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Short communication

Simulating phosphorus removal from a vertical-flow constructed wetland grown with *C. alternifolius* species

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ABSTRACT

Vertical flow constructed wetland (VFCW) is a promising technique for removal of excess nutrients and certain pollutants from wastewaters. The aim of this study was to develop a STELLA (structural thinking, experiential learning laboratory with animation) model for estimating phosphorus (P) removal in an artificial VFCW (i.e., a substrate column with six zones) grown with umbrella papyrus (*Cyperus alternifolius*) species under a wetting-to-drying cycle. Simulations showed that rate of soluble P (SP) leaching was highest at the top zone (i.e., Zone 1) and decreased gradually with increasing zone number due to the adsorption, clogging, and plant uptake when the SP flowed through the zones. Our simulations further revealed that the best time for an optimal removal of SP from the wastewater was within the first week because the adsorption capacity of the substrate in the VFCW was highest at this time period. In general, the cumulative amounts of total P (TP) were in the following order: adsorption (53.3%) > leaching (13.5%) > uptake (0.49%). Adsorption of P was a major mechanism for P removal from the VFCW system. This study suggested that the STELLA model developed is a useful tool for estimating P removal from wastewater in VFCWs.

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1. Introduction

Phosphorus (P) is an essential nutrient to all forms of life in aquatic ecosystems. However, enrichment of P can result in eutrophication of lakes and reservoirs and excessive periphyton growth in surface water (Sutula et al., 2004). Phosphorus in aquatic systems may be derived from naturally occurring P in soils, but significant amounts may also be contributed to aquatic systems by anthropogenic sources such as fertilized fields, animal wastes, wastewater treatment plants, and industries that use P in cleaning processes (Djodjic et al., 2004; Bond et al., 2006). Most surface water bodies have low P concentrations because phosphate is easily immobilized. Therefore, an increase in P concentrations could result in eutrophication of surface waters. The concentrations of biologically available P in excess in surface water can lead to diverse problems such as toxic algal blooms, hypoxia with low dissolved oxygen, fish kills, and loss of biodiversity (Ouyang, 2005). In addition to seriously degrading aquatic ecosystems, P enrichment in surface waters can also impair the use of water for drinking, industry, agriculture, and recreation.

Constructed wetland (CW) is gaining acceptance for removal of excess nutrients and certain pollutants from wastewaters in recent years (Beutel et al., 2009; Katsenovich et al., 2009; Zurit et al., 2009; Cui et al., 2013; Vymazal, 2014). Several mathematical models have been developed to estimate the removal efficiency of contaminants from CWs (Martin and Reddy, 1997; Langergraber and Šimùnek, 2005). Langergraber and Šimùnek (2005) developed the CW2D (constructed wetland 2D) model for variably saturated water flow and multi-component reactive transport in the CW systems. This model has improved our understanding of contaminant removal from the CW systems. Limitations of this model are that it does not include the floodwater layer, uptake and accumulation of contaminants in plant tissues, substrate clogging, and leaf transpiration. In addition, vast amounts of input parameters are required for running the CW2D model. These input parameters are sometimes difficult to obtain through experimentation for model calibrations, validations, and applications.

Recently, Ouyang et al. (2010a,b) developed two STELLA models for estimation of water and N dynamics in a vertical flow constructed wetland (VFCW). These two models were successfully

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applied to estimate water and N dynamics in the VFCW with a growing *Cyperus alternifolius* wetland plant. However, no efforts have yet been devoted to estimating P dynamics in the same VFCW system, which are totally different from those of N. The objectives of this study were to: (1) develop a STELLA model to estimate the fate and transport of P through the substrate as well as the uptake and accumulation of P by a wetland plant in a VFCW system; (2) calibrate and validate the model using experimental data; and (3) apply the model to predict removal efficiency of P from the VFCW during plant growth. Interested readers should consult the water dynamic model of Ouyang et al. (2010a) and N dynamic model of Ouyang et al. (2010b) for a comprehensive understanding of the present study.

2. Materials and methods

2.1. Model development

A schematic diagram showing a conceptual model for the fate, transport, and uptake of P in a VFCW with a growing plant is given in Fig. 1. Four major mechanisms for P dynamics in the VFCW included in the study were: (1) application of wastewater P, (2) adsorption of soluble P (SP) by substrate, (3) uptake of SP, and (4) leaching of SP. In this study, the artificial VFCW (i.e., a soil column) was divided into six zones, whereas the plant species was partitioned into three compartments, namely the root, stem, and leaf compartments (Fig. 1). The total P (TP) concentration in the STELLA model was partitioned into insoluble P (IP) and SP fractions (Fig. 2).

