DANIEL RUSS HITCHCOCK
Monitoring, Quantifying, and Simulating the Internal Biological Processes of a Constructed Municipal Wastewater Treatment Wetland in the Georgia Piedmont
(Under the Direction of MATTHEW C. SMITH)

The internal physical, chemical, and biological processes and interactions are often neglected in constructed wetland design, operations, and maintenance procedures, although a tremendous amount of research has been conducted and numerous publications exist concerning natural and constructed freshwater marsh wetland structure and function. The research presented in this dissertation was conducted in order to better understand the biological and ecological processes by which a constructed wetland treats wastewater in the Georgia Piedmont. The primary objective of this study was to better understand and estimate the processes that govern the fate and transport of nutrients through such a system. The major biogeochemical and ecological processes involved in treatment of wastewater with constructed wetlands include: 1) the uptake and assimilation of nutrients by vegetation; 2) the contribution of dead vegetative biomass to the organic content of sediment; 3) the microbial decomposition of vegetative organic material; 4) the microbial activity resulting in nitrification of ammonia-nitrogen and denitrification of nitrate-nitrogen; and 5) the physicohemical and microbial processes leading to the sorption and decomposition of phosphorus compounds. A monitoring and modeling approach was used in this study to attempt to better understand the processes responsible for wastewater treatment. The focal study site was the Tignall Water Reclamation Facility, located in Tignall, GA.

INDEX WORDS: Wastewater, Treatment, Wetlands, Nutrients, Model, Tignall, Georgia, Ecological engineering

MONITORING, QUANTIFYING, AND SIMULATING THE INTERNAL BIOLOGICAL PROCESSES OF A CONSTRUCTED MUNICIPAL WASTEWATER TREATMENT WETLAND IN THE GEORGIA PIEDMONT

by

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CHAPTER 1

INTRODUCTION

Background

Freshwater marsh wetlands have been proven to be effective natural buffers at the land-water interface for maintaining good water quality in many aquatic systems (Good et al., 1978; Kadlec and Kadlec, 1979; Mitsch, 1994; Reed et al., 1995; U. S. EPA, 2000). Similarly, in small communities, constructed treatment wetlands often provide a cost-effective and energy efficient natural alternative to conventional wastewater treatment facilities in the treatment of industrial and domestic wastewaters (Tilton et al., 1976; Hammer, 1989; Moshiri, 1993; Reed et al., 1995, Kadlec and Knight, 1996; U. S. EPA, 2000). Traditionally, expected performance of these natural treatment systems has been based on first-order, plug-flow kinetics, using familiar biological design models which are used to design conventional wastewater treatment systems (Wetzel, 1993; Reed et al., 1995). Consequently, first-order reduction models for water quality parameters, typically 5-day biochemical oxygen demand (BOD_5), are used as the basis for determining hydraulic detention time (t), followed by the determination of the required wetland treatment size (Reed et al., 1995; U. S. EPA, 2000). Specifically, the state of Georgia's Department of Natural Resources (GA DNR) recommends that the retention time for a free water surface wetland system design be based on the following equation (GA DNR, 1995):

$$\frac{C_e}{C_o} = Ae^{-0.7K_t(A_v)^{1.75}(t)} \qquad (1\text{-}1)$$

where: C_e = effluent BOD_5 concentration (mg L^{-1})
C_o = influent BOD_5 concentration (mg L^{-1})
A = fraction of BOD_5 not removed as settleable solids,
typically ~ 0.52
A_v = specific surface area for microbial activity (m^2 m^{-3}),
typically ~15.7
K_T = temperature dependent rate constant (day^{-1}) = K_{20} $(1.1)^{T-20}$
where: K_{20} is the rate constant at 20°C,
typically 0.0057 day^{-1}
t = hydraulic detention time (days)

and subsequently, the wetland size is based on the following equation (GA DNR, 1995):

$$t = \frac{LWdn}{Q} \qquad (1\text{-}2)$$

where: t = hydraulic detention time (days)
L = length (m)
W = width (m)
d = depth (m)
n = "porosity", typically 0.65-0.75 (Reed et al., 1995)
Q = average flow rate (m^3 d^{-1})

This design model is based on a "black box" approach (Heliotis and DeWitt, 1983), where predicted system outputs of water quality parameters (usually BOD_5 concentrations) are based primarily on input and retention time, and the required wetland size is a function of desired removal efficiencies, porosity, and wastewater flow rate.

Domestic wastewater generally contains high levels of oxygen-depleting organic material, suspended materials, nutrients such as nitrogen and phosphorus, pathogenic organisms, and metals (Reed et al., 1995). The physical and biochemical pathways by which these wastewater components cycle through the environment vary tremendously (Canale, 1976; Klopatek, 1978; Valiela and Teal, 1978; Emsley, 1980; Reddy and Graetz,

1988; Vymazal, 1995). With respect to nutrients, for example, ammonia-nitrogen is likely to be transformed into nitrate-nitrogen by microbial nitrification, while being ultimately transformed to nitrous oxide (N_2O) then nitrogen gas (N_2) by microbial denitrification and finally emitted to the atmosphere. Also, nitrate-nitrogen is very soluble in water and tends to be transported by runoff and infiltration. On the other hand, phosphorus readily adsorbs to soil and is primarily transported and retained in sediment. In many communities, secondary treated wastewater is polished by being routed through a wetland system with the goal of nutrient sequestration via uptake by vegetation, ammonia-nitrogen and nitrate-nitrogen reduction by microbial nitrification-denitrification, and phosphorus retention in sediments, ideally limiting the amount of nutrient that reaches the receiving waters (Reed et al., 1995).

Seasonal variability in environmental conditions such as temperature and precipitation, as well as variable vegetation density and microbial characteristics, often lead to varying wetland treatment performance. Different types of vegetation require different levels each of nitrogen and phosphorus to survive. This is due to the fact that different plants are composed of variable quantities of these nutrients, and they assimilate these nutrients at different rates via a variety of mechanisms. Also, microbial transformation processes vary for different nutrient types and abundances, while certain chemical pathways are controlled by environmental conditions such as temperature, pH, redox potential, and dissolved oxygen (DO) concentration. Transport and transformation differences are often reflected by differing nutrient concentrations in sediment and water over space and time. For example, in many free water surface wetland systems, dead organic material accumulates in shallow areas of the system, leading to preferential flow and a substantial decrease in retention time, subsequently leading to decreased treatment performance.

Justification

Although a tremendous amount of research has been conducted and numerous publications exist concerning natural and constructed freshwater marsh wetland structure and function, the internal physical, chemical, and biological processes and interactions are often neglected in constructed wetland design, operations, and maintenance procedures.

"Black box" studies on natural or constructed wetlands that receive wastewaters have demonstrated that wetlands can be very effective in the short term at reducing suspended solids and nutrient concentrations in wastewater. However, over the long term, some of those functions can break down and the wetland may become a source of contaminants as it releases stored materials. For example, aquatic treatment systems and constructed wetland systems that have been designed based on BOD removal often have difficulty meeting NPDES (National Pollutant Discharge and Elimination Systems) permit compliance with respect to ammonia-nitrogen. In order to understand why multiple treatment goals may not be reached, there is a need to advance from input-output models based on first-order rate constants and focus on the mechanisms by which wetlands interact with materials (e.g. nutrients) in surface water. Kadlec (2000) recently published a paper describing the inadequacies of using a first-order approach to modeling wetland systems. Kadlec makes the argument that model parameters (rate constants) are typically regarded as true constants and do not depend on factors such as hydraulic loading rate and influent concentrations. Kadlec follows his argument by presenting a test wetland simulation that takes into consideration vegetation resistance, treatment effects of vegetation, and retention time distributions.

The internal understanding of the system is necessary in order to design, operate, and maintain constructed wetlands that will serve a desired function (e.g. nutrient reduction) for a long time (Johnston, 1993), as well as trouble-shooting the system if a problem arises. As with any young technology (as the historical perspective of the literature review illustrates), many questions concerning the optimization of constructed

wetlands for treatment must be answered. This project focused on answering questions pertaining to the dynamic biogeochemical and ecological processes within a treatment wetland system in north Georgia. These questions were addressed by taking a monitoring and modeling approach in order to identify, quantify, and estimate the roles and rates of the processes responsible for wastewater treatment.

Objectives

The primary objective of this study was to better understand and estimate the processes that govern the fate and transport of nutrients through a constructed treatment wetland system in North Georgia. The vast amount of research on natural wetland systems provided a solid foundation for this study. Specifically, the following questions were addressed:

1) What are the primary biological processes responsible for wastewater treatment in a constructed wetland system in north Georgia?

2) What are the microbial populations in a wetland system constructed for municipal wastewater treatment in north Georgia?

3) What is the role of wetland vegetation (intentionally planted and volunteer) on specific treatment processes?

4) How and at what rate is the decomposition of organic matter mediated by microorganisms in the constructed wetland system?

5) How and at what rate are the removal of nutrients mediated by microorganisms in the constructed wetland system?

6) What effects do seasonal fluctuations in parameters, such as temperature, have on 1) through 5) above?

7) What recommendations, if any, can be made on constructed wetland design, operations, and maintenance based on the answers to 1) through 6) above?

Dissertation Overview

This dissertation consists of six chapters. This chapter summarizes the problem and describes overall objectives of the dissertation research. Chapter 2 provides the results of a thorough literature review in order to present the reader with pertinent background information pertaining to the dissertation research. Chapter 3 describes the results of a two-year-long effort of monitoring a wastewater treatment wetland in the Georgia Piedmont in the interest of understanding the spatial and temporal variability of nutrient dynamics in a wetland cell. Chapter 4 describes the results of a study focused on identifying some of the microbial populations in a wastewater treatment wetland, as well as assessing their roles in wastewater treatment. Chapter 5 presents a compartmentalized nutrient model for the wastewater treatment wetland, including calibration and validation of the model with data collected from the wastewater wetland. Finally, Chapter 6 summarizes conclusions of the dissertation research, including how this research addressed the objectives of the project.

References

Canale, R. P. 1976. Modeling Biochemical Processes in Aquatic Ecosystems. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Emsley, J. 1980. The phosphorus cycle. In: Hutzinger, O., Ed., The Handbook of Environmental Chemistry, Vol. 1, Part A, The Natural Environment and the Biogeochemical Cycles, Springer-Verlag, Berlin, p. 161.

Georgia Department of Natural Resources (GA DNR). 1995. Guidelines for Constructed Wetlands for Municipal Wastewater Treatment Facilities. Environmental Protection Division, Water Protection Branch, Atlanta, GA.

Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY.

Hammer, D. A. (Ed.). 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Inc., Boca Raton, FL.

Heliotis, F. D., and C. B. DeWitt. 1983. A conceptual model of nutrient cycling in wetlands used for wastewater treatment: a literature analysis. *Wetlands*, 3: 134-152.

Johnston, C. A. 1993. Mechanisms of Wetland-Water Quality Interaction. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 293-299.

Kadlec, R. H. 2000. The inadequacy of first-order treatment wetlands models. *Ecol Eng.*, 15: 105-109.

Kadlec, R. H., and J. A. Kadlec. 1979. Wetlands and Water Quality. In: Grecian, P. E., J. R. Clark, and J. E. Clark (Eds.). 1979. Wetland Functions and Values: the State of Our Understanding. American Water Resources Association, Minneapolis, MN, pp. 436-456.

Kadlec, R. H., and R. L. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL.

Klopatek, J. M. 1978. Nutrient Dynamics of Freshwater Riverine Marshes and the Role of Emergent Macrophytes. In: Good, R. E., D. F. Whigham, and R. L. Simpson (eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential, Academic Press, New York, NY, pp. 195-216.

Mitsch, W. J. (Ed.). 1994. Global Wetlands: Old World and New. Elsevier Publishers, New York, NY.

Moshiri, G. A. (Ed.). 1993. Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL.

Reddy, K. R., and D. A. Graetz. 1988. Carbon and Nitrogen Dynamics in Wetland Soils. In: Hook, D. D., et al., (Eds.), The Ecology and Management of Wetlands, Vol. 1: Ecology of Wetlands. Timber Press, Portland, OR., pp. 307-318.

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

Tilton, D. L., R. H. Kadlec, and C. J. Richardson (Eds.). 1976. Freshwater Wetlands and Sewage Effluent Disposal. The University of Michigan Press, Ann Arbor, MI.

U. S. Environmental Protection Agency. 2000. Constructed Wetlands Treatment of Municipal Wastewaters. National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH. EPA/625/R-99/010.

Valiela, I., and J. M. Teal. 1978. Nutrient Dynamics: Summary and Recommendations. In: Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY, pp. 259-263.

Vymazal, J. 1995. Algae and Element Cycling in Wetlands. Lewis Publishers, Boca Raton, FL.

Wetzel, R. G. 1993. Constructed Wetlands: Scientific Foundations are Critical. In: Moshiri, G. A., Ed., Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 3-7.

CHAPTER 2

WASTEWATER AND WETLANDS: A LITERATURE REVIEW

Historical Perspective

The concept of utilizing natural wetlands for wastewater treatment has existed for at least100 years (Kadlec and Knight, 1996). Between 1967 and 1972, H. T. Odum and colleagues conducted studies on municipal effluent recycling in constructed estuarine ponds and salt marshes, and soon after, in 1973, conducted studies on municipal effluent recycling in natural cypress wetlands (Tilton et al., 1976; Ewel and Odum, 1984; Kadlec and Knight, 1996). Concurrent to Odum's work, Kadlec and associates explored the treatment of municipal wastewater in natural and engineered wetlands located in cold climate regions (Kadlec and Knight, 1996). Also in 1973, the first intentionally engineered wetland treatment pilot systems in North America were constructed at Brookhaven National Laboratory near Brookhaven, NY. These pilot systems combined a marsh wetland with a pond and a meadow in series and were known as the meadow/marsh/pond (MMP) treatment system (Kadlec and Knight, 1996).

Over the last 25 years, with the advances in wetland treatment technology and the development of wetland design and monitoring regulations by the U. S. EPA and by state environmental protection agencies, the use of constructed wetlands for municipal wastewater treatment has become common practice (U. S. EPA, 1983, 1987, 1988, 2000; GA DNR, 1995; Kadlec and Knight, 1996). Currently, Florida has several of the largest constructed wetland treatment areas in the world, including Lakeland and Orlando constructed wetlands, both of which were started in 1987. Each wetland has about 500 ha for advanced treatment of municipal wastewater (Kadlec and Knight, 1996). The largest

constructed treatment wetland is the 1800-ha Kis-Balaton project in Hungary, which has been in operation since 1985 (Kadlec and Knight, 1996). With the increased use of this wastewater treatment technology, however, it suffices to say that constructed wetland wastewater treatment technology is still in its infancy.

Wetland Definition, Structure and Function

Scientific consensus of what constitutes a wetland has been subjectively influenced by definitions that attempt to encompass regulatory and environmental concerns (Kadlec and Knight, 1996). Wetlands are generally defined in terms of hydrology and vegetation. Wetlands are areas where the soil is saturated with water or where shallow standing water results in the absence of plant species which depend on aerobic soil conditions (Kadlec and Knight, 1996). In particular, a freshwater marsh wetland is a freshwater wetland dominated by emergent, herbaceous plant species adapted to intermittent or continuous flooding (Tilton et al., 1976; Kadlec and Knight, 1996). Constructed treatment wetlands are those wetlands that are built expressly for water quality treatment (Hammer, 1992). A macrophyte-based wastewater treatment system is defined as a wastewater treatment system in which aquatic macrophytes have a key function in relation to the cleaning of wastewater (Brix, 1993). The term macrophyte refers to vascular plants that have tissues that are easily visible (Kadlec and Knight, 1996).

Constructed wetland structure generally consists of five typical components : 1) underlying strata; 2) hydric soils; 3) detritus; 4) flooded zone; and 5) emergent vegetation (Kadlec and Knight, 1996). The underlying strata generally consists of unaltered organic, mineral, or lithic strata which are typically saturated with or impervious to water and are below the active root zone of wetland vegetation. Hydric soils consist of the mineral to organic soil layer of the wetland which is infrequently to continuously saturated with water and contains roots, rhizomes, tubers, tunnels, burrows, and other active connections

to the surface environment. Detritus is considered to be the accumulation of live and dead organic material in a wetland which consists of dead emergent plant material, dead algae, living and dead animals (mostly invertebrates), and microbes (fungi and bacteria). The flooded zone is the portion of the wetland that is flooded by standing water and wastewater and provides habitat for aquatic organisms including fish and other vertebrate animals, submerged and floating plant species that depend on water for buoyancy and support, living algae, and populations of microbes. Emergent vegetation is the vascular, rooted plant species which contain structural components that emerge above the water surface, including both herbaceous and woody plant species (Kadlec and Knight, 1996).

Wetland ecosystem productivity is generally high compared to other ecosystems (Mitsch, 1994; Mitsch et al., 1994a). Ecosystems dominated by aquatic macrophytes (Figure 2-1) are among the most productive in the world, largely due to ample light, water, nutrients, and the presence of plants that have developed morphological and biochemical adaptations enabling them to take advantage of these optimum conditions (Westlake, 1963). This high productivity of ecosystems dominated by aquatic macrophytes results in high microbial activity in these systems and therefore an increased capacity to decompose organic matter and to retain and recycle nutrients (Brix, 1993; Ansola et al., 1995). This relationship forms the fundamental basis for the concept of constructed treatment wetland technology. Table 2-1 provides mechanisms for the removal of wastewater constituents in macrophyte-based treatment systems.

Hydrology and Water Quality

The water status of a wetland defines its extent and is a determinant of species composition in natural and constructed wetlands (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996). More importantly in terms of treatment wetland design, the flows into and out of a wetland, as well as storage volume of the wetland, determine the length of

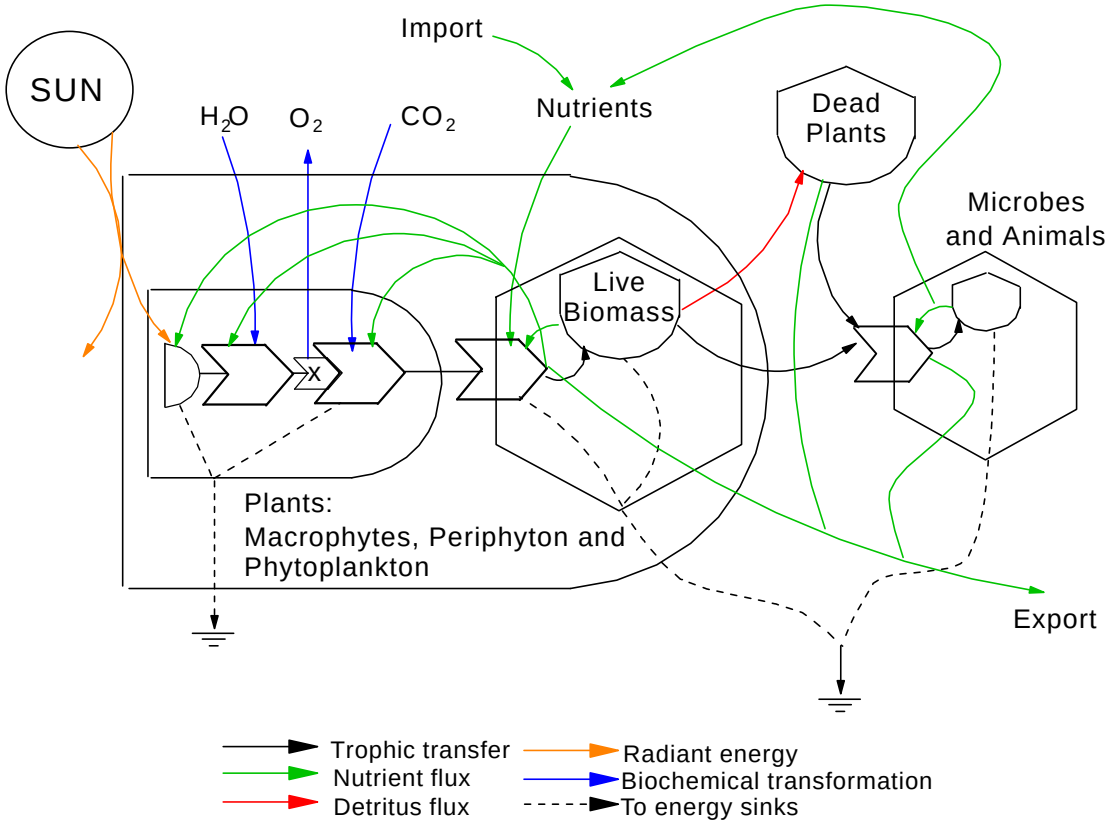


Figure 2-1. Energy Budget of a Macrophyte-Based Wetland Ecosystem Including Production and Respiration Pathways Using Odum's Energy Circuit Symbols (Odum, 1983) (Diagram modified from Kadlec and Knight, 1996).

Table 2-1. Removal Mechanisms in Macrophyte-Based Wastewater Treatment Systems (Brix, 1993)

Wastewater Constituent	*Removal Mechanisms*
Suspended Solids	- Sedimentation/filtration
BOD	- Microbial degradation (aerobic and anaerobic) - Sedimentation (accumulation of organic matter/sludge on sediment surface)
Nitrogen	- Ammonification-nitrification-denitrification - Plant uptake
Phosphorus	- Soil sorption (adsorption-precipitation reactions with aluminum, iron, calcium, and clay particles) - Plant uptake
Pathogens	- Sedimentation/filtration - Natural die off - Solar radiation - Excretion of antibiotics from roots of macrophytes - Competition/predation with other organisms

time that water spends in the wetland system, and subsequently, determine the opportunity for interactions between wastewater constituents and the wetland ecosystem (Johnston, 1993; Reed et al., 1995; Kadlec and Knight, 1996). A water budget for a wetland cell (Figure 2-2) provides a summary of the inputs and outputs that are generally associated with constructed wetlands. Because of the steep inward bank slope, bank loss (Q_b) is usually equal to zero unless a severe storm event occurs. Groundwater fluxes (Q_r and Q_d) are often assumed to be zero due to the regulatory design requirement of impervious liners at the base of each wetland cell. Therefore, a water balance can be written as follows (all units in $m^3\ d^{-1}$):

$$Q_i + P + Q_c = Q_o + ET \qquad (2\text{-}1)$$

where: Q_i = wastewater inflow
Q_o = wastewater outflow
Q_c = catchment flow
P = precipitation
ET = evapotranspiration

The daily evapotranspiration rate per square meter of surface area was estimated to be between 1.7 and 2.1 mm d^{-1} for a marsh system in Illinois (Konyha et al., 1995). For 100 surface wetlands in North America, 1.00 cm d^{-1} is the 40^{th} percentile (Kadlec and Knight, 1996). Evapotranspiration losses approach a daily average per square meter of surface area of 0.50 cm d^{-1} in summer in the southern U. S.; consequently, more than half the daily added water may be lost to evapotranspiration under those circumstances (Kadlec and Knight, 1996). Wetland evapotranspiration per square meter of surface area has been estimated to be as low as 0.25 to 0.8 cm d^{-1} in Nevada, where an arid climate prevails (Laczniak et al., 1999). Daily evapotranspiration rates for a 1.5 ha peatland in New York have been estimated to range from 13.6 to 40 m^3 d^{-1}, or 0.09 to 0.27 cm m^{-2} d^{-1} (Drexler et al., 1999). Werner and Kadlec (2000) considered total maximum evapotranspiration for one day to be 0.3 cm in the stochastic simulation of treatment wetlands.

The length of time that a particle of water spends in the wetland system is known as the hydraulic retention time (t). In general, the retention time equals the volume of the system (V) divided by the average flow rate of water through the system (Q_{avg}) . More specifically for wetlands, the porosity of the system (n) must be considered due to the space occupied by vegetation and litter, and hydraulic retention time can be determined using the following equation (Reed et al., 1995):

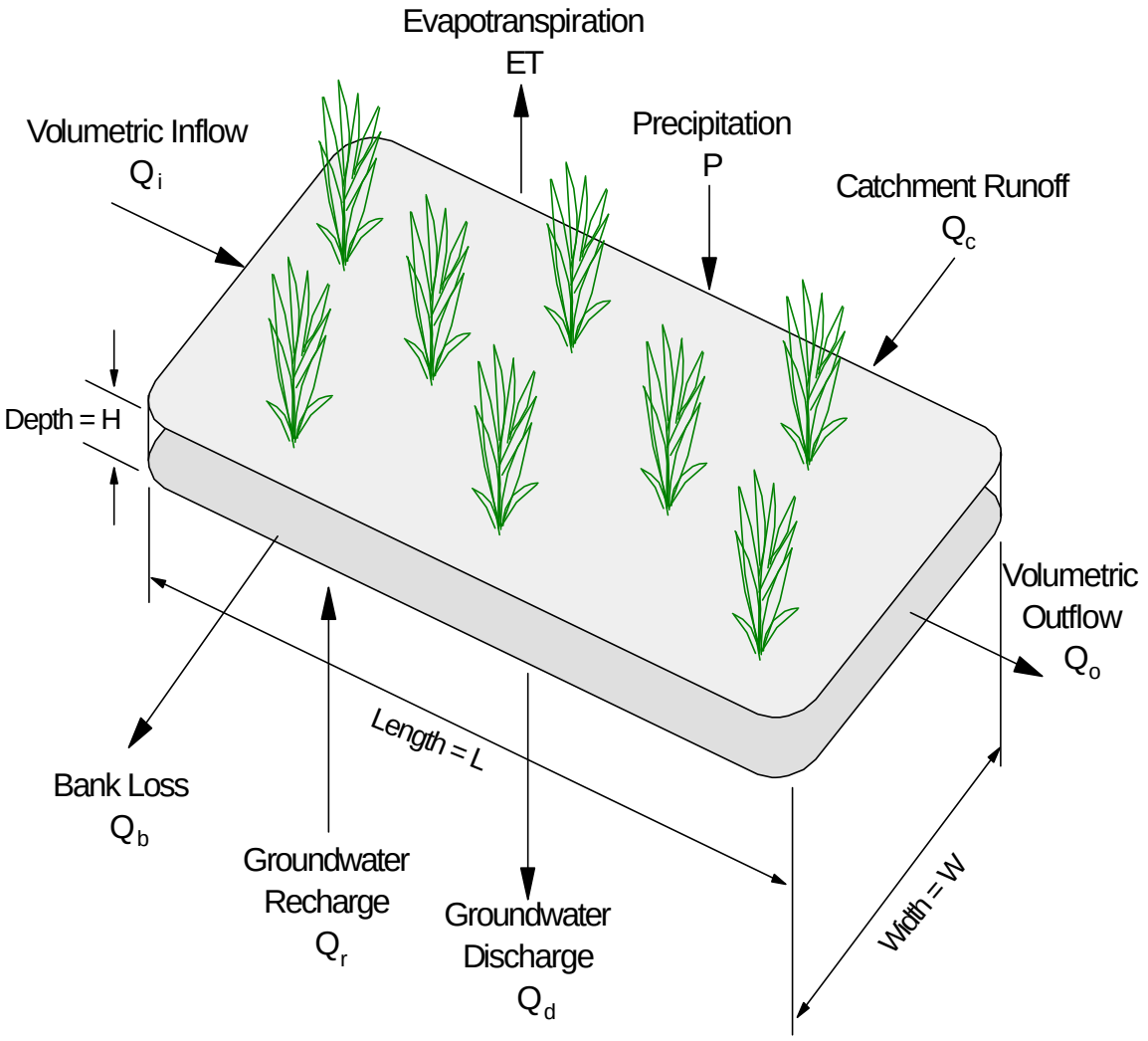


Figure 2-2. Water Budget of a Treatment Wetland Cell
(Modified from Kadlec and Knight, 1996).

$$t = \frac{nV}{Q_{avg}} \qquad (2\text{-}2)$$

where: t = hydraulic detention time (days)
V = wastewater volume (m^3)
n = "porosity", typically 0.65-0.75 (Reed et al., 1995) ($m^3\ m^{-3}$)

Porosity, or the space available for water to flow through the wetland cell(s), is generally estimated to be 0.65 to 0.75, or lower if considering dense, mature vegetation (Reed et al., 1995). The equation for hydraulic retention time is substituted into an equation for first-order BOD reduction for a plug flow reactor system to yield (Reed et al., 1995):

$$\frac{C_e}{C_o} = A\exp\left[\frac{-0.7K_t(A_v)^{1.75}(L)(W)(y)(n)}{Q}\right] \qquad (2\text{-}3)$$

where: C_e = effluent BOD_5 concentration ($mg\ L^{-1}$)
C_o = influent BOD_5 concentration, ($mg\ L^{-1}$)
A = fraction of BOD_5 not removed as settleable solids, typically 0.52
A_v = specific surface area for microbial activity, $m^2\ m^{-3}$, typically 15.7
K_T = temperature dependent rate constant (day^{-1}) = $K_{20}\ (1.1)^{T-20}$
where K_{20} is the rate constant at 20°C, typically 0.0057 day^{-1}
L, W, Y, n, Q = as previously defined

Note that the A_v value is a measure of the surface area available in the system for the development of attached-growth organisms. The above equation denotes the current recommended method for treatment wetland design in the state of Georgia (GA DNR, 1995).

Nutrients

In general, decomposition is defined as the chemical breakdown of a compound into simpler compounds, often accomplished by microbial metabolism (Reddy and Graetz, 1988; Vymazal, 1995). Bacteria and fungi are the primary microbes responsible for the decomposition of vegetative organic matter into simpler organic matter and inorganic matter (McGill et al., 1979). The major biological processes responsible for decomposition are mineralization (also known as ammonification in terms of nitrogen) and respiration. Mineralization is defined as the conversion of an organic form of an element into an inorganic form as a result of microbial metabolism (Reddy and Graetz, 1988; Vymazal, 1995). Respiration is defined as catabolic reactions producing ATP in which either organic or inorganic compounds are the primary electron donors and exogenous compounds are the ultimate electron acceptors (Reddy and Graetz, 1988; Vymazal, 1995). Typically, extracellular enzymes produced by microorganisms break down the larger complex polymers of vegetative detritus (inputs), such as cellulose, lignin, and protein, into monomeric organic units such as sugars, phenols, and amino acids (Reddy and Graetz, 1988; Vymazal, 1995). These simpler units are subsequently decomposed by aerobic and anaerobic respiration.

The major macronutrients that are conserved in the decomposition process are carbon, sulfur, nitrogen, and phosphorus (Vymazal, 1995). The biological mechanisms by which decomposition occurs depend on the redox potential (E_h) of the particular medium (soil or water). Figure 2-3 summarizes the integrated carbon, nitrogen, and sulfur transformation processes occurring in wetland sediments given certain ranges of redox potential.

Aerobic respiration, which depends on a steady supply of oxygen, leads to the decomposition of monomeric units into carbon dioxide and water, as follows (Vymazal, 1995):

$$(CH_2O) + O_2 \rightarrow CO_2 + H_2O \qquad (2\text{-}4)$$

Below the aerobic zone (I), facultative anaerobic bacteria can utilize NO_3^-, oxidized manganese compounds, and then ferric iron compounds as electron acceptors. Below the Fe^{3+} reduction zone (II), anaerobic respiration occurs, which can be carried out by either facultative anaerobes or obligate anaerobes (Vymazal, 1995):

$$(CH_2O)_6 \rightarrow 2\ CH_3CHOHCOOH \text{ (lactic acid)} \qquad (2\text{-}5)$$

or:

$$(CH_2O)_6 \rightarrow 2CH_3CH_2OH + 2\ CO_2 \text{ (ethanol)} \qquad (2\text{-}6)$$

Under extremely reduced conditions (E_h > 300 mV), methane formation can occur, either by acetic acid reduction (Vymazal, 1995):

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (2\text{-}7)$$

or by the reduction of electron acceptors and then acetic acid decarboxylation (Vymazal, 1995):

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O \qquad (2\text{-}8)$$

$$CH_3COOH + 3\ H_2 \rightarrow 2\ CH_4 + 2\ H_2O \qquad (2\text{-}9)$$

The microbial oxidation of methane can also lead to CO_2 production. In general, the overall products of organic carbon decomposition are CO_2, CH_4, alcohols, organic acids, energy, and biomass (outputs). Pinney et al. (2000) have reported on the transformations in dissolved organic carbon (DOC) through laboratory-scale reactors in which *Typha* (cattail) was planted. During their three-month study, approximately 5 to 8% of the total cattail biomass was leached as DOC, 45-60% remained in the reactor as accumulated

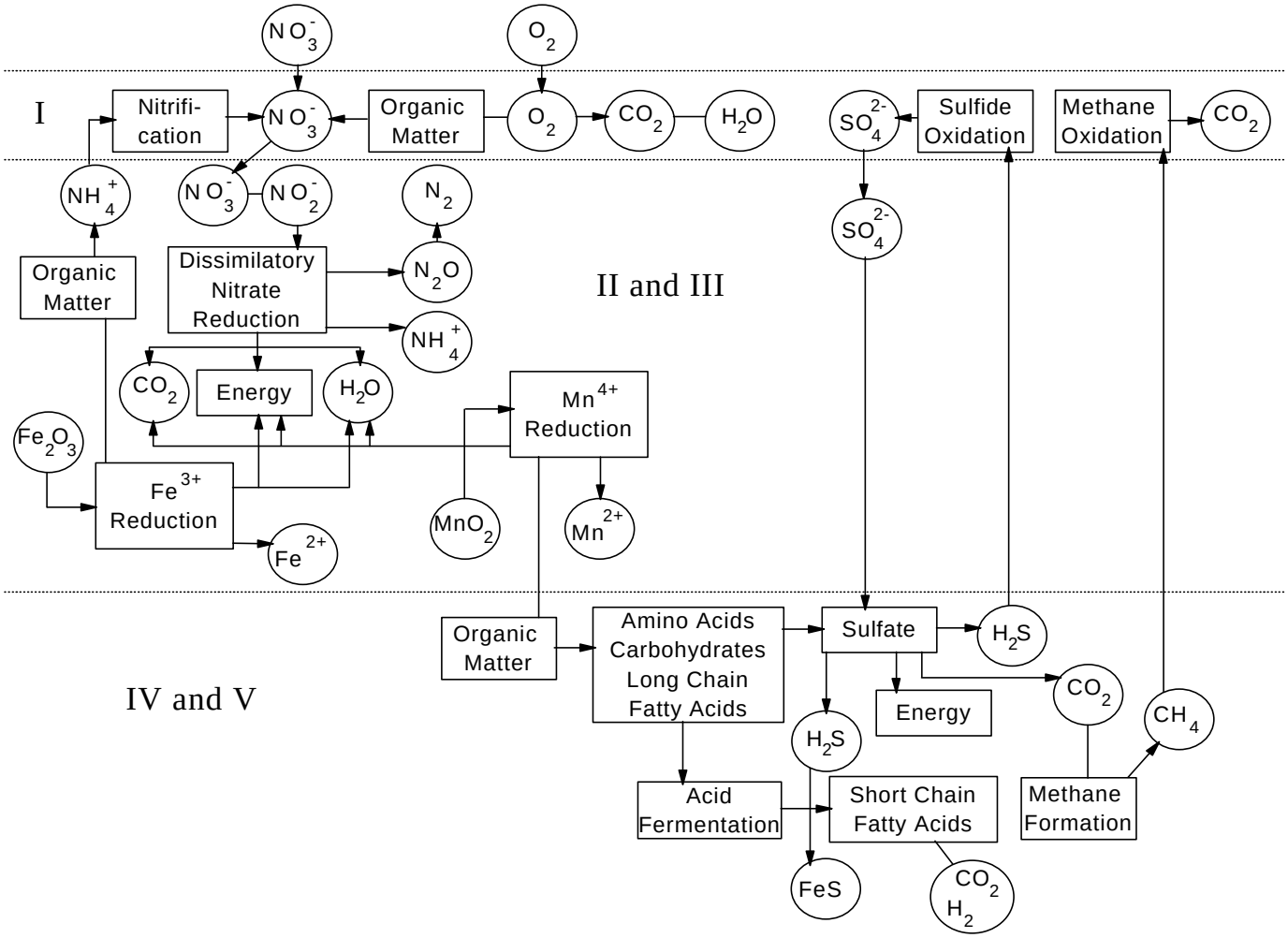


Figure 2-3. Pathways of Organic Carbon Decomposition in a Wetland. I = Aerobic Respiration Zone (E_h >= 300 mV); II and III = Facultative Anaerobic Zone (E_h = 0 to 300 mV); IV and V = Obligate Anaerobic Zone (E_h = -300 to 0 mV) (Reddy and Graetz, 1988).

biomass, and the remainder of the carbon (30-50%) exited as particulate organic carbon or was respired. Chanton et al. (1993) have explored the rates of methane emission from emergent aquatic macrophyte systems in which *Typha* spp. (cattail) and *Cladium* spp. (sawgrass) was planted. Results from the study showed that *Typha* stands emitted approximately 124 to 163 mg m^{-2} d^{-1} of methane, while *Cladium* stands emitted approximately 30 to 60 mg m^{-2} d^{-1} of methane.

The sulfur cycle is very important in the oxidation of organic carbon. Sulfur-reducing bacteria require an organic substrate, such as lactate, to form acetate and other products (Vymazal, 1995):

$$2\ CH_3CHOHCOO^- + SO_4^{2-} + 3\ H^+ \rightarrow 2\ CH_3COO^- + 2\ CO_2 + 2\ H_2O + HS^- \quad (2\text{-}10)$$

and

$$CH_3COO^- + SO_4^{2-} \rightarrow 2\ CO_2 + 2\ H_2O + HS^- \quad (2\text{-}11)$$

Sulfur transformations depend largely on environmental conditions such as pH and redox potential, and therefore determine the type of bacteria present. For example, organic sulfur can be mineralized into sulfate (SO_4), then sulfur-reducing bacteria are responsible for the dissimilatory sulfate reduction (not shown in Figure 2-3) as follows (Vymazal, 1995):

$$SO_4^{2-} + \text{lactate} \rightarrow H_2S + \text{acetate} + CO_2 \quad (2\text{-}12)$$

$$SO_4^{2-} + \text{acetate} \rightarrow H_2S + CO_2 \quad (2\text{-}13)$$

The oxidation of sulfides can lead to elemental sulfur and sulfates (Vymazal, 1995):

$$2\ H_2S + O_2 \rightarrow 2\ S + 2\ H_2O + \text{energy} \quad (2\text{-}14)$$

$$2\ S + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4 + \text{energy} \quad (2\text{-}15)$$

The products of sulfur transformations from decomposition of organic matter include H_2S and H_2SO_4 (outputs).

A fundamental concept of wastewater treatment by constructed wetlands is based on the ability of these systems to retain and recycle nutrients, especially nitrogen and phosphorus. The biogeochemical pathways by which nutrient removal occurs are complex, and they are often dependent on environmental conditions such as pH, dissolved oxygen (DO) concentration, redox potential (ORP), and temperature. In a wetland, nutrient reduction pathways, especially that of nitrogen, are highly integrated with the pathways responsible for the decomposition of organic material (Figure 2-3). This organic material originates from the high organic content of wastewater introduced to the system, as well as decaying vegetation and decomposing microorganisms within the system.

Nitrogen reduction in a wetland system occurs via a microbial nitrification-denitrification pathway (Figure 2-4). The oxygen-requiring (aerobic) reactions of nitrification can be summarized by the following system of equations (Vymazal, 1995):

$$NH_4^+ + 1\,½\,O_2 \rightarrow NO_2^- + 2\,H^+ + H_2O \qquad (2\text{-}16)$$

$$NO_2^- + ½\,O_2 \rightarrow NO_3 \qquad (2\text{-}17)$$

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O \qquad (2\text{-}18)$$

Nitrification rates in general have been reported to range from 0.025 to 0.160 g m^{-2} d^{-1} (U. S. EPA, 1985). Nitrification rates for riparian wetlands have been estimated to be 0.08 to 0.10 g m^{-2} d^{-1} (Dørge, 1994). Nitrification rates for wetland systems have been reported to be 2.8 to 3.4 nM cm^{-3} h^{-1} (Howard-Williams and Downes, 1993). Also, the effects of temperature on nitrification rates are noteworthy. Ammonia removal and nitrification rates have been reported to decrease as much as 20% in model wetland systems where temperature was changed from 23 to 5 ^oC (Lee et al., 1999).

Denitrification, which generally requires an anaerobic environment, can be summarized as follows (Vymazal, 1995):

$$6\,(CH_2O) + 4\,NO_3^- \rightarrow 4\,HCO_3^- + 2\,N_2O + 2\,H_2O \qquad (2\text{-}19)$$

$$5\,(CH_2O) + 4\,NO_3^- \rightarrow H_2CO_3 + 4\,HCO_3^- + 2\,N_2 + 2\,H_2O \qquad (2.20)$$

The overall nitrogen product of the nitrification-denitrification reaction system (assuming 100% efficiency and reaction completion) is nitrogen gas (N_2), which leaves the wetland system and enters the atmosphere. Nitrate reductase activity has been reported to be three or four orders of magnitude higher for freshwater sediments than for overlying water (Jones, 1979). Denitrification rates in general have been reported to range from 0.002 to 0.100 g m^{-2} d^{-1} (U. S. EPA, 1985). Denitrification rates of 0.12 g m^{-2} d^{-1} (sediment) to 0.48 g m^{-2} d^{-1} (litter) have been estimated in artificial shallow water systems (Weisner et al., 1994). DeLaune et al. (1996) have explored denitrification in bottomland hardwood wetlands; they reported estimates of nitrogen export from the water column of between 7.5 mg m^{-2} d^{-1} and 11.5 mg m^{-2} d^{-1}. Lusby et al. (1998) have reported on the comparison of nitrification and denitrification potentials in organic and sandy sediments with redox potential values ranging from -50 to +50 mV. The nitrification and denitrification potentials were much greater in the organic sediments (32 ± 49 and 165 ± 150 ng per gram sediment per day, respectively) than in the sandy sediments (-1 ± 3 and 2 ± 5 ng per gram sediment per day, respectively). Denitrifying potential was more than five times higher than nitrifying potential in the organic sediments. Denitrification rates have been estimated to range from 0.04 to 0.24 g m^{-2} d^{-1} using simulations considering the interaction and spatial distribution of wetland nitrogen processes (Martin and Reddy, 1997).

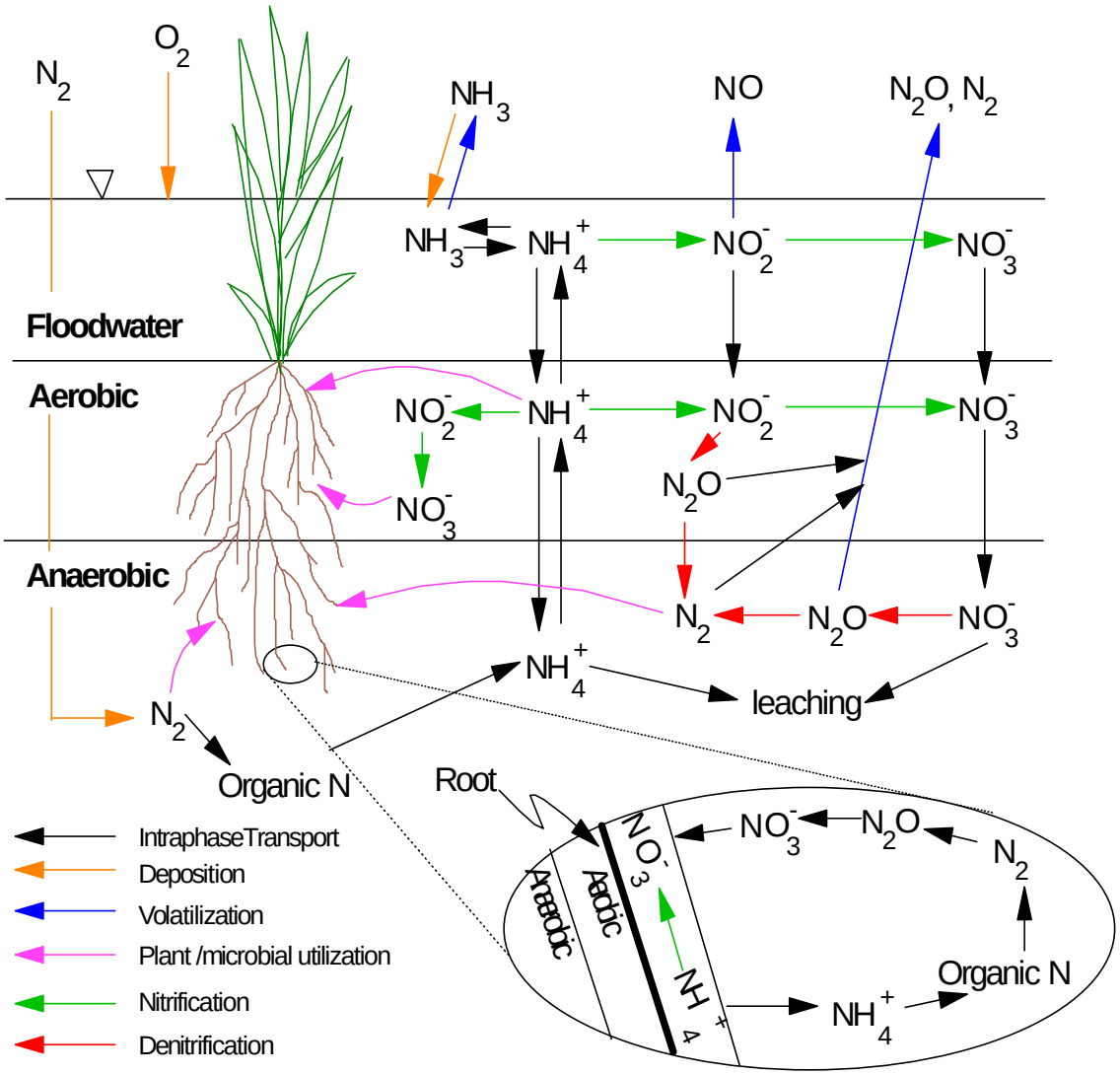


Figure 2-4. Nitrogen Compound Transport and Transformations in a Wetland System (Modified from Reddy and Graetz, 1988).

Phosphorus generally behaves differently than nitrogen in an aquatic system (Figure 2-5). Two separate cycles are often used to describe the phosphorus cycle in these systems, the internal cycle and the external cycle. The internal, or biological, cycle is summarized as follows (Vymazal, 1995):

$$(PO_4\text{-}P)_{water} \xrightarrow{\text{primary production}} \text{cell-}PO_4 \xrightarrow{\text{mineralization}} (PO_4\text{-}P)_{water} + (\text{Org-}P)_{water} \quad (2\text{-}21)$$

and the external, or geochemical, cycle is as follows (Vymazal, 1995):

$$(PO_4\text{-}P)_{water} \xrightarrow{\text{sediments}} (PO_4\text{-}P)_{water} + (\text{Org-}P)_{water} \quad (2\text{-}22)$$

Another notable property of phosphorus is that its prevalent inorganic form in the environment, orthophosphate, occurs in ionic equilibrium in natural waters (Vymazal, 1995):

$$H_3PO_4 \;\underset{\text{pH = 2.2}}{]}\; H_2PO_4^- \;\underset{\text{pH = 7.2}}{]}\; HPO_4^{2-} \;\underset{\text{pH = 12.3}}{]}\; PO_4^{3-} \quad (2\text{-}23)$$

with $H_2PO_4^-$ and HPO_4^{2-} being the predominant species over pH range of 5 to 9. Overall, a net gain in bound sediment phosphorus is often expected in aquatic systems (Canale, 1976; Emsley, 1980), and especially in constructed wetland systems (Mitsch and Reeder, 1991; Cooke, 1992; Mitsch et al., 1995; U. S. EPA, 2000). Mitsch and Reeder (1991) have estimated phosphorus sedimentation rates to be as high as 0.01 to 0.04 g m^{-2} d^{-1}, with an estimated net phosphorus retention rate of 2.9 mg m^{-2} d^{-1}, in coastal freshwater wetlands. Mitsch et al. (1995) have reported phosphorus retention in constructed

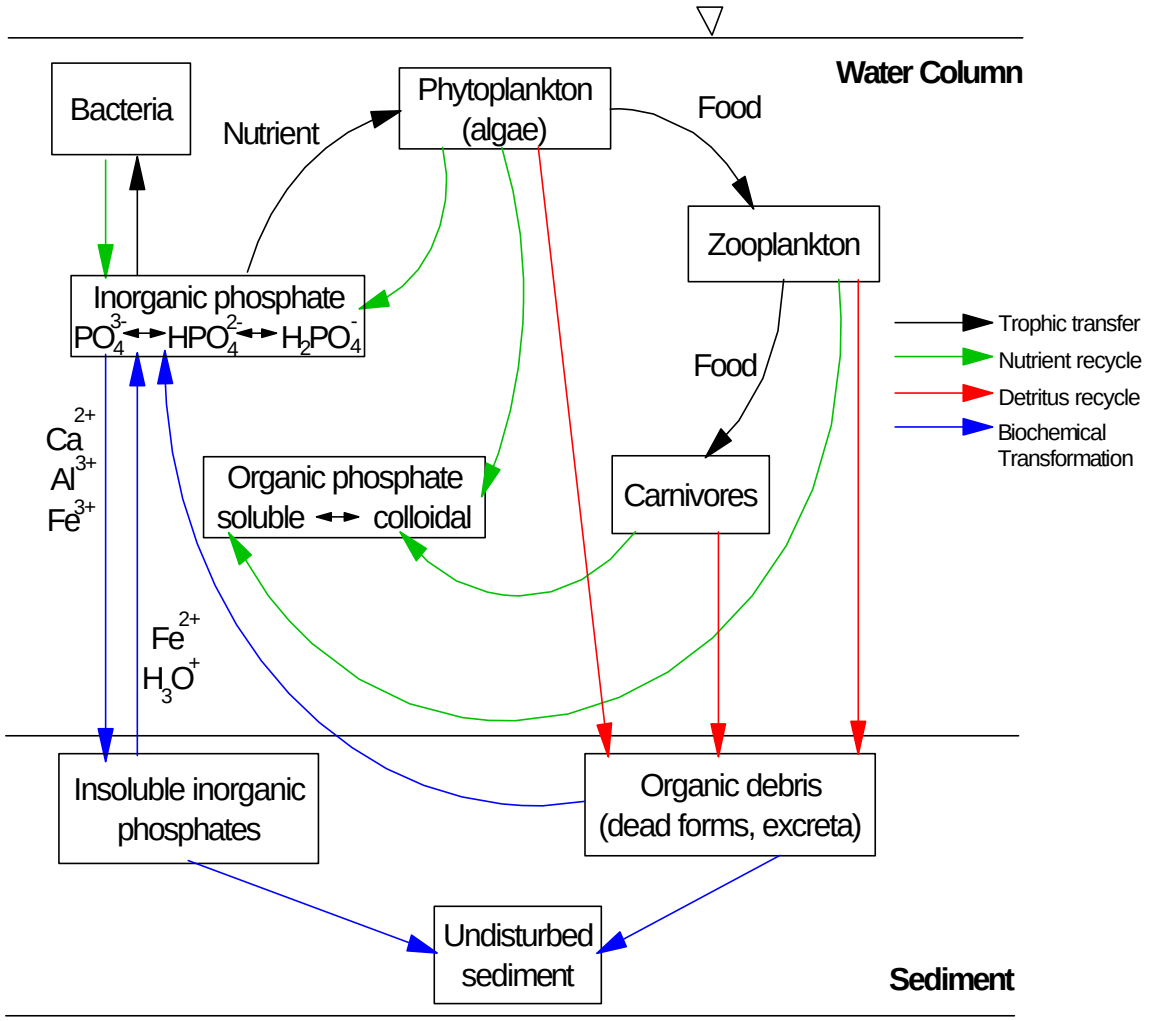


Figure 2-5. Phosphorus Compound Transport and Transformations in a Wetland System (Modified from Emsley, 1980, and Vymazal, 1995).

freshwater riparian marshes to range from 0.5 to 3 g m^{-2} yr^{-1}. Braskerud (2000) has reported overall phosphorus removal to be 0.05 to 0.2 g m^{-2} d^{-1} in wetlands receiving nonpoint source runoff. Cooke (1992) has reported estimated phosphorus deposition rates of up to 30 g m^{-2} d^{-1} in a wetland after a decade of receiving sewage effluent.

Sediment deposition plays an important role in the sequestration of nutrients in wetland systems. Vargo et al. (1998) have conducted experiments reflecting the role of sedimentation on plant decomposition, concluding that sediment deposition had little influence on the net flux of nutrients from decaying plant tissues. Morris and Bowden used a value of 0.1 g cm^{-2}, or 10.2 mg m^{-2} d^{-1}, for annual deposition of organic matter on to marsh surface in simulations of sedimentation, mineralization, and decomposition. Fennessy et al. (1994a) have estimated average daily sedimentation rates based on hydraulic loading rate (HLR) during low flow conditions (HLR = 1.0 to 2.3 cm d^{-1}) in freshwater wetlands to be 21.2 g m^{-2} d^{-1} on an annual basis, and 56.2 g m^{-2} d^{-1} based on summer months. Fennessy et al. (1994a) have also estimated average daily sedimentation rates during high flow conditions (HLR = 5.0 to 5.5 cm d^{-1}) in freshwater wetlands to be 25.5 g m^{-2} d^{-1} on an annual basis, and 49.2 g m^{-2} d^{-1} based on summer months.

Wetland Ecology

The ecological structures of natural and constructed wetlands are similar in many respects. The components of the wetland ecosystem (Figure 2-6) are: 1) vegetation; 2) microbial consortia; 3) invertebrates, and 4) vertebrates (fish, birds, mammals). These components, especially vegetation and microbial consortia, are primarily responsible for the mediation of the biochemical pathways described in the previous section.

