0.5 is used in the retarded rate curve. The error bars on the BOD_5 curve indicate the standard deviations (±).

CONCLUSIONS

The wetland modeled as an aerobic-anaerobic system mimics the field conditions for dissolved oxygen. The model takes into account the possible mechanisms of oxygen addition and consumption, viz., atmospheric reaeration, plant oxygen release, wastewater oxygen demand, and biomass oxygen demand. The modeling results indicate that, for Hanson Lake SFCWs, ~ 64% BOD removal occurs aerobically and rest is removed anaerobically. The findings of this study confirm that constructed wetlands should not be designed as a pure aerobic system.

The proposed models with further refinements will be able to evaluate the contribution of aerobic and anaerobic degradation of carbonated matters and DO distribution in the wetland. For example, one can evaluate the relative contribution of roots by changing K_R or that of reaeration by changing K_a to see the simulation curves. The contribution of plants may change depending upon their type, extend, and health. Reaeration will also change depending on the geographic location, season, and environmental setting of the wetland (Stein & Hook 2005). Using this model one may also evaluate the wetland by varying aerobic and anaerobic contributions along the length of the SFCW (e.g., initial 1/5 section: 30-70, between 2/5 and 3/5: 50-50, between 3/5 and 4/5: 60-40, and at the last 1/5 section: 70-30). This model can be further modified to include nitrification and temperature effects even though we are not discussing these in this paper.

Sensitivity analyses are conducted for the simulated DO curve with respect to K, K_{ar}, and r_{BM} (Equation 3), and for K_{an} (Equation 4). Sensitivity is analyzed for the reported (USEPA 2000) range of the first order BOD rate constant ($K = 0.1$ to $1.104\,d^{-1}$) in SFCWs. It is found that K is a very sensitive parameter (data not shown) indicating the need for careful selection of K for the model. The sensitivity of the anaerobic degradation rate constant (K_{an}) is evaluated within the range of 1–10 (Metcaff & Eddy 2003). K_{an} is found to be not very sensitive in the range $3–10\,d^{-1}$, but $K_{an} < 3\,d^{-1}$ gives lower DO (data not shown). The biomass oxygen demand rate (r_{BM}) is found to be another sensitive input for the model (data not shown). It is important to use an appropriate r_{BM} value in the model.

In the past, variations in BOD removal in SFCWs were modeled with retardation effects or non–uniform flow (Crities & Tchobanoglous 1998; Grismer 2005). Results of this study indicate that variations in BOD removal and the DO distribution can be explained by distributing BOD removal into aerobic and anaerobic processes and incorporating the role of plant roots. The present study sheds light on how to incorporate the rhizosphere processes into wetland design, and confirms that both aerobic and anaerobic processes play roles in meeting the BOD in a constructed wetland. The authors have proposed a way to incorporate rhizosphere contribution and allocate the wastewater BOD load to the aerobic and anaerobic processes in a SFCW. However, further research is necessary to refine the model and determine the values of some of the parameters used in the modified DO deficit and associated BOD model. In the present form the model should serve as a stimulator for further work in this area. Incorporation of further complexities of aerobic and anaerobic processes, nitrogen cycle, temperature, and seasonal variations will make this model more acceptable.

REFERENCES

APHA; AWWA; WEF 1995 *Standard Methods for the Examination of Water and Wastewater*, 18th Edition. APHA, Washington, DC.

Armstrong, W. 1978 Root aeration in the wetland condition. In: Hook, D. D. & Crawford, R. M. M. (eds) *Plant Life in Anaerobic Environments*. Ann Arbor Science Publishers, Ann Arbor, MI, pp. 269–297.

Armstrong, W., Armstrong, J. & Beckett, R. M. 1990 Measurement and modeling of oxygen release from roots of phragmites australis. In: Cooper, P. F. & Findlater, B. C. (eds) *Constructed Wetlands in Water Pollution Control, Advances in Water Pollution Control*. Pergamon Press, Oxford, UK, pp. 41–52.

Bezbaruah, A. N. & Zhang, T. C. 2003 Performance of a constructed wetland with a sulfur-limestone denitrification section for nitrogen removal from wastewater. *Environ. Sci. Technol.* **37**, 1690–1697.

Bezbaruah, A. N. & Zhang, T. C. 2004 pH, redox, and oxygen microprofiles in rhizosphere of bulrush (*scirpus validus*) in a constructed wetland treating municipal wastewater. *Biotechnol. Bioeng.* **88**, 60–70.

Bezbaruah, A. N. & Zhang, T. C. 2005 Quantification of oxygen release by bulrush (*scirpus validus*) roots in a constructed treatment wetland. *Biotechnol. Bioeng.* **89**, 308–318.

Bezbaruah, A. N., Zhang, T. C. & Stansbury, J. S. 2001 Lab-scale subsurface flow constructed wetlands for nitrogen removal

from municipal wastewater. *Proceedings of WEFTEC 2001*. Water Environment Federation, Alexandria, VA.

Brix, H. & Schierup, H. 1990 Soil oxygenation in constructed reed beds: the role of macrophyte and soil-atmosphere interface oxygen transport. In: Cooper, P. F. & Findlater, B. C. (eds) *Constructed Wetlands in Water Pollution Control*. Pergamon Press, Oxford, UK, pp. 53–66.

Campbell, C. S. & Ogden, M. H. 1999 *Constructed Wetlands in the Sustainable Landscape*. John Wiley & Sons, New York, NY.

Chapra, S. C. 1997 *Surface Water-Quality Modeling*. McGraw Hill, New York, NY.