The rate of wastewater TP applied to a VFCW is measurable during the CW operations. Leaching of SP through each of the six soil zones can be obtained by

$$L_i^{SP} = Q_i C_i \tag{1}$$

where L is the leaching rate of SP (mg/h), Q is the water flow rate (cm^3/h), C is the concentration of SP (mg/cm^3), and i denotes the ith zone. The water flow rate (Q) can be obtained from our previous STELLA model for water dynamics (Ouyang et al., 2010a).

The rate of SP adsorption by the substrate in each soil zone can be described by our empirical equation as

$$S_i^{SP} = \omega C_i^{\alpha} \tag{2}$$

where S is the rate of SP adsorption (mg/h), ω is the rate coefficient (cm^3/h), α is the power constant (dimensionless), and C is the concentration of SP (mg/cm^3).

The rates of SP (primarily orthophosphate) taken up by roots from the soil near the root zone and transport from roots to stems as well as from stems to leaves are characterized using the following three equations (Ouyang, 2008):

$$R_{SP}^{root} = Q_{plant} C_{SP}^{root} \delta^{root} \beta_{transf}^{root} \tag{3}$$

$$R_{SP}^{stem} = Q_{plant} C_{SP}^{stem} \delta^{stem} \beta_{transf}^{stem} \tag{4}$$

$$R_{SP}^{leaf} = Q_{plant} C_{SP}^{leaf} \delta^{leaf} \beta_{transf}^{leaf} \tag{5}$$

where R is the rate of SP uptake (mg/h), Q_{plant} is the rate of water movement through the plant compartments (cm^3/h), C is the concentration of SP (mg/cm^3), δ is the coefficient that controls the intake of SP across the compartment membranes among roots, stems, and leaves (dimensionless), and β is the coefficient characterizing the transformation of SP into organic P in the roots, stems, and leaves (dimensionless). Both the values of δ and β were obtained through model calibration.

The STELLA software was employed to implement the P dynamics described above and the resulting STELLA model is presented in Fig. 2. In this figure, the rectangles are stocks that graphically represent the masses of P species. The flow symbols (represented by double lines with arrows and switches) represent the rates of P transport into or out of the stocks. The other variables are converters (represented by empty circles) that denote the rules or conditions controlling the stocks and flows with the use of connectors (represented by single lines with arrows). Once the STELLA model was developed, the initial values for stocks, equations for flows, and input values for converters were assigned. Detailed model input parameter values for P dynamics are given in Table 1. It should be kept in mind that the P dynamics were fully coupled with the water dynamics in the VFCW system as described in Ouyang et al. (2010a). Therefore, the water and P dynamic models constructed with STELLA were executed simultaneously for simulations.

2.2. Model calibration and validation

Model calibration was accomplished by adjusting the coefficients of δ and β in Eqs. (3)–(5) to match the model predictions with observed data obtained from our previous experiment (Cui et al., 2009). In this experiment, we investigated wastewater, nitrogen, and P dynamics in an artificial VFCW grown with

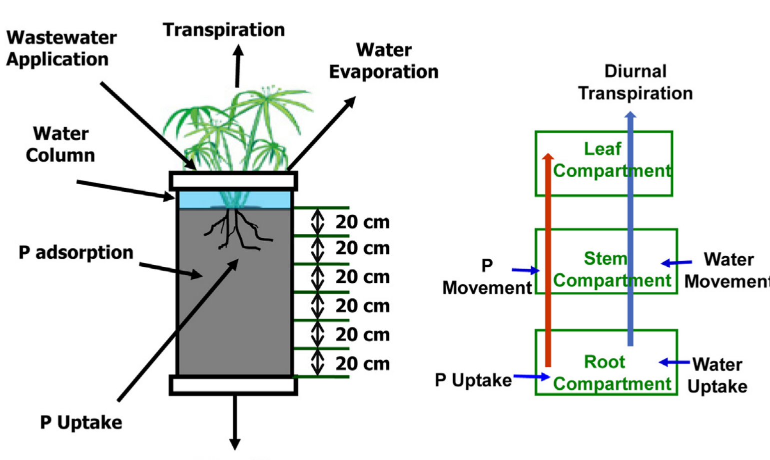

Fig. 1. A conceptual model for P dynamics in a vertical-flow constructive wetland (A) and a compartmental model for water and P uptake and transport in a plant species (B). The radius of the column was 10 cm, giving a total volume of 37699 cm^3.