The vegetation responsible for primary production in a wetland system can be divided into two broad categories: 1) macrophytes, and 2) algae (Kadlec and Knight, 1996). The types of macrophytes associated with a wetland include: 1) emergent

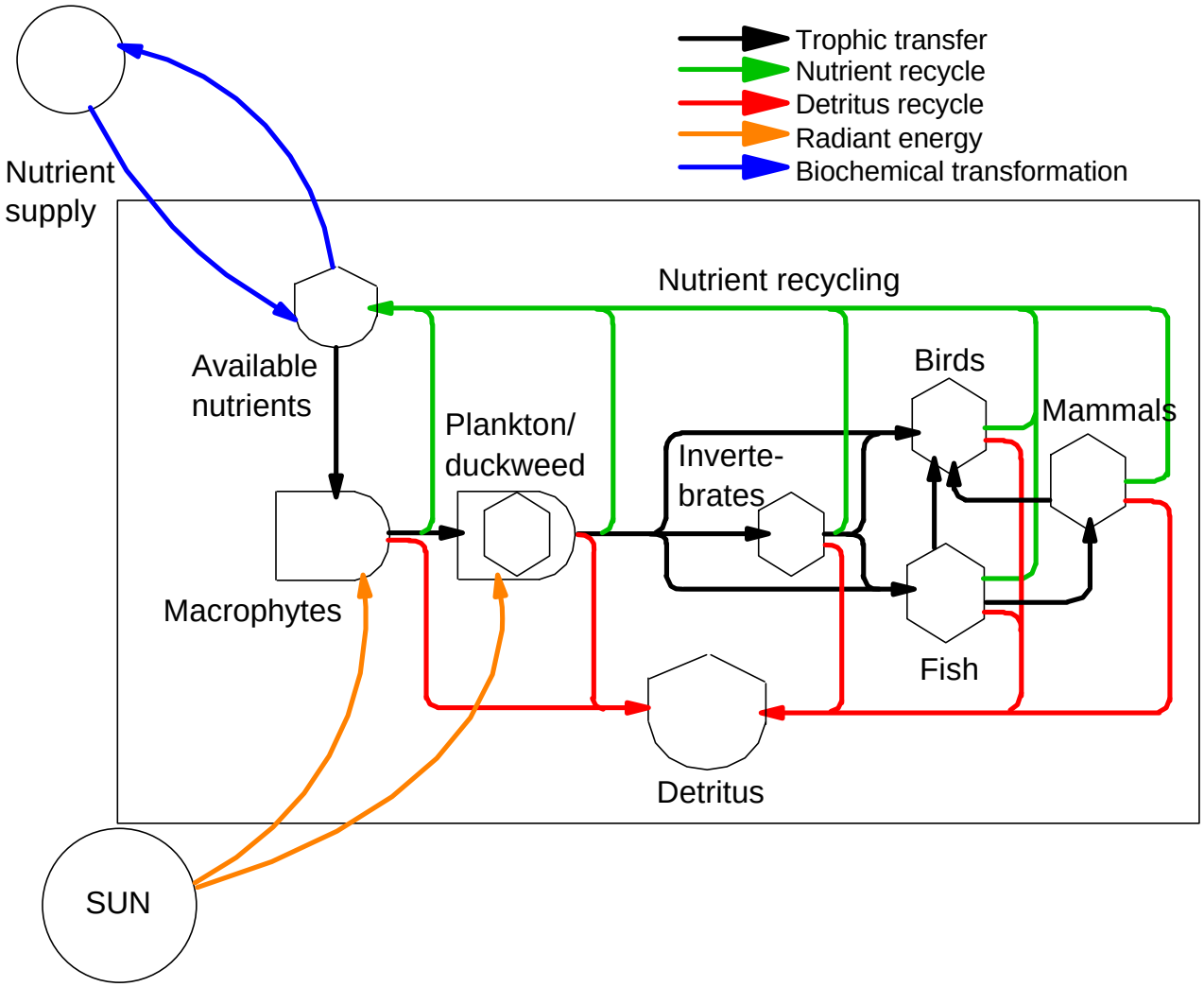


Figure 2-6. Trophic Dynamics in a Constructed Wetland Ecosystem (Modified from Kadlec and Knight, 1996).

herbaceous plants; 2) emergent woody plants; 3) floating-leaved vegetation; and 4) submerged aquatic vegetation (Kadlec and Knight, 1996). The types of algae associated with a wetland can be summarized in four categories based on their ecological niche: 1) filamentous algae; 2) periphyton; 3) phytoplankton, and 4) benthic algae (Kadlec and Knight, 1996). Each type of vegetation has an important role in the overall performance of the CW system, but these roles are often not distinct and may fluctuate seasonally. It has been suggested that the primary role of macrophytes in wetland systems is to pump nutrients from the sediments, thus making them available through leaching and decomposition (Klopatek, 1978). Researchers have summarized estimates of standing stock vegetative biomass for a variety of wetland macrophytes (Heliotis and DeWitt, 1983). In particular, they summarized estimates of standing stock vegetative biomass to be 190 to 680 g m^{-2} for *Typha latifolia* and 90 to 150 g m^{-2} for *Scirpus americanus* in wetland plots in South Carolina (Heliotis and DeWitt, 1983). Also, summarized estimates of peak standing stock nitrogen and phosphorus biomass values have been reported to be 5.35 g m^{-2} and 0.77 g m^{-2}, respectively for *Typha*, and 1.66 g m^{-2} and 0.23 g m^{-2}, respectively for *Scirpus* (Heliotis and DeWitt, 1983). The nutrient content, dynamics, and growth of a cattail crop (*Typha* spp.) have been measured and reported (Martín and Fernández, 1992). Also, nutrient tissue concentrations and subsequent decomposition rates have been measured for *Phragmites* and *Typha* species (Mason and Bryant, 1975). The nitrogen and phosphorus tissue concentrations in 41 wetland plants have been measured and reported, including a comparison across habitats and functional groups (McJannet et al., 1995). Nitrogen tissue percentages in terms of dry weight range from 0.6 to 2.2%, while phosphorus tissue percentages in terms of dry weight range from 0.18 to 0.5%. Koerselman and Meuleman (1996) have indicated the usefulness of assessing vegetation nitrogen-to-phosphorus ratios in detecting the nature of nutrient limitation in wetland ecosystems. In nutrient studies of cattail (*Typha*) crops, percentages of shoot to root biomass range from 35% (winter) to 85% (summer) (Martín and Fernández, 1992).

Plant nitrogen biomass of *Scirpus, Typha,* and *Juncus* wetland plant species ranged from 1.0 to 1.5% plant dry weight, while plant phosphorus biomass ranged from 0.2 to 0.4% plant dry weight (McJannet et al., 1995). Plant nitrogen biomass of *Typha* species ranged from 1.0% to 2.8% (shoots) and from 1.5% to 2.9% (roots and rhizomes) (Martín and Fernández, 1992). Fennessy et al. (1994b) have explored macrophyte productivity under differing hydrologic regimes, finding that productivity was higher under higher flow conditions, most likely due to increased nutrient availability. While providing the role of nutrient uptake, rooted macrophytes also provide oxygen to anaerobic parts of the water column and sediments via internal transport mechanisms (Kadlec and Knight, 1996).

Plankton often contribute to nitrification-denitrification, but in nutrient-enriched systems such as treatment facilities, algae is often a nuisance, contributing to high TSS and BOD (Reed et al., 1995). Duckweed provides a shading mechanism against algal blooms while contributing to nutrient removal (Reed et al., 1995). Cronk and Mitsch (1994a; 1994b) have demonstrated the effects of varying hydrologic regimes on periphyton productivity in artificial and natural surfaces in constructed wetlands. Periphyton growth was higher in high flow wetlands, and this relationship was attributed to higher nutrient availability. Robinson et al. (1997a) also found higher algal productivity under more flooded conditions. The researchers found that phytoplankton productivity increased with water depth, while other types of algae decreased in productivity (Robinson et al.,1997b). Also, they found that emergent macrophyte density decreased after flooding, leading to increased open water area (Robinson et al., 1997a). Wu and Mitsch (1998) have spatially and temporally characterized algal patterns in wetland systems, demonstrating that dense algal mats acted as nutrient filters, shaping the spatial distribution of nutrients that in turn affect the spatial pattern of algae by limiting the growth at locations further away from the inflow.

The microbial community that is responsible for the nitrification-denitrification reduction of nitrogen compounds and the decomposition of organic material in wetland

systems can be divided into two primary groups: 1) bacteria and 2) fungi. Bacteria are unicellular, procaryotic organisms that are classified by their morphology, chemical staining characteristics, nutrition, and metabolism (Kadlec and Knight, 1996). Table 2-2 summarizes the groups that are important to wastewater treatment and wetlands. Fungi are chemoheterotrophic organisms that obtain their energy and carbon requirements from organic material (Kadlec and Knight, 1996). Most fungi are saprophytic, that is, they degrade dead organic matter. Fungi are ecologically important in wetlands because they mediate a significant proportion of the recycling of carbon and other nutrients in wetland and aquatic environments. Aquatic fungi typically colonize niches on decaying vegetation made available following completion of bacterial use. Saprophytic fungal growth prepares dead organic matter for ingestion and further biodegradation by larger consumers (Kadlec and Knight, 1996). In short, fungi contribute greatly to the primary production of a wetland ecosystem.

Microbial growth, the uptake, assimilation, and transformation of nutrients, and the decomposition of organic substrates are often represented by chemical and bacterial kinetic models. Kinetic relationships may, in turn, be used to link biochemical pathways with ecological processes, depending on the availability of substrates, nutrients, and/or prey. Zero-order kinetics assume that the rate of change (e.g. growth, decomposition, etc.) is constant, as follows:

$$\frac{dS}{dt} = k \qquad (2\text{-}24)$$

where: S = the amount of substrate
k = rate constant
t = time

Table 2-2. Classification of Bacteria Important in Wetland Treatment Systems (Kadlec and Knight, 1996).

Group	*Representative Genera*	*Comments*
Phototrophic bacteria	*Rhodospirillum, Chlorobium*	Nonsymbiotic N fixers
Gliding bacteria	*Beggiatoa, Flexibacter, Thiothrix*	Filamentous bacteria found in activated sludge; *Beggiatoa* oxidizes hydrogen sulfide
Sheathed bacteria	*Sphaerotilus*	Filamentous bacteria implicated in reduced sludge settling rates in sewage treatment plants
Budding and/or appendaged bacteria	*Caulobacter, Hyphomicrobium*	Aquatic bacteria growing attached to surfaces
Gram-negative aerobic rods and cocci	*Pseudomonas, Zooglea, Azotobacter, Rhizobium*	*Pseudomonas* spp. denitrifies NO_2^- to N_2 under anaerobic conditions and can oxidize hydrogen gas; *Azotobacter* spp. is a nonsymbiotic N fixer; *Rhizobium* is a symbiotic N fixer
Gram-negative facultative anaerobic rods	*Escherichia, Salmonella, Shigella, Klebsiella, Enterobacter, Aeromonas*	*E. coli* is the predominant coliform in feces; *Salmonella* and *Shigella* are both human pathogens; *Klebsiella* and *Enterobacter* are nonsymbiotic N fixers and are in the total coliform group
Gram-negative anaerobic bacteria	*Desulfovibrio*	Reduces sulfate to hydrogen sulfide

Table 2-2 (cont'd). Classification of Bacteria Important in Wetland Treatment Systems (Kadlec and Knight, 1996).

Gram-negative chemolithotrophic bacteria	*Nitrosomonas, Nitrobacter, Thiobacillus*	*Nitrosomonas* catalyze the conversion of NH_4^+ to NO_2^-; *Nitrobacter* oxidize NO_2^- to NO_3^-; *T. ferrooxidans* oxidize ironsulfides producing Fe^{+3} and SO_4^{-2}
Methane-producing bacteria	*Methanobacterium*	Anaerobic bacteria of wetland sediments that convert carbonate to methane
Gram-positive cocci	*Streptococcus*	Fecal streptococci include human species (*S. faecalis* and *S. faecium*) and animal species (*S. bovis, S. equinus, S. avium*)
Endospore-forming rods and cocci	*Clostridium, Bacillus*	*C. botulinium* survives in soils and bottom sediments of wetlands and causes avian botulism; some *Clostridium* spp. are nonsymbiotic N fixers; *B. thuringiensis* is an insect pathogen; *B. licheniformis* denitrifies NO_2^- to N_2O
Actinomycetes and related organisms	*Nocardia, Frankia, Streptomyces*	Filamentous bacteria; *Nocardia* is implicated in sludge bulking in sewage treatment; *Frankia* is a symbiotic N fixer with alder trees

First-order kinetic models represent the growth or decomposition as being proportional to the amount of substrate available, as follows:

$$\frac{dS}{dt} = kS \qquad (2\text{-}25)$$

The two previous examples of kinetics are based on the assumption that growth or decomposition is independent of microbial biomass. Second-order kinetics are often used to estimate the decomposition of a substrate, where the rate of change in substrate over time (dS/dt) is proportional to the amount of substrate (S) and the amount of microbial biomass decomposing the substrate (B), as follows:

$$\frac{dS}{dt} = -kSB \qquad (2\text{-}26)$$

Under optimal conditions, zero-, first-, and second-order kinetics may be appropriate for substrate-biomass kinetics; however, conditions are rarely optimal in natural systems. Some kinetic models take into consideration certain limitations on nutrient availability. One example of growth kinetics with limitation is the Michaelis-Menten equation, which assumes that growth occurs as a non-linear function of the amount of substrate available, as follows:

$$\frac{dS}{dt} = \frac{\mu_{max}[S]}{K_m + [S]} \qquad (2\text{-}27)$$

where: μ_{max} = maximum rate of growth/decomposition
K_m = S concentration at which ½ μ_{max} occurs

Another example of non-linear growth kinetics occurs with respect to microbial biomass, and is similar to Michaelis-Menten kinetics. This kinetics model, known as the Monod equation, is as follows:

$$\frac{dB}{dt} = \mu B \qquad (2\text{-}28)$$

where: B = microbial biomass
μ = growth rate, or:

$$\mu = \frac{\mu_{max}[S]}{K_m + [S]} \qquad (2\text{-}29)$$

A third example of non-linear growth/decomposition kinetics is known as three-half order kinetics, because it can be used for first- or second-order kinetics (Brunner and Focht, 1984):

$$\frac{dS}{dt} = -k_1 - aBS \qquad (2\text{-}30)$$

where: k_1 = rate constant (given here for decomposition)
a = proportionality constant

Note that if B remains constant, the equation is pseudo-first-order, while if biomass (B) changes, then the expression is pseudo-second-order.

Wetland Models

In the early 1970s, computer models were emerging as useful tools in understanding the dynamics of nutrients in ecosystems. A computer model of nitrogen transformations in soils was developed (Mehran and Tanji, 1974), which accounted for processes including nitrogen mineralization, nitrification, and denitrification. Jørgenson et al. (1975) described a submodel for the exchange of phosphate at the anaerobic mud-water interface, by which simulated phosphorus released from sediment was determined by means of the change of phosphorus concentration in the water phase. Techniques for

developing ecological models that simulated the relationships between nutrients and population dynamics were emerging (Wiegert, 1979; Wiegert, 1993).

Many simulation models exist for natural wetland ecosystems. In the late 1970s and early 1980s, ecological simulation models were being published for cypress swamps (Mitsch et al., 1982; Dierberg and Brezonik, 1983; Ewel and Odum, 1984), water hyacinth marshes and Everglades swamps in Florida (Bayley and Odum, 1976; Mitsch et al., 1982), for the Okefenokee Swamp in south Georgia and north Florida (Auble et al., 1984; Patten, 1984); for bottomland hardwood forests in Arkansas and wetlands in Kentucky (Mitsch et al., 1982), for swamp bayou complexes in Louisiana (Hopkinson and Day, 1980; Mitsch et al., 1982), and for marsh-bog ecosystems in Michigan and Wisconsin (Dixon and Kadlec, 1975; Mitsch et al., 1982). These models have been used to assess environmental impact due to management of wetlands, to describe the patterns of energy and nutrient dynamics, to estimate hydrologic conditions and storage capacity, and to organize concepts, theories, and data collection in wetlands. In 1984, Rao et al. published a simulation of nitrogen dynamics in flooded soils, which considered interactions between water and sediment, including oxidized and reduced sediment layers. In 1985, a thorough review and evaluation of 87 mathematical wetlands models for accuracy, articulation, and effectiveness was published (Costanza and Sklar, 1985). Also in 1985, the spatial heterogeneity of wetland ecosystems was begun to be considered in modeling efforts. Sklar et al. (1985) developed a dynamic spatial simulation for modeling coastal wetland habitat succession. This modeling tool was composed of interacting cells which projected habitat changes as a function of marsh type, hydrology, subsidence, and sediment transport.

In the late 1980s, advances in computer technology led to better numerical processing capabilities, and the resulting improvements led to the development of more highly complex wetlands models. For example, models linking hydrology and nutrient behavior in natural wetlands were developed which included a nutrient model with nine

solid compartments and three water compartments (Kadlec and Hammer, 1988). Simulated nutrient variables included soil composition, soil water, and biotic factors, as well as surface water concentrations. Also in 1988, a model which links productivity to hydrology and nutrient cycling in natural forested wetlands was developed (Mitsch, 1988; Mitsch et al., 1988). The same year, a natural wetland simulation model was developed that predicts water quality and nutrient cycling when factors such as wetland type, inflow of water, and nutrient concentrations are provided (Brown, 1988). Also in 1988, a compartmental model was developed for modeling nutrient retention by a reed swamp and wet meadow in Denmark, which consisted of a nitrogen component (Figure 2-7), a phosphorus component (Figure 2-8), and a hydrologic component (Figure 2-9) (Jørgensen et al., 1988; Jørgensen, 1988a, 1988b) The forcing functions of this natural system model included: 1) precipitation; 2) nitrogen in rain water; 3) phosphorus in rain water; 4) inflows of water; 5) evapotranspiration; 6) temperature in each zone; 7) air temperature; 8) soil pH, and 9) plant biomass (Jørgensen et al., 1988). In 1991, a model was published which predicted the retention of phosphorus in a natural freshwater coastal wetland (Mitsch and Reeder, 1991). This simulation model estimated the roles of primary productivity, sedimentation, resuspension, and hydrology (Figures 2-10 and 2-11) using STELLA® modeling software package [High Performance System (HPS), 1989-1998]. A modification of this same simulation model was used at the ecosystem level in 1994 to predict phosphorus retention rates and compare them with results from empirical models and field studies of Lake Erie natural coastal wetlands (Mitsch et al., 1994b). Also in 1994, a general model for nitrogen removal in natural wetland systems was developed using STELLA® (Jørgensen, 1994). Dorge (1994) also developed a model based on the knowledge of nitrogen dynamics in freshwater ecosystems. This model, which was based on a hydrological submodel, also had a complex biological submodel consisting of eight state variables: nitrate and ammonia in surface water and the interstitial water, microbial, plant, adsorbed, and detrital organic nitrogen. In 1997, Martin and Reddy

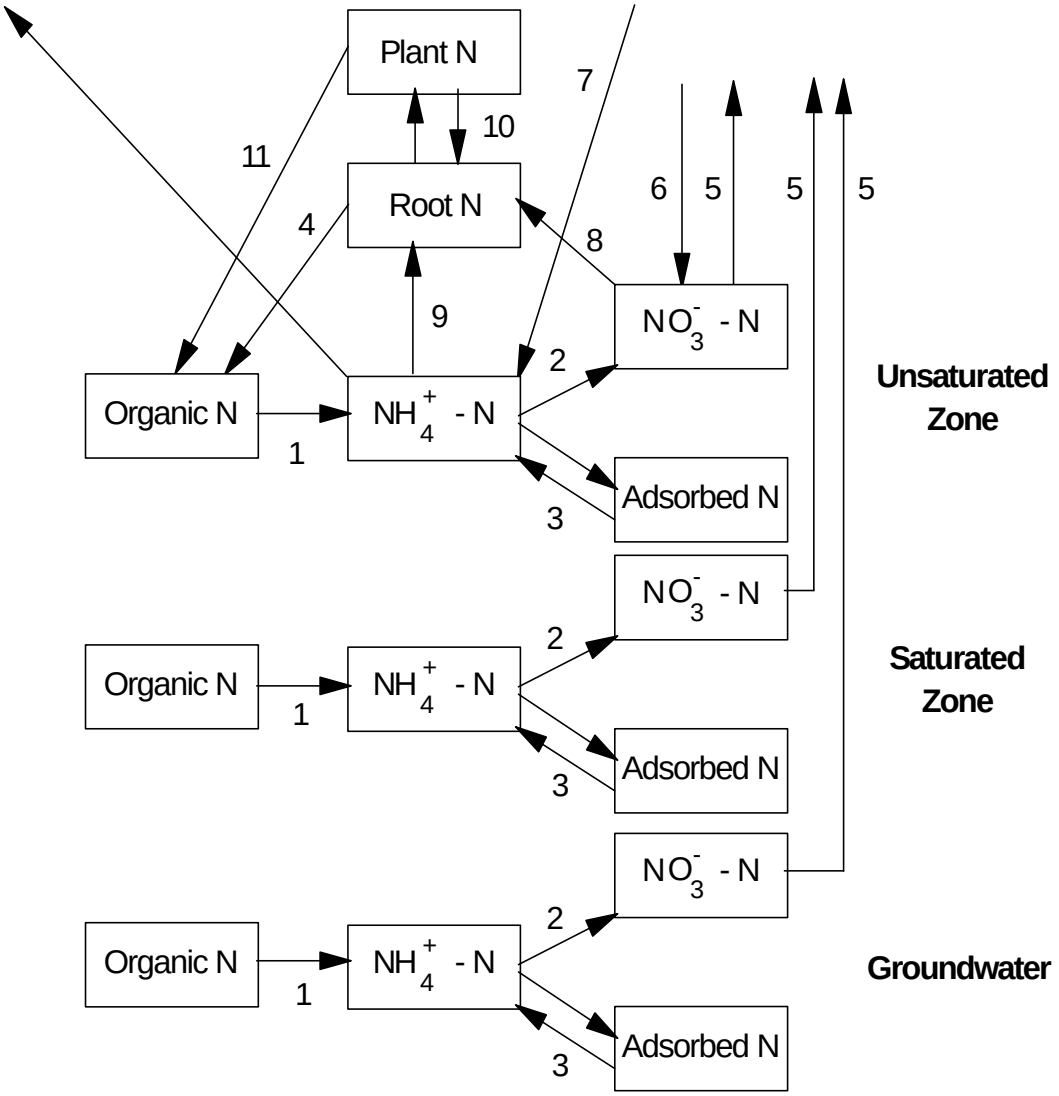


Figure 2-7. Nitrogen Submodel of Danish Wet Meadow. 1 = mineralization, 2 = nitrification, 3 = adsorption, 4 = volatilization, 5 = denitrification, 6 = deposition, 7 = nitrogen fixation, 8 = plant uptake of nitrate-N, 9 = plant uptake of ammonia-N, 10 = transport of N from roots to plant, and 11 = plant/root N to organic N by decomposition (Jørgensen, 1988b).

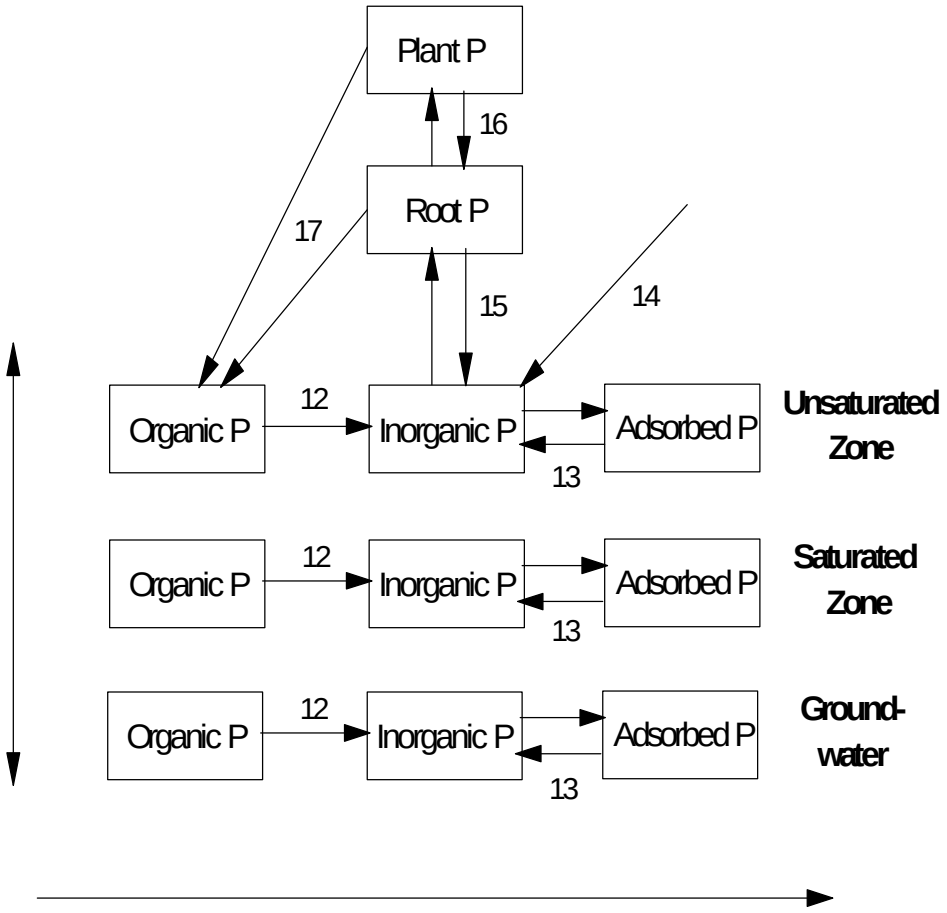


Figure 2-8. Phosphorus Submodel of Danish Wet Meadow. 12 = mineralization, 13 = adsorption, 14 = deposition, 15 = plant uptake of P, 16 = transport of P from roots to plant, 17 = plant/root P to organic P by decomposition (Jørgensen, 1988b).

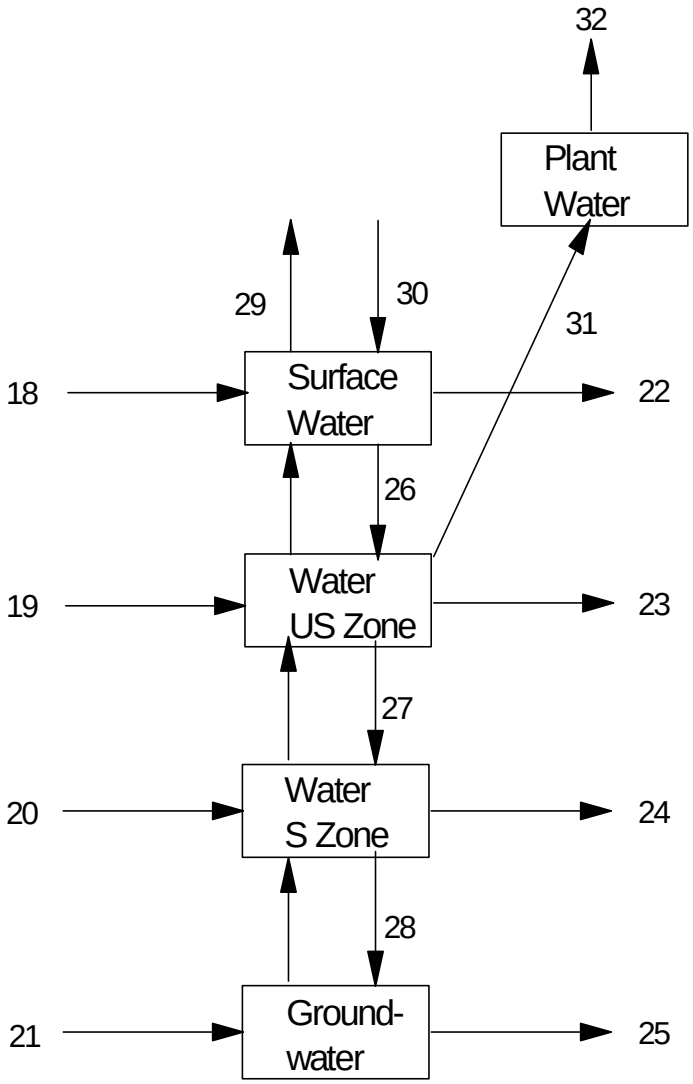


Figure 2-9. Hydrologic Submodel of Danish Wet Meadow. Flows 18-21 are horizontal inflows to parcel; 22-25 are outflows from parcel; 26-28 are exchanges of water between zones; 29 is precipitation; 30 is evaporation from surface; 31 is plant water uptake; 32 is transpiration through plants (Jørgensen, 1998b).

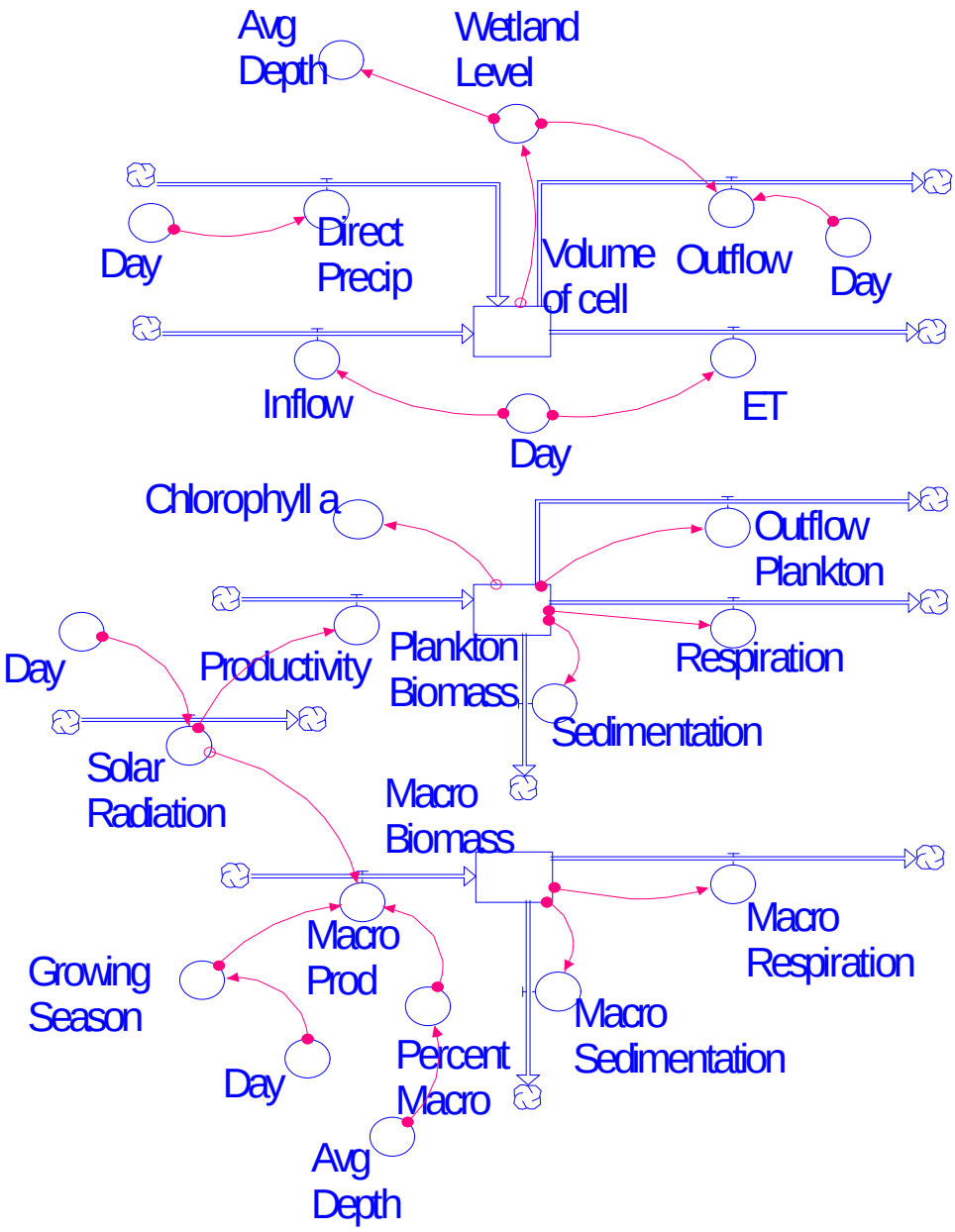


Figure 2-10. STELLA® Diagram for Productivity Submodule of Natural Wetland System Model (Mitsch and Reeder, 1991).

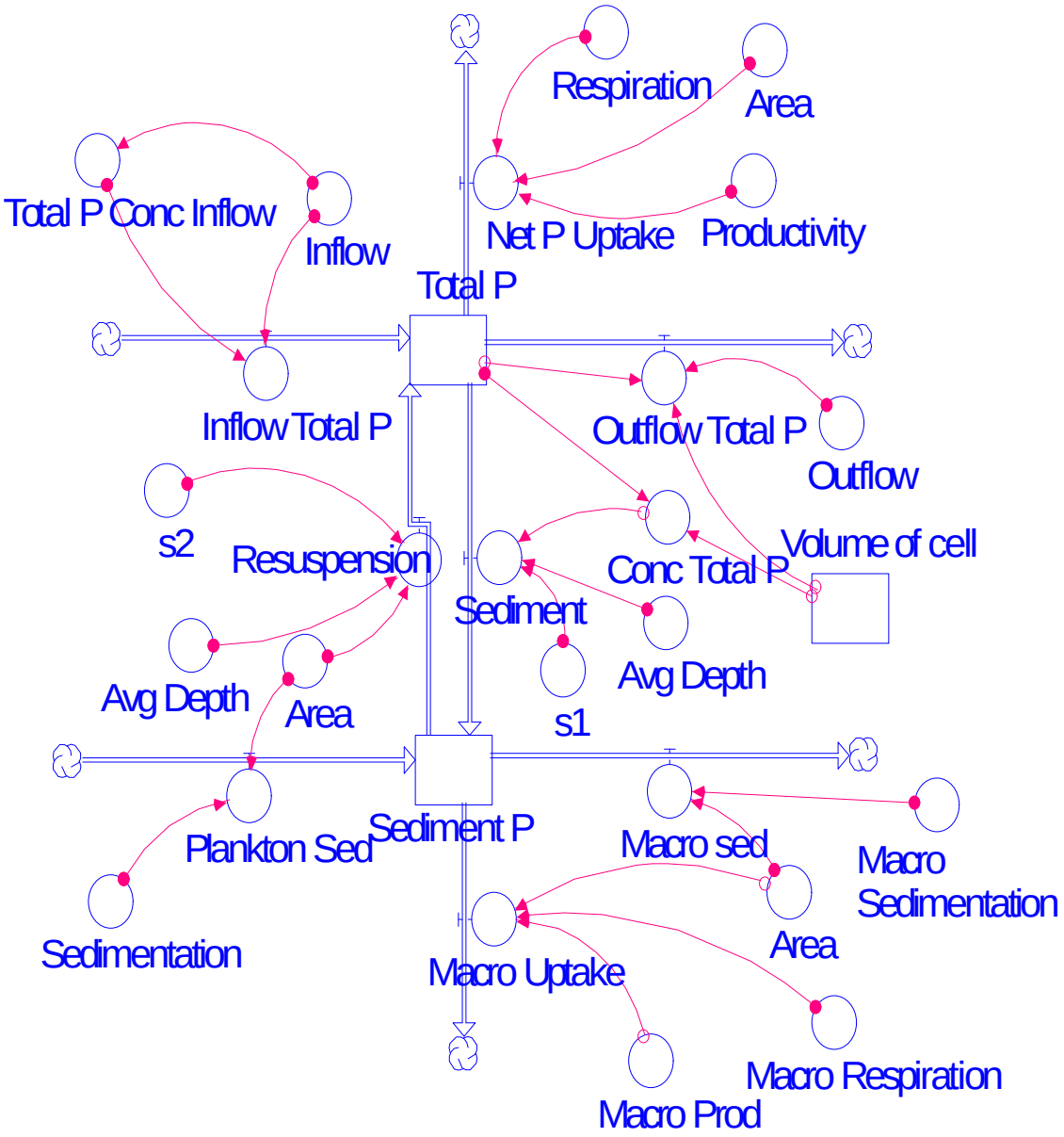


Figure 2-11. STELLA® Diagram for Phosphorus Submodule of Natural Wetland System Model (Mitsch and Reeder, 1991).

developed a model using STELLA® software that attempted to address the interaction and spatial distribution of wetland nitrogen processes. This spatially-explicit, two-dimensional model considered many nitrogen transformations, including enzyme hydrolysis, mineralization, nitrification, ammonium adsorption and desorption, ammonia volatilization, denitrification, and vegetative assimilation and decay (Martin and Reddy, 1997).

In 1993, the Riparian Ecosystem Management Model (REMM) was being developed to evaluate management alternatives in riparian areas for mitigating nonpoint source pollution, particularly nutrient loading (Sheridan et al., 1993; Altier et al., 1993; Lowrance et al., 1998). This model simulates physical, chemical, and biological functions of riparian buffers, which are often similar in function to constructed wetlands. The nutrient dynamics include the transport and transformation of carbon, nitrogen, and phosphorus within the buffer strip. Simulation of carbon dynamics is based largely on the Century Model (Parton et al., 1987). Carbon is continually transformed between residue and soil organic pools, where each pool has an associated mineralization rate, efficiency, and C:N and C:P ratios. Nitrogen and phosphorus transformations correspond with the C cycle, and all rates associated with nutrient dynamics are assumed to be first-order in REMM. The procedure for the simulation of photosynthesis in the plant growth part of REMM is based on the FOREST-BGC model (Running and Coughlan, 1988). Photosynthesis is calculated as a function of leaf area index (LAI), daylength, mesophyll conductance of CO_2, and stomatal conductance of H_2O. These conductances are limited by control functions based on effects of nutrient availability, light, temperature, humidity, and leaf water potential (Altier et al., 1993).

By 1995, models were beginning to be published for constructed wetland systems. Efforts in developing accurate and effective wetland hydrologic models were being published, based on the premise that establishing an appropriate hydrologic regime is the single most important factor in a successful constructed wetland project (Hammer, 1992;

Mitsch and Gosselink, 1993; Roberts, 1993). Konyha et al. (1995) expressed the importance and advantages of using continuous models in the interest of the hydrologic design of wetlands. Their modeling effort resulted in SWAMPMOD, which simulated detailed hydrologic processes through two components: freely drainable water and plant-available water. Also in 1995, a STELLA® simulation model was developed to estimate and predict phosphorus retention in constructed freshwater riparian marshes (Mitsch et al., 1995). This model was developed based on the widely used Vollenweider model for lake studies and the implementation of a Q_{10} factor. Vollenweider (1969) created a simple model of phosphorus retention in lakes with a model structure consisting of a single state variable representing total phosphorus concentration and pathways representing phosphorus loading, flushing, and sedimentation. The Q_{10} factor takes into consideration microbial processes by doubling biological activity with every 10 ^{o}C increase in water temperature (Howard-Williams, 1985).

In the past decade, constructed wetland models have incorporated the concept of "self-design", or self-organization (Mitsch and Jørgensen, 1989a and 1989b). Self-design is defined as the natural capability of an ecosystem to manipulate its physical and chemical environment by natural system shifts, substituting species, reorganizing food chains, adapting as individual species, and ultimately designing a system that is ideally suited to the environment that is superimposed upon it. In other words, when designing these wetland treatment systems, humans participate as the choice generator and as a facilitator of matching environments with ecosystems, but nature does the rest (Mitsch and Jørgensen, 1989a; Mitsch and Jørgensen, 1989b). Ecosystems and ecological processes are used, not replaced, in ecological engineering (Odum, 1983; Odum, 1989). A theoretical model was developed that simulated the self-design of the fish community in a newly created freshwater wetland (Metzker and Mitsch, 1997). Also, whole ecosystem experiments and simulations based on the self-design of created wetlands have been conducted (Mitsch et al., 1998).

In 1997, improvements in hydrologic models for wetlands continued. Feng and Molz (1997) developed a two-dimensional diffusion-based wetland flow model. This model, called WETFLOW, was based on implicit finite-difference approximations of the spatial flows defined by a fixed rectangular domain. A major assumption of this model was that irregular boundaries of the actual flow domain never extended outside of the overall rectangular flow domain. A similar modeling approach was taken by Restrepo et al. (1998), where a wetland simulation module for the MODFLOW groundwater model was developed. This model considered the vertical and horizontal flux components of the wetland-aquifer interaction, as well as surface flow, precipitation, and evapotranspiration. Each layer of the wetland-aquifer interaction was based on the the ratio of hydraulic conductivity along a column to hydraulic conductivity along a row. In 1999, Drexler et al. developed a water budget model for a peatland in New York. This water budget was linked to a nutrient loading model in order to assess impacts to wetlands for human activities such as agricultural nutrient loading, road building, water diversion, and surface/groundwater pollution (Drexler et al., 1999). Most recently, Werner and Kadlec have developed a stochastic simulation of partially-mixed, event-driven stormwater treatment wetlands. According to the study, simulated rain events and runoff produced a more realistic influent to a stormwater treatment wetland than did averaged inlet flow and concentration. Network flow models provided a more realistic prediction of the internal flows of a treatment wetland than did a plug flow or complete mixing estimation (Werner and Kadlec, 2000).

In 1998, phosphorus retention in the Everglades was predicted using nonparametric Bayesian regression (Qian and Reckhow, 1998). The primary use of this model was to support decision-making in sizing the proposed constructed wetlands in south Florida as well as keeping a practical management strategy. This design and management model, however, neglected consideration for the biological processes that occur with the wetland system. For example, the model does not consider design

decisions for optimizing system performance and maximizing wetland lifespan, such as: 1) plant species specifications, such as plant selection, amount, and placement, 2) operational decisions, such as operating depth for optimal plant growth and microbial activity, and 3) maintenance strategies, such as plant harvesting and sludge removal.

Kadlec (2000) recently published a paper describing the inadequacies of using a first-order approach to modeling wetland systems. Kadlec makes the argument that model parameters (rate constants) are typically regarded as true constants and do not depend on factors such as hydraulic loading rate and influent concentrations. Kadlec follows his argument by presenting a test wetland simulation that takes into consideration vegetation resistance, treatment effects of vegetation, and retention time distributions.

Wetland Design Guidance

Recently, the U. S. Environmental Protection Agency (2000) has provided a manual for municipal wastewater treatment wetlands. This document provides substantial general background information on treatment wetland systems, as well as guidance for the design, construction, operation, and maintenance of free water surface wetland systems. Performance expectations and design criteria for biochemical oxygen demand, nitrogen, and phosphorus removal were presented in the manual. In summary, this manual moves away from process-based design procedures and toward rule of thumb guidance.

Summary

The vast amount of literature presented in this review provides a solid knowledge foundation and support toward exploring the objectives expressed in the introduction. The numerous published studies on wetland nutrient dynamics have given necessary information and provided valuable reference for this study. Published models identifying, simulating and predicting the fate and transport of nutrients in wetlands, both natural and

constructed, provide fundamental background for the modeling efforts explored in this study.

References

Altier, L. S., R. R. Lowrance, R. G. Williams, J. M. Sheridan, D. D. Bosch, R. K. Hubbard, W. C. Mills, and D. L. Thomas. 1993. An Ecosystem Model for the Management of Riparian Areas, Riparian Ecosystems in the Humid U. S.: Functions, Values, and Management, March 15-18, Atlanta, GA.

American Public Health Association (APHA). 1980. Standard Methods for the Examination of Water and Wastewater, 15th ed. American Water Works Association and Water Pollution Control Federation, Washington, D. C.

Ansola, G., C. Fernández, and E. de Luis. 1995. Removal of organic matter and nutrients from urban wastewater by using an experimental emergent aquatic macrophyte system. *Ecological Engineering*, 5:13-19.

Auble, G. T., B. C. Patten, R. W. Bosserman, and D. B. Hamilton. 1984. A hierarchical model to organize integrated research on the Okefenokee Swamp. In: Cohen, A. D. et al. (Eds.), The Okefenokee Swamp: its natural history, geology, geochemistry. Duke University Press, Durham, NC.

Bayley, S, and H. T. Odum. 1976. Simulation of interrelations of the Everglades marsh, peat, fire, water, and phosphorus. *Ecol. Model.* 2:169-188.

Braskerud, B. C. 2000. Measurement and modelling of phosphorus retention in small constructed wetlands treating agricultural non-point source pollution. 7th International Conference on Wetland Systems for Water Pollution Control, Nov. 11-16, Lake Buena Vista, FL, pp. 75-86.

Brix, H. 1993. Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL, pp. 9-22.

Brown, M. T. 1988. A simulation model of hydrology and nutrient dynamics in wetlands. *Comput. Environ. Urban Syst.*, 12(4):221-237.

Brunner, W, and D. D. Focht. 1984. Deterministic Three-Half-Order Kinetic Model for Microbial Degradation of Added Carbon Substrates in Soil. *Applied and Environmental Microbiology*, 47(1):167-172.

Canale, R. P. 1976. Modeling Biochemical Processes in Aquatic Ecosystems. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Chanton, J. R., G. J. Whiting, J. D. Happell, G. Gerard. 1993. Contrasting rates and diurnal patterns of methane emission from emergent aquatic macrophytes. *Aq. Bot*. 46:111-128.

Christensen, N., W. J. Mitsch, and S. E. Jørgensen. 1994. A first generation ecosystem model of the Des Plaines River experimental wetlands. *Ecological Engineering*, 3: 495-521.

Cooke, J. G. 1992. Phosphorus removal processes in a wetland after a decade of receiving a sewage effluent. *J. Environ. Qual*. 21:733-739.

Costanza, R., and F. H. Sklar. 1985. Articulation, accuracy, and effectiveness of mathematical models: a review of freshwater wetland applications. *Ecol. Model.* 27:45-68.

Cronk, J. K., and W. J. Mitsch. 1994a. Aquatic metabolism in four newly constructed freshwater wetlands with different hydrologic inputs. *Ecological Engineering*, 3: 449-468.

Cronk, J. K., and W. J. Mitsch. 1994b. Periphyton productivity on artificial and natural surfaces in constructed freshwater wetlands under different hydrologic regimes. *Aq. Bot.* 48:325-341.

DeLaune, R. D., R. R. Boar, C. W. Lindau, and B. A. Kleiss. 1996. Denitrification in bottomland hardwood wetland soils of the Cache River. *Wetlands* 16:309-320.

Dierberg, F. E., and P. L. Brezonik. 1983. Nitrogen and phosphorus mass balances in natural and sewage-enriched cypress domes. *J. Appl. Ecol.* 20:323-337.

Dixon, K. R., and J.A. Kadlec. 1975. A model for predicting the effects of sewage effluent on wetland ecosystems. Publication No. 3, Univ. of Michigan Wetlands Ecosystem Research Group, Ann Arbor, MI.

Dorge, J. 1994. Modeling nitrogen transformations in freshwater wetlands - estimating nitrogen-retention and removal in natural wetlands in relation to their hydrology and nutrient loadings. *Ecol. Model.* 75:409-420.

Drexler, J. Z., B. L. Bedford, A. T. DeGaetano, and D. I. Siegel. 1999. Quantification of the water budget and nutrient loading in a small peatland. *J. Am. Wat. Res. Assoc.* 35:753-769.

Emsley, J. 1980. The phosphorus cycle. In: Hutzinger, O., Ed., The Handbook of Environmental Chemistry, Vol. 1, Part A, The Natural Environment and the Biogeochemical Cycles, Springer-Verlag, Berlin, p. 161.

Ewel, K. C., and H. T. Odum (Eds.). 1984. Cypress Swamps. University Presses of Florida, Gainesville, FL.

Feng, K., and F. J. Molz. 1997. A 2-D, diffusion-based, wetland flow model. *J. Hydrol.* 196:230-250.

Fennessy, M. S., C. C. Brueske, and W. J. Mitsch. 1994a. Sediment deposition patterns in restored freshwater wetlands using sediment traps. *Ecological Engineering*, 3: 409-428.

Fennessy, M. S., J. K. Cronk, and W. J. Misch. 1994b. Macrophyte productivity and community development in created freshwater wetlands under experimental hydrological conditions. *Ecological Engineering*, 3: 469-484.

Georgia Department of Natural Resources (GA DNR). 1995. Guidelines for Constructed Wetlands for Municipal Wastewater Treatment Facilities. Environmental Protection Division, Water Protection Branch, Atlanta, GA.

Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY.

Hagiwara, H., and W. J. Mitsch. 1994. Ecosystem modeling of a multi-species integrated aquaculture pond in South China. *Ecological Modelling*, 72:41-73.

Hammer, D. A. (Ed.). 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Inc., Boca Raton, FL.

Hammer, D. A. 1992. Creating Freshwater Wetlands. Lewis Publishers, Boca Raton, FL.

Heliotis, F. D., and C. B. DeWitt. 1983. A conceptual model of nutrient cycling in wetlands used for wastewater treatment: a literature analysis. *Wetlands*, 3:134-152.

High Performance Systems (HPS), Inc. 1989-1998. STELLA® Simulation Software.

Hopkinson, C. S., Jr., and J. W. Day, Jr. 1980. Modeling hydrology and eutrophication in a Louisiana swamp forest ecosystem. *Env. Management* 4:325-335.

Howard-Williams, C. 1985. Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective. *Freshwater Biol.,* 15:391-431.

Howard-Williams, C., and M. T. Downes. 1993. Nitrogen Cycling in Wetlands. In: Burt, T. P., A. L. Heathwaite, and S. T. Trudgill (Eds.), Nitrate: Processes, Patterns, and Management, John Wiley and Sons, New York, NY.

Johnston, C. A. 1993. Mechanisms of Wetland-Water Quality Interaction. In: Moshiri, G. A. (Ed.), Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 293-299.

Jones, J. G. 1979. Microbial nitrate reduction in freshwater sediments. *J. Gen. Microbiol.* 115:27-35.

Jørgenson, S. E. 1988a. Modelling Eutrophication of Shallow Lakes. In: Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.), Wetland Modelling, Elsevier Publishers, Amsterdam, pp. 177-188.

Jørgenson, S. E. 1988b. Modelling of Wetlands. In: Marani, A. (Ed.), Advances in Environmental Modelling, Elsevier Publishers, Amsterdam, pp. 535-544.

Jørgenson, S. E. 1994. A general model of nitrogen removal by wetlands. In: Mitsch, W. J. (Ed.). Global Wetlands: Old World and New, Elsevier Publishers, New York, NY, pp. 575-583.

Jørgenson, S. E., L. Kamp-Nielson, and O. S. Jacobsen. 1975. A submodel for anaerobic mud-water exchange of phosphate. *Ecol. Model*. 1:133-146.

Jørgenson, S. E., C. C. Hoffmann, W. J. Mitsch. 1988. Modelling Nutrient Retention by a Reedswamp and Wet Meadow in Denmark. In: Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.), Wetland Modelling, Elsevier Publishers, Amsterdam, pp. 133-151.

Kadlec, R. H. 2000. The inadequacy of first-order treatment wetlands models. *Ecol Eng*., 15:105-109.

Kadlec, R. H., and J. A. Kadlec. 1979. Wetlands and Water Quality. In: Grecian, P. E., J. R. Clark, and J. E. Clark (Eds.). 1979. Wetland Functions and Values: the State of Our Understanding. American Water Resources Association, Minneapolis, MN, pp. 436-456.

Kadlec, R. H., and D. E. Hammer. 1988. Modeling Nutrient Behavior in Wetlands. *Ecol. Modelling*, 40:37-66.

Kadlec, R. H., and R. L. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL.

Klopatek, J. M. 1978. Nutrient Dynamics of Freshwater Riverine Marshes and the Role of Emergent Macrophytes. In: Good, R. E., D. F. Whigham, and R. L. Simpson (eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential, Academic Press, New York, NY, pp. 195-216.

Koerselman, W., and A. F. M. Meuleman, 1996. The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. *J. Appl. Ecol.* 33:1441-1450.

Konyha, K. D., D. T. Shaw, and K. W. Weiler. 1995. Hydrologic design of a wetland: advantages of continuous modeling. *Ecological Engineering* 4:99-116.

Laczniak, R. J., DeMeo, G. A, Reiner, S. R., and LaRue-Smith, J., and W. E. Nylund. 1999. Estimates of Ground-Water Discharge as Determined From Measurements of Evapotranspiration, Ash Meadows Area, Nye County, Nevada Water-Resources Investigations Report 99-4079.

Lee, M. A., J. S. Stansbury, and T. C. Zhang. 1999. The effect of low temperatures on ammonia removal in a laboratory-scale constructed wetland. *Wat. Environ. Res.* 71:340-347.

Lowrance, R. R., L. S. Altier, R. G. Williams, S. P. Inamdar, D. D. Bosch, J. M. Sheridan, D. L. Thomas, and R. K. Hubbard. 1998. The riparian ecosystem management model: simulator for ecological processes in riparian zones. First Federal Interagency Hydrologic Modeling Conference, April 19-23, Las Vegas, NV.

Lusby, F. E., M. M. Gibbs, A. B. Cooper, and K. Thompson. 1998. Fate of groundwater ammonium in a lake edge wetland. *J. Environ. Qual.* 27:459-466.

Mason, C. F., and R. J. Bryant. 1975. Production, Nutrient Content and Decomposition of Phragmites communis Trin. And Typha angustfolia L. *Journal of Ecology*, 63: 71-95.

Martín, I., and J. Fernández, 1992. Nutrient dynamics and growth of a cattail crop (Typha latifolia L.) Developed in an effluent with high eutrophic potential-application to wastewater purification systems. *Biores. Technol.* 42:7-12.

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

McGill, W. B., H. W. Hunt, G. G. Woodmansee, and J. O. Reuss. 1979. PHOENIX, a model of the dynamics of carbon and nitrogen in grassland soils. In: Clark, F. E., and T. Rosswall (Eds.), Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies, and Management Impacts, *Ecol. Bull*. 33:49-115.

McJannet, P. A. Keddy, and F. R. Pick. 1995. Nitrogen and phosphorus tissue concentrations in 41 wetland plants: a comparison across habitats and functional groups. *Functional Ecol.* 9:231-238.

Mehran, M., and K. K. Tanji. 1974. Computer modeling of nitrogen transformations in soils. *J. Environ. Qual.* 3:391-396.

Metzker, K., and W. J. Mitsch. 1997. Modelling self-design of the aquatic community in a newly created freshwater wetland. *Ecol. Modelling,* 100: 61-68.

Mitsch, W. J. 1988. Productivity-Hydrology-Nutrient Models of Forested Wetlands. In: Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.), Wetland Modelling. Elsevier Publishers, Amsterdam, pp. 115-132.

Mitsch, W. J. (Ed.). 1994. Global Wetlands: Old World and New. Elsevier Publishers, New York, NY.

Mitsch, W. J., J. W. Day, Jr., J. R. Taylor, and C. Madden. 1982. Models of North American Freshwater Wetlands-A Review. In: Proceedings of the SCOPE/UNEP International Scientific Workshop on Ecosystem Dynamics in Freshwater Wetlands and Shallow Water Bodies 2, 5-32.

Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.). 1988. Wetland Modelling. Elsevier Publishers, Amsterdam.

Mitsch, W. J., and S. E. Jørgensen (Eds.). 1989a. Ecological Engineering: An Introduction to Ecotechnology. John Wiley and Sons, New York, NY.

Mitsch, W. J., and S. E. Jørgensen. 1989b. Introduction to Ecological Engineering. In: Mitsch, W. J., and S. E. Jørgensen (Eds.), Ecological Engineering: An Introduction to Ecotechnology, John Wiley and Sons, New York, NY, pp. 3-12.

Mitsch, W. J., and B. C. Reeder. 1991. Modelling nutrient retention of a freshwater coastal wetland: estimating the roles of primary productivity, sedimentation, resuspension and hydrology. *Ecol. Modelling*, 54: 151-187.

Mitsch, W. J., and J. G. Gosselink. 1993. Wetlands. Van Nostrand Reinhold, New York, NY.

Mitsch, W. J., R. H. Mitsch, and R. E. Turner. 1994a. Wetlands of the Old and New Worlds: ecology and management. In: Mitsch, W. J. (Ed.). Global Wetlands: Old World and New, Elsevier Publishers, New York, NY, pp. 3-56.

Mitsch, W. J., B. C. Reeder, and D. M. Robb. 1994b. Modelling ecosystem and landscape scales of Lake Erie coastal wetlands. In: Mitsch, W. J. (Ed.), Global Wetlands: Old World and New. Elsevier Publishers, New York, NY, pp. 563-574.

Mitsch, W.J., J. K. Cronk, X. Wu, R. W. Nairn, and D. L. Hey. 1995. Phosphorus retention in constructed freshwater riparian marshes. *Ecol. Applications* 5, 830-845.

Mitsch, W. J., X. Wu, R. W. Nairn, P. E. Weihe, N. Wang, R. Deal, and C. E. Boucher. 1998. Creating and Restoring Wetlands: A Whole-ecosystem Experiment in self-design. *BioScience* 48:1019-1030.

Morris, J. T., and W. B. Bowden. 1986. A mechanistic, numerical model of sedimentation, mineralization, and decomposition for marsh sediments. *Soil Sci. Soc. Am. J.* 50:96-105.

Moshiri, G. A. (Ed.). 1993. Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL.

Odum, H. T. 1983. Systems Ecology: An Introduction. John Wiley and Sons, New York, NY.

Odum, H. T. 1989. Ecological Engineering and Self-Organization. In: Mitsch, W. J., and S. E. Jørgensen, (Eds.), Ecological Engineering: An Introduction to Ecotechnology. John Wiley and Sons, New York, NY.

Parton, W. J., D. S. Schimel, C. V. Cole, and D. S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains Grasslands. *Soil Sci. Soc. Am. J.*, 51: 1173-1179.

Patten, B. C. 1984. Systems evaluation of Okefenokee Swamp. *Trans. N. Am. Wildl. Nat. Res.* 49: 281-296.

Pinney, M. L., P. K. Westerhoff, and L. Baker. 2000. Transformations in dissolved organic carbon through constructed wetlands. *Wat. Res.* 34:1897-1911.

Qian, S. S., and K. H. Reckhow. 1998. Modeling phosphorus trapping in wetlands using nonparametric Bayesian regression. *Water Resources Research*, 34(7): 1745-1754.

Rao, P. S. C., R. E. Jessup, and K. R. Reddy. 1984. Simulation of nitrogen dynamics in flooded soils. *Soil Sci.* 138:54-62.

Reddy, K. R., and D. A. Graetz. 1988. Carbon and Nitrogen Dynamics in Wetland Soils. In: Hook, D. D., et al., (Eds.), The Ecology and Management of Wetlands, Vol. 1: Ecology of Wetlands. Timber Press, Portland, OR., pp. 307-318.