Chen, S., Wang, G. T. & Xue, S. K. 1999 Modeling BOD removal in constructed wetlands with mixing cell method. *J. Environ. Eng.* **125**, 64–71.

Crites, R. & Tchobanoglous, G. 1998 *Small and Decentralized Wastewater Management Systems*. McGraw-Hill, Boston, MA.

Geelhoed, J. S., van Riemsdijk, W. H. & Findenegg, G. R. 1999 Simulation of the effect of citrate exudation from roots on the plant availability of phosphate on goethite. *Euro. J. Soil Sci.* **50**, 379–390.

Gerke, S., Baker, L. A. & Xu, Y. 2001 Nitrogen transformation in a wetland receiving lagoon effluent: sequential model and implication for water reuse. *Water Res.* **35**, 3857–3866.

Gersberg, R. M., Lyon, S. R., Brenner, R. & Elkins, B. V. 1991 Integrated wastewater treatment using artificial wetlands: a gravel marsh case study. In: Hammer, D. A. (ed.) *Constructed Wetlands for Wastewater Treatment*. Lewis Publications, Chelsea, MI, pp. 145–152.

Grismer, M. E. 2005 Simulation evaluation of the effects of non-uniform flow and degradation parameter uncertainty on subsurface-flow constructed wetland performance. *Water Environ. Res.* **77**, 3047–3053.

Kadlec, R. H. 2000 The inadequacy of first-order treatment wetland models. *Ecol. Eng.* **15**, 105–119.

Kadlec, R. H. & Knight, R. L. 1996 *Treatment Wetland*. CRC Press, Boca Raton, FL.

Kirk, G. J. D. 1999 A model of phosphate solubilization by organic anion excretion from plant roots. *Euro. J. Soil Sci.* **50**, 369–378.

Liehr, S. K., Kozub, D. D., Rash, J. K., Sloop, G. M., Doll, B., Rubin, A. R., House, C. H., Hawes, S. & Burks, D. 2000 *Constructed Wetlands Treatment of High Nitrogen Landfill Leachate*, Project 94-IRM-U. Water Environment Research Foundation, Alexandria, VA.

Liu, W. 2002 *The Study of Subsurface Flow Constructed Wetland System with Empirical Design Models, Compartmental Analysis and Multivariate Statistical Analysis*, Ph.D. dissertation, University of Nebraska-Lincoln.

Marahatta, R.C. 2004 *Multi-Scale Modeling of a Vegetated Submerged Bed System with Application in Organic Matter Removal and Clogging*, Ph.D. dissertation, University of Nebraska-Lincoln.

Marschner, H., Römheld, V. & Cakmak, I. 1987 Root-induced changes of nutrient availability in the rhizosphere. *J. Plant Nutr.* **10**, 1175–1184.

Martin, J. F. & Reddy, K. R. 1997 Interaction and spatial distribution of wetland nitrogen processes. *Ecol. Model.* **105**, 1–21.

McBride, G. B. & Tanner, C. C. 2000 Modeling biofilm nitrogen transformation in constructed wetland mesocosms with fluctuating water levels. *Ecol. Eng.* **14**, 93–106.

Metcalf & Eddy, Inc 2003 *Wastewater Engineering: Treatment and Reuse*, 4th edition. McGraw Hill, Boston, MA.

Neori, A., Reddy, K. R., Čiškova-Končalova, H. & Agami, M. 2000 Bioactive chemicals and biological-biochemical activities and their functions in the rhizospheres of wetland plants. *Bot. Rev.* **66**, 350–378.

Ragusa, S. R., McNevin, D., Qasem, S. & Mitchell, C. 2004 Indicators of biofilm development and activity in constructed wetlands microcosms. *Water Res.* **38**, 2865–2873.

Reed, S. C., Crites, R. W. & Middlebrooks, E. J. 1995 *Natural Systems for Waste Management and Treatment*, 2nd edition. McGraw-Hill, New York, NY.

Rittman, B. E. & McCarty, P. L. 2001 *Environmental Biotechnology: Principles and Applications*. McGraw Hill, Boston, MA.

Rochfort, Q. J., Anderson, B. C., Crowder, A. A., Marsalek, J. & Watt, W. E. 1997 Field-scale studies of subsurface flow constructed wetlands for stormwater quality enhancement. *Water Qual. Res. J. Can.* **32**, 101–117.

Rousseau, D. P. L., Vanrolleghem, P. A. & Pauw, N. D. 2004 Model-based design of horizontal subsurface flow constructed treatment wetlands: a review. *Water Res.* **38**, 1484–1493.

Shepherd, H. L., Grismer, M. E. & Tchobanoglous, G. 2001 Treatment of high-strength winery wastewater using a subsurface flow constructed wetland. *Water Environ. Res.* **73**, 394–403.

Stein, O. R. & Hook, P. B. 2005 Temperature, plants, and oxygen: how does season affect constructed wetland performance? *J. Environ. Sci. Health* **40**, 1331–1342.

Tchobanoglous, G. & Schroeder, E. D. 1987 *Water Quality*. Massachusetts, Addison-Wesley Publishing Company, Reading, MA.

United States Environmental Protection Agency 1988 *Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment (Design Manual)*, EPA/625/1-88/022. Office of Research and Development, U.S. EPA, Washington, DC.

United States Environmental Protection Agency 2000 *Constructed Wetlands Treatment of Municipal Wastewaters (Manual)*, EPA/625/R-99/010. Office of Research and Development, U.S. EPA, Cincinnati, OH.

Wynn, T. M. & Liehr, S. K. 2001 Development of a constructed subsurface-flow wetland simulation model. *Ecol. Eng.* **16**, 519–536.