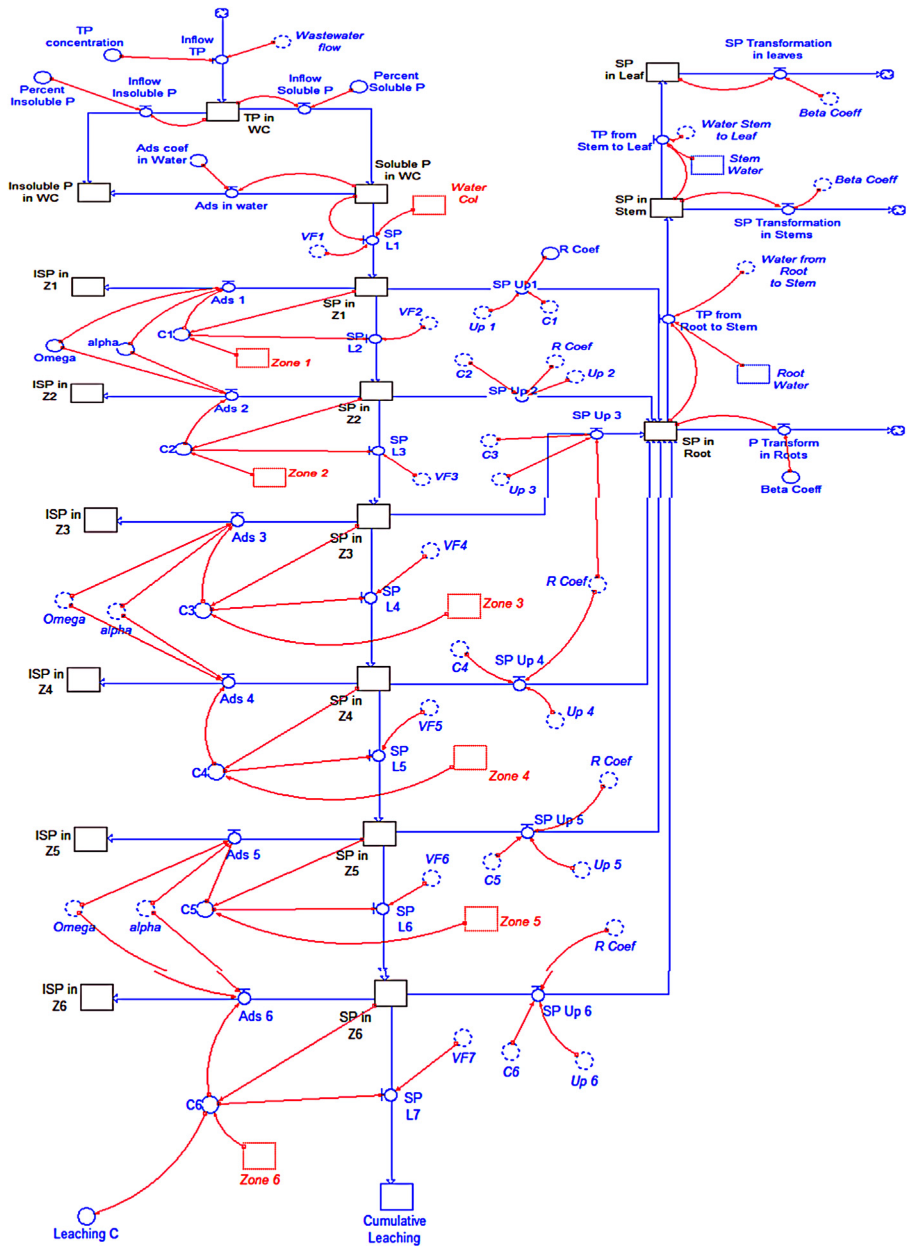

Fig. 2. Phosphorus dynamic model developed with STELLA.