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

Restrepo, J. I., A. M. Montoya, and J. Obeysekera. 1998. A wetland simulation module for the MODFLOW ground water model. *Groundwater* 36:764-770.

Roberts, L. 1993. Wetlands trading is a loser's game, say ecologists. *Science* 260:1890-1892.

Robinson, G. G. C., S. E. Gurney, and L. G. Goldsborough. 1997a. Response of benthic and planktonic algal biomass to experimental water-level manipulation in a prairie lakeshore wetland. *Wetlands* 17:167-181.

Robinson, G. G. C., S. E. Gurney, and L. G. Goldsborough. 1997b. The primary productivity of benthic and planktonic algae in prairie wetland under controlled water-level regimes. *Wetlands* 17:182-194.

Running, S. W. and J. C. Coughlan. 1988. A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecol. Modelling*, 42, 125-154.

Sheridan, J. M., R. G. Williams, L. S. Altier, R. R. Lowrance, W. C. Mills, D. L. Thomas. 1993. Hydrologic Modeling for Riparian Management. ASAE International Winter Meeting, December 14-17, Paper No. 932598.

Sklar, F. H., R. Costanza, and J. W. Day. 1985. Dynamic spatial simulation modeling of coastal wetland habitat succession. *Ecol. Model.* 29:261-281.

Tilton, D. L., R. H. Kadlec, and C. J. Richardson (Eds.). 1976. Freshwater Wetlands and Sewage Effluent Disposal. The University of Michigan Press, Ann Arbor, MI.

U. S. Environmental Protection Agency. 1983. Phase I Report: Freshwater Wetlands for Wastewater Management. Office of Water, Washington, D. C. EPA 904/9-83-107.

U. S. Environmental Protection Agency. 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling, 2nd. ed. Environmental Research Laboratory, Office of Research and Development, Athens, GA. EPA/600/3-85/040.

U. S. Environmental Protection Agency. 1987. Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal. Office of Water, Washington, D. C. EPA/430/09-88-055.

U. S. Environmental Protection Agency. 1988. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. Office of Water, Washington, D. C. EPA/625/1-88/022.

U. S. Environmental Protection Agency. 2000. Constructed Wetlands Treatment of Municipal Wastewaters. National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH. EPA/625/R-99/010.

Valiela, I., and J. M. Teal. 1978. Nutrient Dynamics: Summary and Recommendations. In: Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY, pp. 259-263.

Vargo, S. M., R. K. Neely, and S. M. Kirkwood. 1998. Emergent plant decomposition and sedimentation: response to sediments varying in texture, phosphorus content, and frequency of deposition. *Env. Exp. Botany* 40:43-58.

Vollenweider, R. A. 1969. A Manual on Methods for Measuring Primary Production in Aquatic Environments. Blackwell Scientific Publications, Oxford.

Vymazal, J. 1995. Algae and Element Cycling in Wetlands. Lewis Publishers, Boca Raton, FL.

Weisner, S. E. B., P. G. Erikkson, W. Granéli, and L. Leonardson. 1994. Influence of macrophytes on nitrate removal in wetlands. *Ambio* 23:363-366.

Werner, T. M., and R. H. Kadlec. 2000. Stochastic simulation of partially-mixed, event driven treatment wetlands. *Ecological Engineering* 14:253-267.

Westlake, D. F. 1963. Comparisons of plant productivity. *Biol. Rev.*, 38, 385-425.

Wetzel, R. G. 1993. Constructed Wetlands: Scientific Foundations are Critical. In: Moshiri, G. A., Ed., Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 3-7.

Wiegert, R. G., 1979. Chapter 8: Population Models: Experimental Tools for Analysis of Ecosystems. In: Analysis of Ecological Systems, D. J. Horn, G. R. Stairs, and R. D. Mitchell, Eds., Ohio State University Press, 233-274.

Wiegert, R. G., 1993. Chapter 9: Compartment Models. In: Biological Data Analysis: A Practical Handbook. J. R. Fry, Ed., Oxford University Press, 345-384.

Wilson, R. F., and W. J. Misch. 1996. Functional assessment of five wetlands constructed to mitigate wetland loss in Ohio, USA. *Wetlands,* 16:436-451.

Wu, X., and W. J. Mitsch. 1998. Spatial and temporal patterns of algae in newly constructed freshwater wetlands. *Wetlands*18(1), 9-20.

CHAPTER 3

SPATIOTEMPORAL CHARACTERIZATION OF A WASTEWATER TREATMENT WETLAND IN THE GEORGIA PIEDMONT [1]

[1]Hitchcock, D. R., and M. C. Smith. 2001. To be submitted to *Wetlands*.

Abstract

The spatial and temporal nature of ecological systems challenge the ability to adequately design engineered natural treatment systems such as wastewater wetlands. The spatial heterogeneity of vegetation, in terms of density as well as species, and sludge deposition often compromises the efficiency of the treatment. The objective of this study is to better understand the spatiotemporal variability within a constructed wastewater wetland system in order to optimize treatment wetland performance in the Georgia Piedmont. The focus of this study involves the determination and evaluation of trends and relationships between water quality parameters and nutrient, solids, and biochemical oxygen demand (BOD) concentrations. In this study, the system has been spatially characterized through water quality monitoring and analyses over two years. Results have shown relationships between temperature, dissolved oxygen concentrations, and redox potential that affect how nutrient concentrations vary over space as well as time. This is especially true for nitrogen compounds, as these parameters typically affect nitrification and denitrification. Also, phosphorus concentrations were closely correlated with solids concentrations, as expected. Water quality dynamics appeared to have little effect on solids and BOD removal percentages. This information may be useful for predicting treatment wetland performance and may be incorporated into future treatment wetland system design models. Understanding the complex processes within a constructed wetland system can aid in the development of operations and maintenance strategies that could improve the efficiency and increase the lifespan of such a system.

Introduction

Over the last 25 years, with advances in wetland treatment technology and the development of wetland design and monitoring regulations by the U. S. EPA and by state environmental protection agencies, the use of constructed wetlands (CW) for municipal wastewater treatment has become common practice (Kadlec and Kadlec, 1979; U. S.

EPA, 1987, 1988, 2000; Hammer, 1989; GA DNR, 1995; Kadlec and Knight, 1996). Pollutant removal mechanisms in constructed wetlands include filtration and sedimentation of solids, decomposition of organic matter, plant uptake of nutrients, microbial nitrification of ammonia and denitrification of nitrate, and the adsorption of phosphorus to sediments (Brix, 1993; Reed et al., 1995, Kadlec and Knight, 1996).

Complex biological processes, including plant-soil-microbial interactions, occur within wetland systems (Canale, 1976; Klopatek, 1978; Valiela and Teal, 1978; Heliotis and Dewitt, 1983; Howard-Williams, 1985; Reddy and Graetz, 1988; Vymazal, 1995; Kadlec and Knight, 1996), and these processes are responsible for the success of treatment wetland systems. The spatial variability of plants and sludge accumulation throughout a wetland cell adds to the system complexity (Good et al., 1978; Johnston, 1993; Reed et al., 1995; Kadlec and Knight, 1996). The relationship between system complexity and the ability of the system to remove nutrients, solids, and organic matter is poorly understood (Wetzel, 1993). Typically, organic material accumulates in some areas of the system, leading to short-circuiting, a decrease in theoretical retention time, and a loss in treatment performance. The focus of this study is to better understand the spatiotemporal variability of these complex processes for improving wetland system performance.

Constructed Wetland Site Description

The Tignall Water Reclamation Facility (Figure 3-1) is comprised of a duckweed (Lemna) system, a partial-mix aeration pond, and a polishing treatment wetland system (Tignall, GA; 33 º 52' 00" N, 82 º 44' 30" W; Pop. ~700). The facility handles the municipal wastewater from approximately 400 homes, several businesses, and two local factories (Davis, 2001), resulting in an average water use of approximately 45 gpcd (gallons per capita per day). Table 3-1 provides typical operating flows and

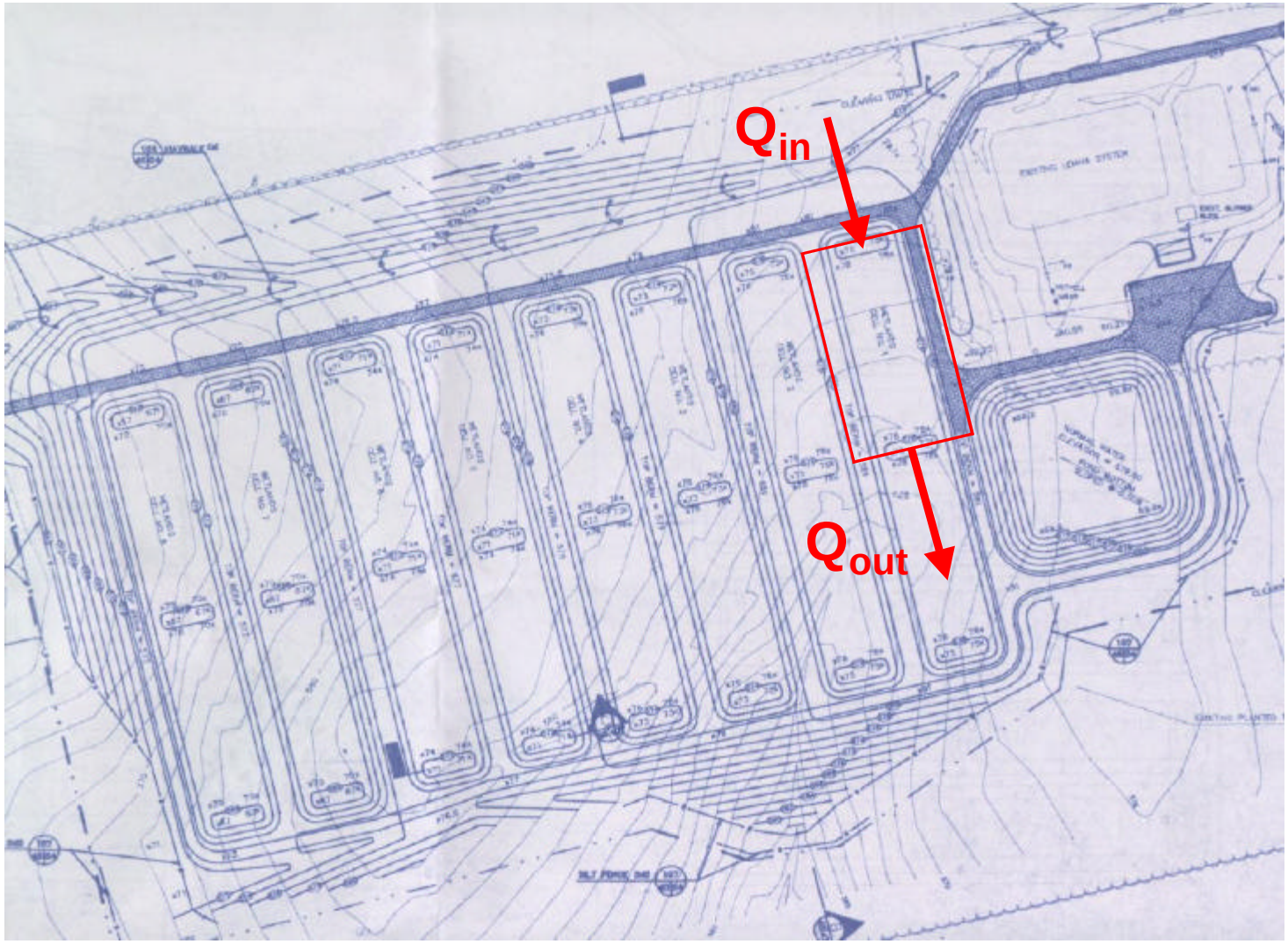


Figure 3-1. Layout of the Tignall Water Reclamation Facility (designed by Precision Planning Inc., Lawrenceville, GA). Diagram includes Lemna system (top right), partial mix aerated pond system (middle right), and constructed wetland system (center to left). The focal cell of this study is given by the designated area.

Table 3-1. Average, Minimum, and Maximum Operating Characteristics for Wetland System of the Tignall Wastewater Reclamation Facility During the Sampling Period from May, 1999 to April, 2001 (Davis, 2001).

Wastewater Characteristic	*Average*	*Minimum (month-year)*	*Maximum (month-year)*
Inflow (gal d^{-1})	31,800	3,700 (May-99)	69,700 (Dec-99)
Outflow (gal d^{-1})	20,620[a] / 9,860[b]	1,100[c] (Dec-99)	66,200 (Feb-00)
Influent BOD (mg L^{-1})	182.4	83 (Feb-00)	266 (Dec-99)
Effluent BOD (mg L^{-1})	7.8	1.7 (Feb-00)	20 (Jan-00 and Jan-01)
Influent TSS (mg L^{-1})	115.1	16 (Feb-00)	220 (Apr-00)
Effluent TSS (mg L^{-1})	4.9	2 (Dec-99, Jan-00, Feb-00 and Mar-00)	13 (Oct-00)
Influent NH_3 (mg L^{-1})	18.7	5.6 (Apr-01)	28 (Dec-00)
Effluent NH_3 (mg L^{-1})	1.6	<0.03 (May-00 and Apr-01)	5.9 (May-99)

[a] not including months without discharge
[b] including months without discharge
[c] does not consider months without discharge

concentrations associated with inflows and outflows from the system. Table 3-2 gives NPDES permitted limits for wastewater discharge from the Tignall wastewater reclamation facility. The system receives municipal wastewater from the city at an average flow rate of 31,800 gal d^{-1} (120 m^3 d^{-1}). The secondary effluent treatment wetland follows a duckweed system and a partial-mix aerated pond, which operate in parallel prior to reaching the wetland.

Table 3-2. NPDES Discharge Limits for Tignall Wastewater Reclamation Facility.

Water Quality Parameter	*Discharge Limit (mg L^{-1})*
BOD	10
TSS	20
NH_3	4

The constructed wetland system (Figure 3-1) was designed in 1992 and constructed in 1993 by Precision Planning of Lawrenceville, GA, and consists of 8 cells each approximately 122 x 18 m bottom surface area and 131 x 21 m top surface area. Each cell is approximately 1.2 m deep, while the operating wastewater depth is between 0.08 to 0.30 m. No liner was installed upon construction. The vegetated area of planted cells is approximately 50 x 18 m.

Initially, two of the total eight cells were planted post-construction with *Schoenoplectus californicus* (giant bullrush) and *Zizaniopsis miliacea* (giant cutgrass), while in 1995, two additional cells were planted with *Schoenoplectus californicus* (giant bullrush) and *Typha latifolia* (cattail), and wastewater flow through the system was limited to the four planted cells. The latter constitutes typical operational procedures at

the Tignall CW. In the summer months, however, rather than discharge, the operator will let wastewater flow through all eight cells and recirculate this wastewater through the wetlands until discharge is necessary.

Materials and Methods

Grab samples were taken every 4-6 weeks from May, 1999 to April, 2001 in the first half of the first wetland cell at the Tignall Water Reclamation Facility (Figure 3-1 in red) at twelve locations (Figure 3-2). These locations were selected based on the distribution of planted vegetation.. Note that, as designated in Figure 3-2, locations 2-1 to 2-3 are downstream of *S. californicus* plantings, locations 3-1 to 3-3 are downstream of *Z. miliacea* plantings, and locations 4-1 to 4-3 are downstream of a second stand of *S. californicus*. Samples were carefully collected in order not to disturb the sediment. Low water depths (less than 2 inches) often required taking several small samples and combining them into a larger container; therefore, vertical sampling within the wetland cell was not possible. These samples were analyzed for nutrient content, solids, and biochemical oxygen demand (BOD). Water quality measurements were taken at the location of each grab sample.

The following water quality parameters were measured at each location within the wetland cell: temperature (^{o}C) , conductivity (µS cm^{-1}), redox potential (ORP, mV), pH, turbidity (NTU), and dissolved oxygen concentration (mg L^{-1}). These parameters were measured using a YSI 6820 data sonde and a YSI 610-D meter. The sonde was calibrated for all parameters prior to each site visit.

Sample Collection and Preparation

Grab samples were immediately placed on ice for transport and storage. These samples were used for BOD and solids analyses (Clesceri et al., 1998). A second set of samples was collected for nutrient analyses at the same locations and preserved in 2 mL

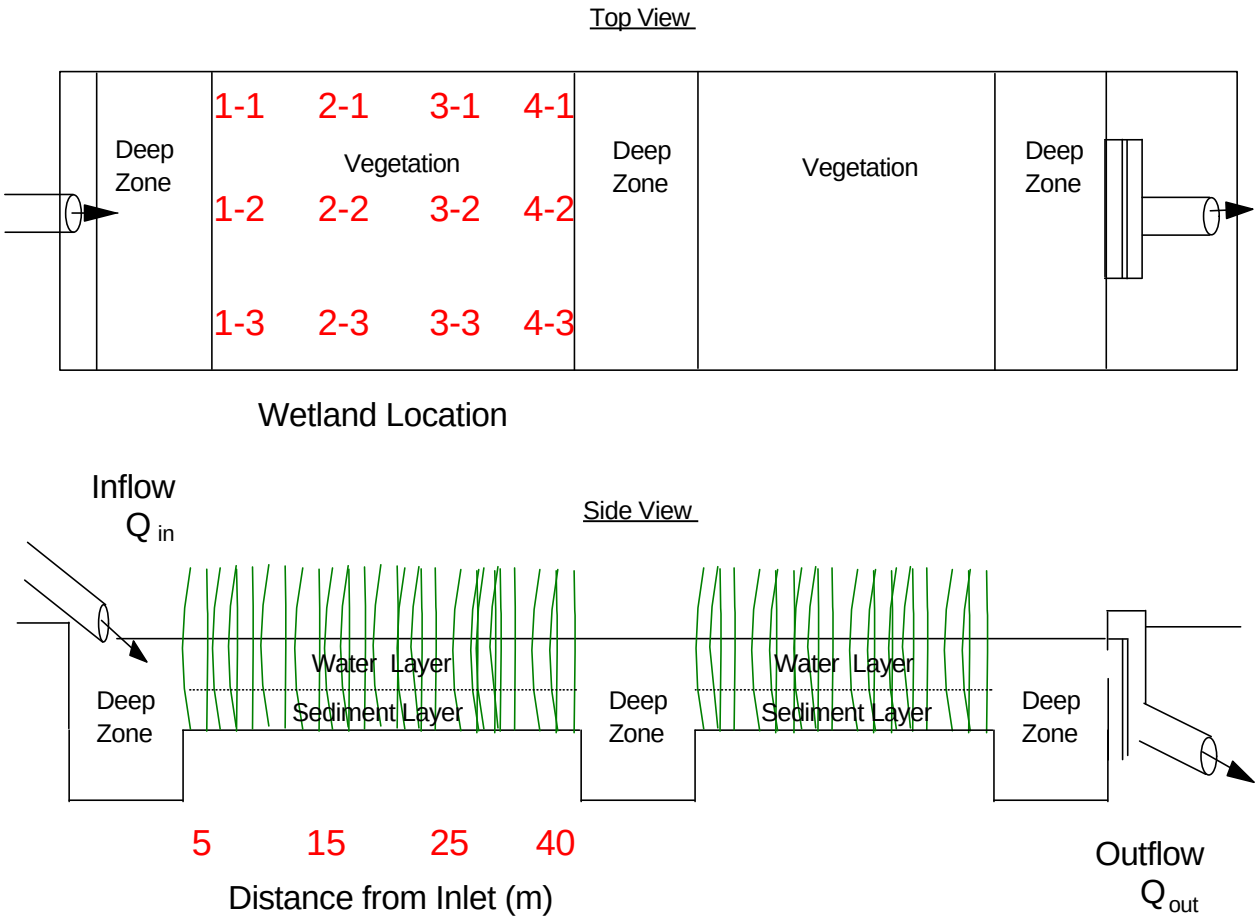


Figure 3-2. Physical Layout of Wetland Cell. Diagram of wetland cell showing locations and sections of monthly grab sample collection. (Not to scale, especially depths, which are exaggerated for the sake of explanation). Distance of cross-sections from inflow pipe are, respective to the flow gradient, 5 m, 15 m, 25 m, and 40 m. Planted vegetation includes *Schoenoplectus californicus* (giant bullrush) and *Zizaniopsis miliacea* (giant cutgrass). The numbers in red indicate point of grab sample collection.

concentrated H_2SO_4 per liter of wastewater sample. Samples were filtered using a 0.45 µm Whatman filter prior to nutrient analyses, and both filtered and non-filtered samples were analyzed for nutrient content for comparison.

Nutrient Analyses

Table 3-3 provides nutrient analyses method information and references. Ammonia-nitrogen (NH_3-N) , nitrate-nitrogen (NO_3-N) and orthophosphate (PO_4) concentrations were determined from acid-preserved samples using a TRAACS™ 2000 automated wet chemistry system with an XYZ model™ autosampler (Bran+Luebbe, Buffalo Grove, IL). For further nutrient concentration determination, water samples were digested in a $CuSO_4$ and sulfuric acid solution prior to Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (TP) analyses using TRAACS™. Quality assurance and quality control included correlation coefficient checks for known standards ($r^2 > 0.99$), dilution checks (% difference < 5%), and duplicate control cup checks throughout each run (% difference < 5%). If any of these controls were not met, the samples were run again.

Table 3-3. Nutrient Compounds Analyzed for Concentrations Using TRAACS 2000 ® (Bran and Luebbe, 1998).

Compound (in H_2O)	*Detection Limit (mg L^{-1})*	*Range (mg L^{-1})*	*TRAACS Method Reference*	*EPA Method Reference*
NH_3	0.0075 or 0.014*	0.014 - 2.000	US-780-86 C	EPA 350.2
NO_3-N	0	0 - 2	US-782-86 C	EPA 325.2
PO_4	0.014	0.014 - 5.000	US-781-86 D	EPA 325.2
TKN	0.04	0.04 - 2.00	US-786-86 B	EPA 351.3
TP	0.014 or 0.024*	0.014 - 5.000	US-787-86 B	EPA 365.4

* Detection limit using EPA method; otherwise, single value is actual limit

Solids and BOD Analyses

Analyses for total solids, volatile solids, and total suspended solids were performed using published standard methods (Clesceri et al., 1998). Non-volatile solids were calculated by subtracting volatile solids from total solids. Biochemical oxygen demand (BOD) analyses were also performed using published standard methods for water and wastewater analyses (Clesceri et al., 1998).

Results

Water Quality Parameters

Water quality parameters for the wetland cell by month and location are presented in Figures 3-3 through 3-5 for temperature, dissolved oxygen concentration, and redox potential (ORP), respectively. Conductivity and pH results are not presented because these values did not change significantly over the sampling period. Conductivity ranged from 500 to 600 $\mu S\ cm^{-1}$ throughout the sampling period for all locations with little exception. The pH during the sampling period ranged from 6.5 to 7.2 for all locations.

Nutrient, Solids, and BOD Analyses

Filtered and non-filtered wastewater samples were analyzed for nutrient content. There was no significant difference ($p > 0.5$) in nitrogen (ammonia, nitrate, and TKN) or phosphorus (orthophosphate and TP) constituents between filtered and non-filtered samples based on ANOVA.

Results from nutrient analyses of grab samples are given in Figures 3-6 to 3-20. Five graphs represent these data in several ways. For ammonia, for example, Figures 3-6 and 3-7(a) and (b) show medians, 25th to 75th, and 5th to 95th percentiles by date, location, and section, respectively. Figure 3-8(a) and (b) show ammonia removal by month in terms of concentration and percentage, respectively. Solids results are presented in a similar manner in Figures 3-21 to 3-32. BOD results are given in Figures 3-33-3-35.

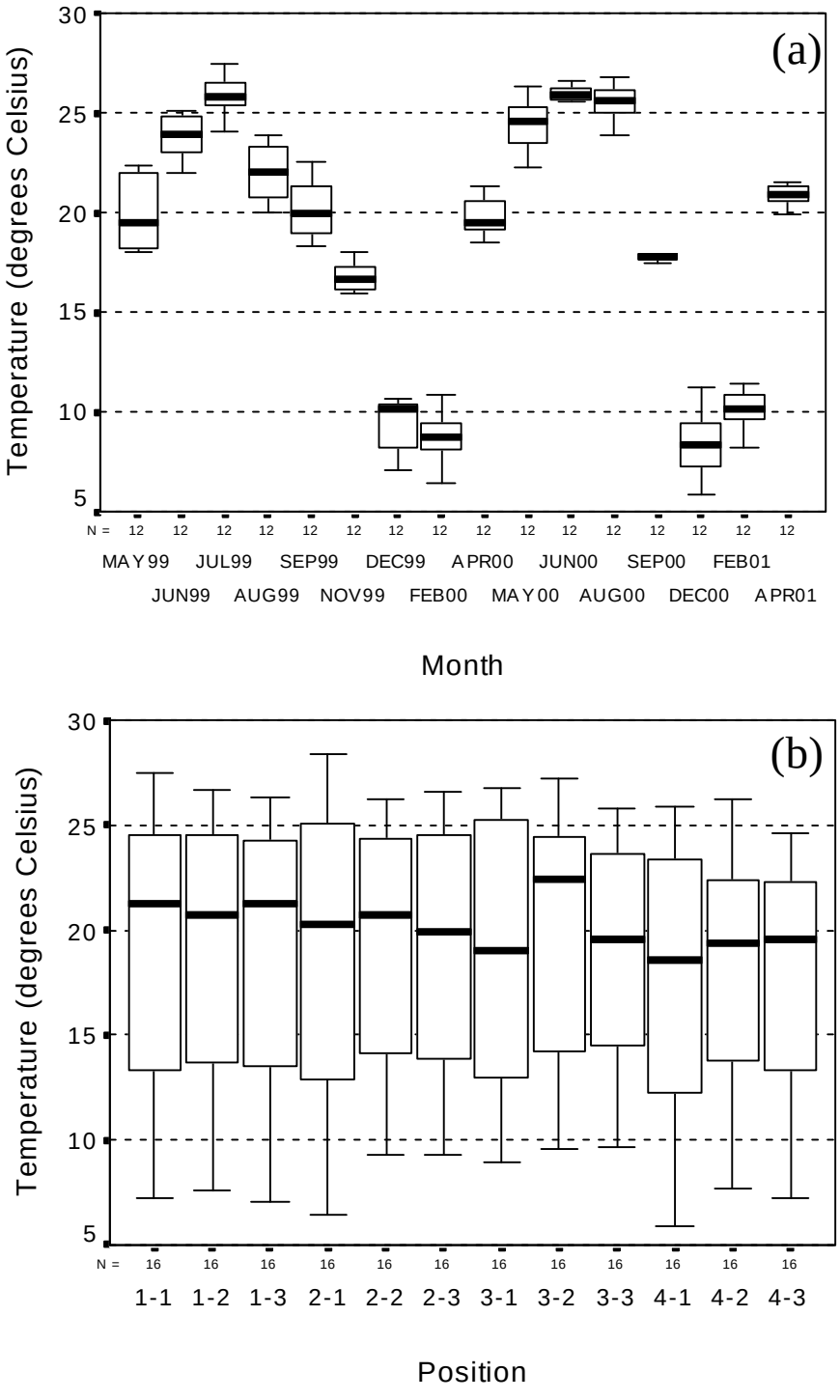


Figure 3-3. Temperature distributions (a) by month, showing seasonal patterns, and (b) by location, showing spatial variability. Medians, 25th/75th, and 5th/95th percentile results are presented.

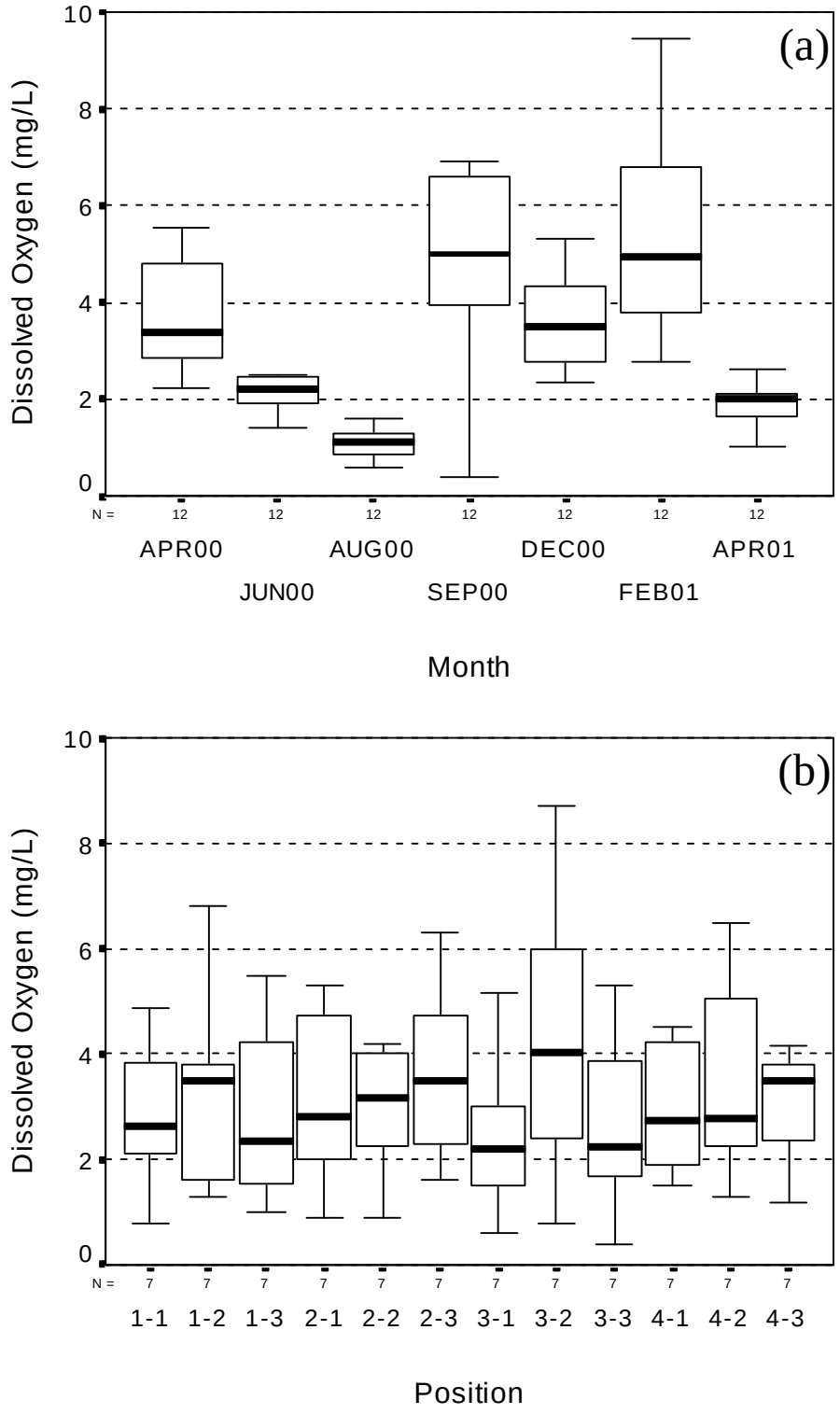


Figure 3-4. Dissolved oxygen concentration distributions (a) by month, showing seasonal patterns, and (b) by location, showing spatial variability. Medians, 25th/75th, and 5th/95th percentile results are presented

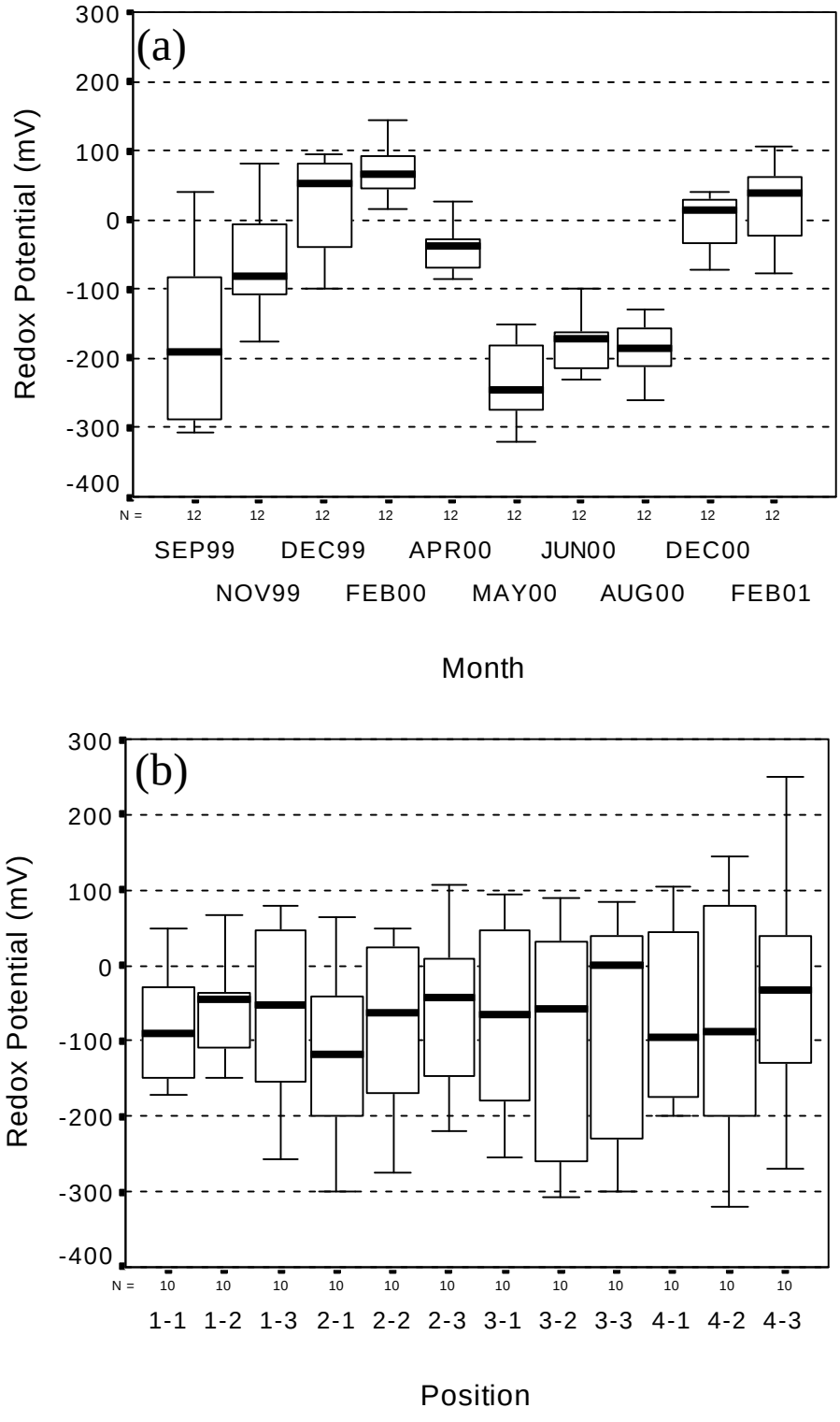


Figure 3-5. Redox potential distributions (a) by month, showing seasonal patterns, and (b) by location, showing spatial variability. Medians, 25th/75th, and 5th/95th percentile results are presented

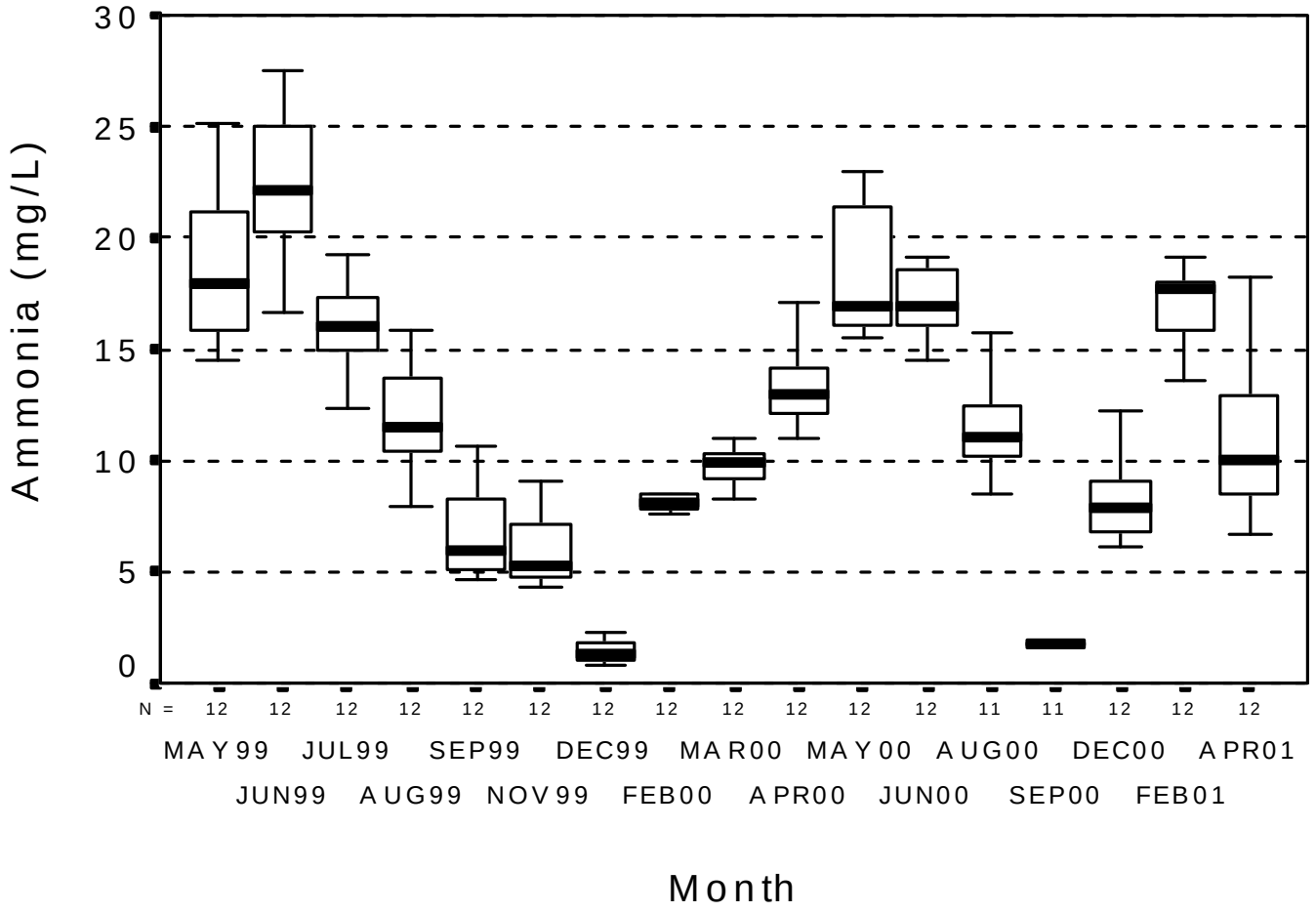


Figure 3-6. Boxplot showing ammonia concentrations over two-year period. Medians, 25th/75th, and 5th/95th percentile results are presented by month.

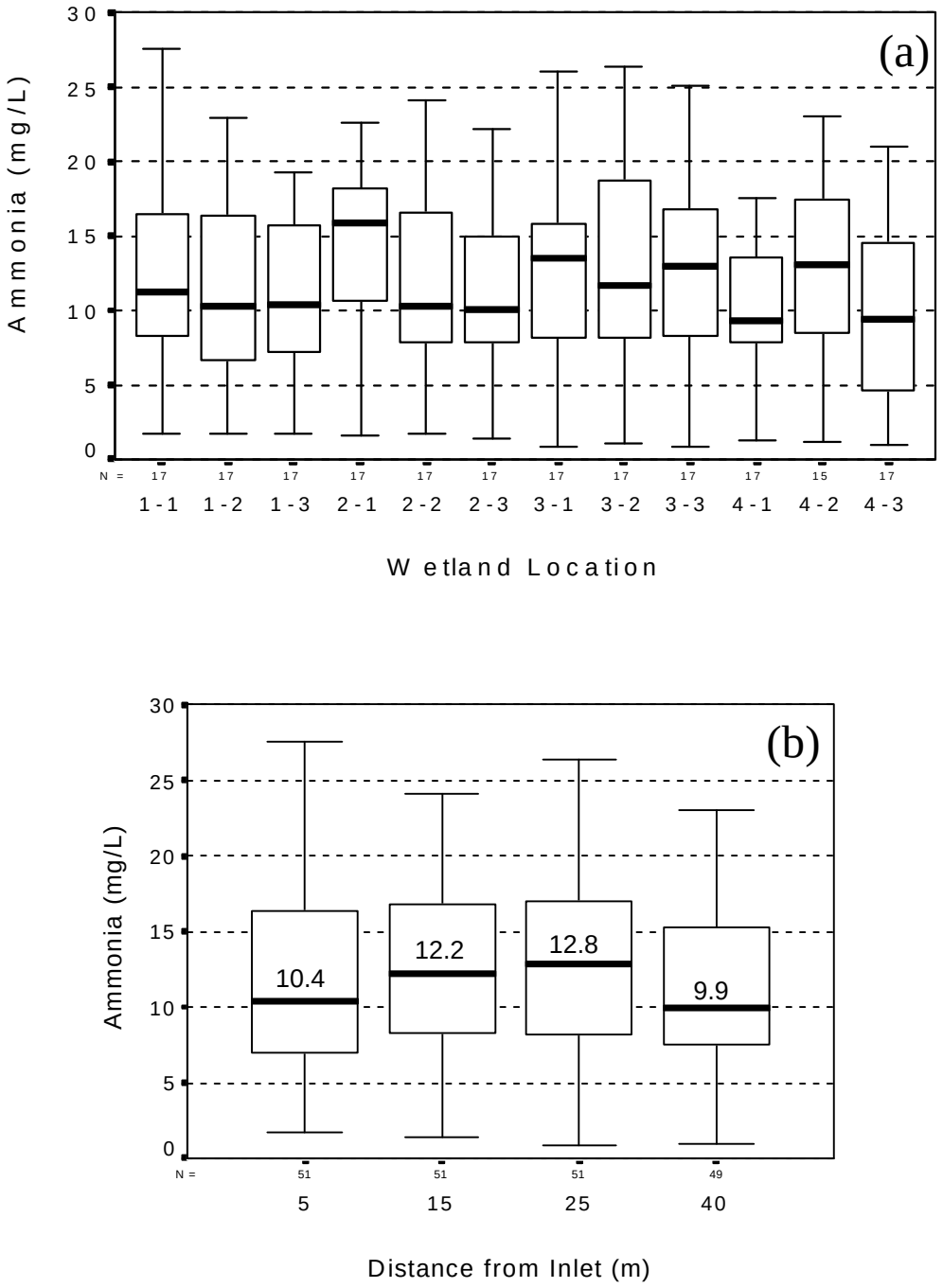


Figure 3-7. Boxplots showing spatial ammonia concentration distribution throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

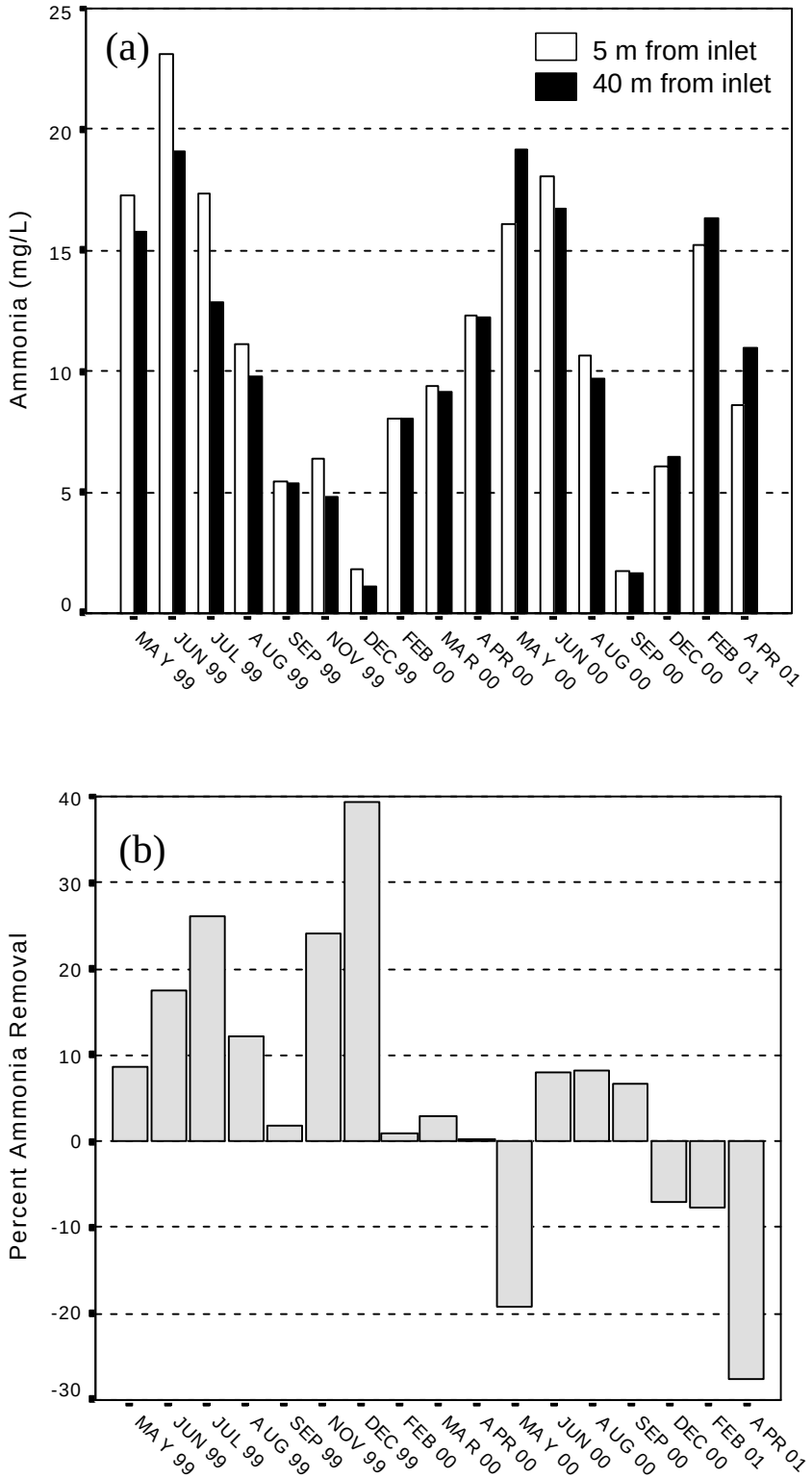


Figure 3-8. Ammonia removal from wetland cell by month shown as (a) ammonia reduction along flow gradient by distance from inlet and (b) percent ammonia reduction between 5 m and 40 m from inlet.

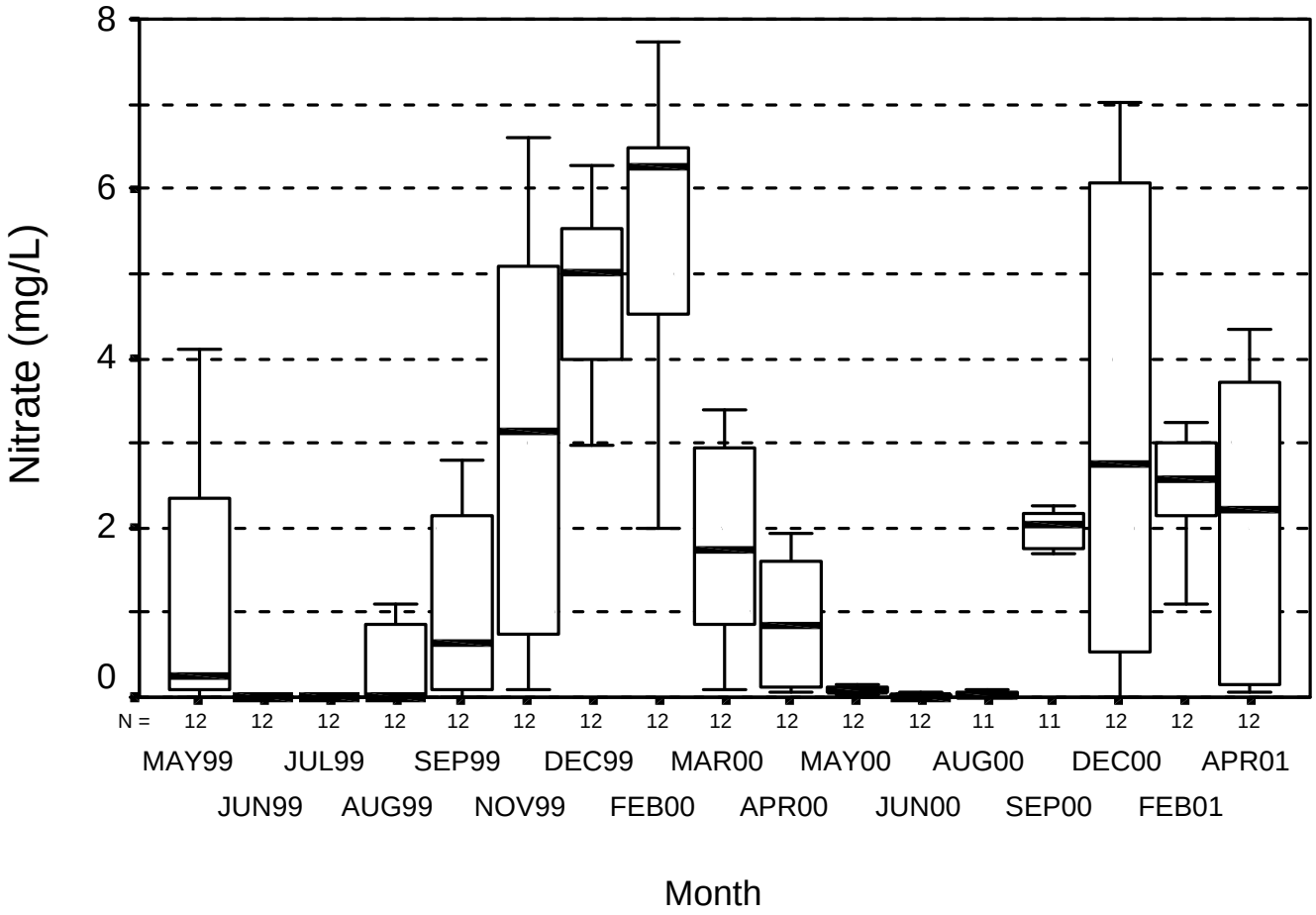


Figure 3-9. Boxplot showing nitrate concentrations over two-year period. Medians, 25th/75th, and 5th/95th percentile results are presented by month.

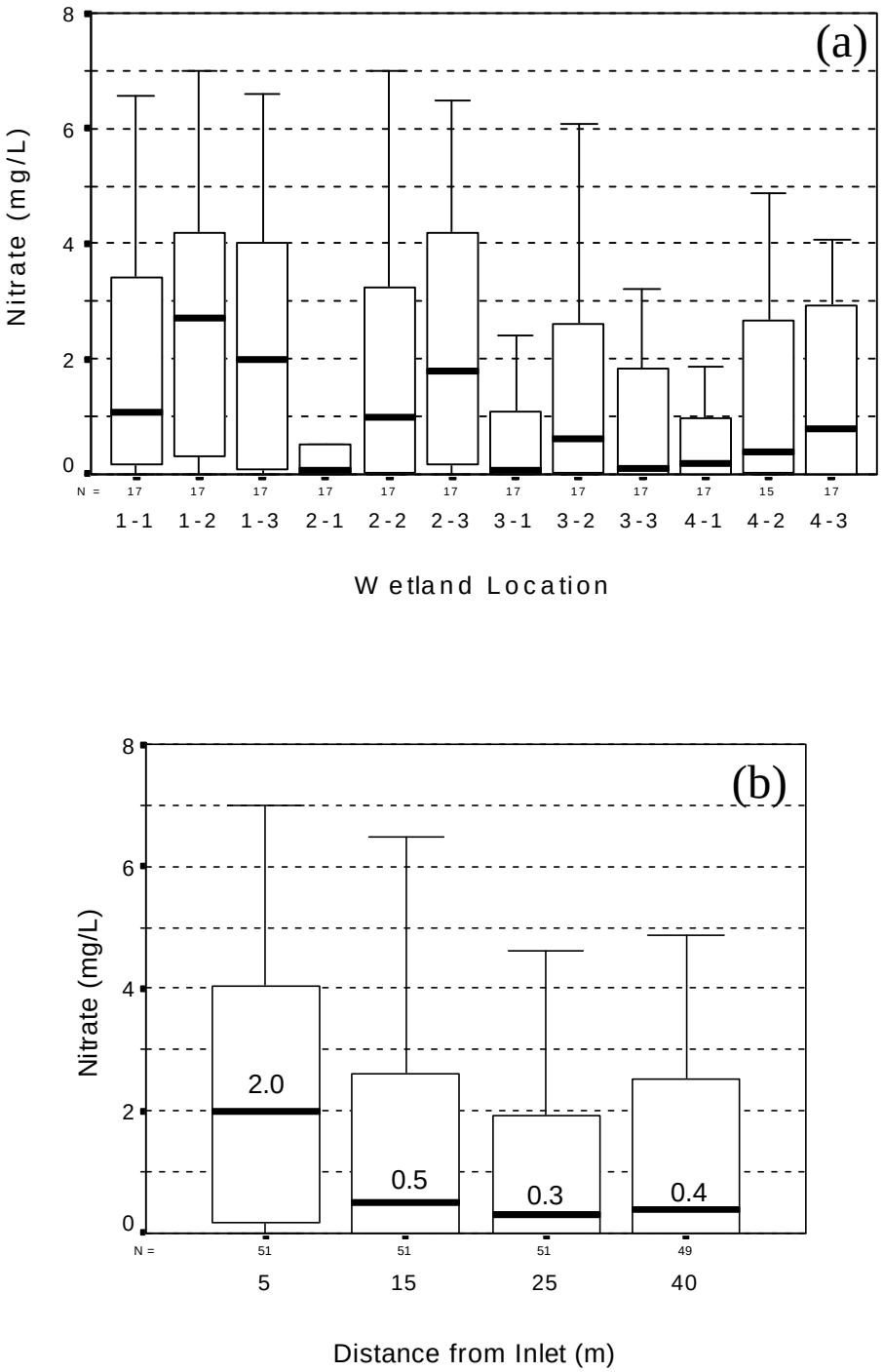


Figure 3-10. Boxplots showing spatial nitrate concentration distribution throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

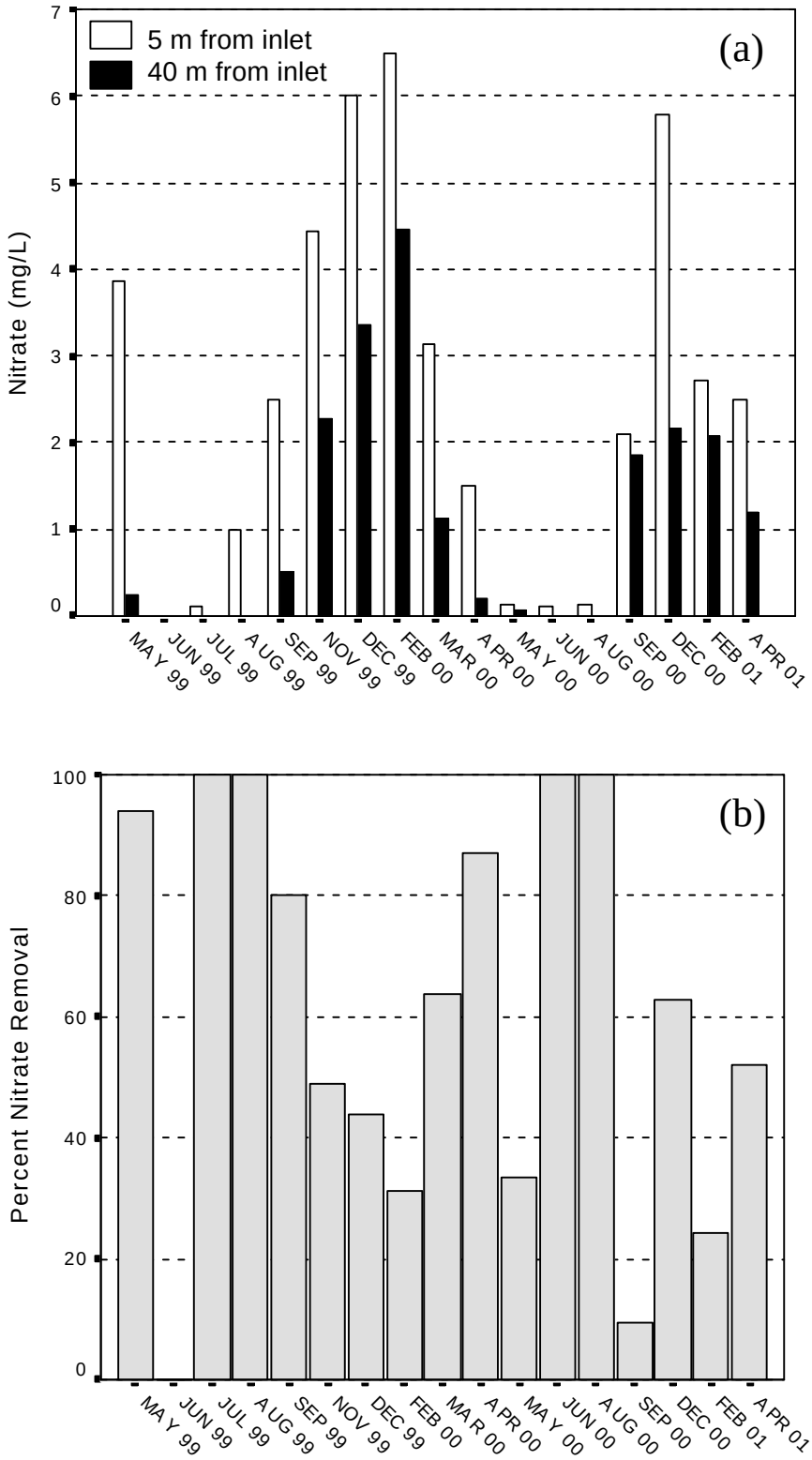


Figure 3-11. Nitrate removal from wetland cell by month shown as (a) nitrate reduction along flow gradient by distance from inlet and (b) percent nitrate reduction between 5 m and 40 m from inlet.