C. alternifolius species. The P data were obtained using the standard methods for the examination of water and wastewater (APHA, 1998). Detailed experimental procedures, sources and properties of substrate and wastewater, and biomass production of *C. alternifolius* can be found in Cui et al. (2009). Table 1 lists all of the input parameter values used for the calibration and validation.

Comparison of the observed and predicted SP leachate concentrations from the bottom of the column showed the following linear regression equation:

$$Y_{SP}^{predicted} = 0.9101 X_{SP}^{observed} (R^2 = 0.9726, \mathrm{RMSE} = 0.23,\ p = 0.00024) \quad (6)$$

Based on a large correlation coefficient (R^2) and low RMSE (root mean square error) and p-value, it can be concluded that very good agreement was obtained between the model predictions and the experimental measurements during the model calibration process.

Model validation is a process to validate the calibrated model by matching the model predictions with experimental measurements (from an independent set of observed data) without changing any input parameters values. The experimental data use for calibration was eight weeks from April 20 to June 20, 2001. Comparison of the predicted and measured SP leachate concentrations from the bottom of the column had $R^2 = 0.756$, RMSE = 0.48, and $p < 0.001$, suggesting reasonable agreement was obtained between predicted and observed values during the model validation process.

3. Results and discussion

To estimate the performance of a VFCW for removal of P from domestic wastewater, a simulation scenario was chosen to investigate the P dynamics for conditions with the presence of the *C. alternifolius* species under a wetting-to-drying timing ratio of 1:3 (i.e., recharging the column for 8 h followed by drying for 24 h). The initial substrate column was saturated with clean water and a single growing *C. alternifolius* plant species was chosen for this simulation. Because water and P dynamics in a VFCW are

Table 1
Input parameter values for model calibration, validation, and simulation.

Water dynamics		
Parameter	Value	Reference
Bulk density (g/cm^3)	1.23	Experimental data
Column inflow rate (cm^3/h)	683	Experimental data
Column cross section area (cm^2)	314	Experimental data
Column diameter (cm)	20	Experimental data
Column depth (cm)	120	Experimental data
Saturated hydraulic conductivity (cm/h)	2.36	Experimental data
Column porosity (except for the first layer)	0.66	Experimental data
Substrate thickness each layer (cm)	20	Assumed
Drainage rate coefficient (1/h)	0.05	Calibrated
Initial root length (cm)	30	Experimental data
P dynamics		
Parameter	Value	Reference
Water column (wastewater)		
Initial influent TP concentration (mg/L)	6.52	Experimental data
Percent of soluble P (SP)	78	Experimental data
Percent of insoluble P (IP)	22	Experimental data
Adsorption of SP by the substrate (C = concentration of SP)	$2.73 \circ C^{0.75}$	Experimental data
Initial SP mass in column (mg)	0.0	Estimate based on measured data
Initial IP mass in column (mg)	0.0	Estimate based on measured data
Wetland plant		
Initial root TP mass (mg)	0.17	Estimate based on measured data
Initial stem TP mass (mg)	0.19	Estimate based on measured data
Initial leaf TP mass (mg)	0.40	Estimate based on measured data
δ coefficient in Eqs. (3) and (4)	18	Calibrated
β coefficient in Eqs. (3) and (4)	0.0001	Calibrated