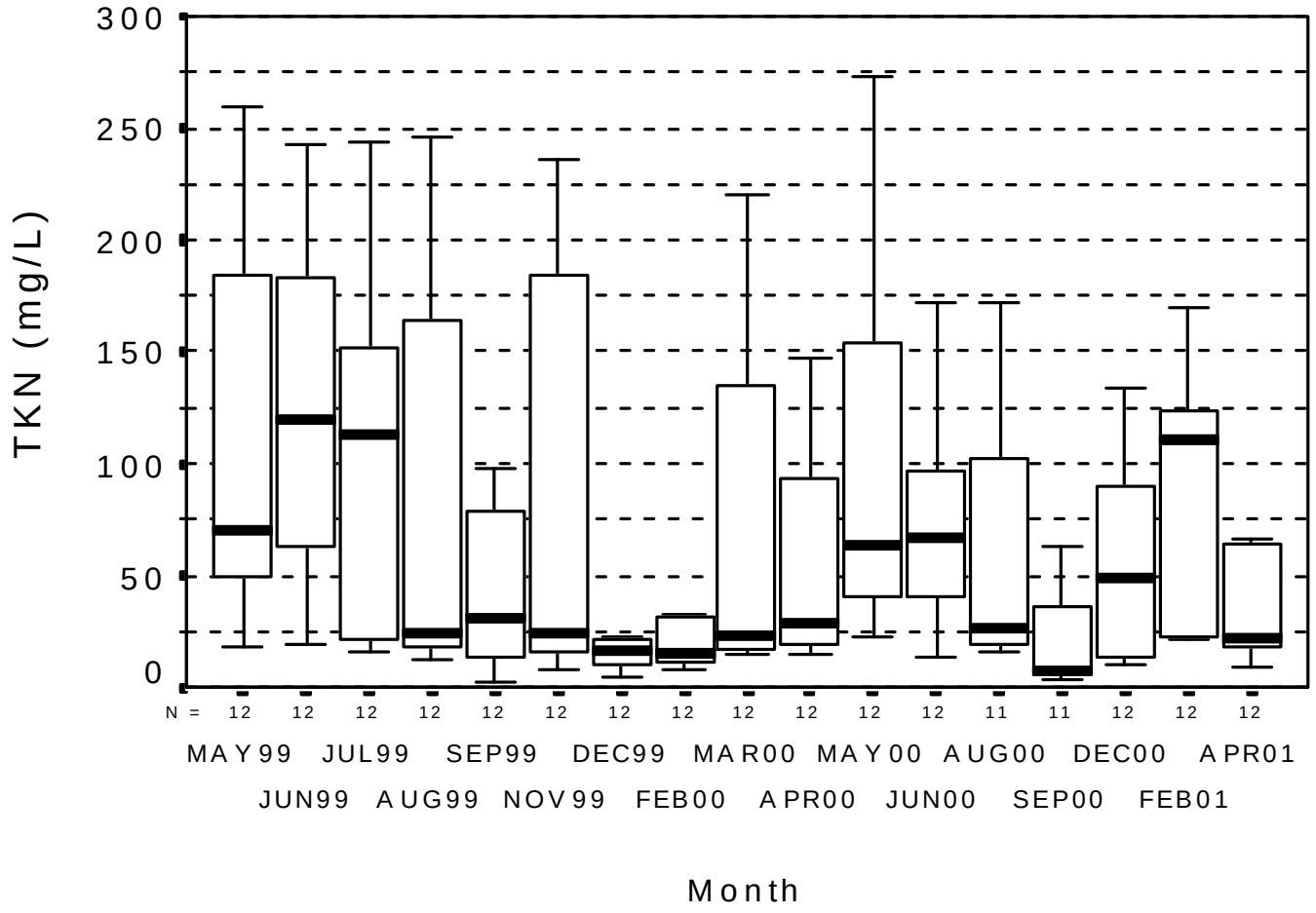


Figure 3-12. Boxplot showing Total Kjeldahl Nitrogen (TKN) concentrations over two-year period. Medians, 25th/75th, and 5th/95th percentile results are presented by month.

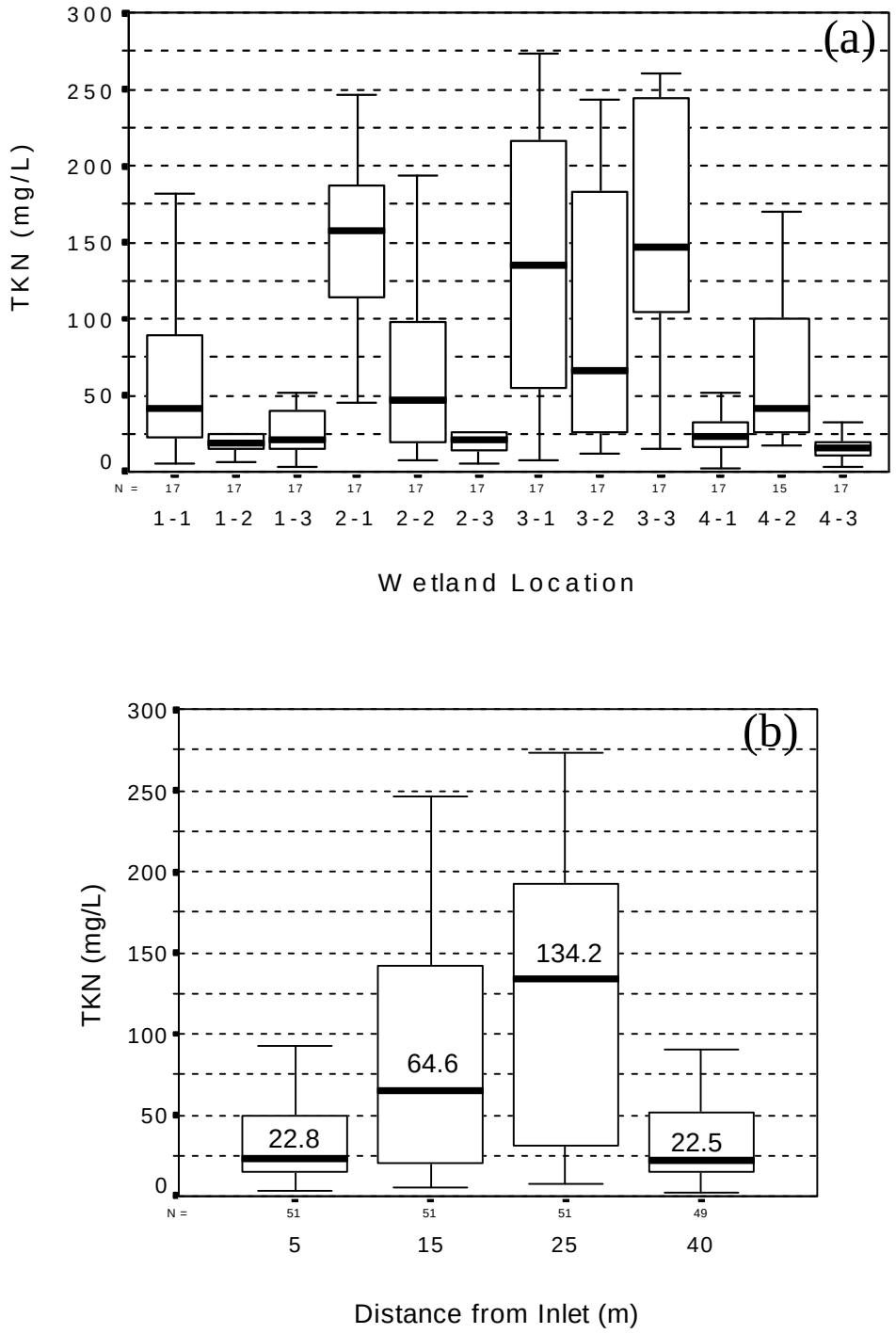


Figure 3-13. Boxplots showing spatial Total Kjeldahl Nitrogen (TKN) concentration distribution throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

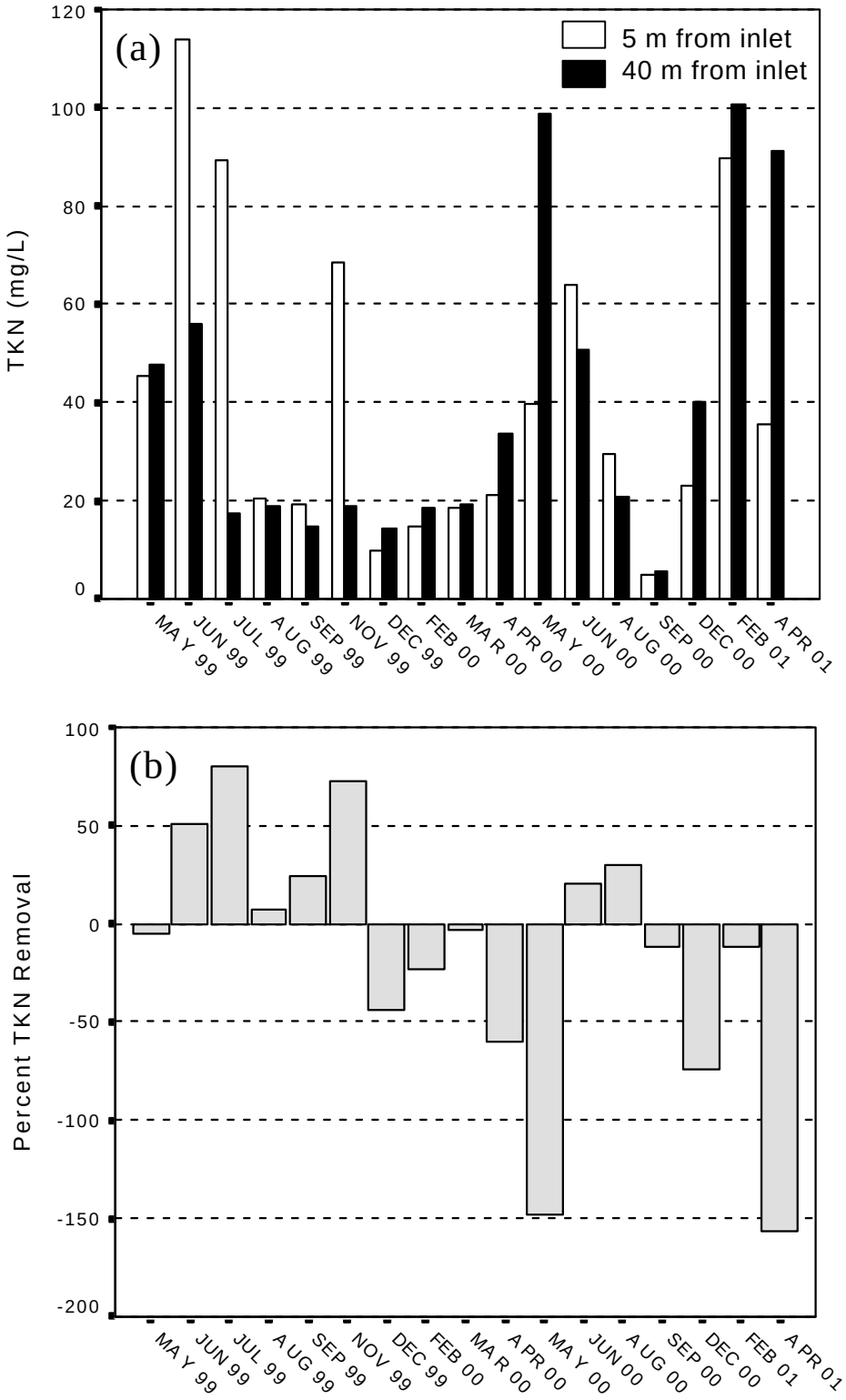


Figure 3-14. Total Kjeldahl Nitrogen (TKN) removal from wetland cell by month shown as (a) TKN reduction along flow gradient by distance from inlet and (b) percent TKN reduction between 5 m and 40 m from inlet.

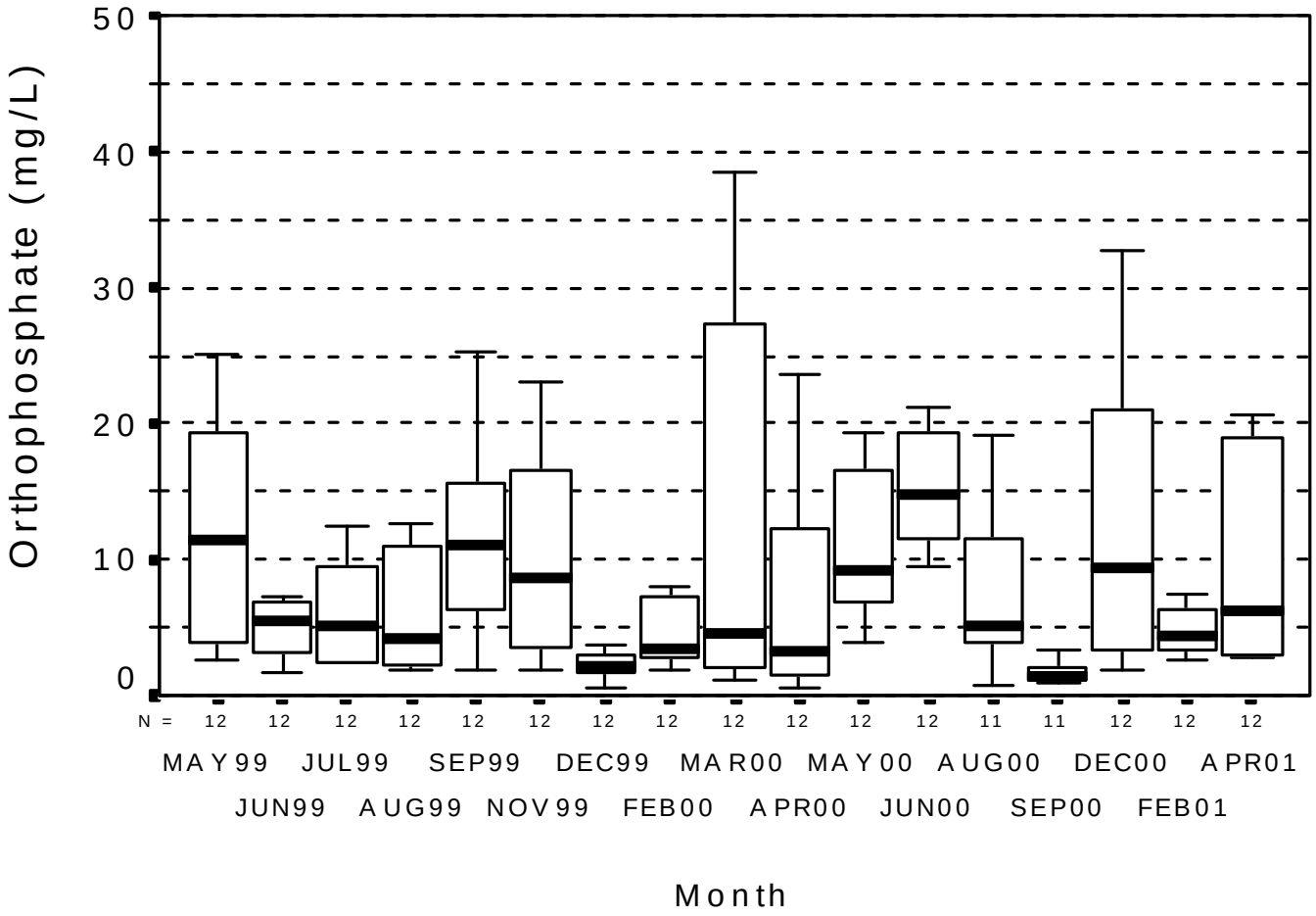


Figure 3-15. Boxplot showing orthophosphate concentrations over two-year period. Medians, 25th/75th, and 5th/95th percentile results are presented by month.

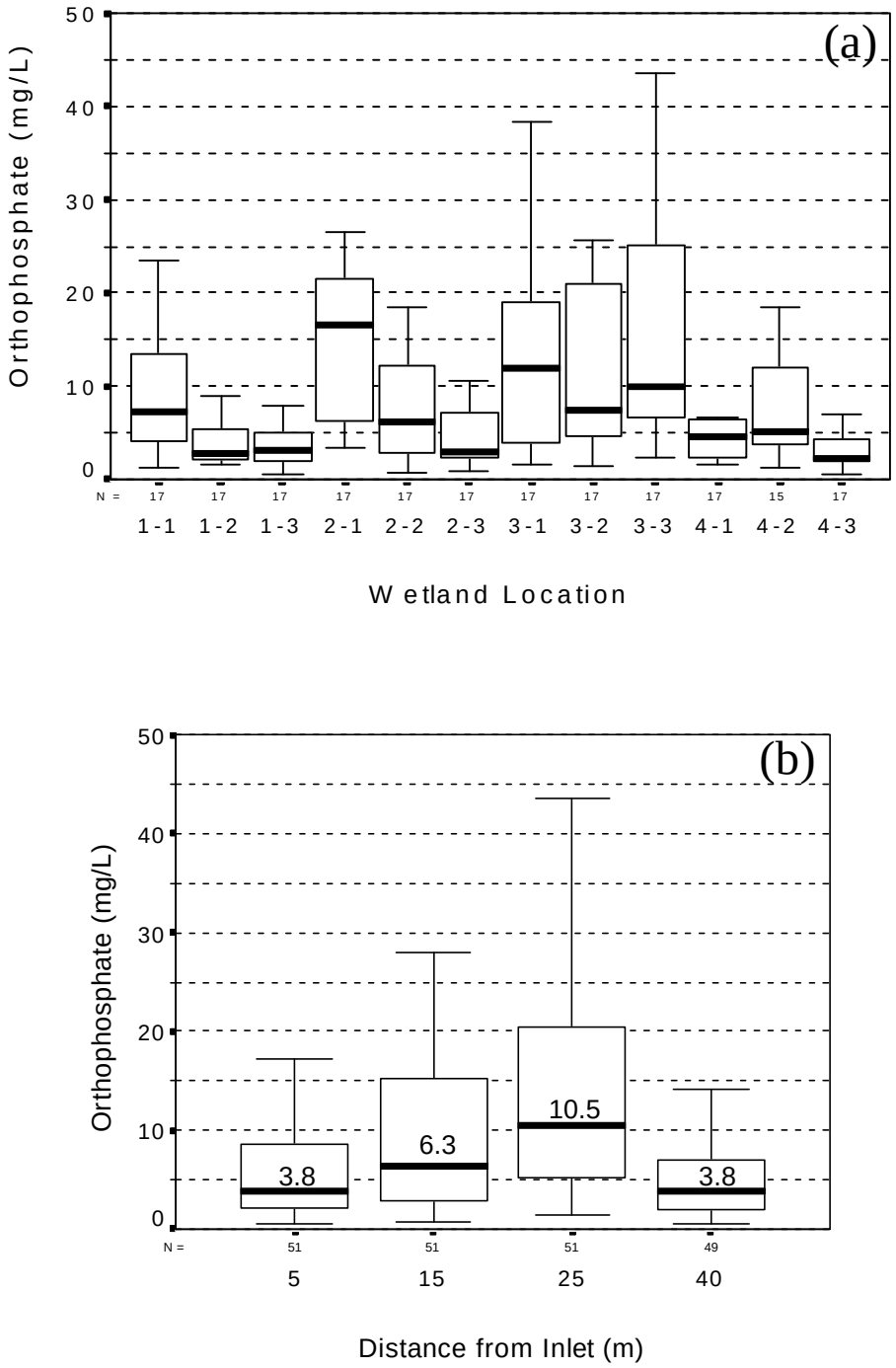


Figure 3-16. Boxplots showing spatial orthophosphate concentration distribution throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

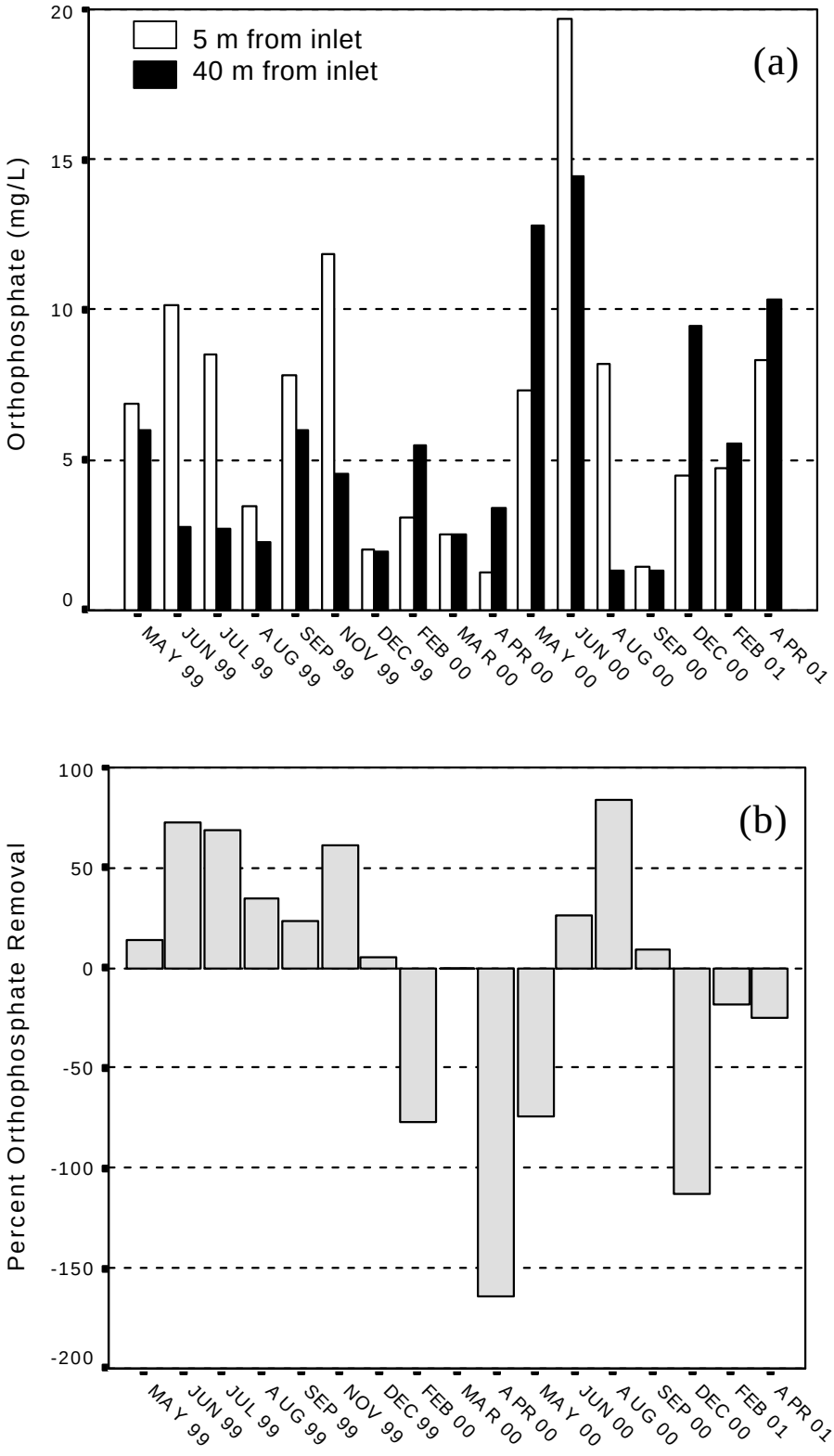


Figure 3-17. Orthophosphate removal from wetland cell by month shown as (a) orthophosphate reduction along flow gradient by distance from inlet and (b) percent orthophosphate reduction between 5 m and 40 m from inlet.

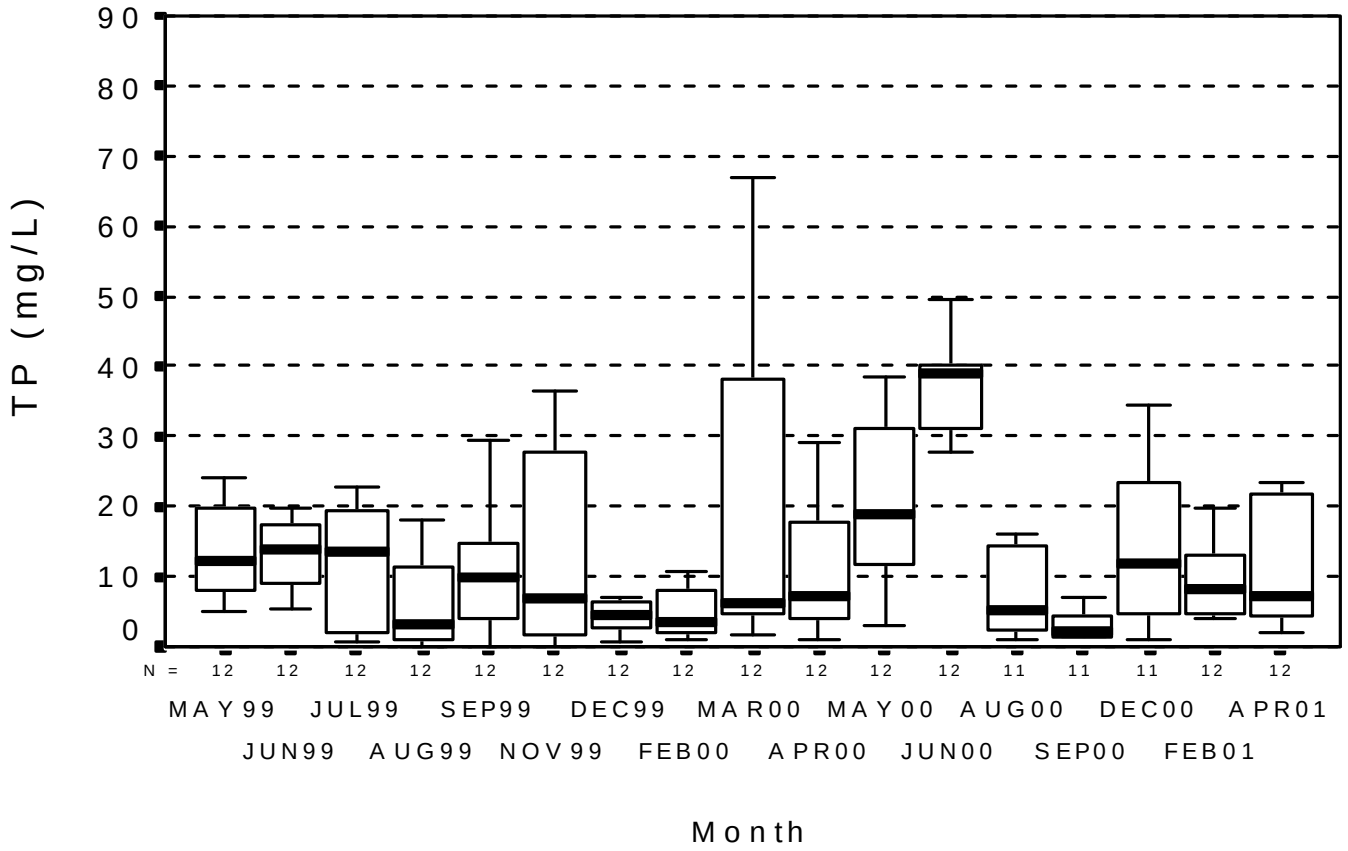
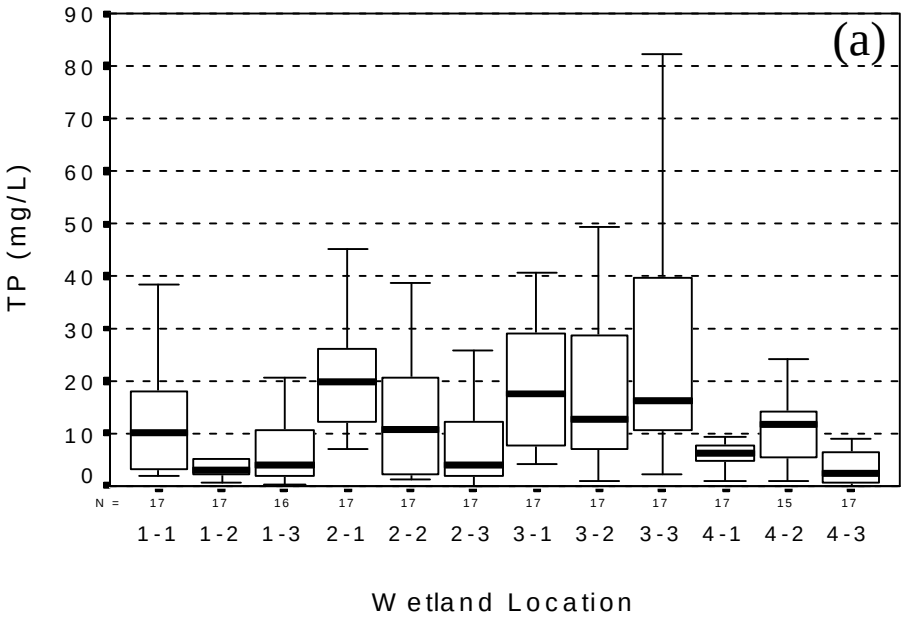


Figure 3-18. Boxplot showing total phosphorus (TP) concentrations over two-year period. Medians, 25th/75th, and 5th/95th percentile results are present



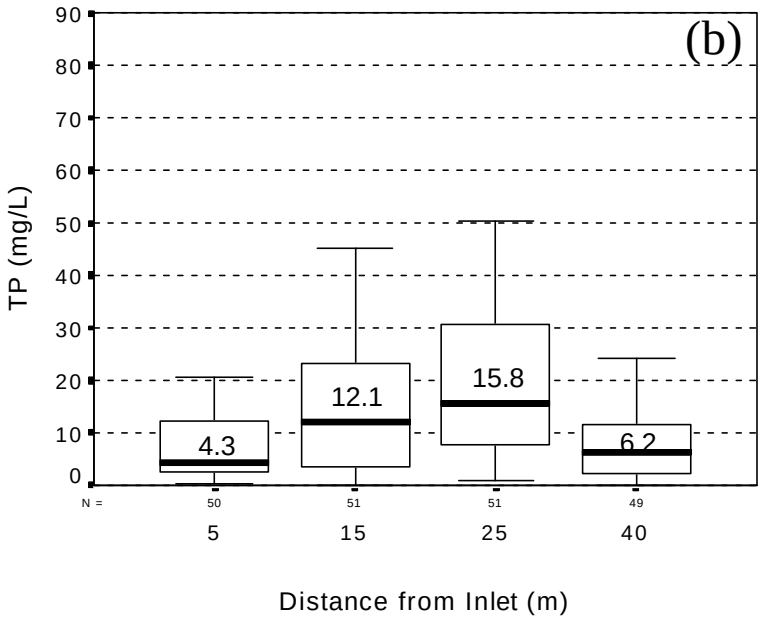


Figure 3-19. Boxplots showing spatial total phosphorus (TP) concentration distribution throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

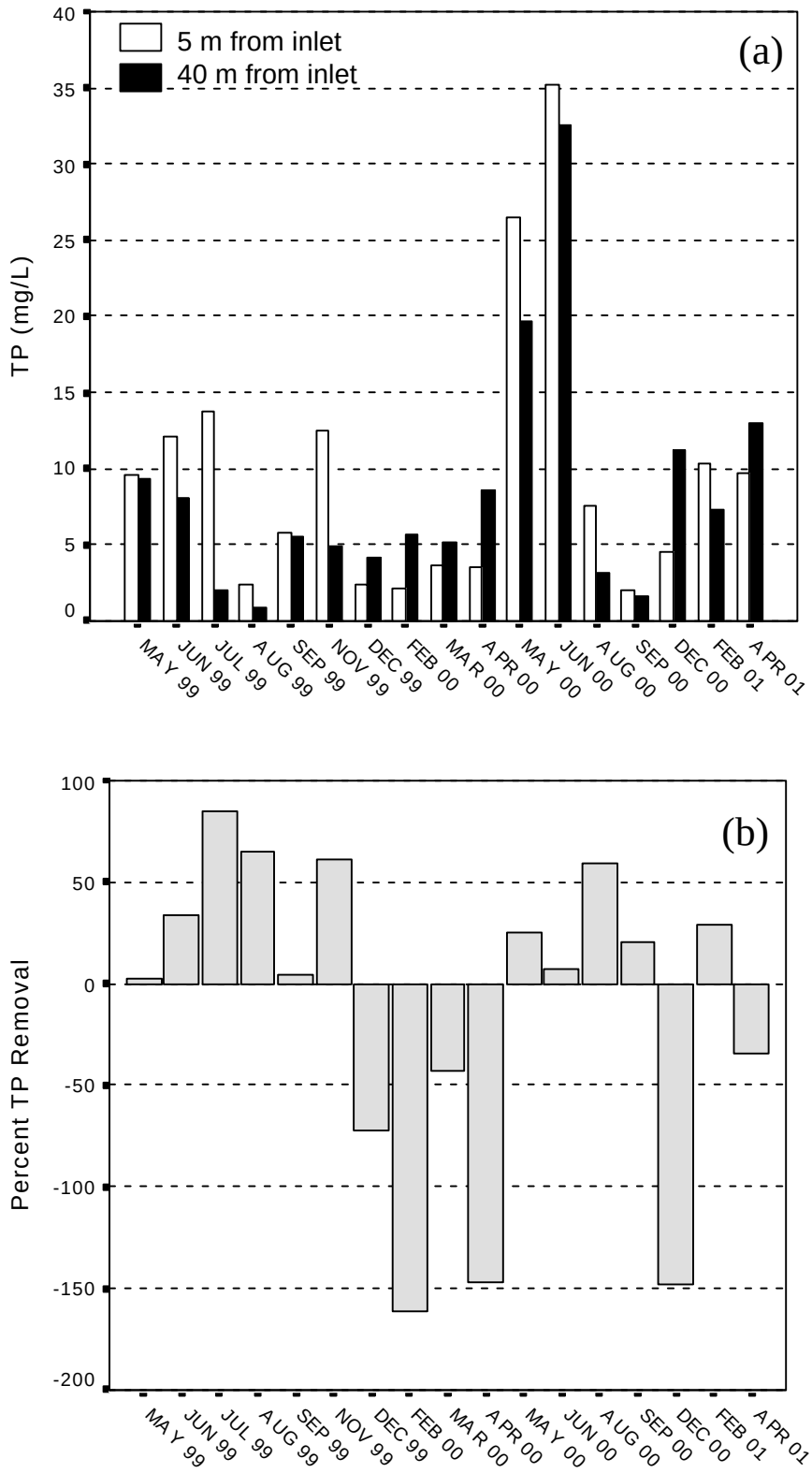


Figure 3-20. Total phosphorus (TP) removal from wetland cell by month shown as (a) TP reduction along flow gradient by distance from inlet and (b) percent TP reduction between 5 m and 40 m from inlet.

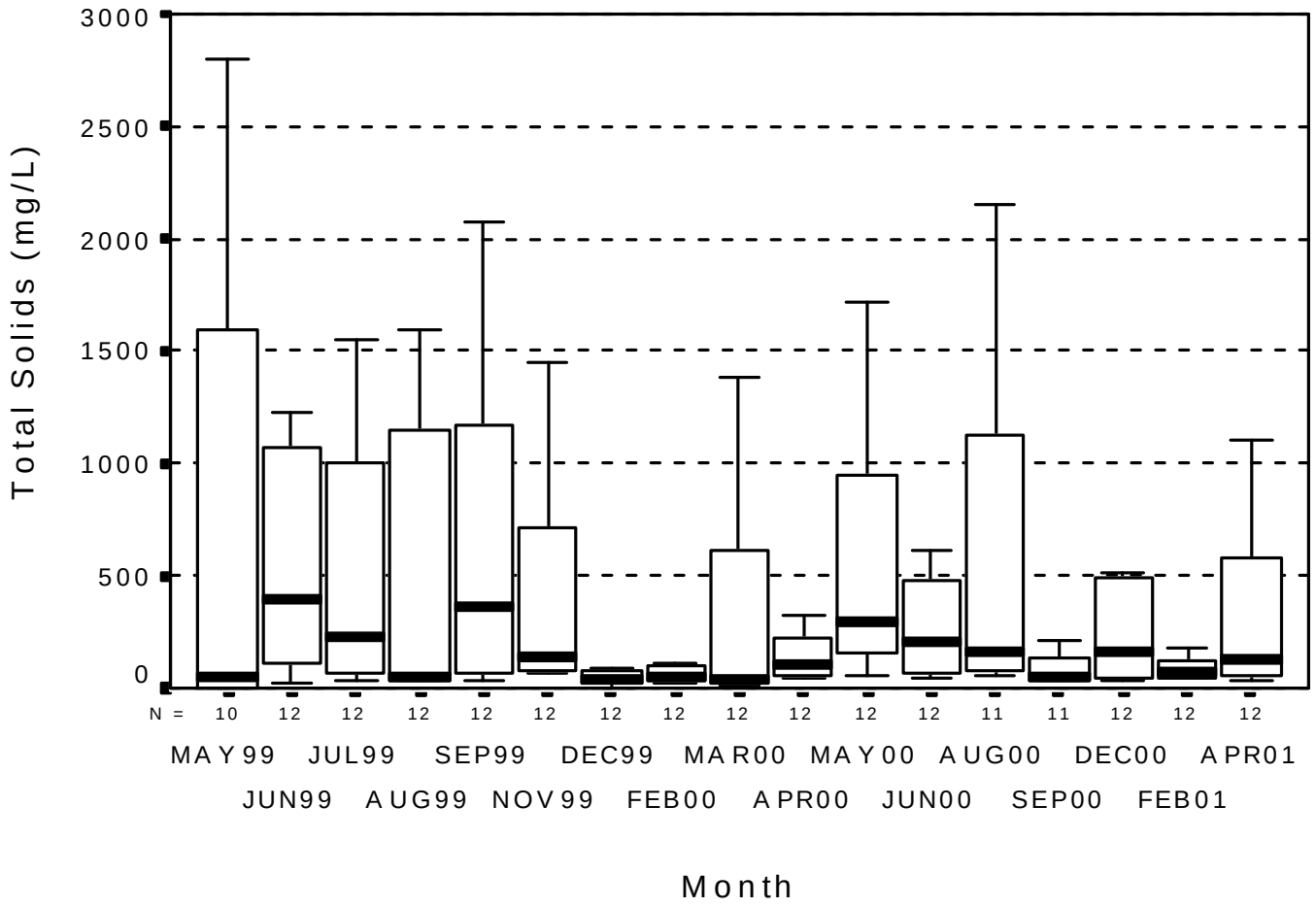


Figure 3-21. Boxplot showing total solids concentrations over two-year sampling period. Medians, 25th/75th, and 5th/95th percentile results are given by month.

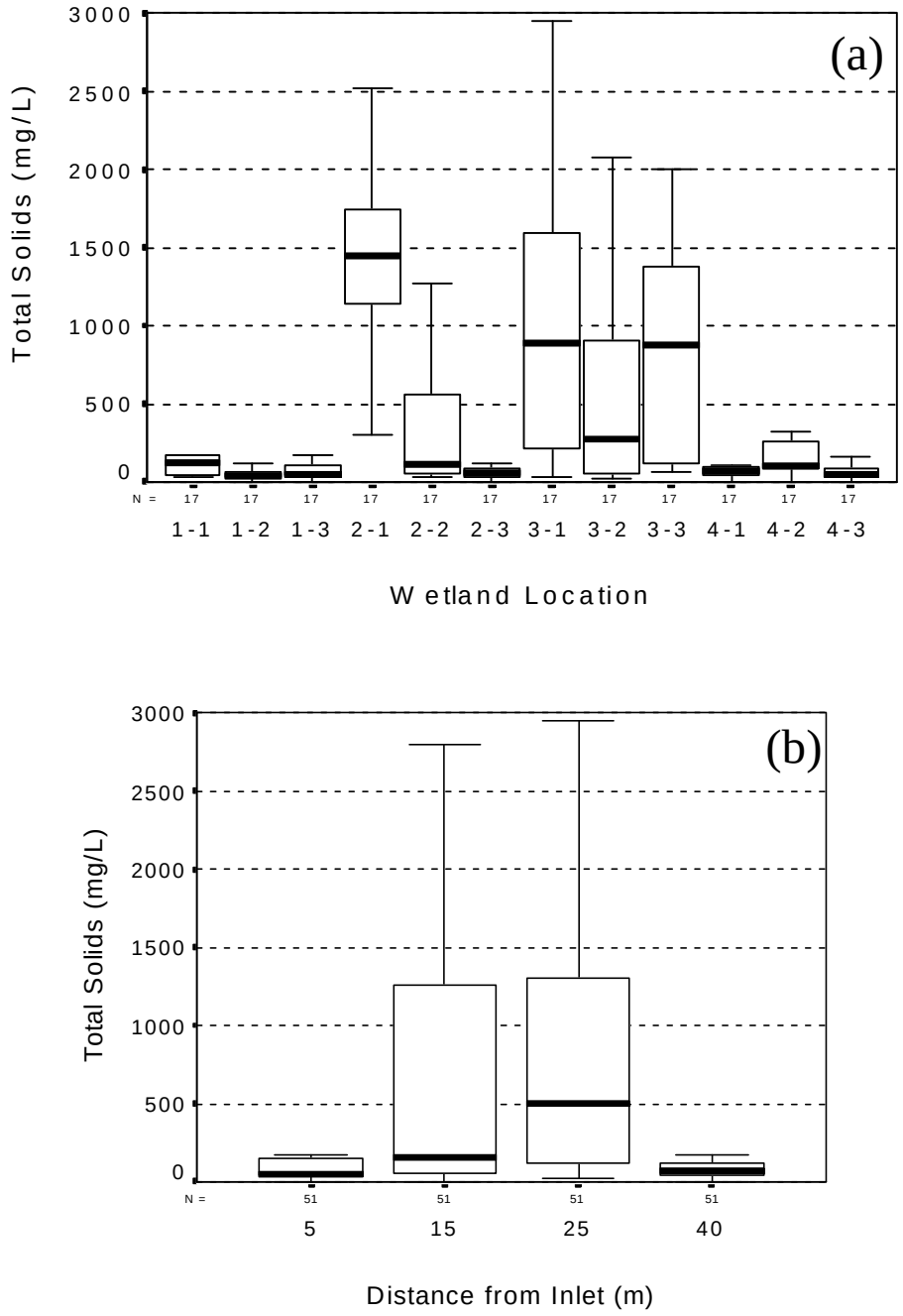


Figure 3-22. Boxplots showing the spatial distribution of total solids concentration throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

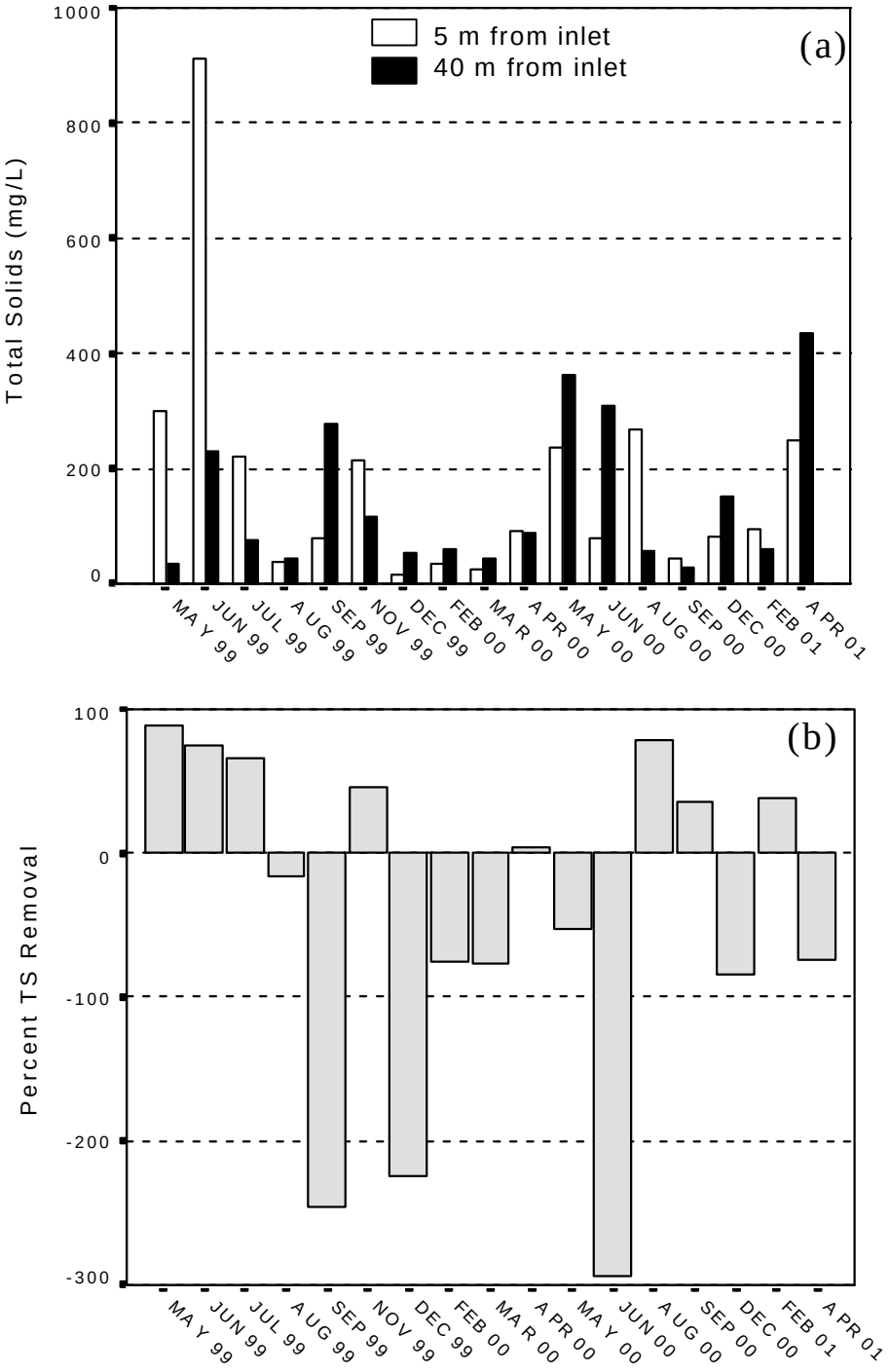


Figure 3-23. Total solids (TS) removal from wetland cell by month shown as (a) TS reduction along flow gradient by distance from inlet and (b) percent TS reduction between 5 m and 40 m from inlet.

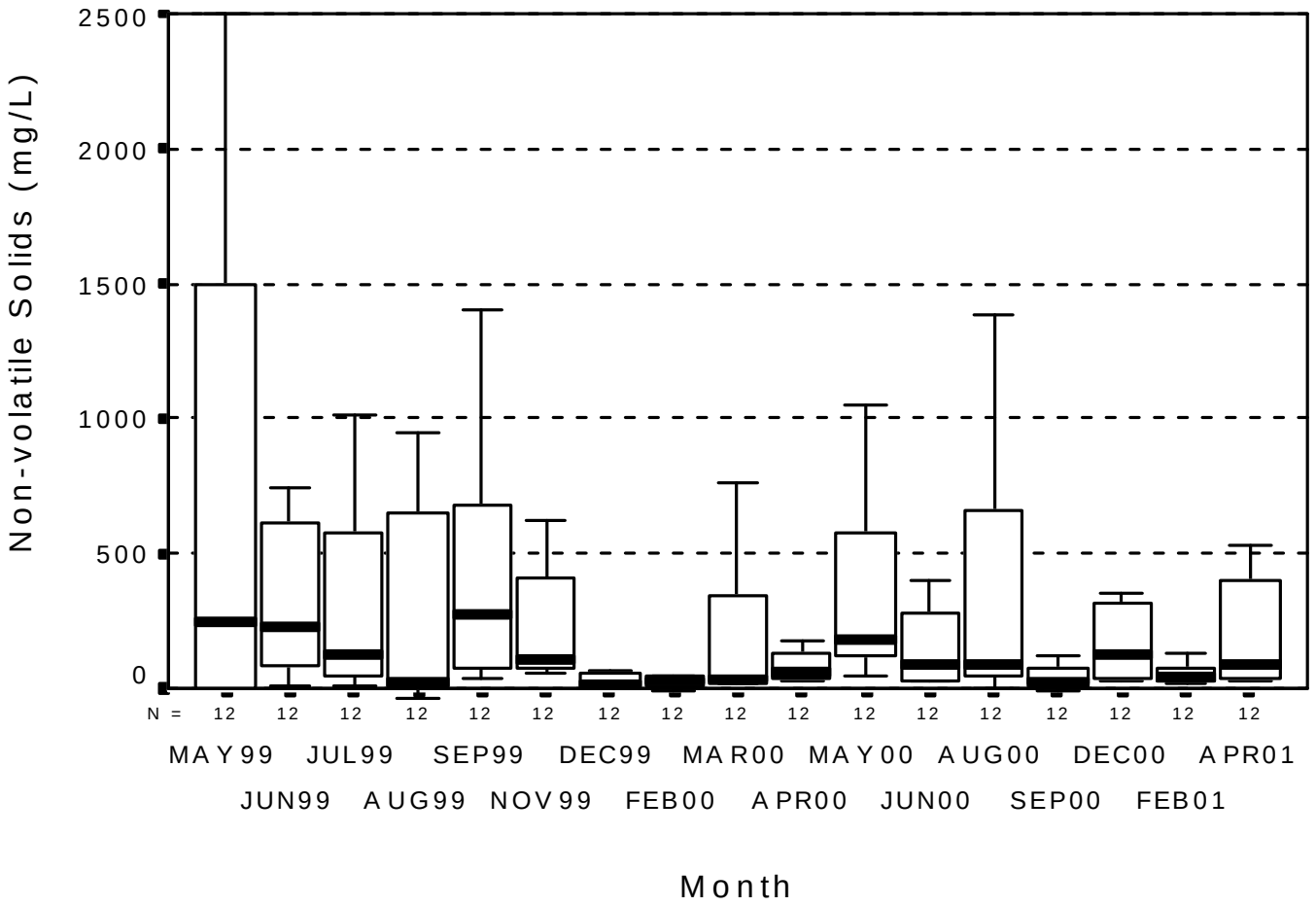


Figure 3-24. Boxplot showing non-volatile solids concentrations over two-year sampling period. Medians, 25th/75th, and 5th/95th percentile results are given by month.

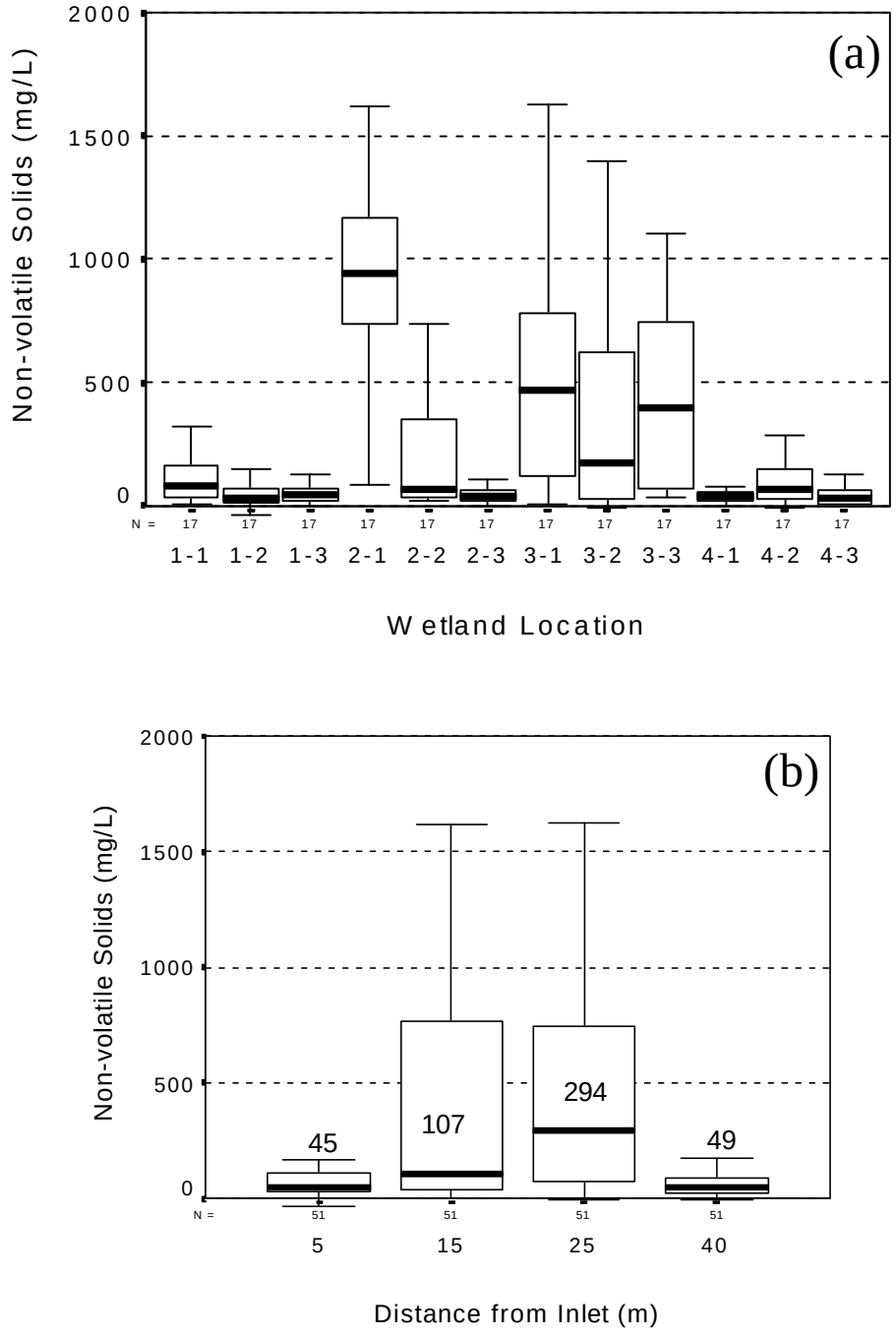


Figure 3-25. Boxplots showing the spatial distribution of non-volatile solids concentrations throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

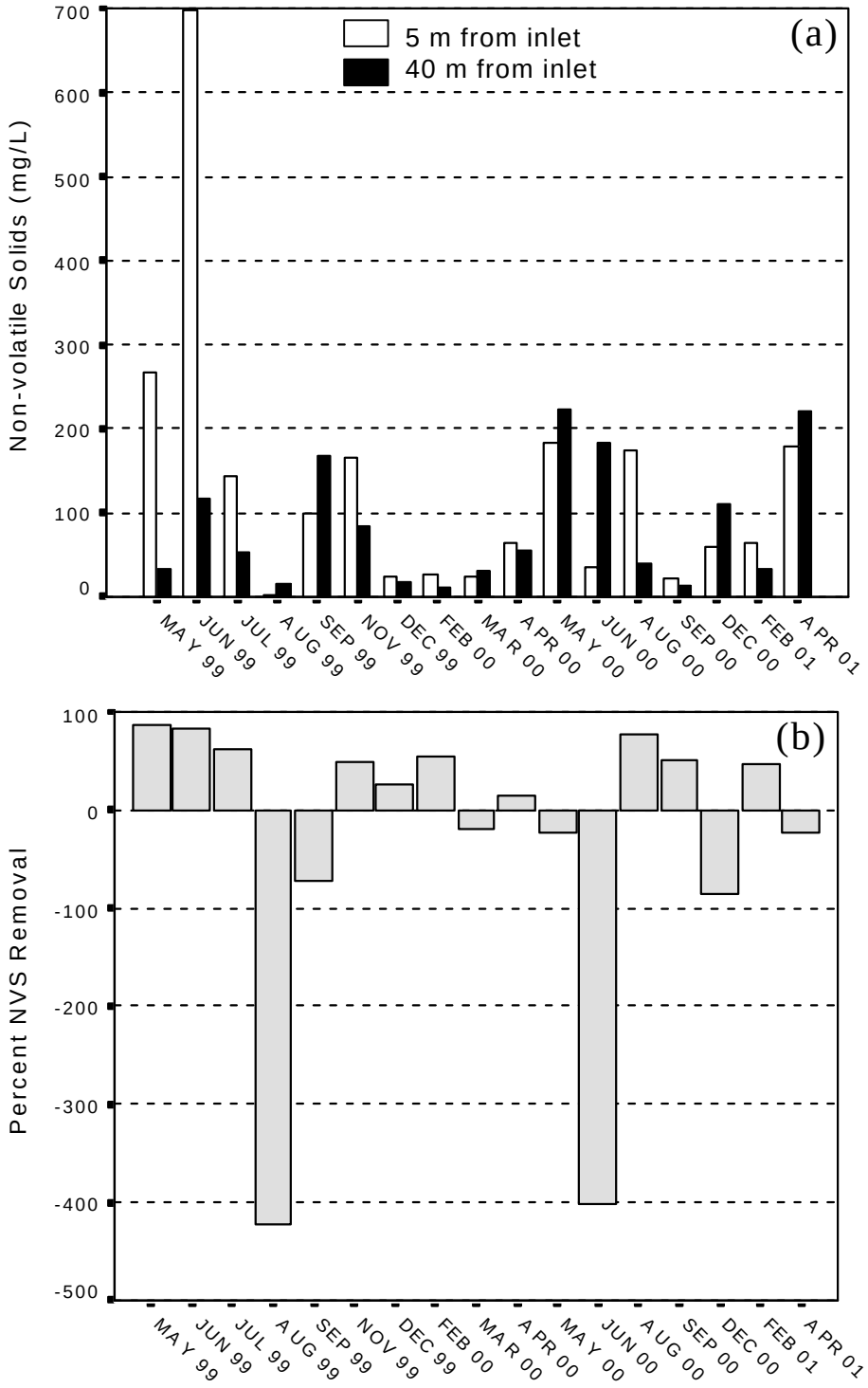


Figure 3-26. Non-volatile solids (NVS) removal from wetland cell by month shown as (a) NVS reduction along flow gradient by distance from inlet and (b) percent NVS reduction between 5 m and 40 m from inlet.

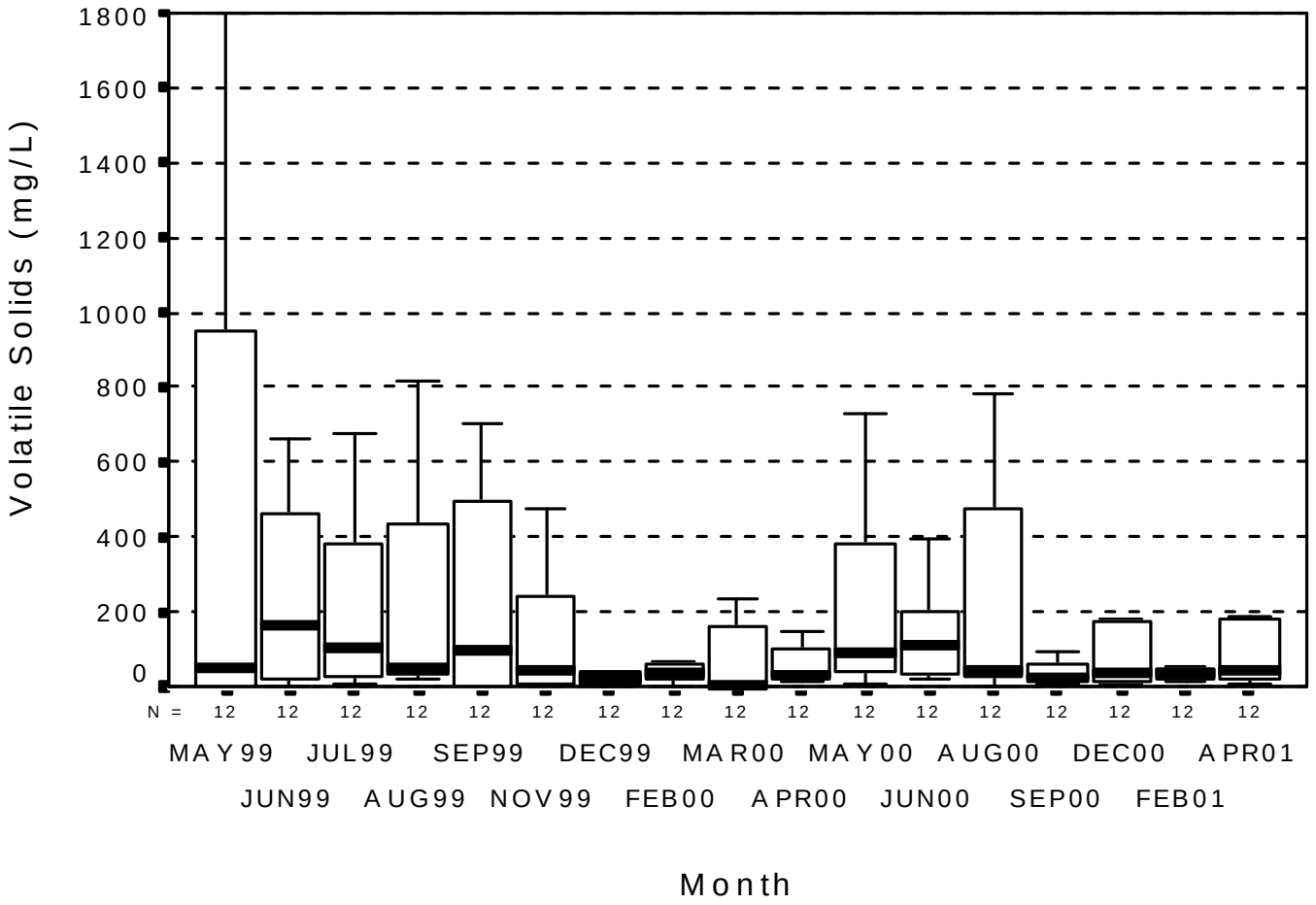


Figure 3-27. Boxplot showing volatile solids concentrations over two-year sampling period. Medians, 25th/75th, and 5th/95th percentile results are given by month.

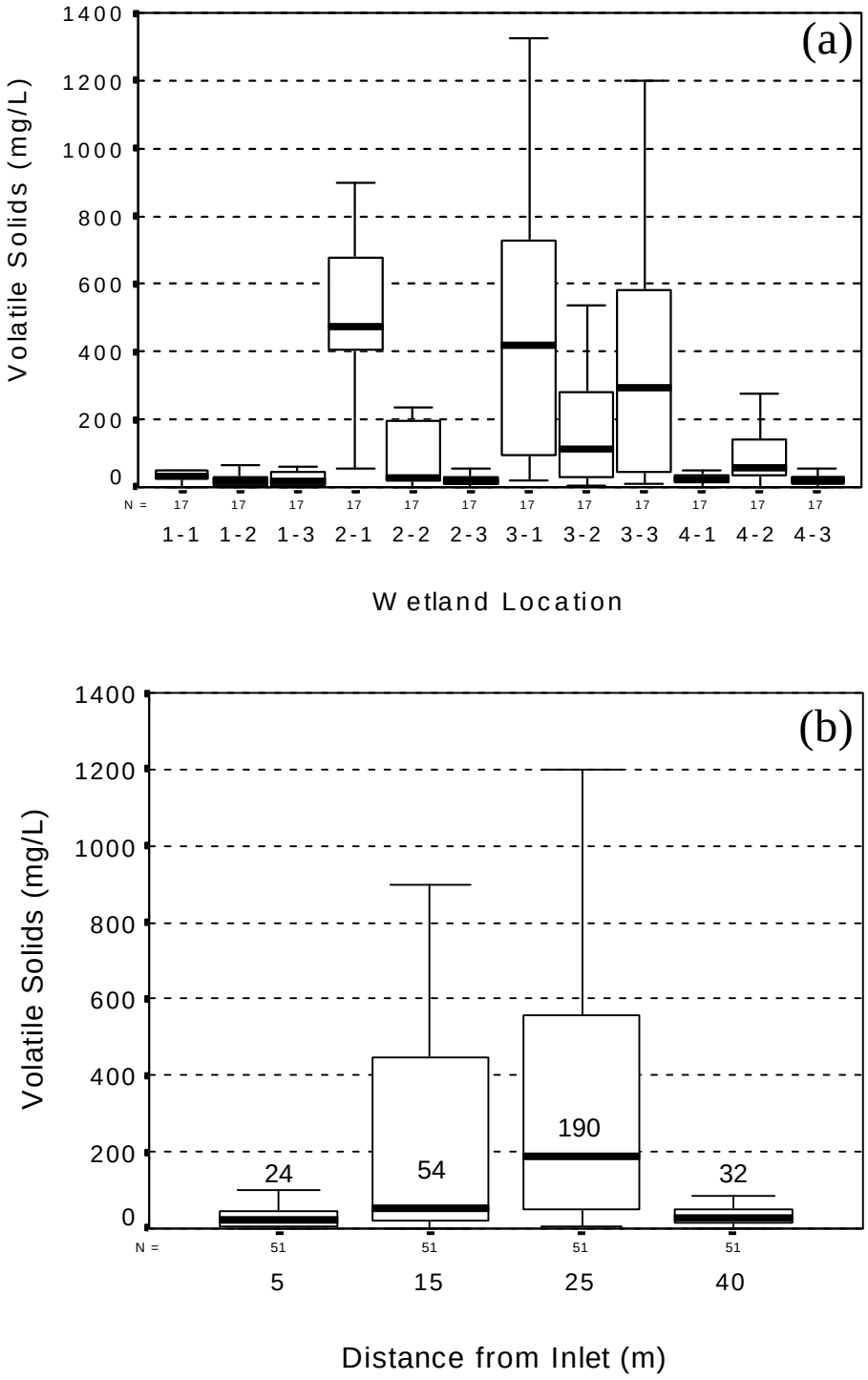


Figure 3-28. Boxplots showing the spatial distribution of volatile solids concentrations throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

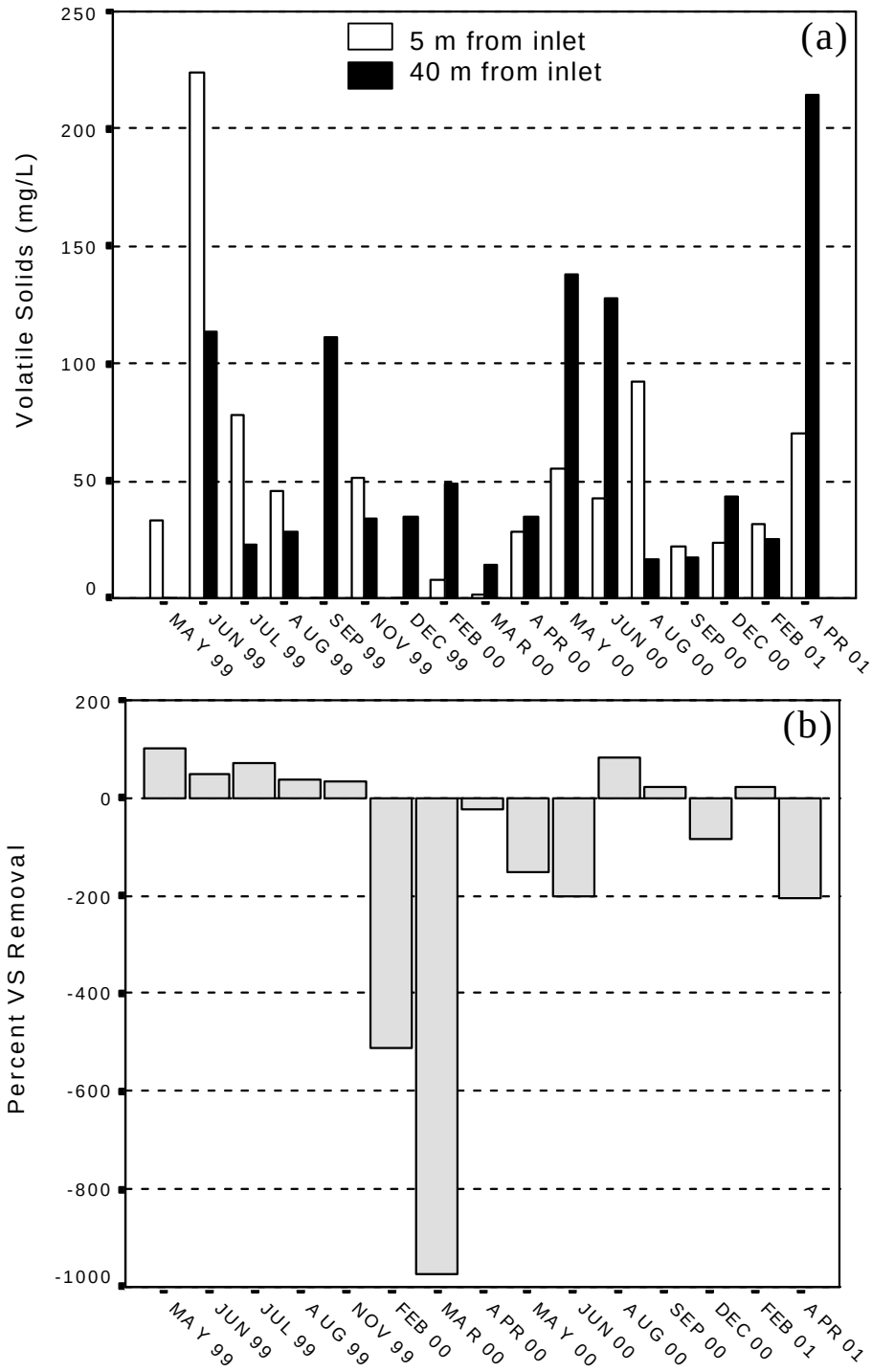


Figure 3-29. Volatile solids (VS) removal from wetland cell by month shown as (a) VS reduction along flow gradient by distance from inlet and (b) percent VS reduction between 5 m and 40 m from inlet.

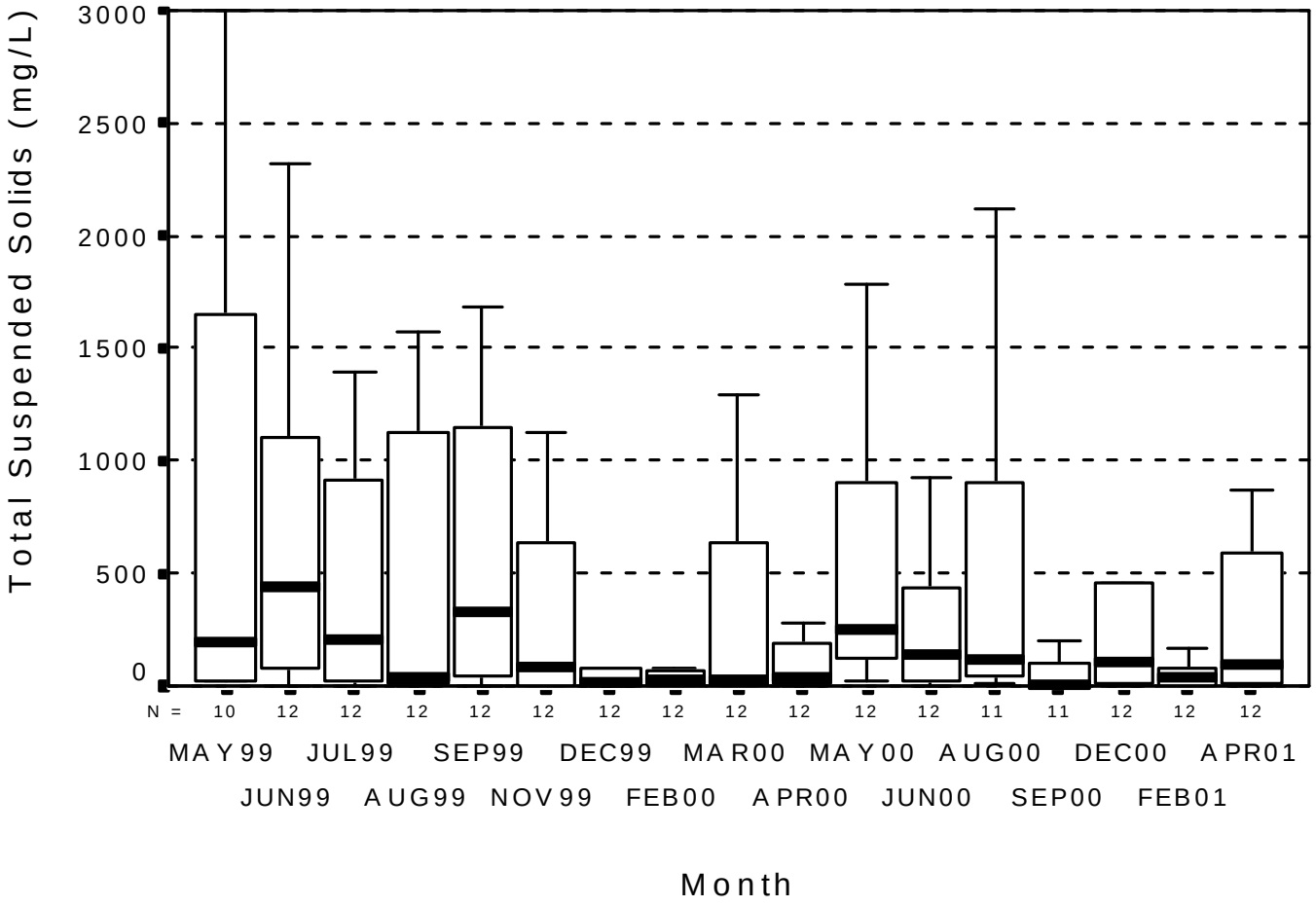


Figure 3-30. Boxplot showing total suspended solids concentrations over two-year sampling period. Medians, 25th/75th, and 5th/95th percentile results are given by month.

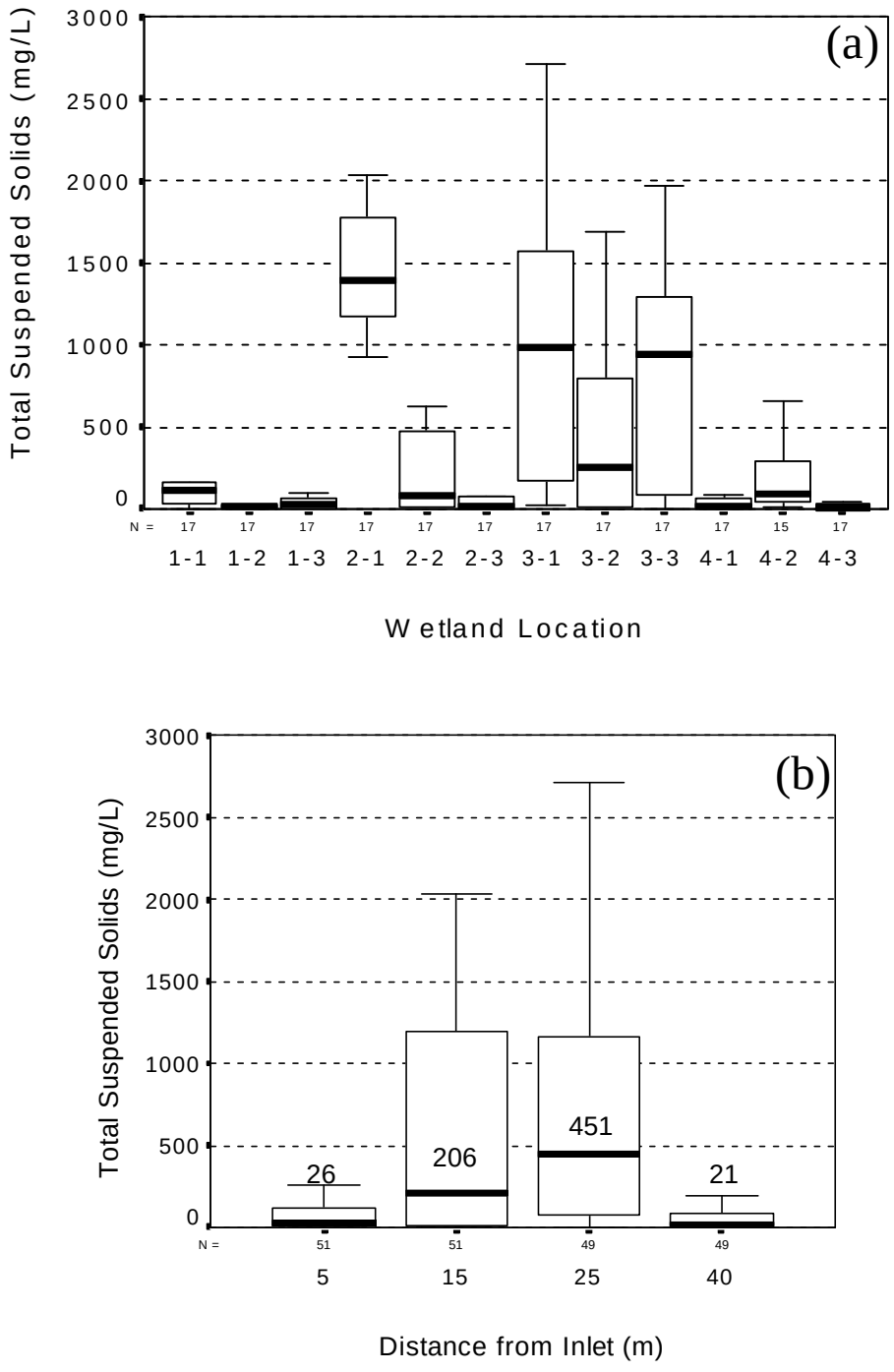


Figure 3-31. Boxplots showing the spatial distribution of total suspended solids concentrations throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

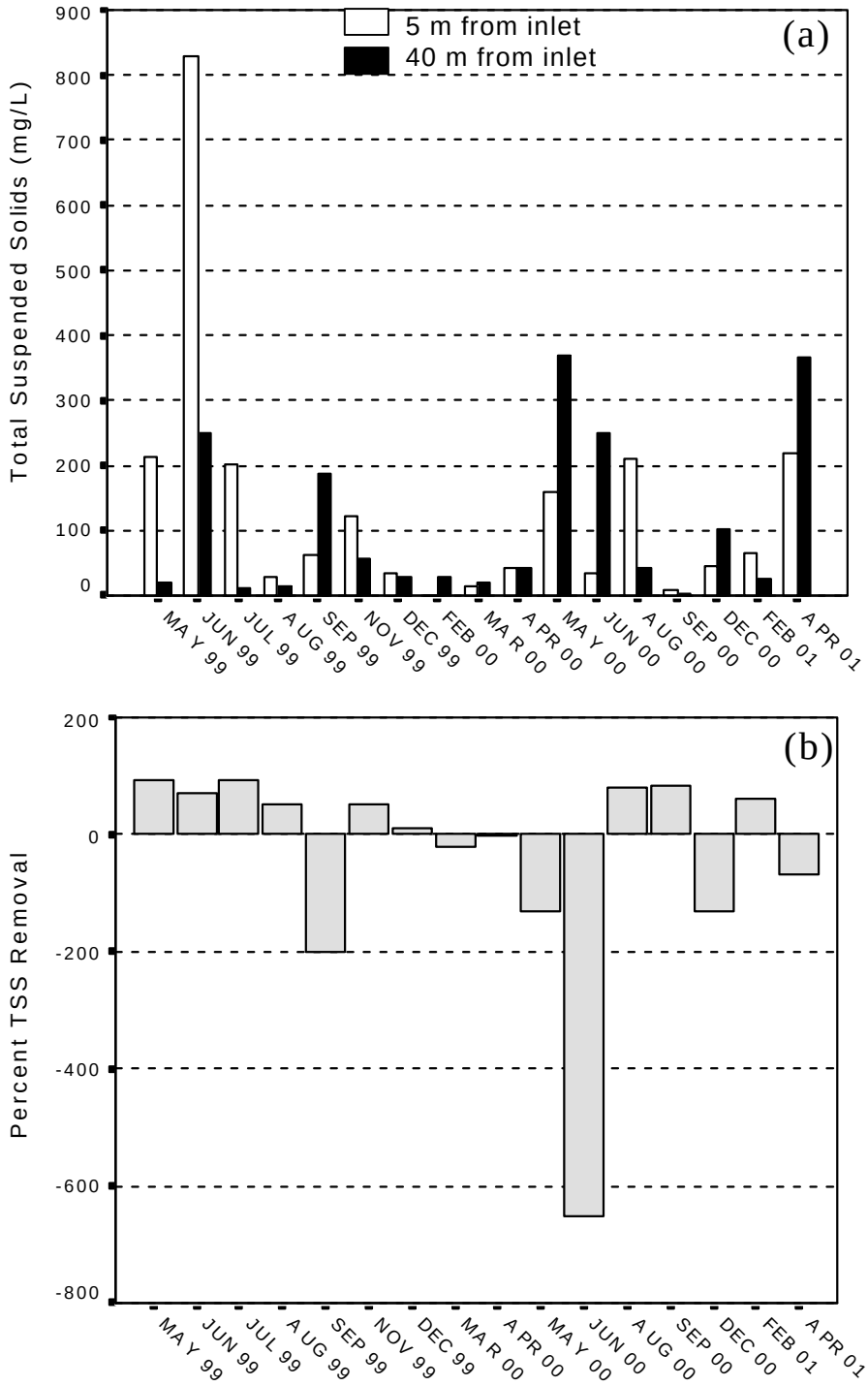


Figure 3-32. Total suspended solids (TSS) removal from wetland cell by month shown as (a) TSS reduction along flow gradient by distance from inlet and (b) percent TSS reduction between 5 m and 40 m from inlet.

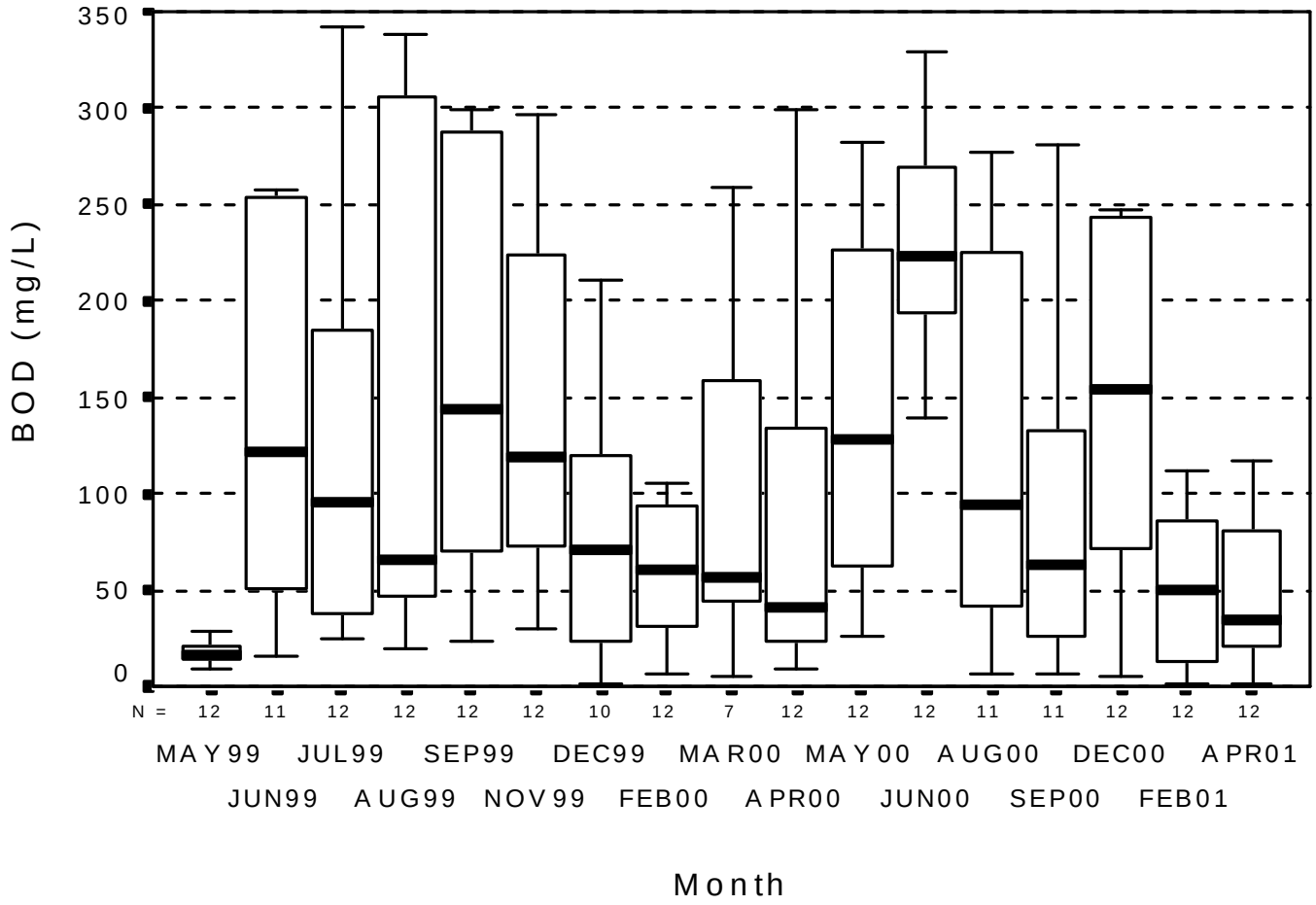


Figure 3-33. Boxplot showing biochemical oxygen demand (BOD) concentrations over two-year sampling period. Medians, 25th/75th, and 5th/95th percentile results are given by month.

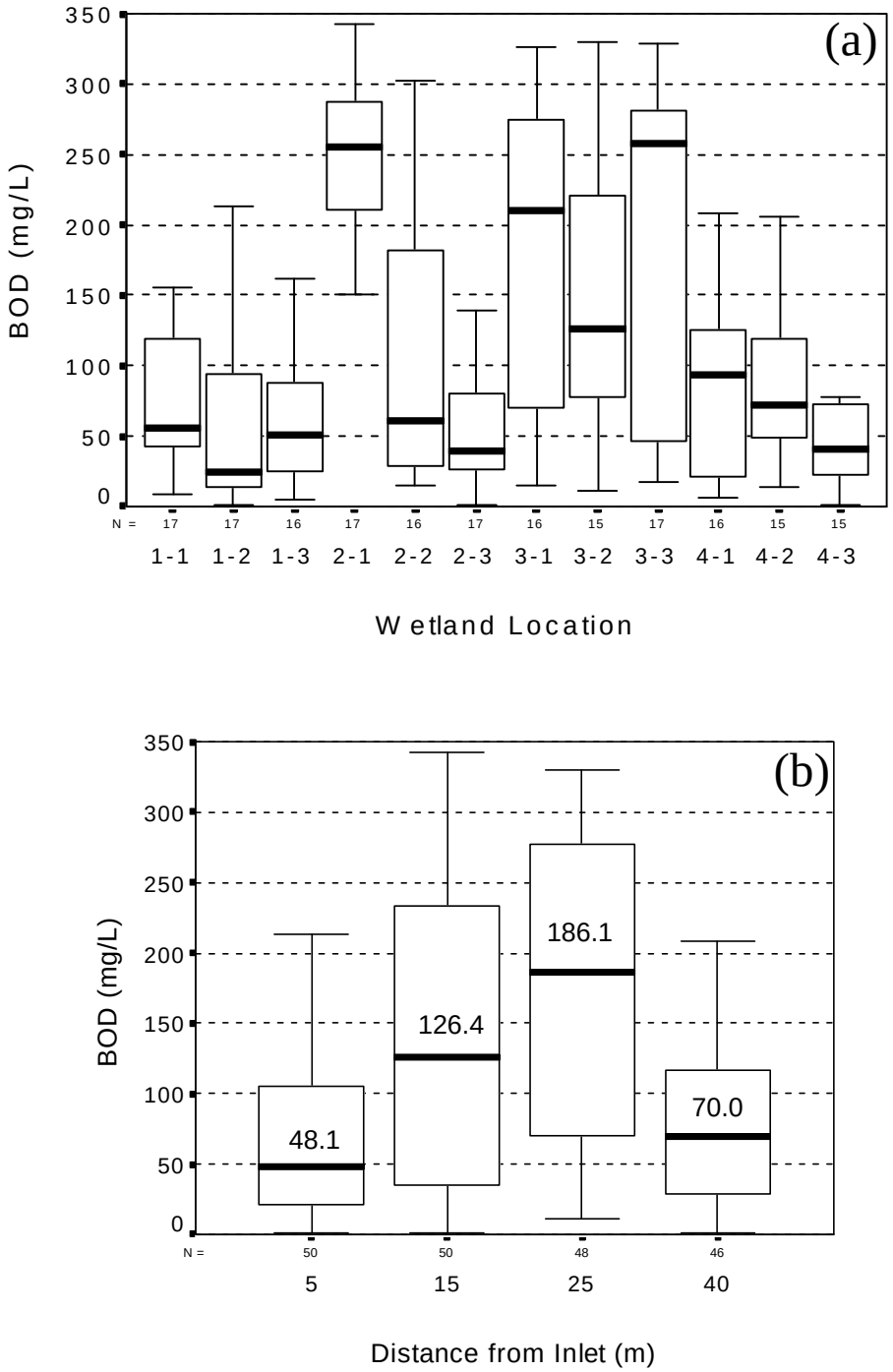


Figure 3-34. Boxplots showing the spatial distribution of biochemical oxygen demand (BOD) concentrations throughout wetland cell (a) by location and (b) by distance from inlet. Medians, 25th/75th, and 5th/95th percentile results are presented Values shown in (b) are median concentrations.

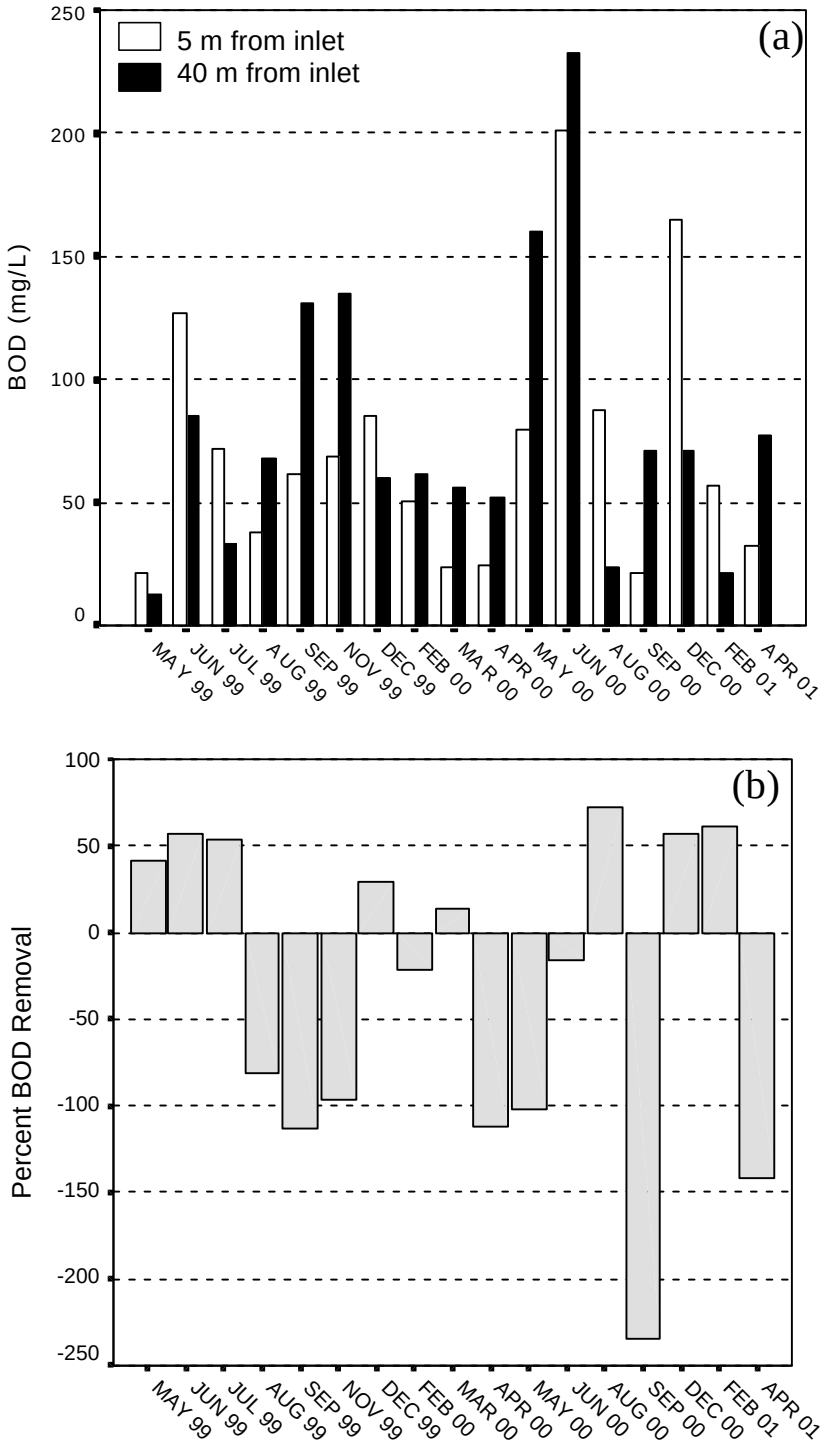


Figure 3-35. Biochemical oxygen demand (BOD) removal from wetland cell by month shown as (a) BOD reduction along flow gradient by distance from inlet and (b) percent BOD reduction between 5 m and 40 m from inlet.

Correlation Coefficients

Tables 3-4 to 3-6 show correlation coefficients between a) water quality parameters, including temperature, pH, conductivity, redox potential (ORP), turbidity, and dissolved oxygen (DO) concentrations; b) between nutrient, solids, and BOD

Table 3-4. Spearman Correlation Coefficients for Water Quality Parameters for Samples Collected at the Tignall Water Reclamation Facility (May, 1999, to April, 2001).

Temp.	pH	Cond.	ORP	Turb.	DO	
1.0	-0.34	0.66	-0.74	0.56	-0.66	Temp
	1.0	**	**	**	**	pH
		1.0	-0.51	**	-0.53	Cond.
			1.0	-0.64	0.73	ORP
				1.0	**	Turb.
					1.0	DO

** indicates lack of significant correlation (p-value = 0.05)

Table 3-5. Spearman Correlation Coefficients for Nutrient, Solids and BOD Concentrations for Samples Collected at the Tignall Water Reclamation Facility (May, 1999, to April, 2001).

	TS	NVS	VS	TSS	BOD
NH_3-N	0.40	0.37	0.38	0.41	**
NO_3-N	-0.47	-0.44	-0.46	-0.45	-0.35
TKN	0.79	0.76	0.76	0.83	0.55
Ortho-PO_4	0.76	0.74	0.68	0.76	0.55
TP	0.72	0.70	0.68	0.76	0.57
BOD	0.61	0.60	0.60	0.58	1.0

** indicates lack of significant correlation (p-value = 0.05)

Table 3-6. Spearman Correlation Coefficients for Water Quality Parameters and Nutrient, Solids and BOD Concentrations for Samples Collected at the Tignall Water Reclamation Facility (May, 1999, to April, 2001).

	Temp.	pH	Cond.	ORP	Turb.	DO
NH_3-N	0.57	-0.43	0.37	-0.38	**	**
NO_3-N	-0.74	0.47	-0.44	0.72	-0.47	0.47
TKN	0.30	-0.23	**	-0.31	**	**
Ortho-PO_4	0.26	**	**	-0.39	**	-0.30
TP	0.30	**	**	-0.37	**	**
TS	0.28	**	**	-0.46	**	-0.34
NVS	0.27	**	**	-0.48	0.30	-0.34
VS	0.25	**	**	-0.33	**	**
TSS	0.30	**	**	-0.45	**	-0.36
BOD	0.22	**	**	-0.43	**	**

** indicates lack of significant correlation (p-value = 0.05)

concentrations, and c) between water quality parameters and nutrient, solids, and BOD results. Nutrient concentrations under consideration include ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), orthophosphate (ortho-PO_4), and total phosphorus (TP). Solids concentrations included total solids (TS), non-volatile solids (NVS), volatile solids (VS), and total suspended solids (TSS). These correlation coefficients were calculated using the bivariate correlations analyses function in SPSS statistical software (SPSS, Inc., 1999).

Discussion

The results of this study showed trends in, and relationships between, the conditions under which the wetland system operates and the effectiveness of wastewater treatment in terms of nutrient removal. This study provided less indication about trends for solids and BOD removal in constructed wetlands with respect to water quality parameters, but the results did provide insight into the relationships between nutrient concentrations, solids concentrations, and biochemical oxygen demand.

Water Quality Parameters

Monitoring water quality parameters over space and time provided information about the environmental conditions under which the treatment wetland system operates, as well as relationships between these measurements. Seasonal fluctuations and ranges in wastewater temperature were demonstrated in this study (Figure 3-3). Dissolved oxygen and redox potential measurements fluctuated in a pattern inversely related to that of temperature (Figures 3-4 and 3-5). The correlation between temperature and dissolved oxygen indicated a strong inverse relationship (r^2 = -0.66), as did the correlation between temperature and redox potential (r^2 = -0.74). Consequently, the correlation between dissolved oxygen concentration and redox potential was high (r^2 = 0.73). Dissolved oxygen and redox potential were both significantly lower in summer months than in winter months.

Nutrients Analyses

The seasonal variability in nitrification rates were demonstrated by relationships between ammonia and nitrogen. Ammonia concentrations decreased (Figure 3-6) while nitrate concentrations increased (Figure 3-9) throughout the winter. These trends were also seen in TKN concentrations over time (Figure 3-12), where TKN is a combined measure of ammonia and organic nitrogen. As expected, TKN concentrations were lower

in the winter. This seasonal trend was probably due to the ability of wastewater to retain higher dissolved oxygen concentrations in colder months, thus encouraging nitrification. As previously discussed, dissolved oxygen concentrations and redox potential were both significantly lower in summer months than in winter months. In general, redox potential shows where the system is aerobic or anaerobic, thus demonstrating the types of microbial activity that may be occurring in the water/sediment matrix over time. The types of microorganisms present in the system are important to the treatment efficiency of the system, as well as the nutrient fluxes that occur. Nitrifiers typically occur in higher redox potentials (Eh > +100 mV), while denitrifiers are typically active in lower redox potentials (-300 mv < Eh < +100 mV) (Howard-Williams, 1985; Reddy and Graetz, 1988; Vymazal, 1995). A successful treatment wetland must have a favorable balance of nitrification and denitrification in order to convert ammonia to nitrate to nitrogen gas, thus removing nitrogen from the wastewater (Reddy and Graetz, 1988; Reed et al., 1995; Kadlec and Knight, 1996).

Solids Analyses

Results showed a strong correlation between solids and nutrient concentrations (Table 3-5). Overall, the correlation coefficients for the different types solids in comparison to the nutrient measurements appeared to be similar (2.1 to 4.7 % coefficient of variation). In comparing the nutrient to solids correlations overall (Table 3-5), TKN, orthophosphate, and TP had the highest correlation with solids concentrations (averaging 0.79, 0.74, and 0.72, respectively), which was considered to be due to the high organic content of the solids. Total Kjeldahl Nitrogen (TKN) and TP concentrations both assess the amount of organic nitrogen and phosphorus in a sample, respectively (Tchobanoglous and Schroeder, 1987, Reed et al., 1995). Also, phosphorus tends to bind to sediment particles (Emsley, 1980; Fennessy et al., 1994; Mitsch et al., 1995), which explains the high correlation between orthophosphate and solids concentrations (averaging 0.74 for

comparison with all solids measurements). Results (Table 3-5) also indicated a significant positive correlation between ammonia and solids concentrations, with correlations averaging 0.39 for comparison with all solids measurements. Results (Table 3-5) also indicated a negative correlation between nitrates and solids, with correlation coefficients averaging -0.46 for comparison with all solids measurements. The high organic content of solids in the wetland deplete oxygen, leading to anaerobic conditions. Anaerobic conditions favor denitrification, leading to decreased nitrate concentrations, while not favoring nitrification, leading to increased ammonia concentrations.

The relationship between solids content and water quality parameters (Table 3-6) is significant but very low, with the highest inverse relationships existing between redox potential and solids concentrations (-0.46 for total solids, -0.48 for non-volatile solids, -0.33 for volatile solids, and -0.45 for total suspended solids). This indicates that the organic nature of these solids contributes to anaerobic conditions, encouraging denitrification.

Measuring the volatile solids in wastewater indicates the amount of organic material at different locations in the system. In vegetated areas where flow is slowed, dead plant biomass from emergent vegetation and duckweed result in sludge accumulation, which subsequently led to higher volatile solids concentrations in the vegetative zone. Also, plant productivity typically varies between different types of plants (Westlake, 1963), as in the case of this study. *Zizaniopsis miliacea* (giant cutgrass) tends to grow and die back very quickly, contributing heavily to dead organic material that reaches the water surface. *Schoenoplectus californicus* (giant bullrush), on the other hand, tends to grow more slowly and remain standing once dead, contributing less to dead organic matter that reaches the water surface. The cutgrass is positioned in the center section of the wetland cell on which this study focuses. The dead organic material contribution of *Z. miliacea* to solids concentrations, especially volatile solids, is very likely.

BOD Analyses

Biochemical oxygen demand signifies the amount of oxygen-demanding organic material that exists in the system (Tchobanoglous and Schroeder, 1987). The correlations between BOD and solids concentrations (Table 3-5) further confirm that the organic constituents associated with wetland solids and sediments influence the dissolved oxygen concentrations and redox potentials, thus affecting nutrient removal from the system. Biochemical oxygen demand appears to be lowest in the early spring (Figure 3-33) and highest in the summer. This may be due to available dissolved oxygen concentrations in the colder months leads to increased decomposition early in the year before the temperature increase and, consequently, dissolved oxygen concentrations decrease. Also, plant selection may be critical in this case, as *Z. miliacea* could contribute significantly to organic content, and subsequently high BOD concentrations.

Treatment Performance

In terms of overall treatment performance from the distance of the inlet along the first vegetative zone, results indicate that all nitrogen concentrations did decrease as expected along the length of the vegetative zone (between 5 m and 40 m from the inlet) (Figures 3-7b, 3-10b, and 3-13b). However, orthophosphate did not decrease at all (Figure 3-16b), and TP increased along the flow gradient (Figure 3-19b). Also, only total suspended solids (TSS) decreased after the vegetative zone. All other solids concentrations increased beyond the vegetative zone. Biochemical oxygen demand increased as well. In all cases, including nitrogen, phosphorus, solids, and BOD, concentrations increased significantly within the vegetative zone. This is possibly due to the accumulation of biomass for dead plant material, as well as the slowed flow allowing solids to settle. Only in the case of nitrate (Figure 3-10b) did the concentrations decrease along the gradient of flow. This is due to the anaerobic conditions of the vegetated zone.

When treatment performance in the vegetative zone was evaluated by month, ammonia concentrations were reduced in 13 of 17 months sampled (Figure 3-8a), ranging from 1 to 38 % removal along the vegetated zone (Figure 3-8b). Nitrate concentrations were reduced in every month (Figure 3-11a), ranging from 9 to 100 % removal along the vegetated zone (Figure 3-11b). Total Kjeldahl nitrogen concentrations were reduced in 7 of 17 months sampled (Figure 3-14a), ranging from 8 to 80 % removal along the vegetated zone (Figure 3-14b). Orthophosphate concentrations were reduced in 10 of 17 months (Figure 3-17a), ranging from 7 to 85 % removal along the vegetated zone (Figure 3-17b). Total phosphorus concentrations were reduced in 11 of 17 months sampled (Figure 3-20a), ranging from 3 to 82 % removal along the vegetated zone (Figure 3-20b). Total solids concentrations were reduced in 8 of 17 months sampled (Figure 3-23a), ranging from 3 to 89 % removal along the vegetated zone (Figure 3-23b). Non-volatile solids concentrations were reduced in 10 of 17 months sampled (Figure 3-26a), ranging from 10 to 90 % removal along the vegetated zone (Figure 3-26b). Volatile solids concentrations were reduced in 8 of 17 months sampled (Figure 3-29a), ranging from 10 to 95 % removal along the vegetated zone (Figure 3-29b). Total suspended solids concentrations were reduced in 9 of 17 months sampled (Figure 3-32a), ranging from 10 to 90 % removal along the vegetated zone (Figure 3-32b). For all solids, removal over the two-year sampling period was high in the early spring compared to other months of the year. Biochemical oxygen demand concentrations were reduced in 8 of 17 months sampled (Figure 3-35a), ranging from 10 to 69 % removal along the vegetated zone (figure 3-35b). The variable nature of organic compounds, phosphorus compounds, solids, and BOD, as well as their apparent close relationships, deserves further investigation.

Conclusions

By monitoring a section of the constructed wetland over a two year period, relationships between water quality parameters and nutrients, solids, and biochemical oxygen demand (BOD) concentrations were determined. High inverse relationships between temperature and dissolved oxygen concentrations existed, while good positive correlations between dissolved oxygen concentration and redox potential were indicated over space and time. Also, high correlations between nutrient concentrations and solids concentrations were indicated in this study.

The spatial distribution of nutrients, solids, and BOD concentrations was explored, indicating that higher concentrations existed within more densely vegetated areas. Also, concentrations increased along the flow gradient of the vegetated area before decreasing, or in some cases not changing significantly, at the end of the vegetated area. The contribution of dead vegetative organic matter, increased filtration due to plant stems and roots, and higher sedimentation from slowed flow due to vegetation resistance were considered to be responsible for higher nutrients, solids, and BOD concentrations in the vegetated area.

Seasonal patterns in nutrient concentrations demonstrated oscillations in ammonia and nitrate concentrations, with ammonia concentrations being high in the summer and low in the winter. The opposite was true for nitrate concentrations. This pattern was attributed to environmental conditions, including temperature, dissolved oxygen concentrations, and redox potential. Winter conditions (low temperature, high dissolved oxygen concentration, high redox potential), appeared to favor nitrification, while summer conditions (high temperature, low dissolved oxygen concentrations, low redox potential) favored denitrification. Seasonal patterns were not detected for other nutrients; however, broader distributions in summer months of nutrients and solids concentrations related to organic matter suggest that higher vegetative biomass may impact wastewater

treatment performance by contributing high organic matter to the system during the peak of the growing season.

This study provided insight into the relationship between water quality parameters, how they affect pollutant removal, and how different wastewater constituents interact within constructed wastewater treatment wetlands. Monitoring water quality parameters, and nutrient, solids, and BOD concentrations within the wetland system is key to understanding the biological processes driving nutrient transformation and transport processes. The fact that organically-bound nutrients were closely related to solids concentrations indicates that, throughout the life span of a wastewater wetland system, sludge accumulation may eventually become a source of pollution, rather than a sink. Improved design strategies, such as plant selection and spacing, as well as effective operational and maintenance strategies, such as recirculation, harvest, and sludge removal, could be incorporated and implemented if spatial and temporal dynamics are better understood and taken into consideration..

References

Bran and Luebbe. 1998. TRAACS Applications. Buffalo Grove, IL.

Brix, H. 1993. Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL, pp. 9-22.

Canale, R. P. 1976. Modeling Biochemical Processes in Aquatic Ecosystems. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Clesceri, L. S., A. E. Greenberg, and A. D. Eaton (Eds.). 1998. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, American Water Works Association and Water Pollution Control Federation, Washington, D. C.

Davis, C. 2001. Personal communication. Tignall Water Reclamation Facility superintendent, Tignall, GA.

Emsley, J. 1980. The phosphorus cycle. In: Hutzinger, O., Ed., The Handbook of Environmental Chemistry, Vol. 1, Part A, The Natural Environment and the Biogeochemical Cycles, Springer-Verlag, Berlin, p. 161.

Fennessy, M. S., C. C. Brueske, and W. J. Mitsch. 1994. Sediment deposition patterns in restored freshwater wetlands using sediment traps. *Ecological Engineering*, 3: 409-428.

Georgia Department of Natural Resources (GA DNR). 1995. Guidelines for Constructed Wetlands for Municipal Wastewater Treatment Facilities. Environmental Protection Division, Water Protection Branch, Atlanta, GA.

Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY.

Hammer, D. A. (Ed.). 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Inc., Boca Raton, FL.

Heliotis, F. D., and C. B. DeWitt. 1983. A conceptual model of nutrient cycling in wetlands used for wastewater treatment: a literature analysis. *Wetlands*, 3: 134-152.

Howard-Williams, C. 1985. Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective. *Freshwater Biol.*, 15: 391-431.

Johnston, C. A. 1993. Mechanisms of Wetland-Water Quality Interaction. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 293-299.

Kadlec, R. H., and J. A. Kadlec. 1979. Wetlands and Water Quality. In: Grecian, P. E., J. R. Clark, and J. E. Clark (Eds.). 1979. Wetland Functions and Values: the State of Our Understanding. American Water Resources Association, Minneapolis, MN, pp. 436-456.

Kadlec, R. H., and R. L. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL.

Klopatek, J. M. 1978. Nutrient Dynamics of Freshwater Riverine Marshes and the Role of Emergent Macrophytes. In: Good, R. E., D. F. Whigham, and R. L. Simpson (eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential, Academic Press, New York, NY, pp. 195-216.

Mitsch, W.J., Cronk, J.K., Wu, X., Nairn, R.W., Hey, D.L., 1995. Phosphorus retention in constructed freshwater riparian marshes. *Ecol. Applications* 5, 830-845.

Reddy, K. R., and D. A. Graetz. 1988. Carbon and Nitrogen Dynamics in Wetland Soils. In: Hook, D. D., et al., (Eds.), The Ecology and Management of Wetlands, Vol. 1: Ecology of Wetlands. Timber Press, Portland, OR., pp. 307-318.

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

SPSS, Inc. 1999. SPSS Graduate Pack 10.0 for Windows. Chicago, IL.

Tchobanoglous, G., and E. D. Schroeder. 1987. Water Quality: Characteristics, Modeling, Modification. Addison-Wesley Publishing Co., Reading, MA.

U. S. Environmental Protection Agency. 1987. Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal. Office of Water , Washington, D. C. EPA/430/09-88-055.

U. S. Environmental Protection Agency. 1988. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. Office of Water , Washington, D. C. EPA/625/1-88/022.

U. S. Environmental Protection Agency. 2000. Constructed Wetlands Treatment of Municipal Wastewaters. National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH. EPA/625/R-99/010.