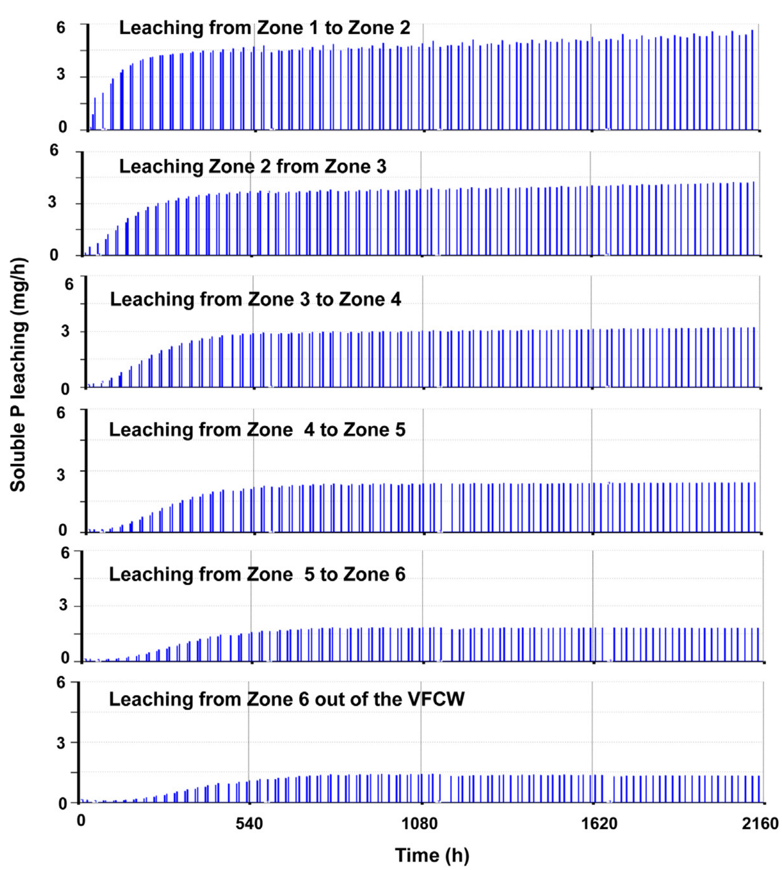

Fig. 3. Leaching of soluble P through VFCW zones as a function of time.

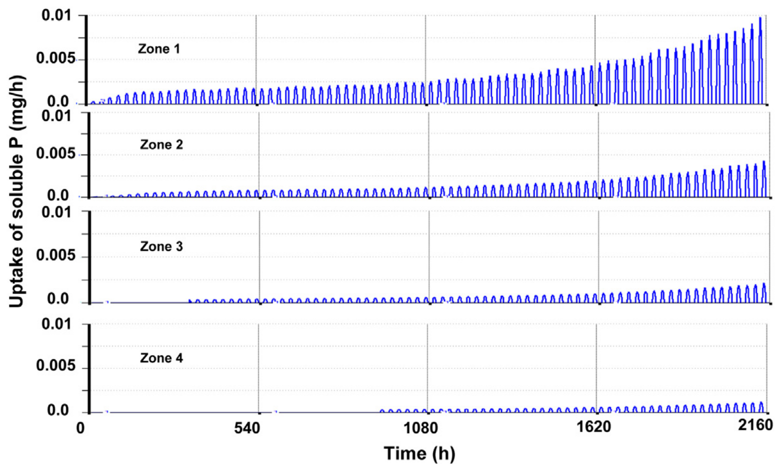

Fig. 4. Uptake of soluble P by roots as a function of time in Zones 1–4.

coupled and interactive phenomena, they must be estimated simultaneously. The water dynamics simulation has been published in our previous report (Ouyang et al., 2010a). In this study, we only focused on P dynamics. The simulation started at 0 h and ended at 2168 h (or 90 days). All of the input parameter values were given in Table 1.

Changes in SP leaching rates from Zone 1 through Zone 6 and out of the VFCW as a function of time for a 90-day simulation period are shown in Fig. 3. The initial SP concentration in the influent wastewater was 4.86 mg/L. In general, the rate of SP leaching was highest at the top zone (i.e., Zone 1) and decreased gradually with increasing zone number (or column depth). The maximum rate of SP leaching was about 5.65 mg/h from Zone 1 to Zone 2, but was 1.40 mg/h from Zone 6 to the column outlet. The former was about 4 times larger than the latter. We attributed this decrease to wastewater SP adsorption, pore clogging, and plant uptake as wastewater flowed through the six zones.

Fig. 3 further revealed that the best time for an optimal removal of SP from the wastewater was within the first week (168 h) as the rate of SP leached out of the VFCW from Zone 6 at this period was lowest (about 0.01 mg/h). Apparently, the adsorption capacity of the substrate in the VFCW was highest within the first week. The rate of SP leaching continued to increase for each zone after the first week probably because most of the substrate adsorption sites were saturated with SP after the first week. Furthermore, the rate of SP leaching through the zones followed the water flow pattern (Ouyang et al., 2010a): breakthrough during wetting period and cessation during drying period. This was so because the SP was dissolved in wastewater.

Uptake of SP by roots showed a decrease from Zone 1 to Zone 4 (Fig. 4). For example, the rate of SP uptake was about 0.0025 mg/h in Zone 1 at 1080 h, but was about 0.0005 mg/h in Zone 4 at the same time period. The former was 5 times higher than the latter and occurred because more actives roots were distributed in Zone 1, which was confirmed by our experimental observation. Fig. 4 also showed the rate of SP uptake by roots increased with time within each zone as a result of the *C. alternifolius* growth. No uptake of SP was observed from 0 to 924 h of the simulation in Zone 4 because the initial root length ($t = 0$) was 30 cm and did not reach this zone during this simulation period (Ouyang et al., 2010a).