Valiela, I., and J. M. Teal. 1978. Nutrient Dynamics: Summary and Recommendations. In: Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY, pp. 259-263.

Vymazal, J. 1995. Algae and Element Cycling in Wetlands. Lewis Publishers, Boca Raton, FL.

Westlake, D. F. 1963. Comparisons of plant productivity. *Biol. Rev.,* 38, 385-425.

Wetzel, R. G. 1993. Constructed Wetlands: Scientific Foundations are Critical. In: Moshiri, G. A., Ed., Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 3-7.

CHAPTER 4

USING THE BIOLOG™ MICROSTATION TO IDENTIFY HETEROTROPHIC GRAM-NEGATIVE BACTERIA FROM A MUNICIPAL WASTEWATER TREATMENT WETLAND[2]

[1]Hitchcock, D. R., and M. C. Smith. 2001. To be submitted to *Advances in Environmental Research*.

Abstract

The complex biological processes that occur in constructed wetlands for wastewater treatment warrant investigation into the microbial ecology of such systems. The objective of this study was to identify the role of Gram-negative microbial populations that exist in a constructed municipal wastewater treatment wetland in the Georgia Piedmont. The contribution of certain microbes to organic matter decomposition, nitrification, and denitrification were investigated. This study was based on the identification of microorganisms using the Biolog™ MicroStation, and the subsequent potential substrate utilization of the identified genera. Environmental conditions such as temperature, dissolved oxygen concentrations, and redox potential were related to the numbers and types of identified microbial populations. Also, the role of identified bacteria in the decomposition of organic material, nitrification, denitrification, and nitrogen fixing was assessed based on their metabolic characteristics. Relationships between identified populations and nutrient, solids, and biochemical oxygen demand (BOD) concentrations were evaluated. Finally, percentages of pathogenic bacteria were identified for the months that were sampled. Knowledge of the microbial populations that contribute to wastewater treatment may be valuable in the future design of wastewater treatment systems. Further work is needed to fully identify the microbial consortium, as well as the roles these bacteria play in wastewater treatment.

Introduction

Over the last 30 years, with the advances in wetland treatment technology and the development of wetland design and monitoring regulations by the U. S. EPA and by state environmental protection agencies, the use of constructed wetlands for municipal wastewater treatment has become common practice (Kadlec and Kadlec, 1979; U. S. EPA, 1987, 1988, 2000; Hammer, 1989; GA DNR, 1995; Kadlec and Knight, 1996). The removal mechanisms by which constructed wetlands treat wastewater include filtration

and sedimentation of solids, decomposition of organic matter, plant uptake of nutrients, microbial nitrification of ammonia and denitrification of nitrate, and the adsorption of phosphorus to sediments (Brix, 1993; Reed et al., 1995, Kadlec and Knight, 1996).

Complex biological processes, including plant-soil-microbial interactions, occur within wetland systems (Canale, 1976; Klopatek, 1978; Valiela and Teal, 1978; Heliotis and Dewitt, 1983; Howard-Williams, 1985; Reddy and Graetz, 1988; Vymazal, 1995; Kadlec and Knight, 1996), and these processes are responsible for the success of treatment wetland systems. The relationship between system complexity and the ability of the system to remove nutrients, solids, and organic matter, is poorly understood (Wetzel, 1993).

Much attention has been focused on the microbiology of conventional wastewater treatment facilities (van Demark and Batzing, 1987). For example, Gram-negative aerobic rods, such as the *Zooglea* genera, are considered to be the main bacteria found in sewage treatment plants, especially in biofilms associated with trickling filters (van Demark and Batzing, 1987). Relatively little information, however, has been published on the microbiology of wastewater treatment wetlands. This is surprising considering the need for understanding the fate of pathogenic organisms, as well as understanding the role of certain organisms in treatment. Table 4-1 gives a summary of the types of Gram-negative bacteria found in wetland treatment systems, as well as some specific examples and descriptions (Kadlec and Knight, 1996).

Microbial analyses were performed using a Biolog™ MicroStation system (Release 3.50, 1993, Hayward, CA), which utilizes a database of over 1,000 microbial groups and species to identify the microbial content of a water sample via a microplate colorimeter. The MicroStation™ system has been used for identifying microorganisms in many environmental situations (Konopka et al., 1998; Boothe et al., 2001), as well as in the identification of heterotrophic microbial communities (Kersters et al., 1997), including

those existing in wastewater activated sludge (Guckert et al., 1996; van Heerden et al., 2001).

Table 4-1. Classification of Gram-negative Bacteria Important in Wetland Treatment Systems (Kadlec and Knight, 1996)

Group	*Representative Genera*	*Comments*
Gram-negative aerobic rods and cocci	*Pseudomonas, Zooglea, Azotobacter, Rhizobium*	*Pseudomonas* spp. denitrifies NO_2^- to N_2 under anaerobic conditions and can oxidize hydrogen gas; *Azotobacter* spp. is a nonsymbiotic N fixer; *Rhizobium* is a symbiotic N fixer
Gram-negative facultative anaerobic rods	*Escherichia, Salmonella, Shigella, Klebsiella, Enterobacter, Aeromonas*	*E. coli* is the predominant coliform in feces; *Salmonella* and *Shigella* are both human pathogens; *Klebsiella* and *Enterobacter* are nonsymbiotic N fixers and are in the total coliform group
Gram-negative anaerobic bacteria	*Desulfovibrio*	Reduces sulfate to hydrogen sulfide
Gram-negative chemolithotrophic bacteria	*Nitrosomonas, Nitrobacter, Thiobacillus*	*Nitrosomonas* catalyze the conversion of NH_4^+ to NO_2^-; *Nitrobacter* oxidize NO_2^- to NO_3^-; *T. ferrooxidans* oxidize ironsulfides producing Fe^{+3} and SO_4^{-2}

Constructed Wetland Site Description

The Tignall Water Reclamation Facility (Figure 4-1) is comprised of a duckweed (Lemna) system, a partial-mix aeration pond, and a polishing treatment wetland system (Tignall, GA; 33 º 52' 00" N, 82 º 44' 30" W; Pop. ~700). The facility handles the municipal wastewater from approximately 400 homes, several businesses, and two local factories (Davis, 2001), resulting in an average water use of approximately 45 gpcd (gallons per capita per day). The system receives municipal wastewater from the city at an average flow rate of 31,800 gal d^{-1} (120 m^3 d^{-1}). This secondary effluent treatment wetland follows a duckweed system and a partial-mix aerated pond, which operate in parallel prior to reaching the wetland.

The constructed wetland system (Figure 4-1) was designed in 1992 and constructed in 1993 by Precision Planning of Lawrenceville, GA, and consists of 8 cells each approximately 122 x 18 m bottom surface area and 131 x 21 m top surface area. Each cell is approximately 1.2 m deep, while the operating depth is between 0.08 to 0.30 m. Initially, two of the total eight cells were planted post-construction with *Schoenoplectus californicus* (giant bullrush) and *Zizaniopsis miliacea* (giant cutgrass), while in 1995, two additional cells were planted with *Schoenoplectus californicus* (giant bullrush) and *Typha latifolia* (cattail), and wastewater flow through the system was limited to the four planted cells. The latter constitutes typical operational procedures at the Tignall Water Reclamation Facility (Davis, 2001). In the summer months, however, rather than discharge, the operator will let wastewater flow through all eight cells and recirculate this wastewater through the wetlands until discharge is necessary.

Materials and Methods

Sample Collection and Preparation

Grab samples were taken in August, 2000, and February, 2001, in the first half of the first wetland cell at the Tignall facility (Figure 4-1 in red) in order to investigate

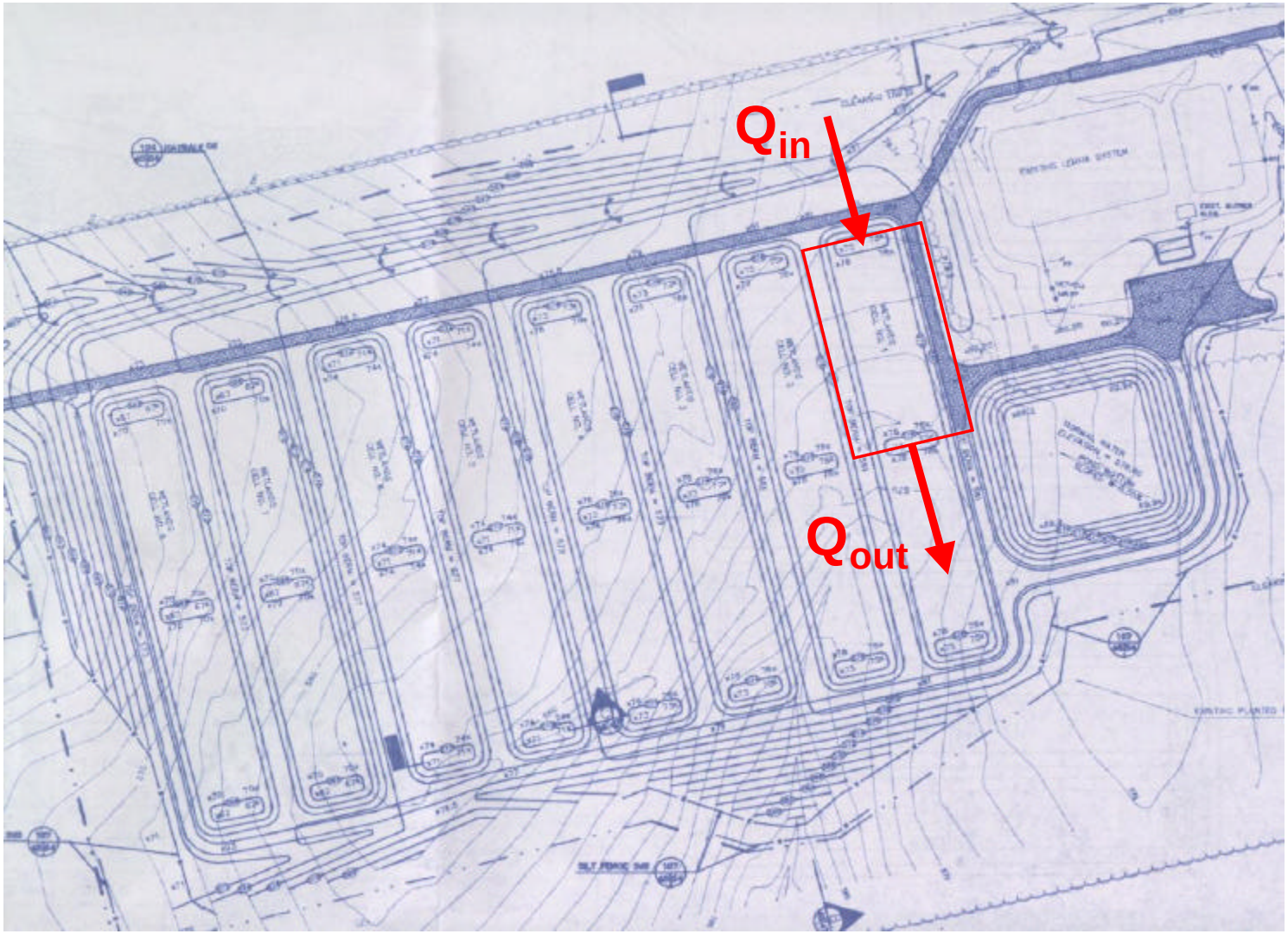


Figure 4-1. Layout of the Tignall Water Reclamation Facility (designed by Precision Planning Inc., Lawrenceville, GA). Diagram includes Lemna system (top right), partial mix aerated pond system (middle right), and constructed wetland system (center to left). The focal cell of this study is given by the designated area.

differences in bacterial populations in the summer and winter. Sample locations were selected based on previous work in the system, which demonstrated spatial and temporal variability of water quality parameters and nutrients, solids, and biochemical oxygen demand (BOD) concentrations throughout the studied part of the treatment wetland of interest. Grab samples of wastewater were collected at four locations along the flow gradient within the first half of the first cell of the treatment wetland (Figure 4-2). Samples were immediately placed on ice for transport and storage. These samples were used for microbiological analyses, biochemical oxygen demand (BOD), and solids analyses, including total, non-volatile, volatile, and total suspended solids (Clesceri et al., 1998). A second set of samples was collected for nutrient analyses at the same locations and preserved in 2 mL concentrated H_2SO_4 per liter of wastewater sample. Water quality measurements were taken at the location of each grab sample.

Water Quality Parameters

The following water quality parameters were measured at each location within the wetland cell: temperature (^oC) , conductivity ($\mu S\ cm^{-1}$), redox potential (ORP, mV), pH, and dissolved oxygen concentration ($mg\ L^{-1}$). These parameters were measured using a YSI 6820 data sonde and a YSI 610-D meter (Yellow Springs, OH). The sonde was calibrated for all parameters prior to each site visit.

Microbiological Analyses

Within 24 hours of sample collection, serial dilutions were conducted and culture plates prepared using the streak-plate method on plates containing Biolog™ Universal Growth Medium (BUGM™). Culture plates were incubated at 20^{o}C for 5-7 days. Bacterial densities were determined per milliliter wastewater sample in colony-forming units (cfu) using counts from plates that fell in the statistically valid range (30-300 cfu).

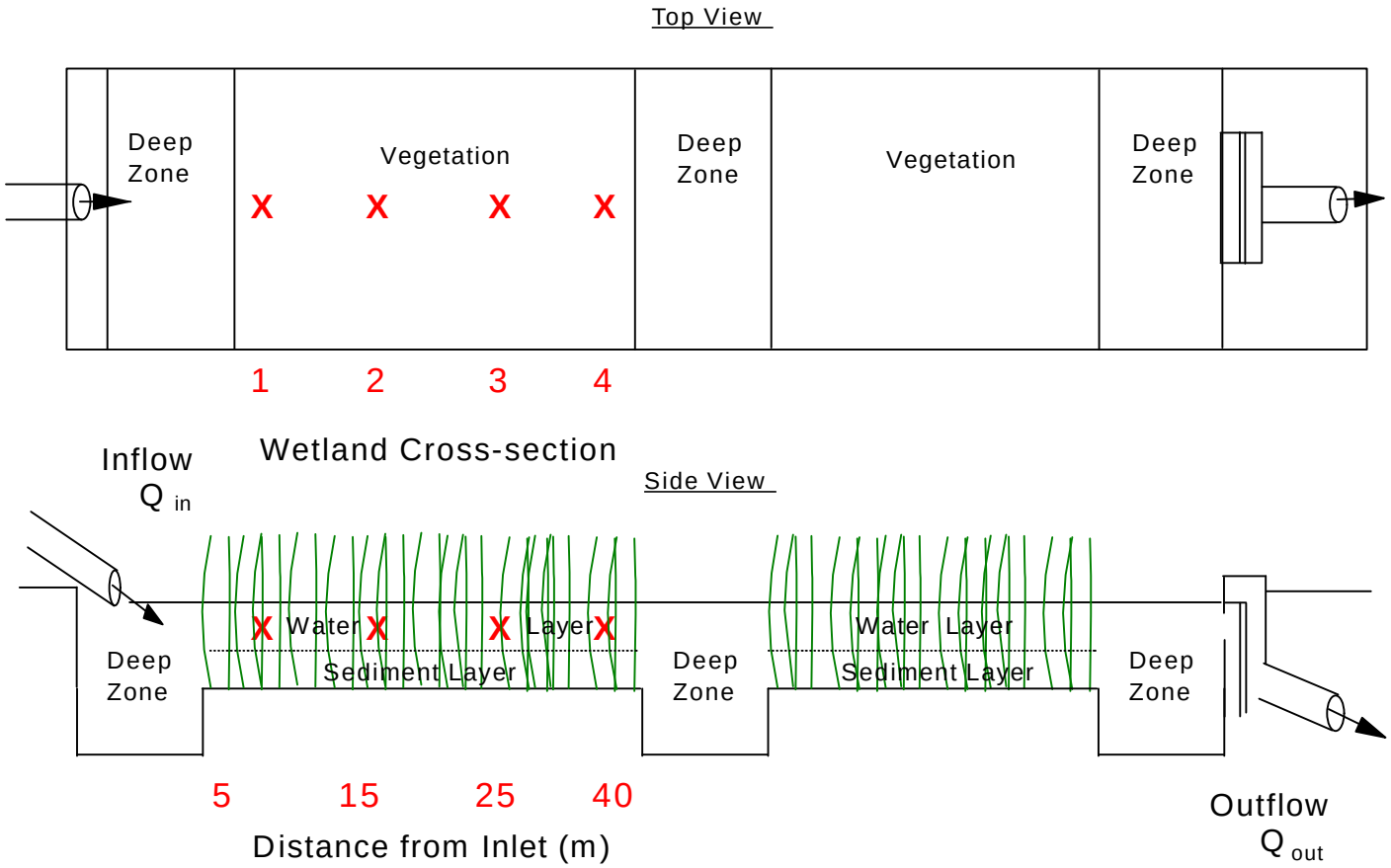


Figure 4-2. Physical Layout of Wetland Cell. Diagram of wetland cell showing locations and sections of monthly grab sample collection. (Not to scale). Distance of cross-sections from inflow pipe are, respective of the flow gradient, 5 m, 15 m, 25 m, and 40 m. Planted vegetation includes *Schoenoplectus californicus* (giant bullrush) and *Zizaniopsis miliacea* (giant cutgrass).

Also, bacterial isolates were prepared from these plates and incubated for another 5-7 days at 20°C. This procedure was repeated until bacterial isolation was ensured and no contamination was visible. Upon isolate preparation, the Gram type and morphology of each isolated organism was determined using an 18-24 hour culture on Plate Count Agar (Biolog™, 1993).

Biolog™ microplate inoculum preparation consisted of adding each isolate to a 0.85 % saline solution suspension tube, in which a given "turbidity" (50-60% of light transmission) was reached so that proper initial bacterial density was ensured. Each solution was then dispensed into a 96-well Biolog™ GN2 microplate with an 8-channel repeating multipipetter. The microplate were incubated for 18-24 hours at 30 °C before being placed into the plate reader for identification (Biolog™, 1993).

Solids and BOD Analyses

Analyses for total solids, volatile solids, and total suspended solids were performed using published standard methods (Clesceri et al., 1998). Non-volatile solids were calculated by subtracting volatile solids from total solids. Biochemical oxygen demand (BOD) analyses were also performed using published standard methods for water and wastewater analyses (Clesceri et al., 1998).

Nutrient Analyses

Ammonia-nitrogen (NH_3-N) , nitrate-nitrogen (NO_3) and orthophosphate (PO_4) concentrations were determined from acid-preserved samples using a TRAACS™ 2000 automated wet chemistry system with an XYZ model™ autosampler (Bran+Luebbe, Buffalo Grove, IL). For further nutrient concentration determination, water samples were digested in a $CuSO_4$ and sulfuric acid solution prior to Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (TP) analyses using TRAACS™. Quality assurance and quality control included correlation coefficient checks for known standards ($r^2 > 0.99$), dilution

checks (% difference < 5%), and duplicate control cup checks (% difference < 5%) throughout each run. If any of these controls were not met, the samples were run again.

Results

Conductivity and pH measurements were relatively similar at all locations for both months. Conductivity ranged from 550 to 650 μS cm^{-1}, while pH ranged from 6.5 to 7.2. Figure 4-3 shows temperature, dissolved oxygen, and redox potential, representing environmental conditions at locations where samples were taken for microbiological analyses. Figure 4-4 gives solids concentrations and biochemical oxygen demand (BOD) for each location by month. Figures 4-5 and 4-6 show nutrient concentrations for nitrogen and phosphorus compounds, respectively, for sampled locations by month.

Table 4-2 summarizes the Gram-negative bacteria that were identified by the Biolog™ MicroStation for given samples taken in August, 2000 and February, 2001.

Discussion

The types of aerobic and facultative anaerobic bacteria identified from the water samples collected from the wastewater wetland indicate a large diversity in microorganisms, which can be expected from an ecosystem with such high nutrient concentrations and such high potential for the decomposition of organic material.

Characteristics of Identified Bacteria

Acinetobacter species are considered to be nonpathogenic and are known to occur naturally in soil, water, and sewage (Krieg, 1984), although it has been estimated that only 0.001% of the total heterotrophic aerobic population in soil and water are acinetobacters (Baumann, 1968). They typically utilize D-glucose as the only hexose, but can utilize

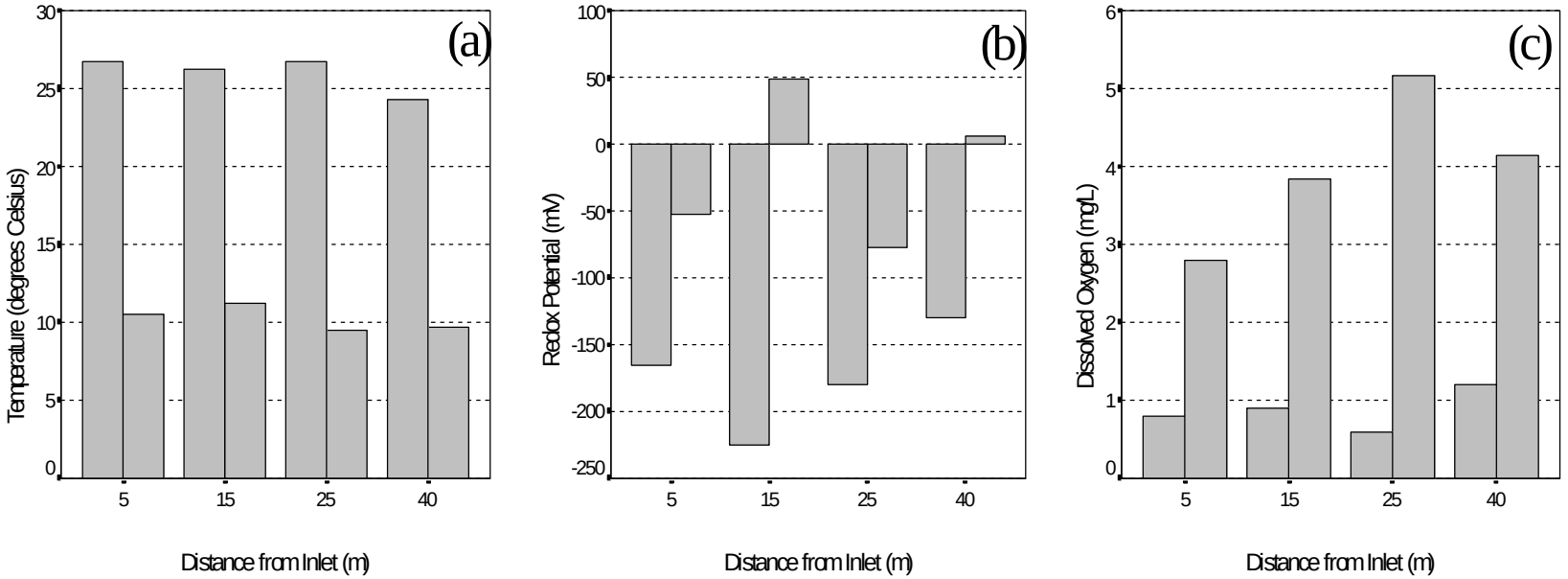


Figure 4-3. Water quality parameters at locations where samples were taken for microbiological analyses in August, 2000 (cross-hatched bars) and February, 2001 (solid bars), given in terms of distance from the wastewater inlet, as follows: (a) temperature; (b) dissolved oxygen, and (c) redox potential.

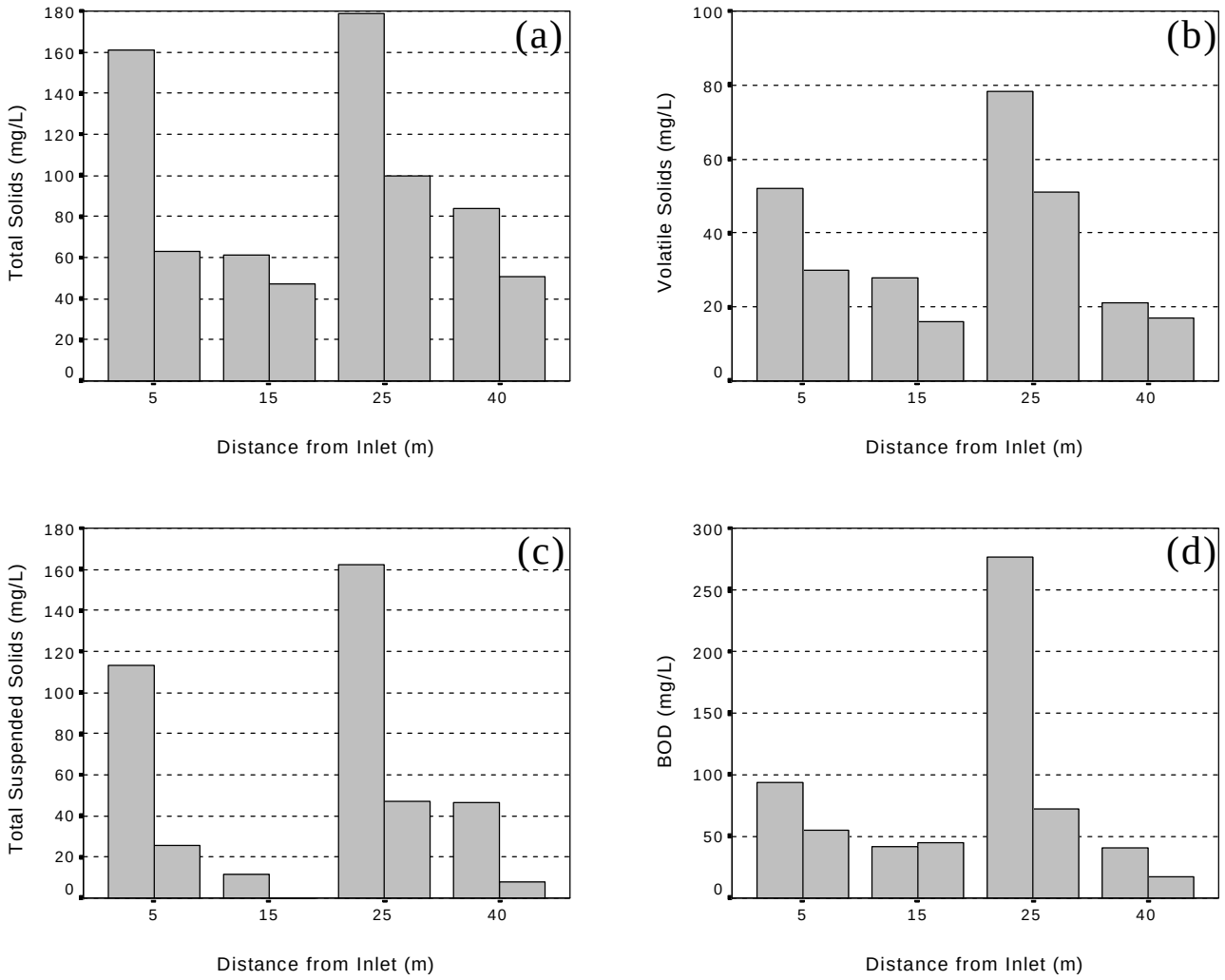


Figure 4-4. Solids concentrations and biochemical oxygen demand (BOD) for each location in August, 2000 (cross-hatched bars) and February, 2001 (solid bars): (a) total solids concentrations; (b) volatile solids concentrations, (c) total suspended solids concentrations, and (d) BOD concentrations.

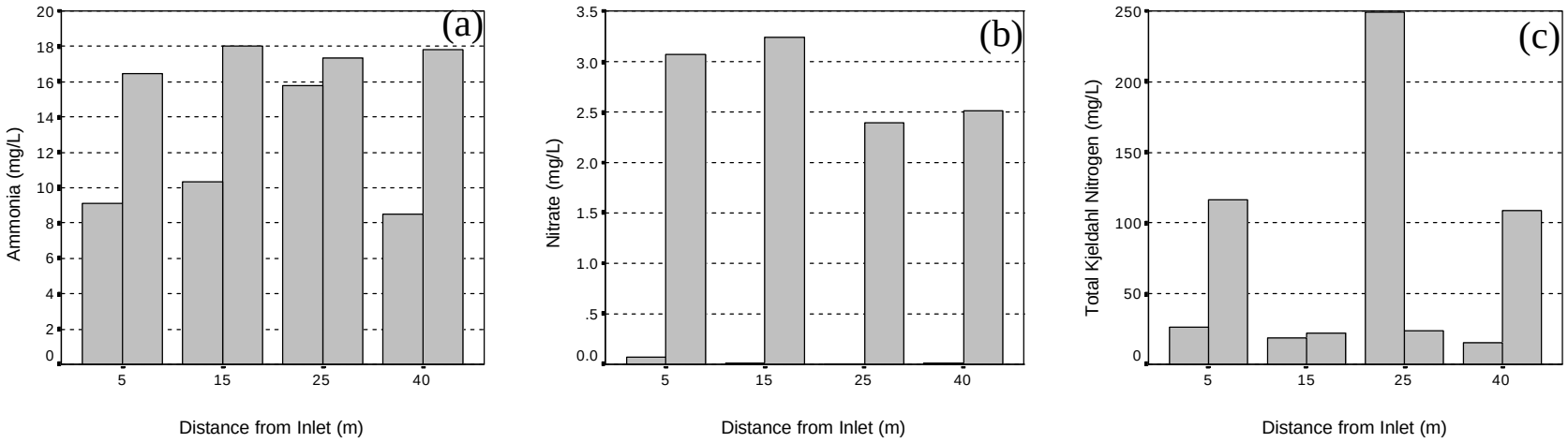


Figure 4-5. Nitrogen compound concentrations for sample locations in August, 2000 (cross-hatched bars) and February, 2001 (solid bars), given in terms of distance from wastewater inlet: (a) ammonia concentrations; (b) nitrate concentrations, and (c) total Kjeldahl nitrogen (TKN) concentrations.

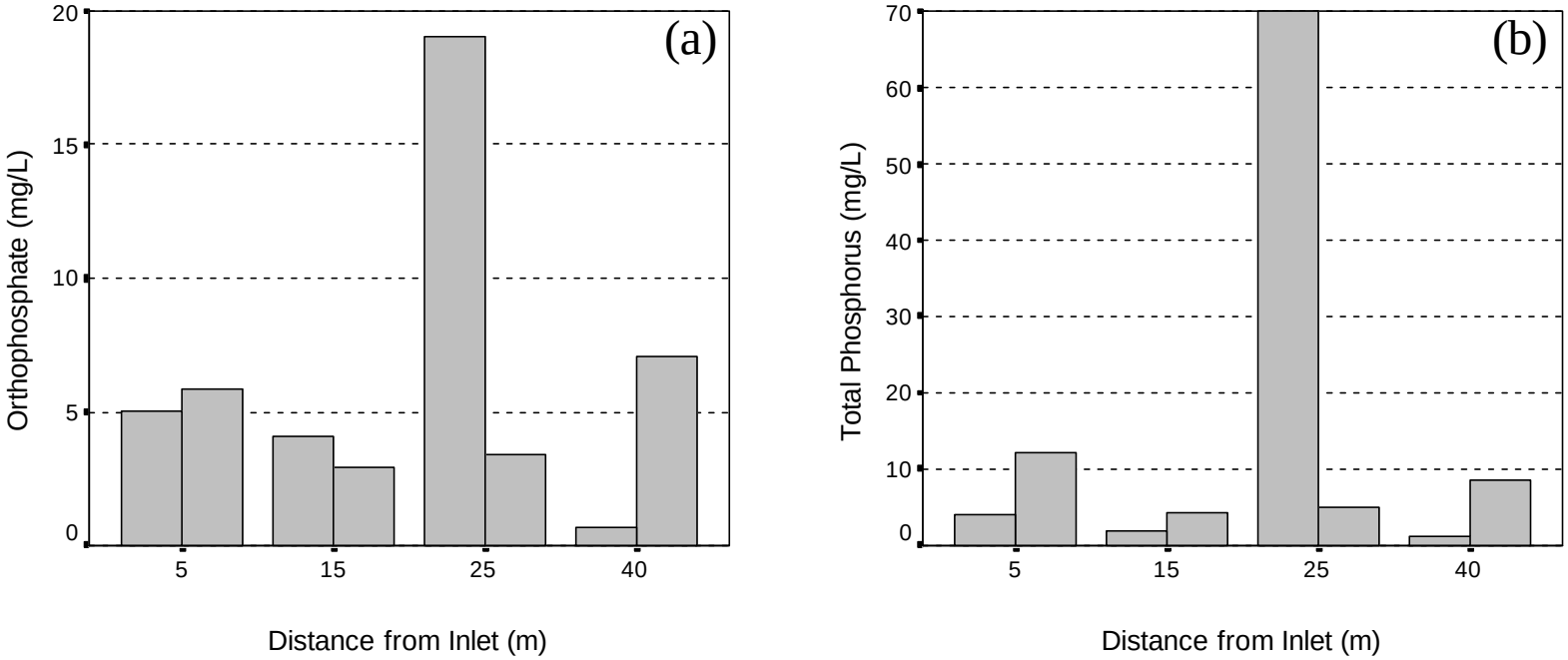


Figure 4-6. Phosphorus compound concentrations for sample locations in August, 2000 (cross-hatched bars) and February, 2001 (solid bars), given in terms of distance from wastewater inlet: (a) orthophosphate concentrations, and (b) total phosphorus (TP) concentrations.

many pentoses, including D-ribose, D-xylose, and L-arabinose (Krieg, 1984). *Acinetobacters* typically use ammonia as their nitrogen source.

Table 4-2. Results of Bacterial Identification Using Biolog™ MicroStation from Municipal Wastewater Wetland Samples Collected in Summer and Winter Months

Position	*August, 2000*	*February, 2001*
1	- *Acinetobacter* genospecies 14 - *Brevundimonas vericularis* - *Burkholderia cocovenenans* - *Escherichia vulneris* - *Pseudomonas fulva*	- *Burkholderia cocovenenans* - *Pseudomonas marginalis* - *synxantha* - *Vibrio harveyi*
2	- *Aquaspirillum peregrinum* ss. *integrum* - *Kluyvera ascorbata* - *Sphingobacterium thalpophilum*	- *Klebsiella pneumoniae ss. pneumoniae*
3	- *Acinetobacter johnsonii* - *Aeromonas hydrophilia* DNA group 1 - *Enterobacter asburiae* - *nimipressuralis* - *Pasteurella granulamatis* - *Pseudomonas aeruginosa* - *fluorescens* biotype G - *maculicola*	- *Burkholderia vietnamiensis* - *Citrobacter freundii* - *Escherichia coli* - *Pseudomonas aureofaciens*
4	- *Aeromonas hydrophilia* DNA group 1 - *Chryseobacterium gleum* - *Photobacterium logei* - *Salmonella* group 1 (*Choleraesuis*) - group 3A (*Arizonae*)	- *Achromobacter cholinophagum* - *Flavobacterium ferrugineum* - *Sphingobacterium thalpophilum* - *Vibrio tubiashii*

The *Escherichia* genus of bacteria., especially *E. coli*, is known as a potentially pathogenic bacteria closely associated with sewage, as well as water and soil quality in the natural environment (Krieg, 1984; Tchobanoglous and Schroeder, 1986). It is not surprising that the species of the *Escherichia* genus comprise a large number of bacteria

found in the wastewater wetland samples. These bacteria are facultative anaerobes, respiring acetate in the presence of oxygen and fermenting glucose and other carbohydrates into pyruvate under anaerobic conditions.

The *Pseudomonas* genus of bacteria is known to be one of the most complex groups of Gram-negative bacteria. The metabolism of *Pseudomonas* is typically respiratory with oxygen as the terminal electron acceptor (Krieg, 1984). *Pseudomonas* can oxidatively degrade low molecular weight organic compounds using oxygenases and can degrade a variety of macromolecules by means of extracellular enzymes (Krieg, 1984). Therefore, *Pseudomonas* species play a large role in the decomposition of organic matter in wastewater wetlands. Many species can also use nitrate as an alternate electron acceptor and can carry out oxygen-repressible denitrification (Krieg, 1984). This latter point is noteworthy for the existence of *Pseudomonas* in wastewater, considering that the denitrification process is partially responsible for the removal of nitrogen in wastewater wetlands. Bacterial species in the *Burkholderia* (Gillis et al., 1995) and *Brevundimonas* (Segers et al., 1994) genera were recently moved from the *Pseudomonas* genus, but exhibit the same metabolic characteristics.

Aquaspirillum species are aerobic bacteria that typically use amino acids or the salts of organic acids as carbon sources and ammonium salts as the nitrogen source. *Aquaspirillum pergrinum* is one species of this genus that is known to catabolize sugars (Krieg, 1984).

Kluyvera species are facultative anaerobes that ferment glucose and can reduce nitrate to nitrite. They are considered to be infrequent opportunistic human pathogens, and *Kluyvera ascorbata* is known to occur in food, water, and sewage (Krieg, 1984).

Aeromonas species are facultative anaerobes that metabolize glucose by both respiration and fermentation, as well as reduce nitrates to nitrite. They are known to occur in freshwater and sewage. Some species are pathogenic to frogs and fish (Krieg, 1984).

Enterobacter species are facultative anaerobes that ferment glucose, while citrate and malonate can be utilized as sole sources of carbon and energy. All *Enterobacter* species are found in the natural environment, including water, soil, and sewage (Krieg, 1984). Species of the *Enterobacter* genus are known to fix molecular nitrogen (Kadlec and Knight, 1996).

Pasteurella species are facultative anaerobes that are capable of fermentative metabolism and reduce nitrate to nitrite. These bacteria are parasitic on the mucous membranes of mammals (rarely human) and birds (Krieg, 1984).

Photobacterium species are capable of respiratory and fermentative metabolism, use ammonium salts as a nitrogen source, and do not denitrify nitrate or fix molecular nitrogen (Krieg, 1984).

Salmonella species are facultative anaerobic bacteria that reduce nitrate to nitrate. They are capable of respiring glucose, and they can use citrate as a sole carbon source. Salmonella species are human intestinal pathogens (Krieg, 1984).

Vibrio species are facultative anaerobes capable of both fermentative and respiratory metabolism. They do not denitrify nitrate or fix molecular nitrogen, and they use molecular oxygen as a universal electron acceptor. They are typically found in aquatic habitats (Krieg, 1984).

Klebsiella pneumoniae is a facultative anaerobe capable of both fermentative and respiratory metabolism. It can use citrate and glucose as a sole carbon source. *Klebsiella* pneumoniae is known to fix molecular nitrogen. It can occur in intestinal contents, as well as soil and water (Krieg, 1984).

Citrobacter freundii is a facultative anaerobe capable of both fermentative and respiratory metabolism. Members of the genus *Citrobacter* occur not only in the feces of humans and other animals with no disorder but also in water, sewage, soil, and food (Krieg, 1984).

Achromobacter species are obligately aerobic, possessing a strictly respiratory type of metabolism with oxygen as the terminal electron acceptor. However, some strains are capable of anaerobic respiration in the presence of nitrate or nitrite. *Achromobacter* occurs in soil and water and are commonly saprophytic (Krieg, 1984).

Flavobacterium species are aerobic bacteria with a strict respiratory type of metabolism. They are widely distributed in soil and water, as well as in raw meats, milk, and other foods. They do not reduce nitrate (Krieg, 1984). The species *Sphingobacterium thalpophilum* (Takeuchi and Yokota, 1992) and *Chryseobacterium gleum* (Vandamme et al., 1994) have been moved from the *Flavobacterium* genus, but they carry the same metabolic and pathogenic characteristics.

Water Quality Parameters and Identified Bacteria

Monitoring water quality measurements indicate the environmental conditions under which certain bacteria thrive in the wastewater wetland system. Typically, the rate of microbial activity is directly related to temperature; therefore, microbial numbers should be higher at higher temperatures. Figure 4-7a compares bacterial density between August, 2000, and February, 2001. Based on samples collected, the number of colony-forming units was much higher in the summer than in the winter for all locations except at 40 m from the inlet. Also in comparing seasons, more species were present in the summer. Twenty-one species total, or an average of 5.25 per location, were identified in August, 2000 (Table 4-2 and Figure 4-7b), where water temperatures averaged 25 ^{o}C (Figure 4-3a). Thirteen species total, or an average of 3.25 per location, were identified in February, 2001 (Table 4-2 and Figure 4-7b), where water temperatures averaged 10 ^{o}C (Figure 4-3a).

Dissolved oxygen and redox potential measurements show at what locations the system is aerobic, anoxic, or anaerobic, thus demonstrating the types of microbial activity that occur at these locations. Fluctuations in aerobic and anaerobic zones in the

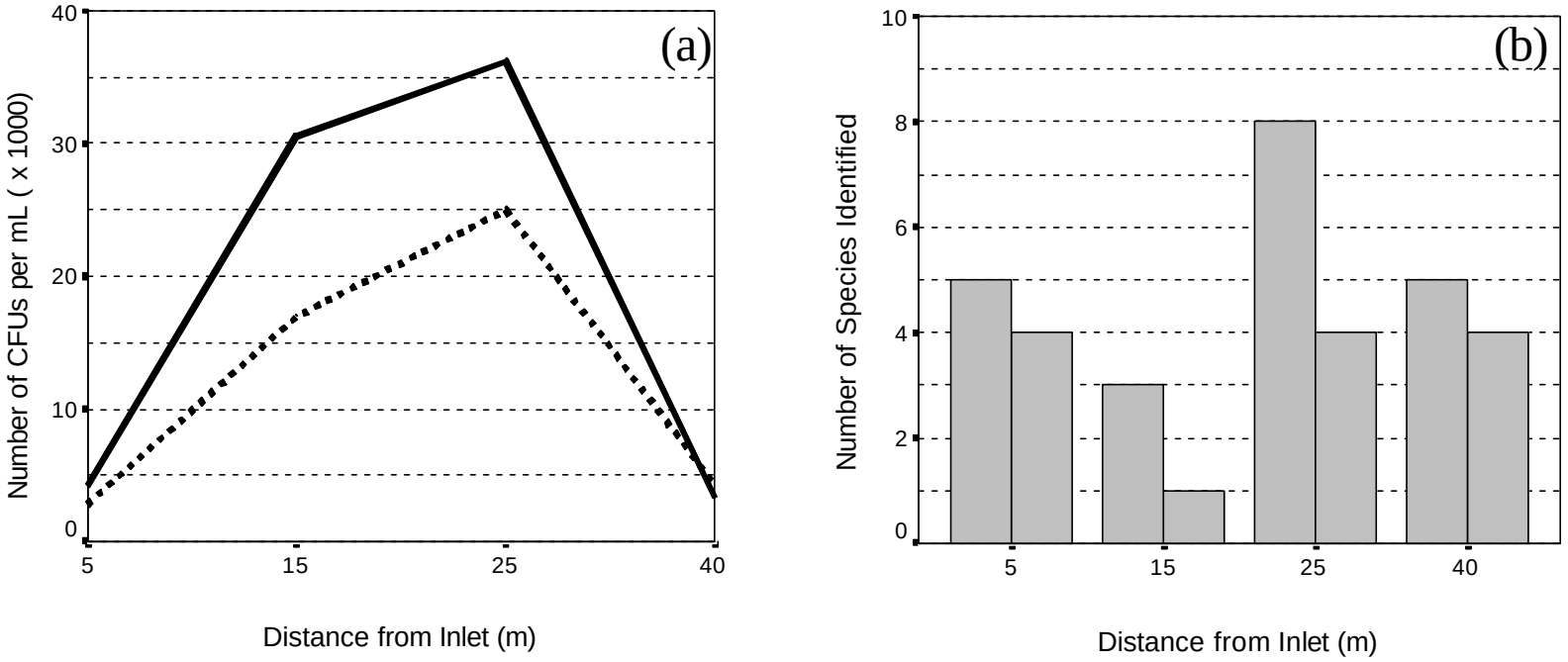


Figure 4-7. (a) Number of colony-forming units (cfu) per milliliter wastewater for samples from August, 2000 (solid line) and February, 2001 (dashed line), given by distance from wastewater inlet, and (b) number of different species identified from samples from August, 2000 (hatched bar) and February, 2001 (solid bar), given by distance from wastewater inlet.

water-sediment matrix over time can affect the types of microbial populations that exist in a given place and time in the wastewater wetland. In August, 2000, redox potentials averaged E_h = -170 mV with a range of -225 mV # E_h #-130 mV, while in February, 2001, redox potentials were higher, averaging E_h = -25 mV with a range of -77 mV # E_h # + 49 mV (Figure 4-3b). Reddy and Graetz (1988) have described the aerobic respiration zone to be E_h $ 300mV, the facultative anaerobic zone to be 0 mV # E_h # 300 mV, and the obligate anaerobic zone to be -300 mV # E_h # 0 mV. In comparing our redox potential data with these ranges, the wetland system appears to be operating under facultative anaerobic to anaerobic conditions. However, in August, 2000, dissolved oxygen concentrations averaged 0.8 mg L^{-1} with a range of 0.6 mg L^{-1} to 1.2 mg L^{-1}, while in February, 2001, dissolved oxygen concentrations averaged 4 mg L^{-1} with a range of 2.8 mg L^{-1} to 5.2 mg L^{-1} (Figure 4-3c). These concentrations indicate that some aerobic conditions must exist, especially in the winter month. Figure 4-8a shows percentages of facultative anaerobic and aerobic bacteria present in samples collected in August, 2000, while Figure 4-8b shows those percentages in samples collected in February, 2001. Aerobic bacterial percentages were higher (61.5%) in winter samples where redox potentials and dissolved oxygen concentrations were higher, compared to those samples from the summer (42.9%), where conditions in the sampled areas of the wetland were more anaerobic.

Solids, BOD, and Identified Bacteria

Measuring the solids concentrations in wastewater treatment wetland samples demonstrates the amount of organic material at different locations in the system. Volatile solids, in particular, are indicators of the degree that organic material is present in solids. Biochemical oxygen demand signifies the amount of oxygen-demanding organic material that exists in the system. This organic material is the food source of both aerobic and anaerobic bacteria. One would expect the bacterial diversity to be higher where higher organic material exists, since decomposers use this biomass as substrate. In both August,

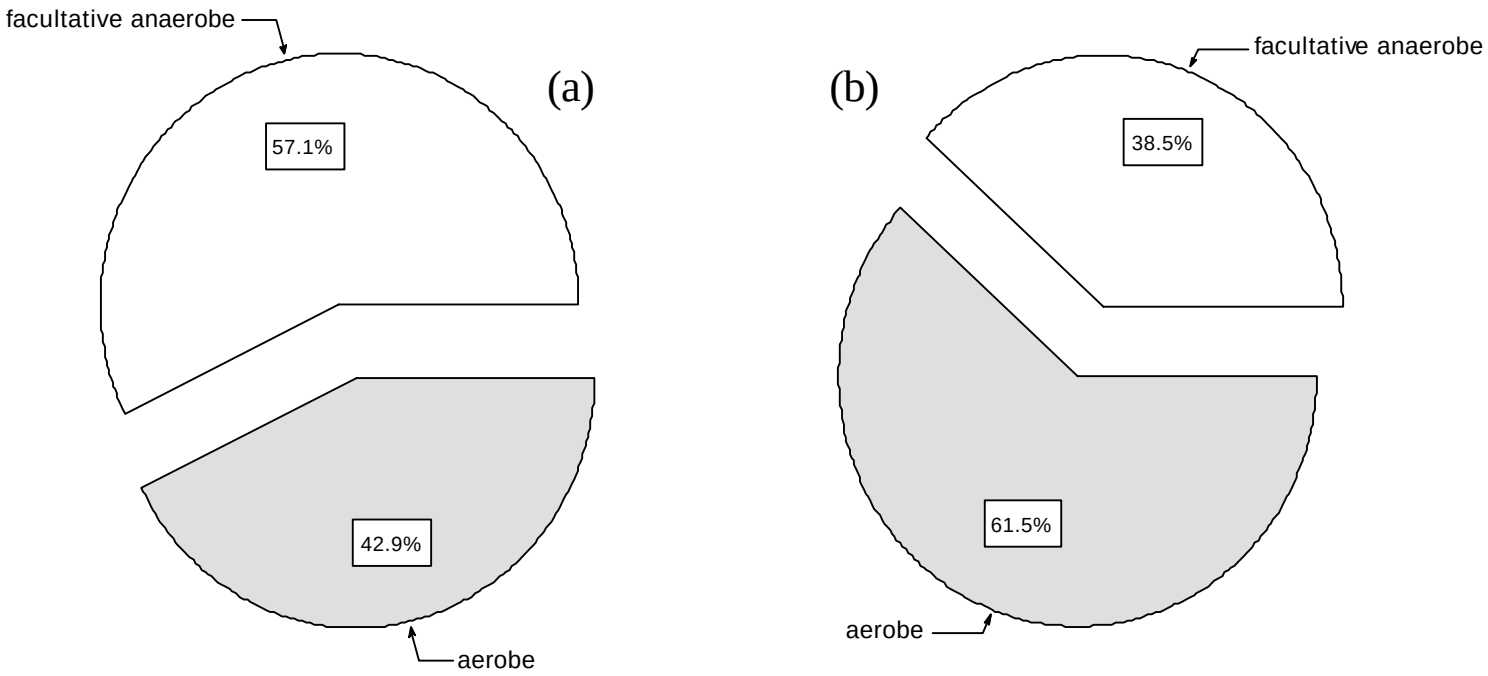


Figure 4-8. Percentages of aerobic and facultative anaerobic Gram-negative bacteria are given for (a) August, 2000 and (b) February, 2001.

2000 and February, 2001, the highest total solids, volatile solids, and total suspended solids, as well as the highest BOD, existed at 25 m from the wastewater inlet (Figures 4-4a-d). Notably, in both months where solids and BOD concentrations were highest, the bacterial density was highest. Also, when comparing the bacterial densities between months, the bacterial density was higher in August, 2000, when the corresponding solids concentrations were higher (Figures 4-4a-c). The Tignall Water Reclamation Facility has been spatially characterized, and it was determined that dead vegetation, including macrophytes and duckweed, contribute significantly to solids concentrations, and subsequently, to sludge accumulation. Therefore, sources of organic material include more than just the wastewater itself. Consequently, the contribution of dead vegetative biomass to solids concentrations and the subsequent relationship with microbial interactions are fundamental to the ecological processes occurring within the treatment wetland.

Nutrients and Identified Bacteria

The amount of certain nutrients appears to be related to the types of microbial populations identified from samples. In August, 2000, ammonia and nitrate concentrations were lower than concentrations in February, 2001 (Figure 4-5a and b). Figure 4-9 shows that the percentage of denitrifiers was higher in August, 2000 (57.1%), than the percentage in found in samples from February, 2001 (38.5%). These results suggest that higher populations of denitrifiers are responsible for lower concentrations of nitrate in the summer. However, the percentages of nitrifiers were similar between the two months. The percentage of nitrogen fixers was higher in February, 2001 (15.4%), than in August, 2000 (9.5%), suggesting that these nitrogen fixers are responsible for higher concentrations of ammonia in the winter. Percentages of bacteria with mixed nitrogen metabolic processes were higher in the winter (15.4%) compared to summer (4.8%), but the effects of such populations were indeterminable based on this study.

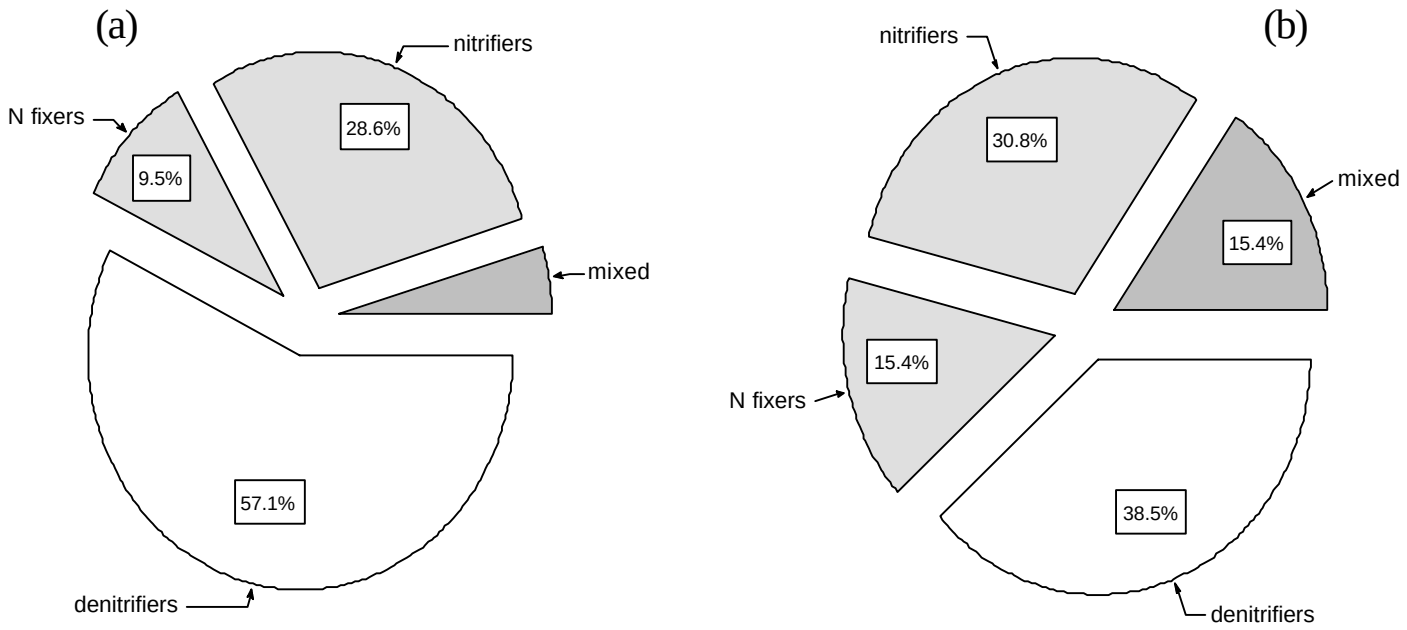


Figure 4-9. Percentages of denitrifying, nitrogen fixing, nitrifiying, and mixed Gram-negative bacteria are given for (a) August, 2000 and (b) February, 2001.

As previously discussed, dissolved oxygen concentrations and redox potential measurements give indication as to what depths the system is aerobic or anaerobic. Consequently, these measurements may be related to the types of microbial activity and nutrient fluxes that can occur at these depths. Nitrification typically occurs in the aerobic respiration zone (E_h $ 300mV), while denitrification occurs in the facultative anaerobic zone (0 mV # E_h # 300 mV) (Reddy and Graetz, 1988). Although redox potential measurements fell below these ranges, dissolved oxygen concentrations suggest that aerobic conditions, and thus nitrification, occurs within the wetland, as further evidenced by the presence of nitrifying bacteria (Figure 4-9a and b). This is true for facultative anaerobic conditions, as well. Further investigation is needed to understand the role of anaerobic bacteria in the treatment wetland.

In concurrent studies, positive correlations between solids concentrations and phosphorus concentrations have been determined at the Tignall Water Reclamation Facility. As was the case with solids distribution from the wastewater inlet, phosphorus concentrations in August, 2000 were highest at 25 m from the inlet (Figures 4-6a and b). Similarly, bacterial densities were highest at 25 m from the inlet in August, 2000 (Figure 4-7a). This trend was not seen in February, 2001, however, where the highest phosphorus concentrations and bacterial densities existed at different distances along the flow gradient. Because the understanding of how the presence of certain bacteria utilize phosphorus in aquatic systems is limited, it is difficult to comment on relationships between the types of bacteria and phosphorus concentrations.

Pathogenic Versus Non-pathogenic Bacteria

Figure 4-10a and 4-10b give percentages of pathogenic and non-pathogenic bacteria for August, 2000 and February, 2001, respectively. The percentage of pathogens was higher in August, 2000 (19.0%) compared to that of February, 2001 (7.7%). The

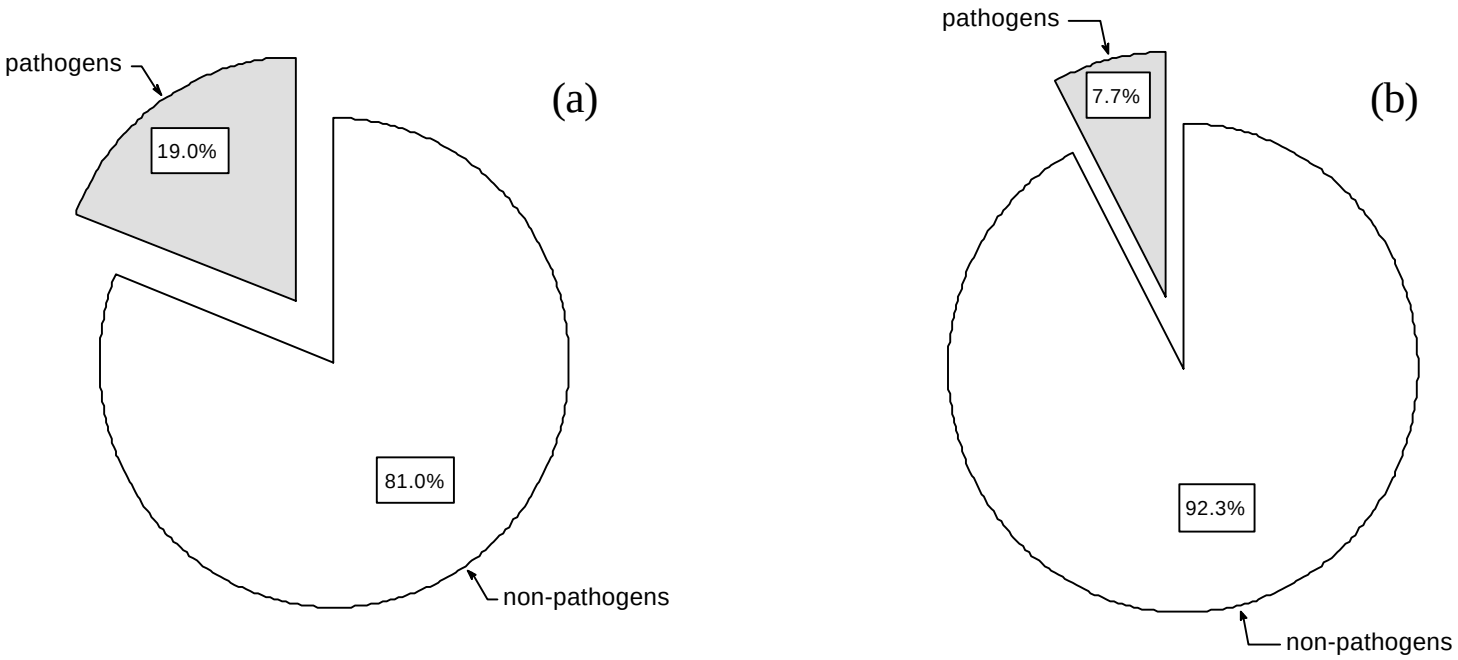


Figure 4-10. Percentages of Gram-negative bacteria that are pathogenic and not pathogenic to humans are given for (a) August, 2000 and (b) February, 2001.

presence of more pathogenic bacteria in the summer may be related to the fact that more pathogenic bacteria identified in this study are facultative anaerobes, and facultative anaerobes were found to be higher in number in summer samples, as previously discussed. Further work is needed to better understand the fate of pathogens in wastewater treatment wetland systems.

Although reproducibility in microbiological identification through the collection of environmental samples is often questionable, this study provides an initial snapshot into the microbial ecology of a wastewater wetland under varying environmental conditions. Future directions should include identifying obligate anaerobic Gram-negative bacteria, all Gram-positive bacteria, and microorganisms other than bacteria, as well as their role in the microbial consortium and in wastewater treatment. Also, more monthly samples should be taken in order to better understand seasonal oscillations in microbial population dynamics and activity. Finally, because metabolic conditions vary so quickly with depth (decreased aerobic activity with increased depth), depth profiles should be coordinated with microbial samples to get a better sense of population variability in the water-sediment matrix.

Conclusions

This study provides some insight into the relationships between environmental conditions and types of bacterial populations in a wastewater treatment wetland. Data suggest that temperature, redox potential, and dissolved oxygen concentrations affect the numbers and types of bacteria. The microbial ecology also appeared to be affected by solids and nutrient concentrations.

The exploration and characterization of microbial populations in the constructed wetland system provided information regarding the identification of Gram negative bacteria, and the functional role of these bacteria in wastewater treatment was assessed. Both obligate aerobic and facultative anaerobic bacteria were found to be present in the

wetland system, indicating a range of aerobic and anaerobic conditions that exist in the wetland. Varying dissolved oxygen concentrations and redox potentials further indicated this range of conditions. Nitrifying bacteria, denitrifying bacteria, and nitrogen fixing bacteria were all present in the wetland.

Relationships between the types of bacteria and water quality parameters such as temperature, dissolved oxygen concentration, and redox potential were explored. Results indicated that higher microbial activity occurred during the summer than in the winter. In the summer, when oxygen may be limited, there was a higher percentage of facultative anaerobic bacteria than in the winter. Also, a higher percentage of denitrifying bacteria were present in the summer than in the winter, reflecting anaerobic conditions because denitrification is known to be favorable under oxygen-limited conditions.

Relationships between the types of bacteria present in the system and solids, BOD, and nutrient concentrations were assessed. In the summer, solids concentrations were higher, indicating a higher presence of organic matter and, subsequently, anaerobic conditions. Also, BOD concentrations were higher in the summer, reflecting more anaerobic conditions. As previously discussed, facultative anaerobic bacteria and denitrifying bacteria were higher in the summer than in the winter. In the summer, both ammonia and nitrate concentrations were lower than in the winter, indicating higher nitrification and denitrification microbial activity in the summer. Ammonia concentrations were twice as high in winter than in summer, while nitrate concentrations were three times as high in winter than in summer. The results indicated favorable nitrification in the winter, and favorable denitrification in the summer.

In conclusion, this study provided an initial snapshot into the microbial ecology of a wastewater wetland under varying environmental conditions. Better understanding of the contribution of bacteria to wastewater wetland treatment performance, the environmental factors affecting this performance, and the fate of pathogenic bacteria in wastewater wetlands deserves further exploration.

References

Baumann, P. 1968. Isolation of *Acinetobacter* from soil and water. *J. Bacteriol.*, 96:39-42.

Biolog™. 1993. Biolog™ MicroStation System Release 3.50 User's Manual. Haywood, CA.

Boothe, D. D. H., Smith, M. C., Gattie, D. K., and K. C. Das. 2001. Characterization of microbial populations in landfill leachate and bulk samples during aerobic bioreduction. *Adv Environ Res*, in press.

Brix, H. 1993. Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL, pp. 9-22.

Canale, R. P. 1976. Modeling Biochemical Processes in Aquatic Ecosystems. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Clesceri, L. S., A. E. Greenberg, and A. D. Eaton (Eds.). 1998. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, American Water Works Association and Water Pollution Control Federation, Washington, D. C.

Davis, C. 2001. Personal communication. Tignall Water Reclamation Facility superintendent, Tignall, GA.

Georgia Department of Natural Resources (GA DNR). 1995. Guidelines for Constructed Wetlands for Municipal Wastewater Treatment Facilities. Environmental Protection Division, Water Protection Branch, Atlanta, GA.

Gillis, M., Vanvan, T., and R. Bardin. 1995. Polyphasic taxonomy in the genus *Burkholderia* leading to an emended description of the genus and proposition of *Burkholderia vietnamiensis* sp-nov for N-2-fixing isolates from rice in Vietnam. *Int. J. Syst. Bacteriol*., 45:274-289.

Guckert, J. B., G. J. Carr, T. D. Johnson, B. G. Hamm, D. H. Davidson, and Y. Kumagai. 1996. Community analysis by Biolog: curve integration for statistical analysis of activated sludge microbial habitats. *Journal of Microbiological Methods*, 27: 183-197.

Hammer, D. A. (Ed.). 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Inc., Boca Raton, FL.

Heliotis, F. D., and C. B. DeWitt. 1983. A conceptual model of nutrient cycling in wetlands used for wastewater treatment: a literature analysis. *Wetlands*, 3: 134-152.

Howard-Williams, C. 1985. Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective. *Freshwater Biol.*, 15: 391-431.

Kadlec, R. H., and J. A. Kadlec. 1979. Wetlands and Water Quality. In: Grecian, P. E., J. R. Clark, and J. E. Clark (Eds.). 1979. Wetland Functions and Values: the State of Our Understanding. American Water Resources Association, Minneapolis, MN, pp. 436-456.

Kadlec, R. H., and R. L. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL.

Kersters, I., L. Van Vooren, L. Verschuere, A. Wouters, J. Mergaert, J. Swings, and W. Verstraete. 1997. Utility of the Biolog System for the Characterization of Heterotrophic Microbial Communities. *System Appl. Microbiol*., 20: 439-447.

Klopatek, J. M. 1978. Nutrient Dynamics of Freshwater Riverine Marshes and the Role of Emergent Macrophytes. In: Good, R. E., D. F. Whigham, and R. L. Simpson (eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential, Academic Press, New York, NY, pp. 195-216.

Konopka, A., Oliver, L., and R. F. Turco. 1998. The use of carbon substrate utilization patterns in environmental and ecological microbiology. *Microbial Ecology*, 35 (2):103-115.

Krieg, N. R., (ed). 1984. Bergey's Manual of Systematic Bacteriology, Vol.1. J. G. Holt, editor-in-chief. Williams & Wilkins Publishing Co., Baltimore, MD.

Reddy, K. R., and D. A. Graetz. 1988. Carbon and Nitrogen Dynamics in Wetland Soils. In: Hook, D. D., et al., (Eds.), The Ecology and Management of Wetlands, Vol. 1: Ecology of Wetlands. Timber Press, Portland, OR., pp. 307-318.

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

Segers, P., Vancanneyt, M., and B. Pot. 1994. Classification of *Pseudomonas diminuta* (Leifson and Hugh, 1954) and *Pseudomonas vesicularis* (Busing, Doll, and Freytag, 1953) in *Brevundimonas* Gen-nov as *Brevundimonas diminuta* comb-nov and *Brevundimonas vesicularis* Comb-nov, respectively. *Int. J. Syst. Bacteriol*., 44:499-510.

Takeuchi, M. and A. Yokota. 1992. Proposals of *Sphingobacterium faecium* sp-nov, *Sphingobacterium piscium* sp-nov, *Sphingobacterium heparinum* comb-nov, *Sphingobacterium thalpophilum* Comb-nov and 2 genospecies of the genus *Sphingobacterium*, and synonymy of *Flavobacterium yabuuchiae* and *Sphingobacterium spiritivorum*. *J. Gen. Appl. Microbiol*., 38:465-482.

Tchobanoglous, G., and E. D. Schroeder. 1987. Water Quality: Characteristics, Modeling, Modification. Addison-Wesley Publishing Co., Reading, MA.

U. S. Environmental Protection Agency. 1987. Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal. Office of Water , Washington, D. C. EPA/430/09-88-055.

U. S. Environmental Protection Agency. 1988. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. Office of Water , Washington, D. C. EPA/625/1-88/022.

U. S. Environmental Protection Agency. 2000. Constructed Wetlands Treatment of Municipal Wastewaters. National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH. EPA/625/R-99/010.

Valiela, I., and J. M. Teal. 1978. Nutrient Dynamics: Summary and Recommendations. In: Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY, pp. 259-263.

Vandamme, P., Bernardet, J. F., and P. Segers. 1994. New perspectives in the classification of the *Flavobacteria* - description of *Chryseobacterium* gen-nov, *bergeyella* gen-nov, and *empedobacter* nom rev. *Int. J. Syst. Bacteriol*., 44:827-831.

van Demark, P. J., and B. L. Batzing. 1987. The Microbes: An Introduction to Their Nature and Importance. Benjamin/Cummings Publishing Co., Menlo Park, CA, pp. 905-914.

van Heerden, J., Ehlers, M. M., and T. E. Cloete. 2001. Biolog for the determination of microbial diversity in activated sludge systems. *Water Sci. Technol.*, 43 (1): 83-90.

Vymazal, J. 1995. Algae and Element Cycling in Wetlands. Lewis Publishers, Boca Raton, FL.

Wetzel, R. G. 1993. Constructed Wetlands: Scientific Foundations are Critical. In: Moshiri, G. A., Ed., Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 3-7.

CHAPTER 5

NUTRIENT MODELING OF A MUNICIPAL WASTEWATER TREATMENT WETLAND IN THE GEORGIA PIEDMONT[3]

[3]Hitchcock, D. R., and M. C. Smith. 2001. To be submitted to *Ecological Engineering*.

Abstract

This study uses a nutrient modeling approach to estimate and evaluate rate constants for specific physical, chemical, and biological processes in a constructed wastewater wetland in north Georgia. Physiochemical and biological rate constants have been estimated and were used to predict treatment performance given the following inputs: 1) influent nutrient concentrations and flow rates; 2) seasonal climatological data (temperature and evapotranspiration), and 3) seasonal vegetation growth. In order to describe, summarize, and estimate the processes governing the wetland treatment of wastewater, the overall treatment system has been modeled with respect to vegetation growth, nutrient cycling, and hydrological relationships. The model simulated carbon, nitrogen, and phosphorus balances, the concentrations of which are related by nutrient mass balances and a volumetric hydrologic component. State variables included vegetation (live shoot, root, standing dead), litter, sediment, and inorganic nutrient compartments. STELLA® software was used for all simulations. Calibration and validation were performed using actual data from the Tignall Water Reclamation Facility in northeast Georgia. The overall objective of this study was to better understand and estimate the rates of processes responsible for wetland treatment performance in the Georgia Piedmont.

Introduction

Constructed wastewater wetland systems have been proven to be successful tools for nutrient removal from wastewater (Tilton et al., 1976; Klopatek, 1978; Kadlec and Kadlec, 1979; U. S. EPA, 1983; U.S. EPA, 1987; U.S. EPA, 1988; Hammer, 1989; Johnston, 1993; Moshiri, 1993; Reed et al., 1995; Kadlec and Knight, 1996; U.S. EPA, 2000). Nutrient behavior in wetland systems has been characterized (Good et al., 1978; Valiela, and Teal,1978; Howard-Williams, 1985; Reddy and Graetz, 1988; Brix, 1993; Vymazal, 1995) and modeled extensively (Jørgenson et al., 1975; Mitsch et al., 1982;

Heliotis and DeWitt, 1983; Costanza and Sklar, 1985; Brown, 1988; Jørgenson, 1988a; Jørgenson, 1988b; Jørgenson et al., 1988; Kadlec and Hammer, 1988; Mitsch et al., 1988; Qian and Reckhow, 1998). STELLA® software (HPS, 1998) has been used to model nutrient dynamics in constructed wetlands (Mitsch et al., 1988; Mitsch and Reeder, 1991; Jørgenson, 1994; Mitsch et al., 1995; Martin and Reddy, 1997). Presently, many wastewater treatment facility designers in the state of Georgia use a first-order kinetics model based on biochemical oxygen demand (BOD) and temperature to design treatment wetland systems (GA DNR, 1995). Kadlec (2000) has recently described the inadequacy of first-order relationships in treatment wetland models. Kadlec makes the argument that model parameters (rate constants) are typically regarded as true constants and do not depend on factors such as hydraulic loading rate and influent concentrations. Kadlec follows his argument by presenting a test wetland simulation that takes into consideration vegetation resistance, treatment effects of vegetation, and retention time distributions (Kadlec, 2000).

In many free water surface wetland systems, dead organic material accumulates in shallow areas of the system, leading to preferential flow and a substantial decrease in retention time. This conceptual cause and effect relationship has led to the development of a compartmentalized model that partitions nutrients into aquatic, vegetation, and sediment components. Rates of biological treatment processes within the system, such as nitrification-denitrification and plant uptake, were estimated using relationships that consider seasonal patterns in evapotranspiration, temperature, dissolved oxygen concentrations, and plant growth characteristics. Rates of physiochemical processes, such as phosphorus adsorption to sediment, were also estimated.

Constructed Wetland Site Description

The Tignall Water Reclamation Facility (Figure 5-1) is comprised of a duckweed (Lemna) system, a partial-mix aeration pond, and a polishing treatment wetland system

(Tignall, GA; 33° 52' 00" N, 82° 44' 30" W; Pop. ~700). The facility handles the municipal wastewater from approximately 400 homes, several businesses, and two local factories (Davis, 2001), resulting in an average water use of approximately 45 gpcd (gallons per capita per day). Table 5-1 provides typical operating flows and concentrations throughout parts of the system. Table 5-2 gives NPDES permitted limits for wastewater discharge from the Tignall wastewater reclamation facility. The system receives municipal wastewater from the city at an average flow rate of 31,800 gal d^{-1} (120 m^3 d^{-1}). This secondary effluent treatment wetland follows a duckweed system and a partial-mix aerated pond, which operate in parallel prior to reaching the wetland.

The constructed wetland system (Figure 5-1) was designed in 1992 and constructed in 1993 by Precision Planning of Lawrenceville, GA, and consists of 8 cells each approximately 122 x 18 m bottom surface area and 131 x 21 m top surface area. Each cell is approximately 1.2 m deep, while the operating wastewater depth is between 0.08 to 0.30 m. The vegetated area of planted cells is approximately 50 x 18 m. Initially, two of the total eight cells were planted post-construction with *Schoenoplectus californicus* (giant bullrush) and *Zizaniopsis miliacea* (giant cutgrass), while in 1995, two additional cells were planted with *Schoenoplectus californicus* (giant bullrush) and *Typha latifolia* (cattail), and wastewater flow through the system was limited to the four planted cells. The latter constitutes typical operational procedures at the Tignall Water Reclamation Facility. In the summer months, however, rather than discharge, the operator allows wastewater to flow through all eight cells and recirculate this wastewater through the wetlands until discharge is necessary.

The constructed wetland system within the Tignall Water Reclamation Facility has previously been spatially characterized through water quality monitoring and nutrient analyses. Seasonal oscillations in ammonia and nitrate concentrations within the wetland shows that treatment performance can be affected by several factors, including temperature, dissolved oxygen concentrations, and vegetation characteristics. The

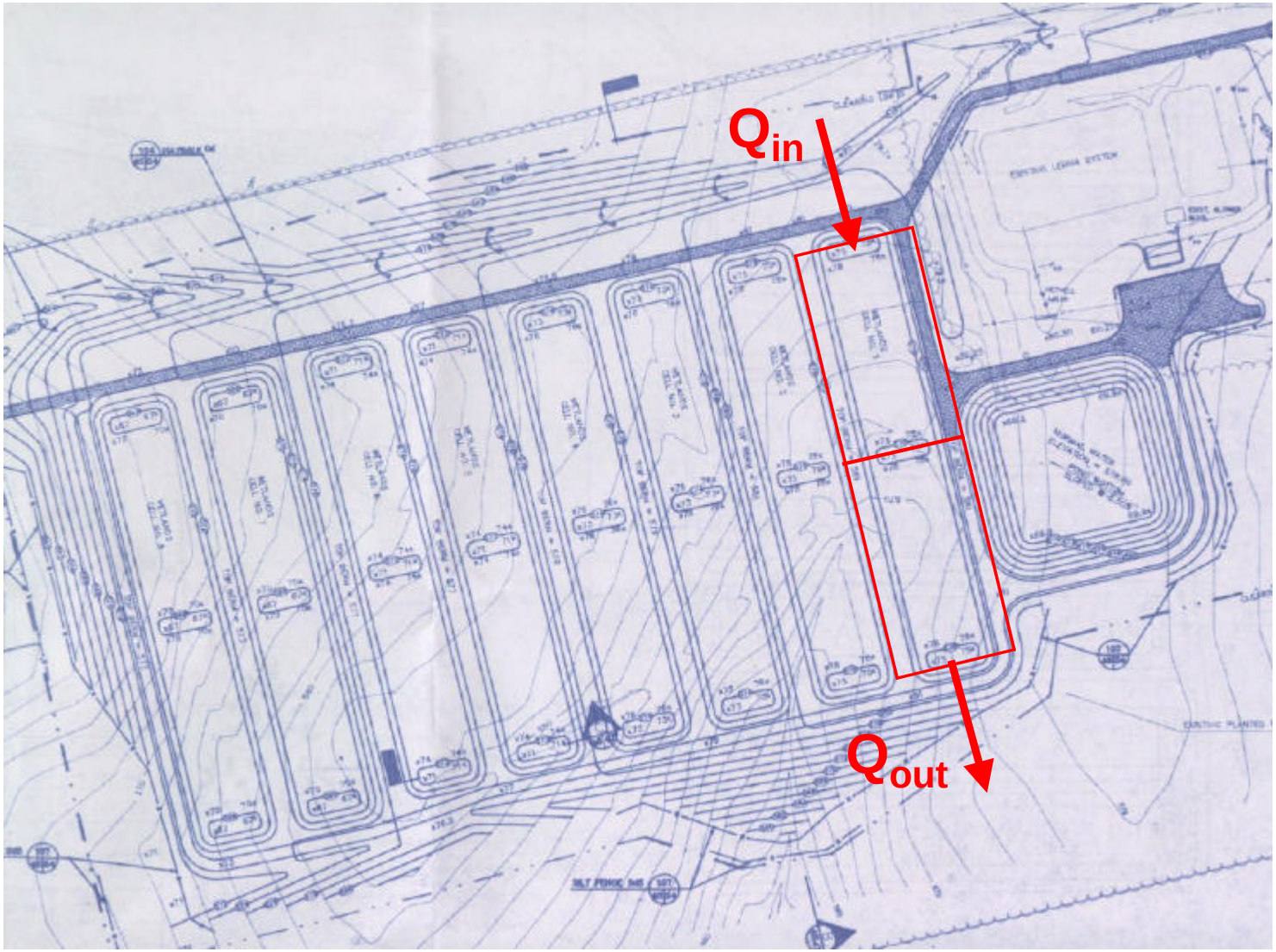


Figure 5-1. Layout of the Tignall Water Reclamation Facility (designed by Precision Planning Inc., Lawrenceville, GA). Diagram includes Lemna system (top right), partial mix aerated pond system (middle right), and constructed wetland system (center to left). The focal cell of this study is given by the designated area.

Table 5-1. Average, Minimum, and Maximum Operating Characteristics for Wetland System of the Tignall Wastewater Reclamation Facility During the Sampling Period from May, 1999 to April, 2001 (Davis, 2001).

Wastewater Characteristic	*Average*	*Minimum (month-year)*	*Maximum (month-year)*
Inflow (gal d^{-1})	31,800	3,700 (May-99)	69,700 (Dec-99)
Outflow (gal d^{-1})	20,620[a] / 9,860[b]	1,100[c] (Dec-99)	66,200 (Feb-00)
Influent BOD (mg L^{-1})	182.4	83 (Feb-00)	266 (Dec-99)
Effluent BOD (mg L^{-1})	7.8	1.7 (Feb-00)	20 (Jan-00 and Jan-01)
Influent TSS (mg L^{-1})	115.1	16 (Feb-00)	220 (Apr-00)
Effluent TSS (mg L^{-1})	4.9	2 (Dec-99, Jan-00, Feb-00 and Mar-00)	13 (Oct-00)
Influent NH_3 (mg L^{-1})	18.7	5.6 (Apr-01)	28 (Dec-00)
Effluent NH_3 (mg L^{-1})	1.6	<0.03 (May-00 and Apr-01)	5.9 (May-99)

[a] not including months without discharge
[b] including months without discharge
[c] does not consider months without discharge

proposed model in this chapter was used to investigate the effects of these factors on the nutrient dynamics of the system.

Table 5-2. NPDES Discharge Limits for Tignall Wastewater Reclamation Facility.

Water Quality Parameter	*Discharge Limit (mg L^{-1})*
BOD	10
TSS	20
NH_3	4

Materials and Methods

Model Development

A nutrient budget was developed based on a mass balance controlled by a hydrologic component, where outflow concentrations were simulated while also taking into account nutrient accumulation in the system due to plant uptake or adsorption to sediment. Processes that affect the transformation of carbon, nitrogen, and phosphorus in wetland systems were simulated, including organic carbon decomposition, nitrification, denitrification, phosphorus sorption to sediment, and plant uptake. Internal environmental controls that affect nutrient transformations were simulated, including those based on temperature and dissolved oxygen concentrations. External controls that affect the hydrologic wetland conditions, including precipitation and evapotranspiration, were also incorporated into simulations.

A water budget (Figure 5-2) and mass balances in the water column for carbon, nitrogen, and phosphorus (Figures 5-3 through 5-5, respectively) have been defined for the system. The model control volume included not only the water column, but also vegetation and sediment. Consequently, the sediment-water interface and vegetation were considered to be within the wetland control volume. Figure 5-6 shows the

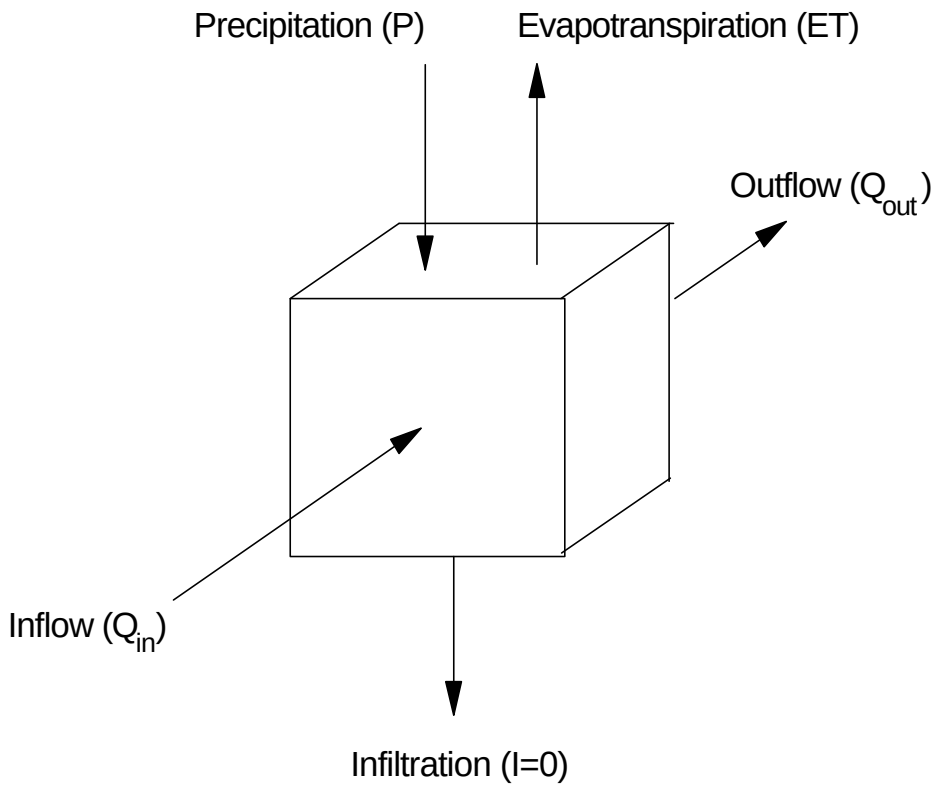


Figure 5-2. Flow diagram showing water balance of a typical constructed wetland system. Note that percolation and infiltration are considered to be negligible compared to other hydrologic processes. Also note that recirculated effluent results in a combined inflow of Q_{in} + Q_{out}.

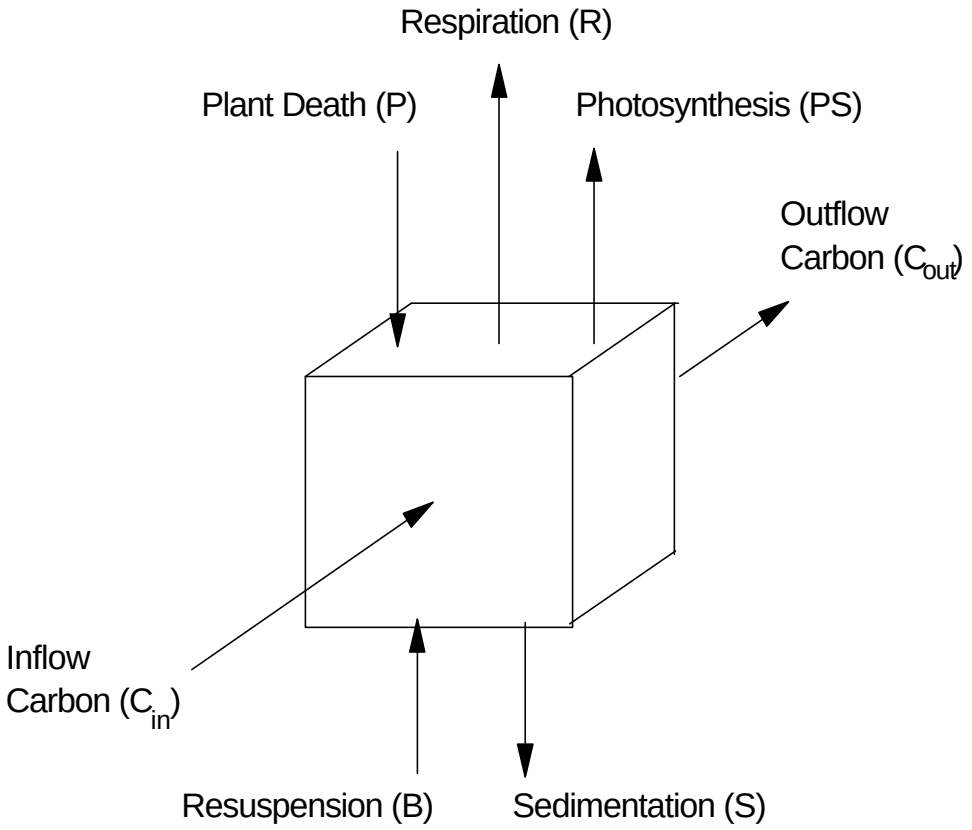


Figure 5-3. Flow diagram of external carbon fluxes considering only the water column as the control volume. Note that recirculated effluent results in a combined carbon mass inflow of $C_{in} + C_{out}$.

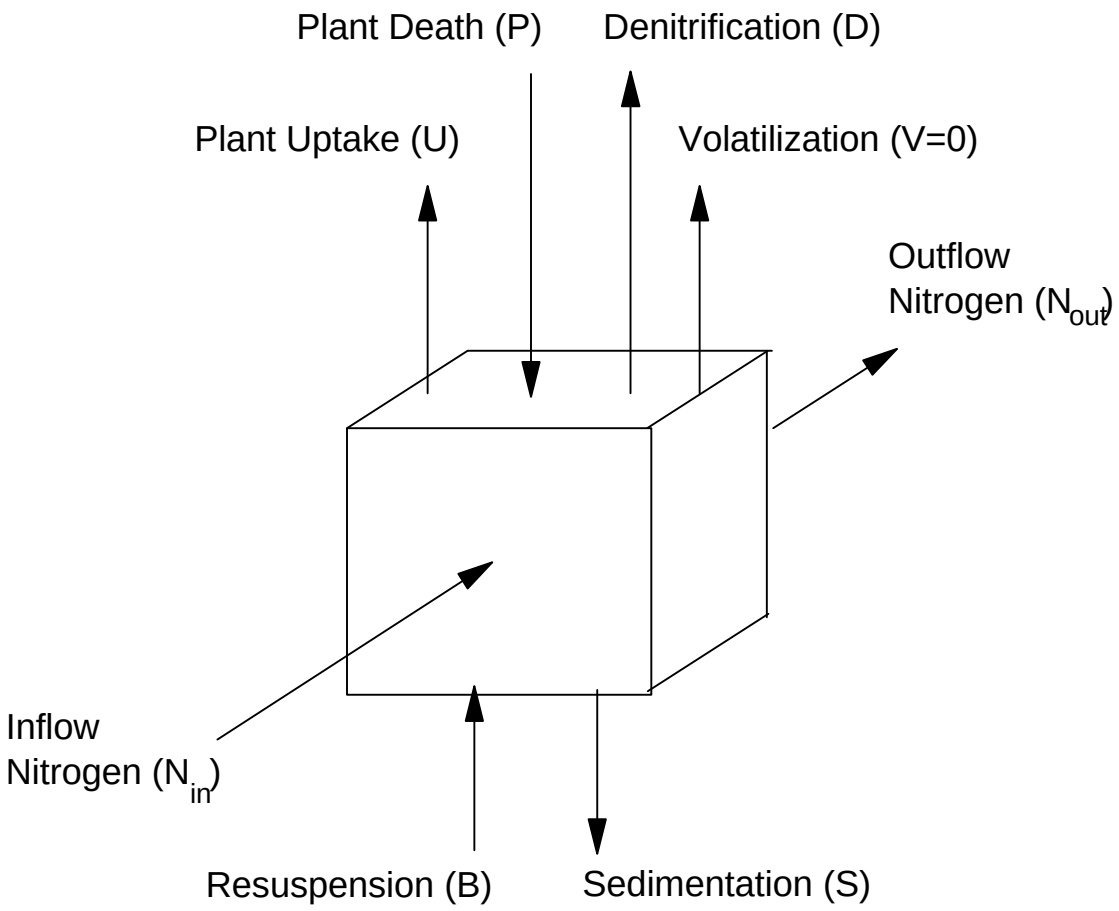


Figure 5-4. Flow diagram of external nitrogen fluxes considering only the water column as the control volume. Note that volatilization is considered negligible among these processes. Also, note that recirculated effluent results in a combined nitrogen mass inflow of $N_{in} + N_{out}$.

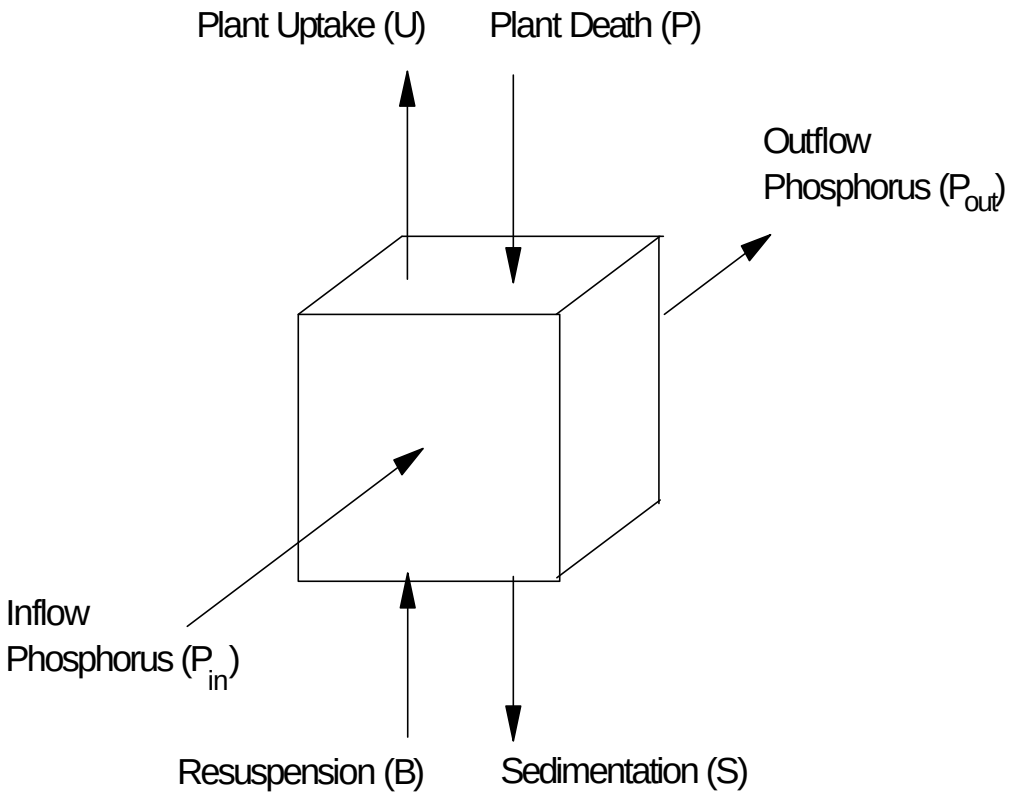


Figure 5-5. Flow diagram of external phosphorus fluxes considering only the water column as the control volume. Note that recirculated effluent results in a combined phosphorus mass inflow of $P_{in} + P_{out}$.

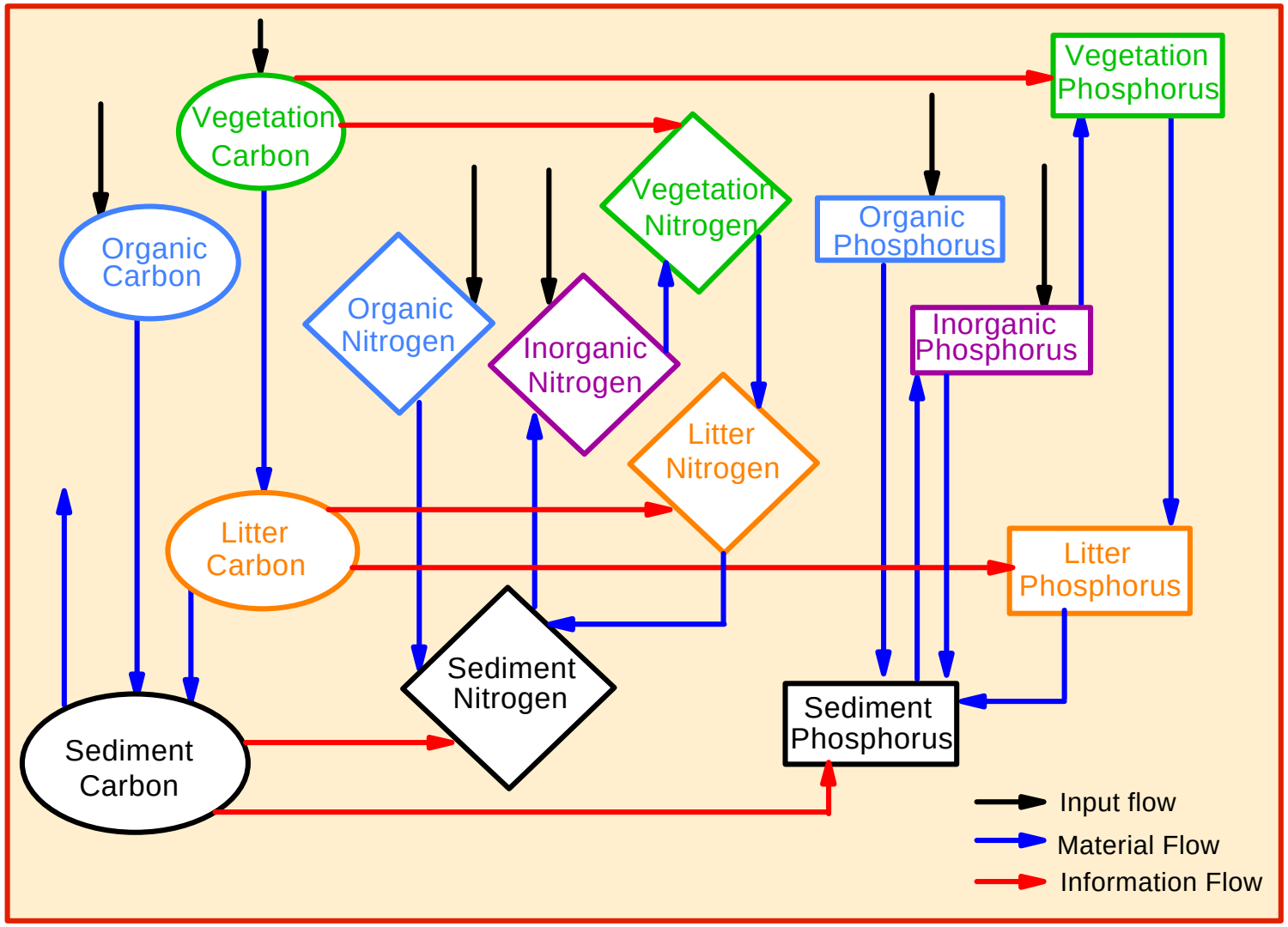


Figure 5-6. Flow diagram of compartmentalized wetland nutrient model. This model not only considered the water column as part of the control volume, but also included vegetation and sediment partitioning within the control volume of the treatment wetland model.

compartmentalization of nutrients within the control volume, as well as the flows between compartments.

Model assumptions. Many assumptions were made in the nutrient modeling effort of the Tignall Water Reclamation Facility. These include a simplified water balance, by which infiltration and percolation were assumed to be negligible compared to other hydrologic flows (Kadlec and Knight, 1996). Seasonal evapotranspiration was estimated based on concepts provided in the literature (Kadlec and Knight, 1996; Kadlec, 1999) Sediment was assumed to be organic, and rates were estimated based on literature values (Morris and Bowden, 1986; Fennessy et al., 1994). Plant growth and death dynamics were based on the PHOENIX model (McGill et al., 1979), in which vegetation compartments include plant shoot and root compartments, as well as compartments for standing dead biomass. Vegetation biomass yields within the wetland cell were estimated based on literature values (Heliotis and DeWitt, 1983; Martín and Fernández, 1992; McJannet et al.,1995) because biomass was not measured at the Tignall Water Reclamation Facility. Vegetation nutrient ratios were estimated based on literature values (Heliotis and DeWitt, 1983; Martín and Fernández, 1992; McJannet et al.,1995).

The hydrology component operated on a volumetric basis and consisted of external flows given in Figure 5-2. Carbon, nitrogen, and phosphorus mass balances were maintained separately in the model, using conserved mass units. Simulated effluent nutrient concentrations were calculated by dividing nutrient mass by wastewater outflow after a given time step. Most mass flows between compartments were related by carbon-to-nitrogen (C:N) or carbon-to-phosphorus (C:P) ratios. Nutrient ratios have been reported to be useful mechanisms for determining nutrient limitations in ecosystems (Koerselman and Meuleman, 1996).

The primary nutrient model components operated on a mass basis and include vegetation, litter, sediment, and inorganic nutrient compartments (Figure 5-6). For each component, STELLA® software (HPS, 1998) was used to simulate the physical, chemical, and biological processes that are responsible for the transformation and transportation of carbon, nitrogen, and phosphorus within the system and between the compartments. In this modeling effort, the nutrients were compartmentalized within the control volume, and these compartments were considered to be the state variables that change over time. Flows which influence these compartments were based on parameters and kinetic relationships that have been found in the literature, as well as those measured in the field. Model parameters that drive flows were calculated, derived from literature values, or estimated during model calibration.

Hydrology component. A water budget for a wetland cell (Figure 5-2) gives a summary of the inputs and outputs that were used to maintain the water balance of the constructed treatment wetland model. The hydrology component of the wetland system simulation has been constructed in STELLA® software using the conceptual framework for the water budget. The forcing functions in the hydrologic balance are precipitation (P), evapotranspiration (ET), and wastewater inflow and outflow (Q_{in} and Q_{out}, respectively), and wastewater volume (WW) was calculated as follows (all units in $m^3\ d^{-1}$):

$$\frac{d(WW)}{dt} = Q_{in} + P - Q_{out} - ET + Q_{recirc} \qquad (5\text{-}1)$$

where: Q_{in} = wastewater inflow
Q_{out} = wastewater outflow
P = precipitation
ET = evapotranspiration
Q_{recirc} = wastewater recirculation,
= 0, if no recirculation
= Q_{out}, if recirculation

Retention time (t) was calculated as follows:

$$t = \frac{V}{Q_{avg}} \quad (5\text{-}2)$$

where: t = hydraulic retention time (days)
V = wastewater volume (m^3)
Q_{avg} = average flow rate [(Q_{in} + Q_{out})/2] (m^3 d^{-1})

Wastewater depth (m) was subsequently calculated as follows:

$$d = \frac{WW}{n * SA} \quad (5\text{-}3)$$

where: WW = wastewater volume (m^3)
n = "porosity", typically 0.65-0.75 (Reed et al., 1995)
SA = wetland surface area (m^2).

Porosity (n) was linked to the vegetation component and was programmed to decrease linearly as plant biomass (Live Shoot Biomass = sum of live shoot C, N, and P, grams) increased in the system. The linear relationship was assumed as follows:

$$n = 1 - 5x10^{-5} * Live\,Shoot\,Biomass \quad (5\text{-}4)$$

This porosity/biomass relationship in Equation (5-4) gives porosity to be 0.5 as the minimum void space per unit wastewater volume during peak season of vegetative growth, while a porosity of 1.0 was the maximum porosity under minimal growth conditions. The assumption was made that a maximum porosity of 1.0 under minimal vegetative growth conditions did not impact wastewater volume. Reed et al. (1995)

recommend a porosity of 0.65 to 0.75 for peak vegetative growth. Peak porosity values were considered to be lower at the Tignall Water Reclamation Facility due to the contribution of duckweed (*Lemna* spp.) to vegetative biomass.

Precipitation (P) was calculated based on rainfall data collected at the constructed wetland site and was adjusted based on wetland surface area to give a volumetric inflow. Data for wastewater inflow (Q_{in}) and outflow (Q_{out}) were provided by the operator of the Tignall Water Reclamation Facility system (Davis, 2001). Monthly average flow data was used as inputs because operational procedures for the wastewater wetland, including recirculation during summer months and pulse flows during low influent conditions, were varied within each month throughout the duration of data collection (Davis, 2001). If recirculation occurred, Q_{recirc} was equal to Q_{out} as shown in Equation (5-1).

Wetland evapotranspiration has been shown to be driven directly by solar radiation (Kadlec and Knight, 1996), with the result that the peak timing of the annual evapotranspiration cycle is the same for all geographical locations (Kadlec, 1999). However, the amplitude of the evapotranspiration cycle is latitude dependent, with larger swings for larger latitudes (Kadlec, 1999). Based on this concept, simulated evapotranspiration (ET) was governed by the use of a seasonal ET factor (ETF) (Figure 5-7) which was normalized to range from 0 to 1.0. Kadlec (1999) showed that summer evapotranspiration rates were twice as high as in the winter, so the ETF was considered to be 0.5 in the winter and 1.0 in the summer with linear interpolation for spring and fall months. The daily evapotranspiration rate was calculated and converted to volumetric flow as follows:

$$ET = k_{ET} * ETF * SA \qquad (5\text{-}5)$$

where:
ET = evapotranspiration rate ($m^3\ d^{-1}$)
k_{ET} = evapotranspiration rate constant ($m\ d^{-1}$)
ETF = seasonal ET factor (unitless) (Figure 5-7)
SA = wetland surface area (m^2)

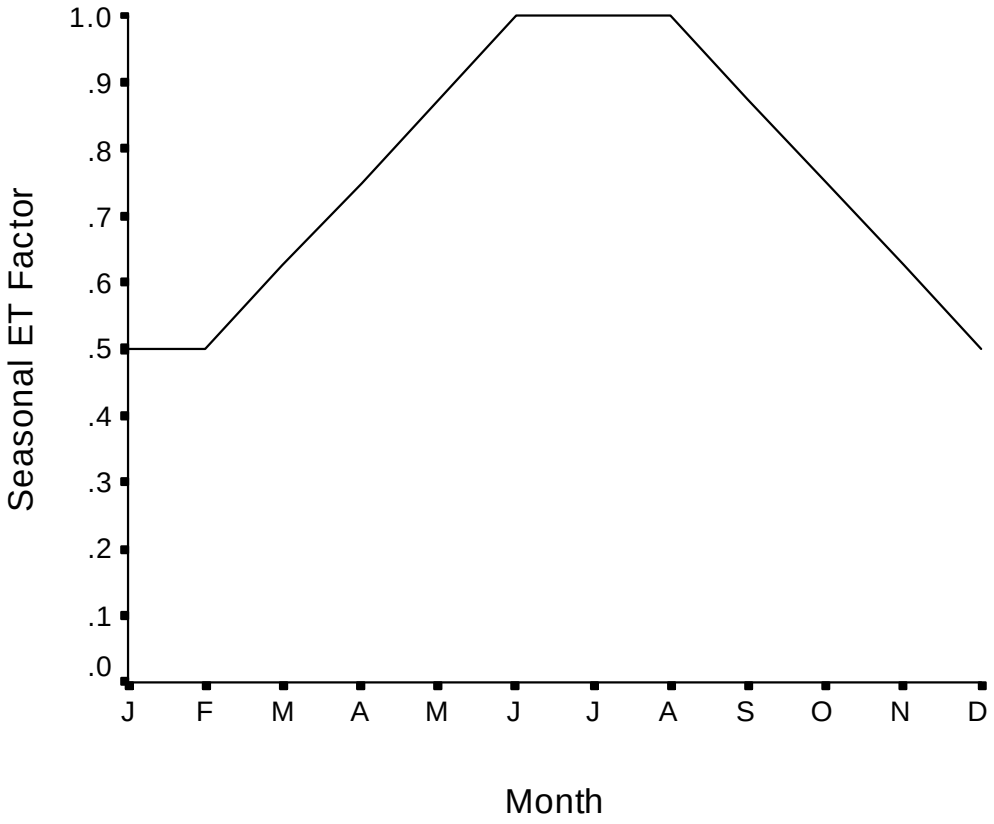


Figure 5-7. Normalized seasonal evapotranspiration (ET) factor (ETF) used to adjust evapotranspiration rates throughout the year. This conceptual relationship was based on seasonal evapotranspiration trends considered by Kadlec (1999) for treatment wetland systems. Evapotranspiration was estimated to be twice as high in summer months than in winter months (Kadlec, 1999). The evapotranspiration rate constant (k_{ET}) allowed for the adjustment of curve amplitude.

An evapotranspiration rate constant (k_{ET}) in Equation (5-5) was used to determine the seasonal amplitude of evapotranspiration during simulation calibration. A rate constant of 0.005 m d^{-1} (Table 5-3) was determined to maintain wastewater depth during calibration simulations when compared to measured depth, and this constant was used for all simulations.

Sediment component. The sediment carbon balance (grams) was based on organic sediment accumulation, litter decomposition, and subsequent respiration, as follows:

$$\frac{d(Sed\ C)}{dt} = Water\ Sediment\ C + Litter\ Sediment\ C - Sediment\ CO_2 \qquad (5\text{-}6)$$

where: Water Sediment C = organic sedimentation rate (g d^{-1})
Litter Sediment C = litter decomposition rate (g d^{-1})
Sediment CO_2 = sediment respiration rate (g d^{-1})

Sediment nitrogen and phosphorus balances (grams) were maintained using sediment carbon-to-nitrogen and carbon-to-phosphorus ratios, respectively. These ratios were used to convert organic carbon sedimentation rates to organic nitrogen and phosphorus sedimentation rates, as well as to convert litter carbon decomposition rates to organic nitrogen and phosphorus decomposition rates. Sediment respiration was replaced by nitrogen fixing rates and phosphorus decomposition rates for nitrogen and phosphorus sediment balances, respectively. These latter two processes are discussed in more detail later.

The sediment component of the model was directly linked to the hydrology component. Total sediment mass was calculated to be the sum of sediment carbon, nitrogen, and phosphorus. Sediment mass accumulation was responsible for change in

Table 5-3. Model Rate Constants and Parameters.

Component	*Constant*	*Description*	*Value*
Hydrology	k_{ET}	ET rate constant	0.005 m d^{-1}
Wastewater Inorganics	k_{nit}	nitrification constant	0.07 d^{-1}
	k_{denit}	denitrification constant	0.5 d^{-1}
	$k_{sorb\ P}$	phosphorus adsorption	0.0002 d^{-1}
Vegetation	k_p	photosynthesis constant	1.1 g m^{-2} d^{-1}
	k_s	shoot death constant	0.1 d^{-1}
	k_r	root death constant	0.01 d^{-1}
	k_d	litter fall constant	0.02 d^{-1}
	CNRoot	root C:N ratio	5 g g^{-1}
	CNShoot	shoot C:N ratio	20 g g^{-1}
	CNDead	standing dead C:N ratio	100 g g^{-1}
	CPRoot	root C:P ratio	10 g g^{-1}
	CPShoot	shoot C:P ratio	30 g g^{-1}
	CPDead	standing dead C:P ratio	100 g g^{-1}
	NH_3 Up Frac	plant NH_3 uptake fraction	0.1
Litter	k_{litter}	litter decomposition constant	0.05 d^{-1}
Sediment	k_{sed}	sedimentation constant	5.0 d^{-1}
	k_{CO2}	respiration rate constant	0.001 d^{-1}
	$k_{N\ fixers}$	nitrogen fixing constant	0.05 d^{-1}
	$k_{decomp\ P}$	P decomposition constant	0.001 d^{-1}
	sed density	sediment density	100 g m^{-3}

sediment volume, which was found using sediment density. Sediment density was considered to be 100 g m^{-3}, based on total solids analyses from previous studies and literature values (Morris and Bowden, 1986). Sediment volume was added to wastewater volume to give a total volume in cubic meters, and total depth was calculated by dividing total volume by surface area.

Sedimentation of solids from wastewater in terms of carbon (Water Sediment C, g d^{-1}) was calculated based on the amount of organic carbon in wastewater (Organic C, grams) as follows:

$$Water\ Sediment\ C = k_{sed} * SF * Organic\ C \quad (5\text{-}7)$$

where: k_{sed} = sedimentation rate constant (d^{-1})
SF = seasonal sedimentation factor (unitless) (Figure 5-8)

The first-order sedimentation constant (k_{sed}) was established to be 5 g m^{-2} d^{-1} (Table 5-3) Morris and Bowden used a value of 0.1 g cm^{-2}, or 10.2 mg m^{-2} d^{-1}, for annual deposition of organic matter onto the marsh surface. Fennessy et al. (1994) have estimated average daily sedimentation rates during low flow conditions (HLR = 1.0 to 2.3 cm d^{-1}) in freshwater wetlands to be 21.2 g m^{-2} d^{-1} on an annual basis, and 56.2 g m^{-2} d^{-1} based on summer months. Fennessy et al. (1994) have also estimated average daily sedimentation rates during high flow conditions (HLR = 5.0 to 5.5 cm d^{-1}) using sediment traps in freshwater wetlands to be 25.5 g m^{-2} d^{-1} on an annual basis, and 49.2 g m^{-2} d^{-1} based on summer months. Higher sedimentation in summer months is considered to be due to the impact of flow resistance from vegetation biomass, resulting in slower wastewater velocity and higher sedimentation. The seasonal sedimentation factor curve (SF) (Figure 5-8) was based on this concept. The Tignall Water Reclamation Facility was considered to operate at low flow conditions (HLR = 2.6 to 4.2 cm d^{-1}) compared to flow condition definitions described by Fennessy et al. (1994).

Litter decomposition (Litter Sediment C, g d^{-1}) was considered to be a first order relationship with litter carbon (Litter C, grams), as follows:

$$Litter\ Sediment\ C = k_{litter} * Litter\ C \quad (5\text{-}8)$$

where: k_{litter} = litter decomposition rate constant (d^{-1})

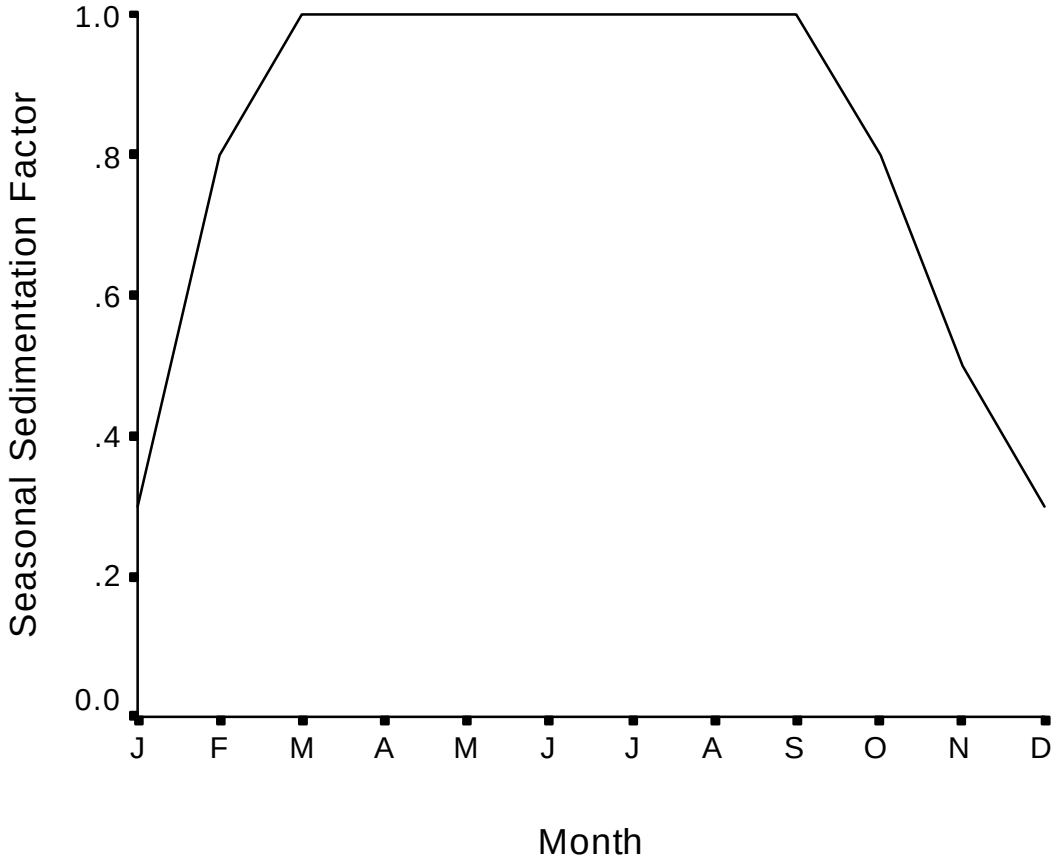


Figure 5-8. Normalized seasonal sedimentation factor (SF) used for seasonal adjustment of sedimentation rates. Fennessy et al. (1994) determined seasonal patterns in sedimentation for created freshwater wetlands. The seasonal sedimentation factor (unitless) was based on their work. Sedimentation rates were considered to be higher in the summer due to flow resistance caused by vegetative growth. Slower wastewater velocities typically result in higher sedimentation rates. The amplitude of the curve is determined by the sedimentation rate constant (k_{sed}).