The simulated mass balance for TP in the VFCW system at 2168 h indicated that about 53.3% of TP from the wastewater was absorbed by the substrate, about 13.5% of TP flowed out of the VFCW system as effluent; about 0.49% of TP was up taken by roots; and the remainder 32.7% was stored and/or clogged in the column as SP or as particulate P. The cumulative removal of TP from the wastewater was in the following order: adsorption > leaching > uptake. Results indicated adsorption of P was a major mechanism for P removal from the VFCW system and is consistent with chemistry of SP in mineral soils (Tan, 2010).

References

APHA, 1998. Standard Methods for the Examination of Water and Wastewater, twentieth ed. American Public Health Association, United Book Press, USA.
Beutel, M.W., Newton, C.D., Brouillard, E.S., Watts, R.J., 2009. Nitrate removal in surface-flow constructed wetlands treating dilute agricultural runoff in the lower Yakima Basin, Washington. Ecol. Eng. 35, 1538–1546.
Bond, C.R., Maguire, R.O., Havlin, J.L., 2006. Change in soluble phosphorus in soils following fertilization is dependent on initial Mehlich-3 phosphorus. J. Environ. Qual. 35, 1818–1824.
Cui, L.H., Ouyang, Y., Chen, Y., Zhu, X.Z., Zhu, W.L., 2009. removal of total nitrogen by *Cyperus alternifolius* from wastewaters in simulated vertical-flow constructed wetlands. Ecol. Eng. 35, 1271–1274.
Cui, L.H., Ouyang, Y., Gu, W.J., Yang, W.Z., Xu, Q.L., 2013. Evaluation of nutrient removal efficiency and microbial enzyme activity in a baffled subsurface-flow constructed wetland system. Bioresour. Technol. 146, 65–662.
Djodjic, F., Börling, K., Bergström, L., 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. J. Environ. Qual. 33, 678–684.
Katsenovich, Y.P., Hummel-Batista, A., Ravinet, A.J., Miller, J.F., 2009. Performance evaluation of constructed wetlands in a tropical region. Ecol. Eng. 35, 1529–1537.
Langergraber, G., Šimùnek, J., 2005. Modeling variably saturated water flow and multicomponent reactive transport in constructed wetlands. Vadoze Zone J. 4, 924–938.
Martin, J.F., Reddy, K.R., 1997. Interaction and spatial distribution of wetland nitrogen processes. Ecol. Modell. 105, 1–21.
Ouyang, Y., 2005. evaluation of river water quality monitoring stations by principal component and factor analysis. Water Res. 39, 2621–2635.
Ouyang, Y., 2008. Modeling the mechanisms for uptake and translocation of dioxane in a soil-plant ecosystem with STELLA. J. Contam. Hydrol. 95, 17–29.
Ouyang, Y., Luo, S.M., Cui, L.H., Liu, Y.H., Qin, Z., 2010a. Estimation of water dynamics in a vertical-flow constructed wetland with a growing plant species. J. Soils Sediments 10, 1219–1228.
Ouyang, Y., Luo, S.M., Cui, L.H., 2010b. Estimation of nitrogen dynamics in a vertical-flow constructed wetland. Ecol. Eng. 37, 453–459.
Sutula, M., Bianchi, T.S., McKee, B.A., 2004. Effect of seasonal sediment storage in the lower Mississippi River on the flux of reactive particulate phosphorus to the Gulf of Mexico. Limnol. Oceanogr. 49, 2223–2235.
Tan, K.H., 2010. Principles of Soil Chemistry, fourth ed. CRC Press Taylor & Francis Group, pp. 390.
Vymazal, J., 2014. Constructed wetlands for treatment of industrial wastewaters: a review. Ecol. Eng. doi:http://dx.doi.org/10.1016/j.ecoleng.2014.09.034.
Zurit, F., Anda, J.D., Belmont, M.A., 2009. Treatment of domestic wastewater and production of commercial flowers in vertical and horizontal subsurface-flow constructed wetlands. Ecol. Eng. 35, 861–869.