The litter sediment rate constant (k_{litter}) was considered to be 0.05 g m^{-2} d^{-1} (Table 5-3). This value was based on values from the published literature (U. S. EPA, 1985; Morris and Bowden, 1986).

Sediment carbon respiration (Sediment CO_2, g d^{-1}) was based on first-order kinetics, where respiration rate was related to the sediment carbon mass (Sediment C, grams), as follows:

$$Sediment\ CO_2 = k_{CO_2} * MAF * Sediment\ C \qquad (5\text{-}9)$$

where: k_{CO2} = maximum respiration rate constant (d^{-1})
MAF = microbial activity factor (0.8-1.0, unitless)

where the respiration rate constant (k_{CO2}) was considered to be 0.001 g m^{-2} d^{-1} (Table 5-3). This value was based on published values ranging from 0.00025 to 0.0015 d^{-1} (U. S. EPA, 1985; Mason and Bowden, 1986). The microbial activity factor (MAF) was used to regulate sediment carbon respiration, nitrogen fixing, and phosphorus decomposition under freezing conditions. At temperatures below 5 ^{o}C, microbial activity was reduced by 20%; In other words, if temperature was greater than 5 ^{o}C, the MAF was equal to 1.0; otherwise, the MAF was equal to 0.8. The utilization of this factor was based on published studies (McGill et al., 1979; Lee et al., 1999).

As discussed previously, nitrogen and phosphorus fluxes were calculated based on C:N and C:P ratios of the respective carbon flux. Ratios for organic constituents were used for water to sediment flux, and ratios for litter were used for litter to sediment flux. However, the flux of sediment nitrogen to inorganic forms were considered to be first-order. Nitrogen fixing (N fixing, g d^{-1}) allowed for organic sediment nitrogen to become available for plant uptake, as follows:

$$N\ fixing = k_{N\ fixers} * MAF * Sediment\ N \quad (5\text{-}10)$$

where: $k_{N\ fixers}$ = nitrogen fixing rate constant (d^{-1})
MAF = microbial activity factor (0.8-1.0, unitless)
Sediment N = sediment nitrogen (g)

The nitrogen fixing rate constant ($k_{N\ fixers}$) used in Equation (5-10) was considered to be 0.0005 d^{-1} . This value was based on published values ranging from 0.0004 to 0.0025 d^{-1} (U. S. EPA, 1985). The microbial activity factor (MAF) was used as described for sediment respiration.

Phosphorus decomposition allowed for sediment phosphorus to become available for plant uptake, while conversely, available phosphorus sorption to sediment was also simulated. The phosphorus balance is described in more detail later.

Vegetation component. The contributions of vegetation to inorganic nitrogen and phosphorus uptake, as well as the influence of dead biomass and detritus to sediment carbon, nitrogen, and phosphorus, were simulated. This was accomplished by dividing the vegetation component into live root, live shoot, and standing dead carbon, nitrogen, and phosphorus compartments (9 compartments total), all of which ultimately lead to the litter component for the respective nutrient (Figure 5-9). This concept of simulating plant growth originated from the PHOENIX model (McGill et al., 1979), which incorporated a standing dead biomass component to vegetative growth simulation. Also, carbon transport dictated the dynamics of plant growth, unless nitrogen or phosphorus was limited. Nitrogen and phosphorus mass fluxes were governed by carbon-to-nutrient requirements, including C:N ratios and C:P ratios for root, shoot, and standing dead vegetation compartments. Nutrient ratio values were based on published studies (McGill

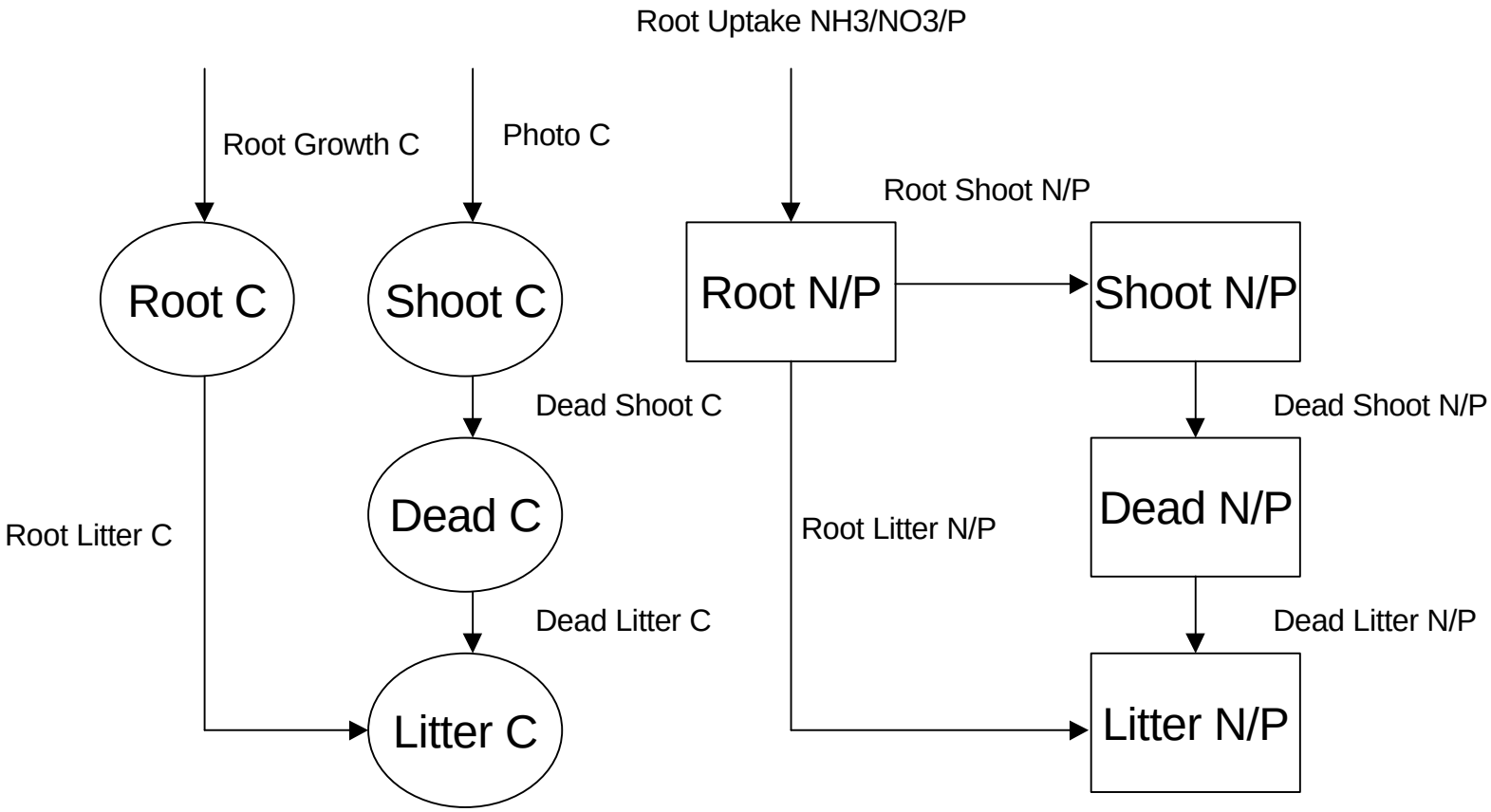


Figure 5-9. Model compartmental structure of vegetation component, showing flows and state variables. Nitrogen and phosphorus dynamics are analogous. Flow equations are provided in Table 5-4.

et al., 1979; Heliotis and DeWitt, 1983; Martín and Fernández, 1992; McJannet et al., 1995) and are presented in Table 5-3.

Vegetative flow equations are summarized in Table 5-4. In Equation (5-11), photosynthesis (Photo C), which was the forcing function for plant growth, was governed by a rate constant (k_p), which was based on literature values (Heliotis and DeWitt, 1983; Howard-Williams and Downes, 1993; Dorge, 1994; Martin and Reddy, 1997) and verified during model calibration. Also, seasonal plant growth was controlled by a plant growth curve (PGC) (Figure 5-10). Root growth in Equation (5-12) (Table 5-4) was simulated separately from shoot growth, but these two flows were related by a root growth curve (RGC) (Figure 5-10). Seasonal root and shoot death rates in Equations (5-13) and (5-14) (Table 5-4), respectively, were adjusted by a plant death curve (PDC) (Figure 5-10). The unitless control factors represented by the plant control curves (PGC, PDC, and RGC) were developed based on the concept of the plant growth dynamics in the PHOENIX model (McGill et al., 1979), as well as on assumed vegetative growth of wetland plants at the Tignall Water Reclamation Facility. The flux of standing dead shoot carbon to litter was calculated with Equation (5-15) (Table 5-4). Root uptake of ammonia and nitrate was calculated using Equations (5-16) and (5-17), respectively (Table 5-4). These rates were adjusted using an ammonia uptake fraction (Table 5-3), which defines proportions by which roots take up ammonia and nitrate. For all simulations, it was assumed that vegetative uptake of ammonia was 10 % that of ammonia and nitrogen. Root uptake of phosphorus was calculated using Equation (5-21) (Table 5-4). Root nutrient uptake was controlled by root growth, which in turn was controlled by photosynthesis (Photo C). Root nutrient requirements were determined by carbon-to-nutrient ratios for roots. Nutrient uptake was limited by the amount of inorganic nitrogen and phosphorus available for plant utilization. If either ammonia, nitrate, or available phosphorus became too low to accommodate plant growth, plant growth went to zero until the appropriate mass of nutrients became available, resulting

Table 5-4. Flow Equations for Model Vegetation Compartments (Figure 5-9).

Vegetation Flow[*]	*Description*	*Rate Equation*[**]	*Equation Number*
Photo C	Photosynthesis	k_p * PGC * (1-RGC)	5-11
Root Growth C	Root growth	Photo C * RGC	5-12
Root Litter C	Root carbon decomposition	k_r * PDC * Live Root C	5-13
Dead Shoot C	Plant shoot death carbon	k_d * PDC * Live Shoot C	5-14
Dead Litter C	Dead shoot carbon to litter	k_s * Standing Dead C	5-15
Root Uptake NH3	Root uptake of ammonia	Root Growth C/CNRoot * NH_3 Uptake Fraction	5-16
Root Uptake NO3	Root uptake of nitrate	Root Growth C/CNRoot * (1-NH_3 Uptake Fraction)	5-17
Root Shoot N	Shoot uptake of root nitrogen	Photo C/CNShoot	5-18
Root Litter N	Root nitrogen decomposition	Root Litter C/CNRoot	5-19
Dead Shoot N	Plant shoot death nitrogen	Dead Shoot C/CNShoot	5-20
Dead Litter N	Dead shoot nitrogen to litter	Dead Litter C/CNDead	5-21
Root Uptake P	Root uptake of phosphorus	Root Growth C/CPRoot	5-22
Root Shoot P	Shoot uptake of root phosphorus	Photo C/CPShoot	5-23
Root Litter P	Root phosphorus decomposition	Root Litter C/CPRoot	5-24
Dead Shoot P	Plant shoot death phosphorus	Dead Shoot C/CPShoot	5-25
Dead Litter P	Dead shoot phosphorus to litter	Dead Litter C/CPDead	5-26

[*] All units are in g d^{-1}

[**] Equations do not include nutrient-limited growth controlling ‘if-then’ statements

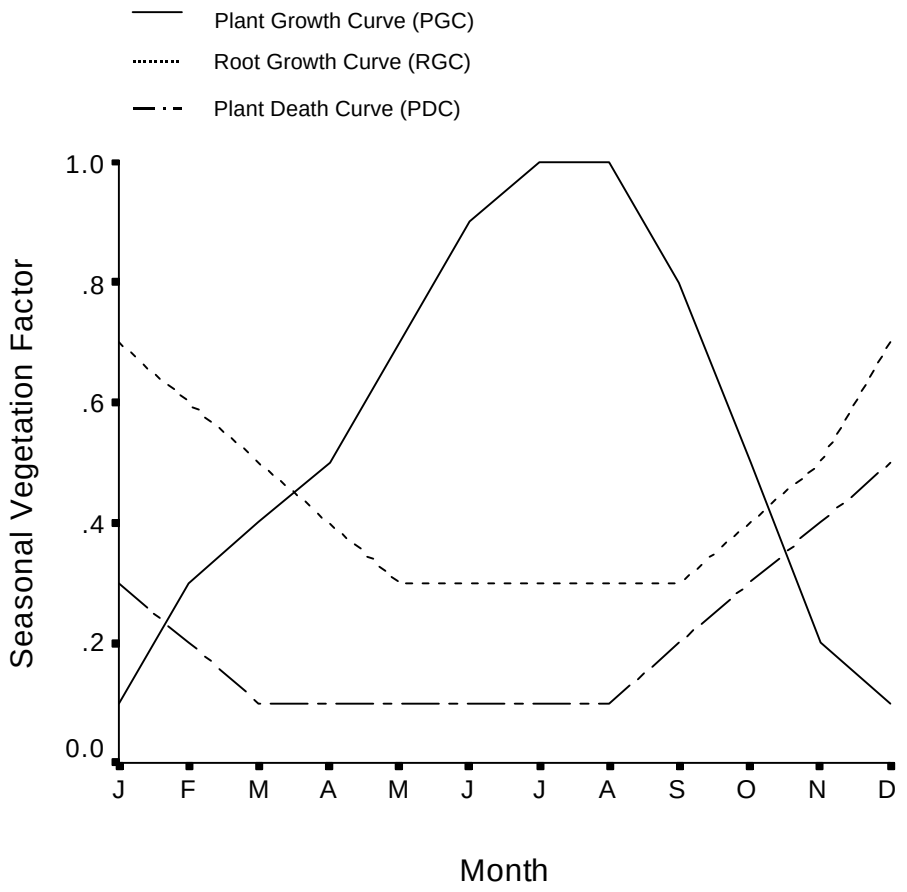


Figure 5-10. Seasonal vegetation control factors, including plant growth curve (PGC), plant death curve (PDC), and root growth curve (RGC). Plant growth and death were used to calculate shoot growth and shoot death, respectively, while root growth and plant death were used to calculate root growth and root death, respectively. These conceptual plant model dynamics were based on the PHOENIX model (McGill, 1979). Specific behavior demonstrated by these curves was assumed based on observed plant growth at the Tignall Water Reclamation Facility.

in an all-or-none nutrient limitation on plant growth. The transfer of nitrogen and phosphorus from roots to shoots was calculated using Equations (5-18) and (5-22), respectively, and was governed by photosynthesis and plant shoot nutrient requirements in the form of carbon-to-nutrient ratios. Root, shoot, and standing dead shoot nutrient decomposition fluxes were calculated based on respective carbon dynamics and nutrient compositions based on carbon-to-nutrient ratios. Equations (5-19) to (5-21) and Equations (5-24) to (5-26) summarize these flow equations for nitrogen and phosphorus, respectively.

Inorganic nutrients. Figures 5-4 and 5-5 show external influences on nitrogen and phosphorus within the wetland system, respectively. Nitrogen and phosphorus cycled through the wetland system in different ways. Inorganic nitrogen compartments included NH3 and NO3. Nitrification and denitrification rates (g d^{-1}) were based on first-order kinetics and controlled by a multiplier dissolved oxygen concentration factor (DOF), as follows:

$$Nitrification = k_{nit} * DOF_{nit} * Ammoniacal\ N \quad (5\text{-}27)$$

where: k_{nit} = nitrification rate constant (d^{-1})
DOF_{nit} = dissolved oxygen factor (0-1, unitless) (Figure 5-11)
Ammoniacal N = ammonia-nitrogen plus ammonium-nitrogen mass (g)

$$Denitrification = k_{denit} * DOF_{denit} * Nitrate\ N \quad (5\text{-}28)$$

where: k_{denit} = denitrification rate constant (d^{-1})
DOF_{denit} = dissolved oxygen factor (0-1, unitless) (Figure 5-11)
Nitrate N = nitrate-nitrogen mass (g)

These first-order rate constants (k_{nit} and k_{denit}) were considered to be 0.07 and 0.5 d^{-1}, respectively (Table 5-3). These values were based on published values (U. S. EPA, 1985; Howard-Williams and Downes, 1993; Dorge, 1994; Martin and Reddy, 1997), which range from 0.025 to 0.200 d^{-1} for nitrification and 0.02 to 1.0 d^{-1} for denitrification. The dissolved oxygen factor for nitrification (DOF_{nit}) was estimated based on an assumed positive linear relationship between dissolved oxygen concentration and nitrification rates. The dissolved oxygen factor for denitrification (DOF_{denit}) was estimated based on an assumed negative linear relationship between dissolved oxygen concentration and denitrification rates. These factors were determined based on dissolved oxygen concentration (DO) ranging from 0.0 to 5.0 mg L^{-1}, as follows:

$$DOF_{nit} = 0.2 * DO \tag{5-29}$$

$$DOF_{denit} = 1 - 0.2 * DO \tag{5-30}$$

Figure 5-11 gives the graphical form of the relationships in Equations (5-28) and (5-29).

Available phosphorus (Available P, grams) was the only inorganic phosphorus compartment in the model. This state variable was connected with sediment phosphorus and plant uptake according to Figure 5-12. Flow equations are given in Table 5-5, except for plant uptake, which is given in Table 5-4 as Equation (5-22), as previously discussed. Inflow orthophosphate mass flux (g d^{-1}) was based on influent orthophosphate concentration (g m^{-3}) and wastewater inflow (m^3 d^{-1}) and was converted to mass by Equation (5-31). Outflow orthophosphate (g d^{-1}) was calculated using Equation (5-32) based on available inorganic phosphorus concentration in the wetland (g m^{-3}) and wastewater outflow rate (m^3 d^{-1}). The contribution of litter phosphorus to sediment phosphorus was calculated by Equation (5-33) as discussed previously. Inorganic and organic sediment phosphorus were connected by sorption and decomposition flows, which were calculated using Equations (5-34) and (5-35),

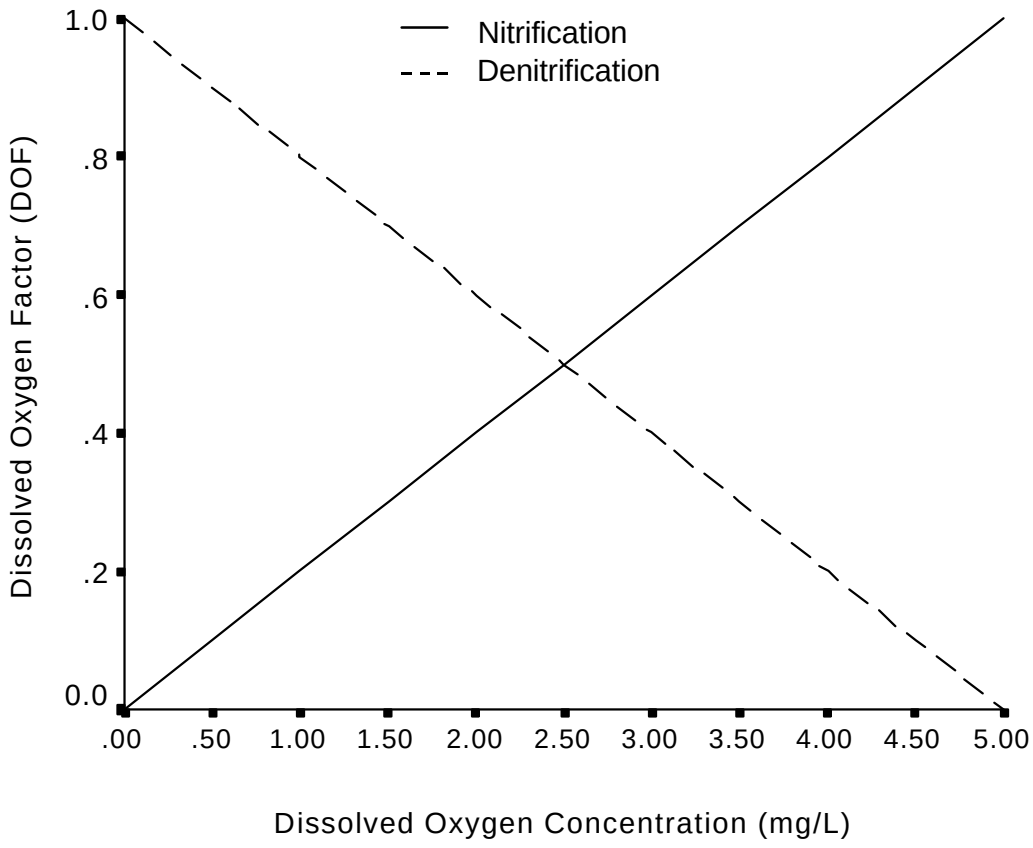


Figure 5-11. Inorganic nitrogen control factors for nitrification and denitrification as related to dissolved oxygen concentration. The linear relationships presented are based on assumptions that nitrification rates increase with dissolved oxygen concentration, while denitrification rates decrease with dissolved oxygen concentration.

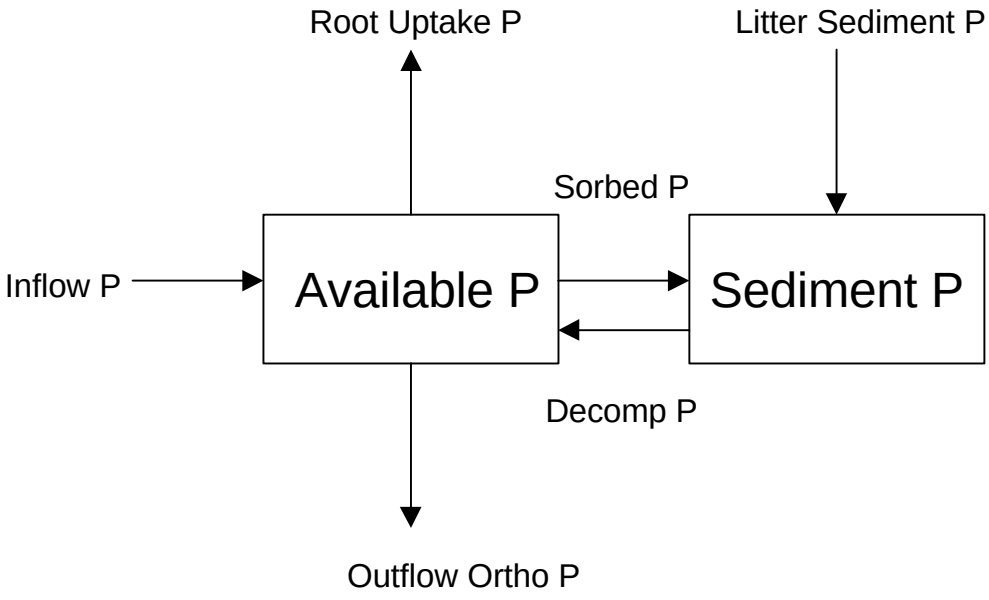


Figure 5-12. Model compartmental phosphorus structure, showing flows and state variables. Flow equations are provided in Table 5-5.

respectively. These processes were modeled based on first-order kinetics. The phosphorus sorption rate constant ($k_{sorb\ P}$) used in simulation was 0.0002 d^{-1} and the phosphorus sediment release rate constant was 0.001 d^{-1} (Table 5-3). These values were based on published values of 0.0002 d^{-1} for sorption (Jørgenson et al., 1975) and ranging 0.0004 to 0.01 d^{-1} for orthophosphate release from sediment (U. S. EPA, 1985).

Table 5-5. Flow Equations for Model Phosphorus Compartments (Figure 5-12).

Phosphorus Flow[*]	*Description*	*Rate Equation*	*Equation Number*
Inflow Ortho P	Influent orthophosphate	Inf Ortho P Conc * Inflow	5-31
Outflow Ortho P	Effluent orthophosphate	Available P * Outflow	5-32
Litter Sediment P	Litter decomposition P	Litter Sediment P/CPLitter	5-33
Sorbed P	P sorption to sediment	k_{sorb} * Available P	5-34
Decomp P	P sediment decomposition	$k_{decomp\ P}$ * MAF * Sediment P	5-35

[*] All units for flow equations are in g m^{-2} d^{-1}

Effluent concentration calculations. Inorganic and organic nutrient dynamics were simulated separately; therefore, effluent concentrations were calculated separately. In both cases, however, the concentration (g m^{-3} = mg L^{-1}) was calculated by dividing the mass flux leaving the wetland (g d^{-1}) by the outflow (m^3 d^{-1}). Ammonia-N, nitrate-N, and orthophosphate concentrations (mg L^{-1}), as well as organic nitrogen and phosphorus concentrations (mg L^{-1}), were calculated in this manner. Total Kjeldahl Nitrogen (TKN) concentration (mg L^{-1}) was calculated as the sum of the ammonia-N outflow concentration and the organic nitrogen outflow concentration. Total phosphorus (TP) concentration (mg L^{-1}) was calculated as the sum of the orthophosphate outflow concentration and the organic phosphorus outflow concentration.

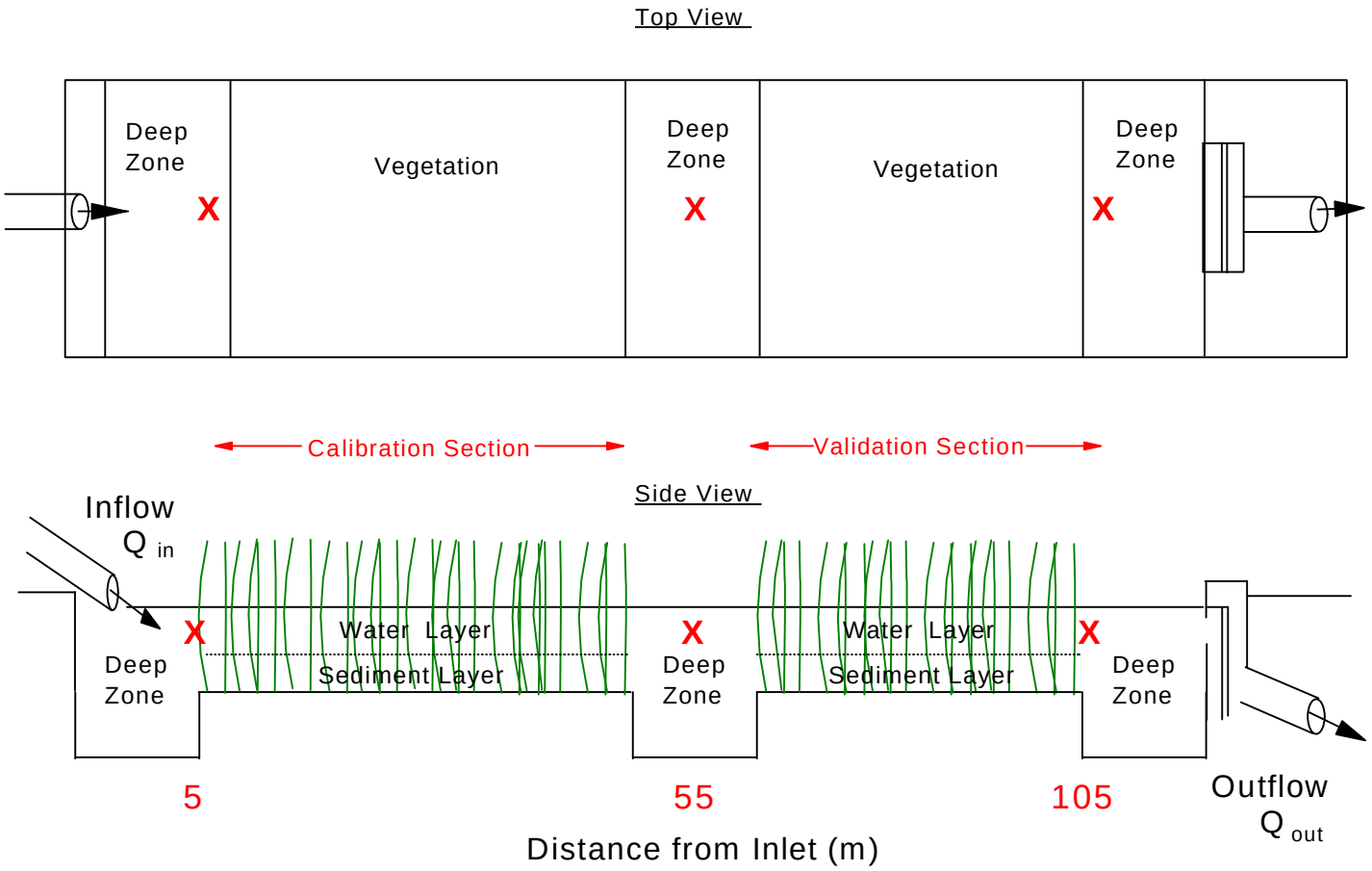


Figure 5-13. Physical layout of wetland cell (not to scale), showing sections sampled for calibration and validation phases of modeling effort in red. Continuous sampling location is represented by X. Distance of sections from inflow pipe are shown in red. Planted vegetation includes *Schoenoplectus californicus* (giant bullrush) and *Zizaniopsis miliacea* (giant cutgrass).

Constructed Treatment Wetland Monitoring

Nutrient monitoring. Daily samples were collected for nutrient analyses at the beginning and end of each half of the first wetland cell (Figure 5-13) using Isco® 6700 automated samplers (Lincoln, NE). These samples were preserved in 2 mL concentrated H_2SO_4 per liter of wastewater sample. Ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3) and orthophosphate (PO_4) concentrations were determined from acid-preserved samples using a TRAACS™ 2000 automated wet chemistry system with an XYZ model™ autosampler (Bran+Luebbe, Buffalo Grove, IL). For further nutrient concentration determination, water samples were digested in a $CuSO_4$ and sulfuric acid solution prior to total Kjeldahl nitrogen (TKN) and total phosphorus (TP) analyses using TRAACS™. Quality assurance and quality control included correlation coefficient checks for standards ($r^2 > 0.99$), dilution checks (% difference < 5%), and duplicate control cup checks throughout each run (% difference < 5%). If any of these controls were not met, the samples were rerun.

Water quality parameters. The following water quality parameters were measured at the beginning and end of each half of the first wetland cell: temperature (^oC), dissolved oxygen concentration (mg L^{-1}), and depth (m). These parameters were measured using YSI ® 6820 data sondes (Yellow Springs, OH) that were connected to each respective Isco ® 6700 automated sampler. The sondes were calibrated once a month for all parameters. Daily rainfall data was collected using an Isco rain gauge also connected to the Isco ® 6700 automated sampler.

Model Calibration

The constructed wetland design model was calibrated using precipitation data and influent and effluent concentration data collected from the first half of the first cell at the Tignall Water Reclamation Facility from February, 2000, to December, 2000. Appendix A gives all simulation equations, relationships, and rate constants for the

calibration simulation using STELLA ® software (HPS, 1998). A daily time step (dt = 1 day) was used during all simulations. The Runge-Kutta 4 numerical approximation method was used to solve rate equations during all simulations. Model inputs were evaluated and parameter estimation was accomplished during the calibration phase of the modeling effort. For calibration, simulated data was statistically compared to actual data using root mean square error (RMSE) values. Calibration steps were taken in the following order:

1) hydrology; 2) vegetation; 3) inorganic nutrient transformations, and 4) sedimentation. This process is described in more detail later.

Model inputs. The first attempts at model calibration focused on the hydrology component. Measured precipitation data, water temperature data, dissolved oxygen concentrations, and monthly average flow data were used as inputs. By adjusting the rate constant for evapotranspiration (k_{ET}), the simulated wastewater depth measurements were compared to actual measured and calculated values to ensure that these values were reasonable; that is, RMSE values were within the measured data range. By satisfying the depth comparisons, seasonal evapotranspiration rates were estimated using the evapotranspiration factor (ETF) (Figure 5-7). These evapotranspiration rates were used during subsequent simulations.

Table 5-6 shows initial conditions for state variables used during model calibration. Recirculation was assumed to occur between yeardays 100 (9Apr00) to 200 (17Jul00). Initially, average influent carbon, nitrogen, and phosphorus concentrations were used for calibration. Once initial calibration was conducted, measured influent concentration data collected from the Tignall Water Reclamation Facility were used as inputs for further calibration.

Table 5-6. Initial Conditions for State Variables Usedduring Calibration and Validation Simulations.*

Component	*State Variable*	*Calibration*	*Validation***
Hydrology	Initial WW Depth	0.08 m	0.02 m
	Initial Sed Depth	0.30 m	0.34 m
Wastewater Organics	Organic C	1000 g	1390 g
	Organic N	300 g	15.25 g
	Organic P	100 g	1 g
Wastewater Inorganics	NH3	300 g	102 g
	NO3	300 g	110 g
	Available P	100 g	28 g
Vegetation	Live Root C	250 g	54285 g
	Live Root N	100 g	2450 g
	Live Root P	100 g	25 g
	Live Shoot C	50 g	57670 g
	Live Shoot N	10 g	2890 g
	Live Shoot P	5 g	1407 g
	Standing Dead C	100 g	1350 g
	Standing Dead N	2 g	4475 g
	Standing Dead P	1 g	45 g
Litter	Litter C	20 g	24750 g
	Litter N	1 g	39 g
	Litter P	3 g	763 g
Sediment	Sediment C	10 g	357 kg
	Sediment N	1 g	970 g
	Sediment P	2 g	7108 g

* Note that initial conditions for entire simulated cell area are given

** Note that initial conditions for the validation simulation were based on conditions of state variables at yearday 227 for the calibration simulation

Model Validation

For model validation, simulated data was statistically compared to actual data using root mean square error (RMSE) values. The constructed wetland model was validated using precipitation, temperature, and dissolved oxygen concentration data, as well as influent and effluent concentration data collected from the second half of the first cell at the Tignall Water Reclamation Facility (Figure 5-13) from August, 2000, to April, 2001. Appendix B gives all simulation equations, relationships, and rate constants for the validation simulation using STELLA ® software (HPS, 1998).

Model Inputs. Table 5-6 gives initial conditions for the validation phase of the modeling effort. These values were based on predicted results from the calibration phase; in other words, the initial conditions for the validation phase were taken from the simulated data for the calibration phase at time = 227 days (17Aug00), the yearday at which the validation simulation began. This was necessary because of the seasonal nature of simulated processes, and the sampling collection period for measured data used in validation simulations overlapped with the sampling collection period for measured data used in calibration simulations.

Results and Discussion

Model Calibration

Table 5-7 gives root mean square error (RMSE) values for the calibration simulation. Root mean square error was calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{j=1}^{N}(s_j - o_j)^2}{N}} \qquad (5\text{-}36)$$

where s_j is the simulated value, o_j is the observed value, and N is the number of data points. Root mean square error (RMSE) indicates the average deviation of the simulated

values in the same units as the measured values. Therefore, the model simulation results were considered acceptable if the RMSE values were within the range of the measured

Table 5-7. Root Mean Square Error (RMSE) Results from Calibration and Validation Phases of Simulation as Calculated using Equation (5-36).

Model Output	*Calibration RMSE*	*Validation RMSE*
depth (m)	0.068	0.096
NO_3 Concentration (mg L^{-1})	0.9	1.6
NH_3 Concentration (mg L^{-1})	7.4	6.1
Ortho-P Concentration (mg L^{-1})	3.1	1.8
TKN Concentration (mg L^{-1})	8.8	5.9
TP Concentration (mg L^{-1})	3.7	1.6

results. Figures 5-14 through 5-20 shows simulated versus measured results from the calibration phase of the modeling effort.

First, the hydrology component was calibrated by the adjustment of evapotranspiration rates. Figure 5-14 shows results of simulated versus measured wastewater depths during the calibration run. The daily evapotranspiration rate used to maintain wastewater volumes and depths within the simulated treatment wetland cell ranged from 0.25 to 0.5 cm d^{-1}, or 2.3 to 4.5 m^3 d^{-1} for the entire simulated wetland cell with an area of approximately 900 m^2. Under the simulated hydrologic conditions, daily retention times averaged approximately 2.5 days, which was expected for the cell of interest. The water balance of the calibration simulation provided estimated evapotranspiration rates for a treatment wetland system in the Georgia Piedmont.

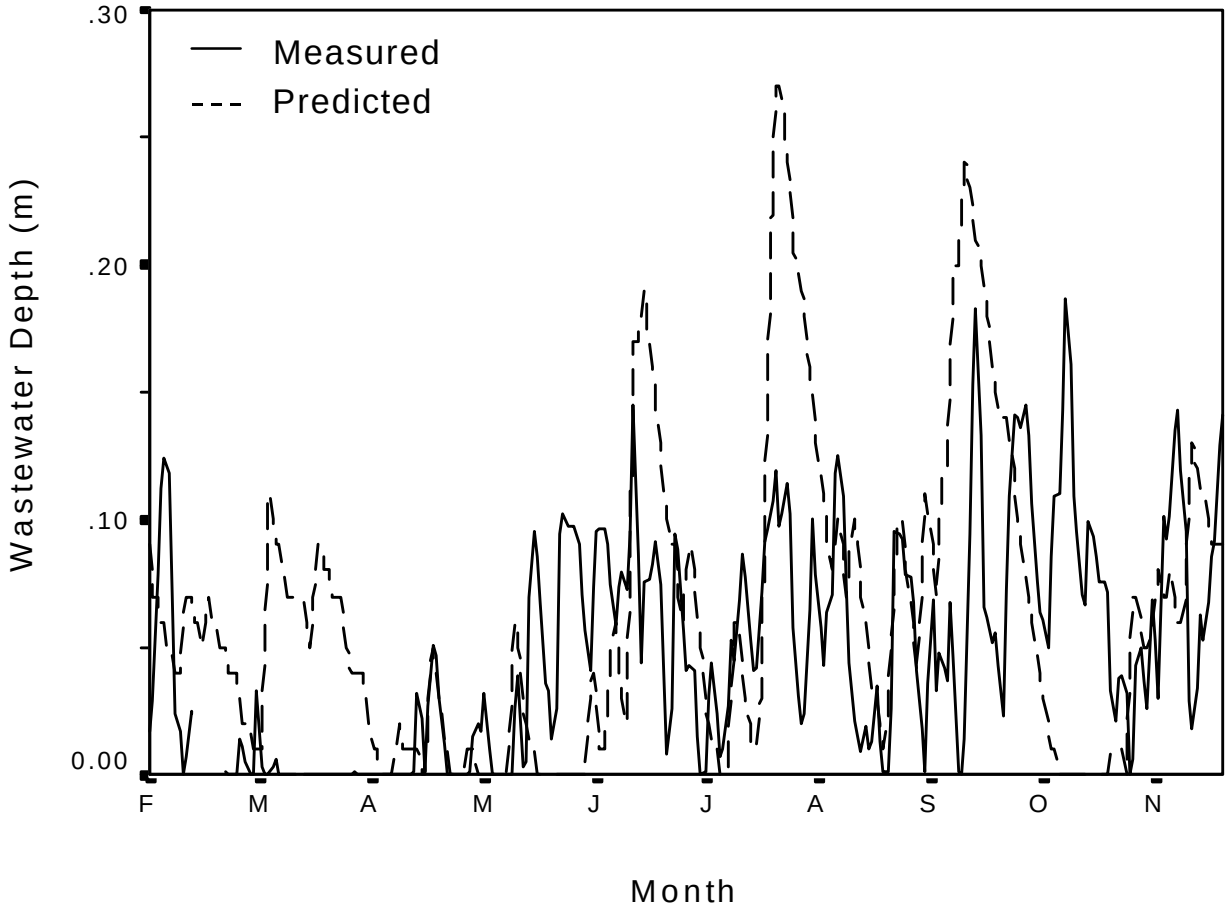


Figure 5-14. Comparison of measured and predicted wastewater depths for the calibration phase of the modeling effort. A wastewater depth of 0.00 m represents measured depth from a datum equivalent to the bottom of the wetland cell. The root mean square error (RMSE) value between measured and simulated data was 0.068 m.

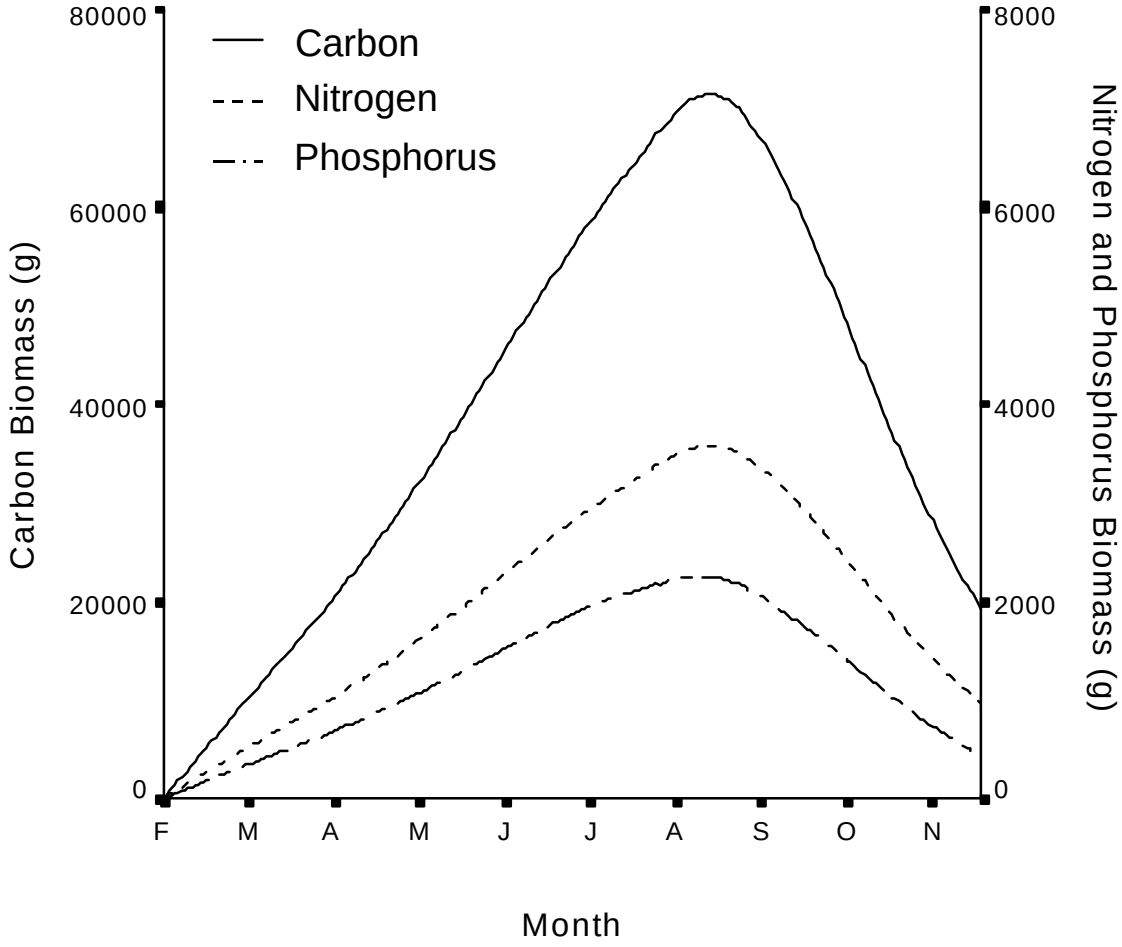


Figure 5-15. Results of vegetation simulation for the calibration phase of the modeling effort, including carbon, nitrogen, and phosphorus biomass.

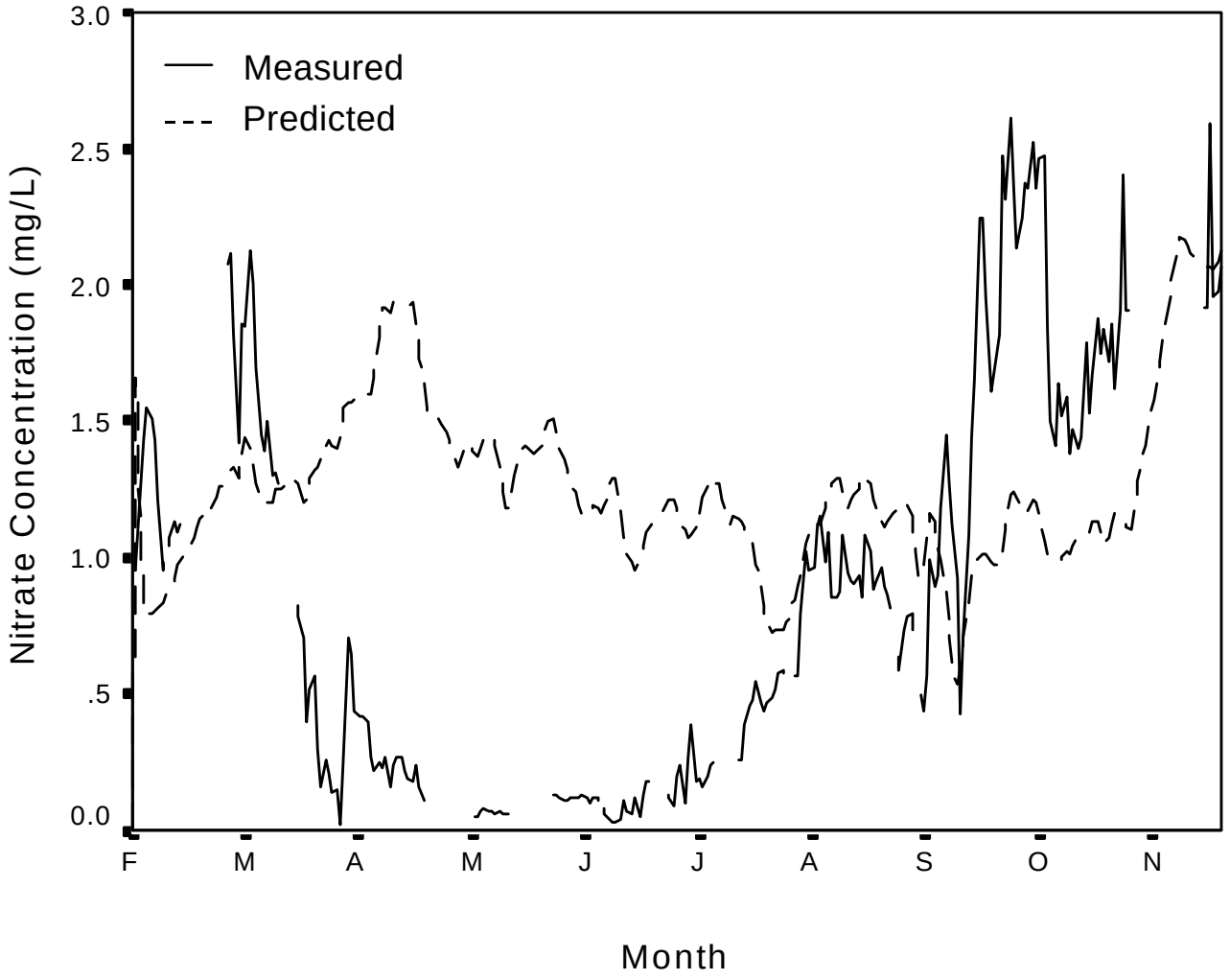


Figure 5-16. Comparison of measured and predicted nitrate concentrations for the calibration phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 0.9 mg L^{-1}.

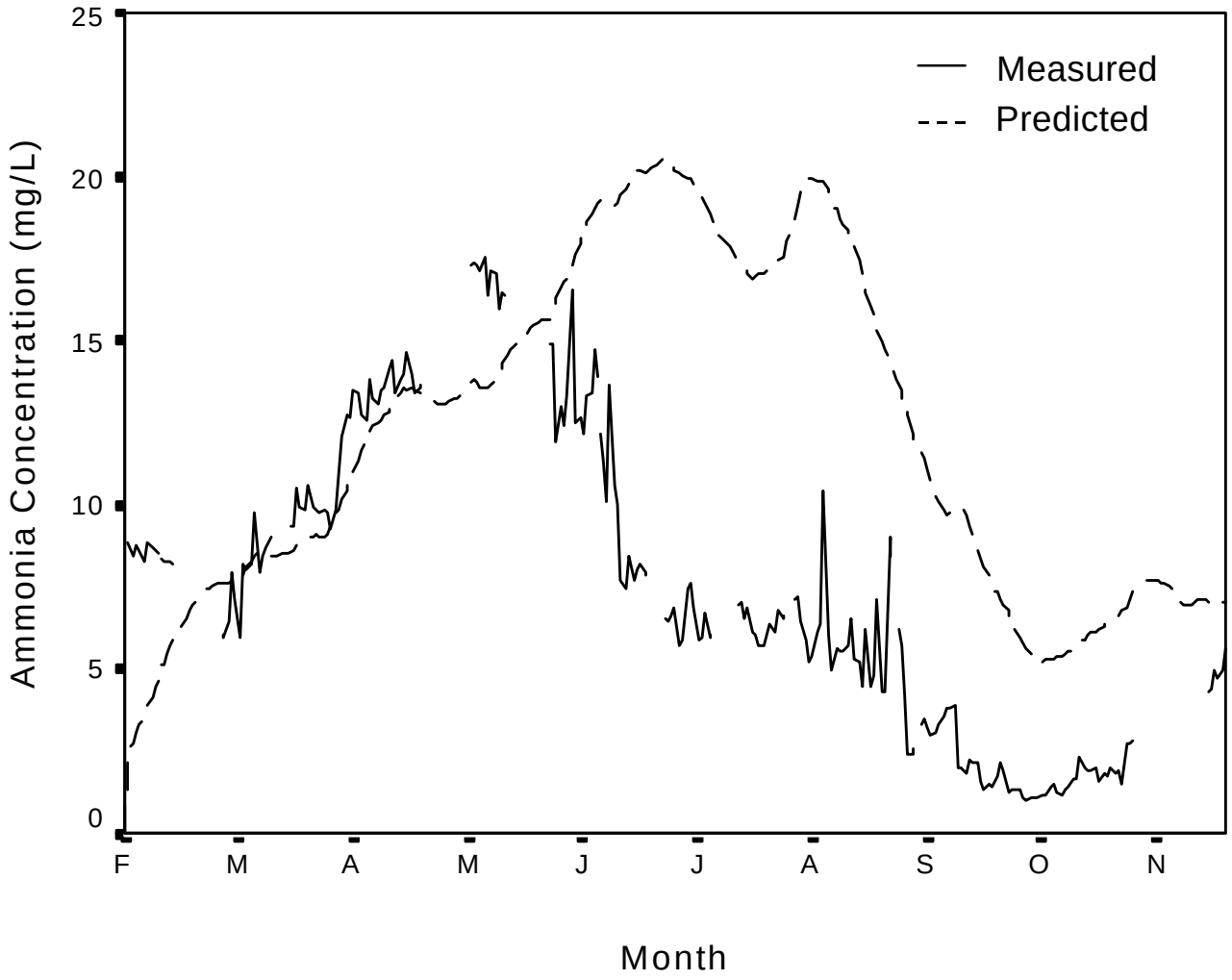


Figure 5-17. Comparison of measured and predicted ammonia concentrations for the calibration phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 7.4 mg L^{-1}.

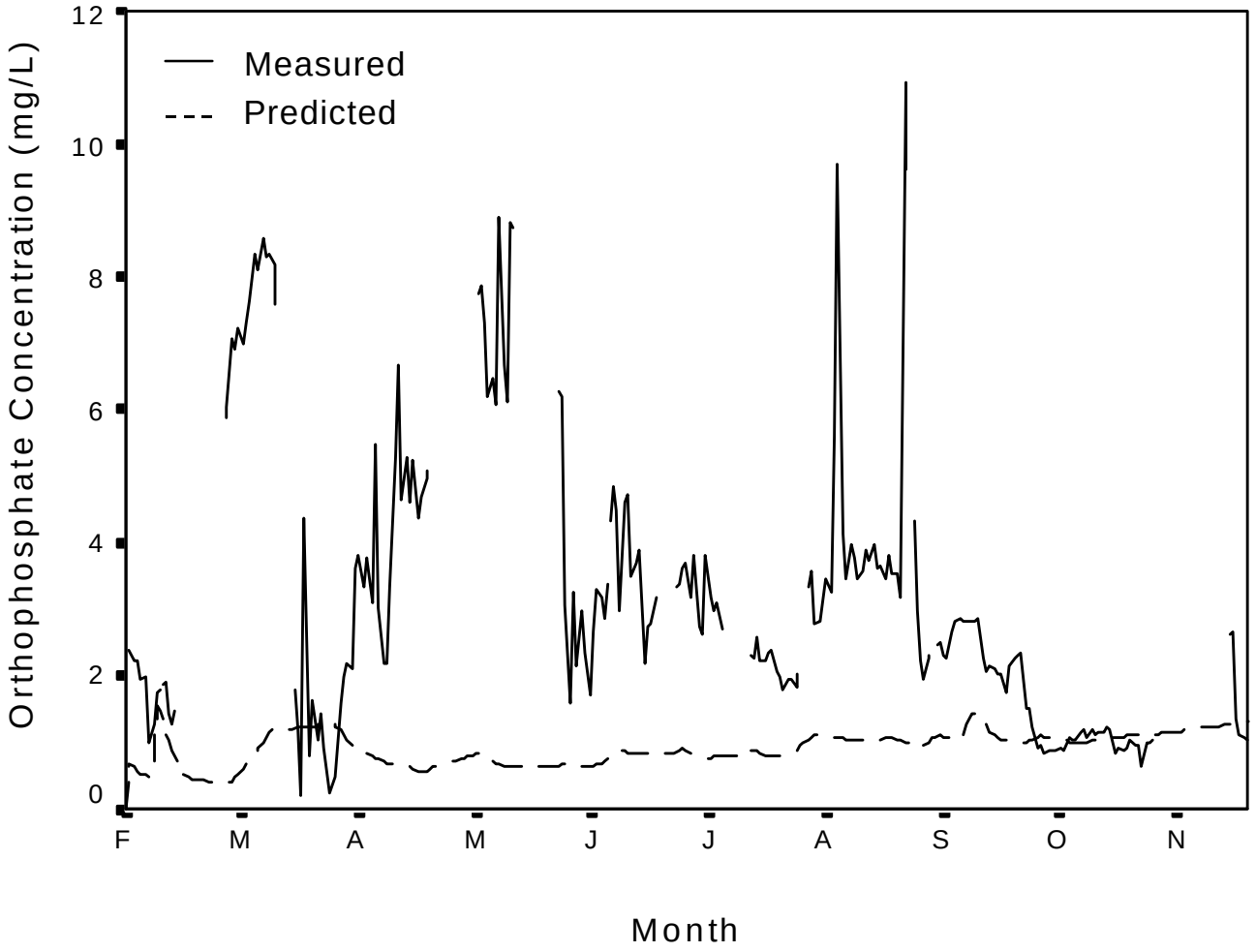


Figure 5-18. Comparison of measured and predicted orthophosphate concentrations for the calibration phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 3.1 mg L^{-1}.

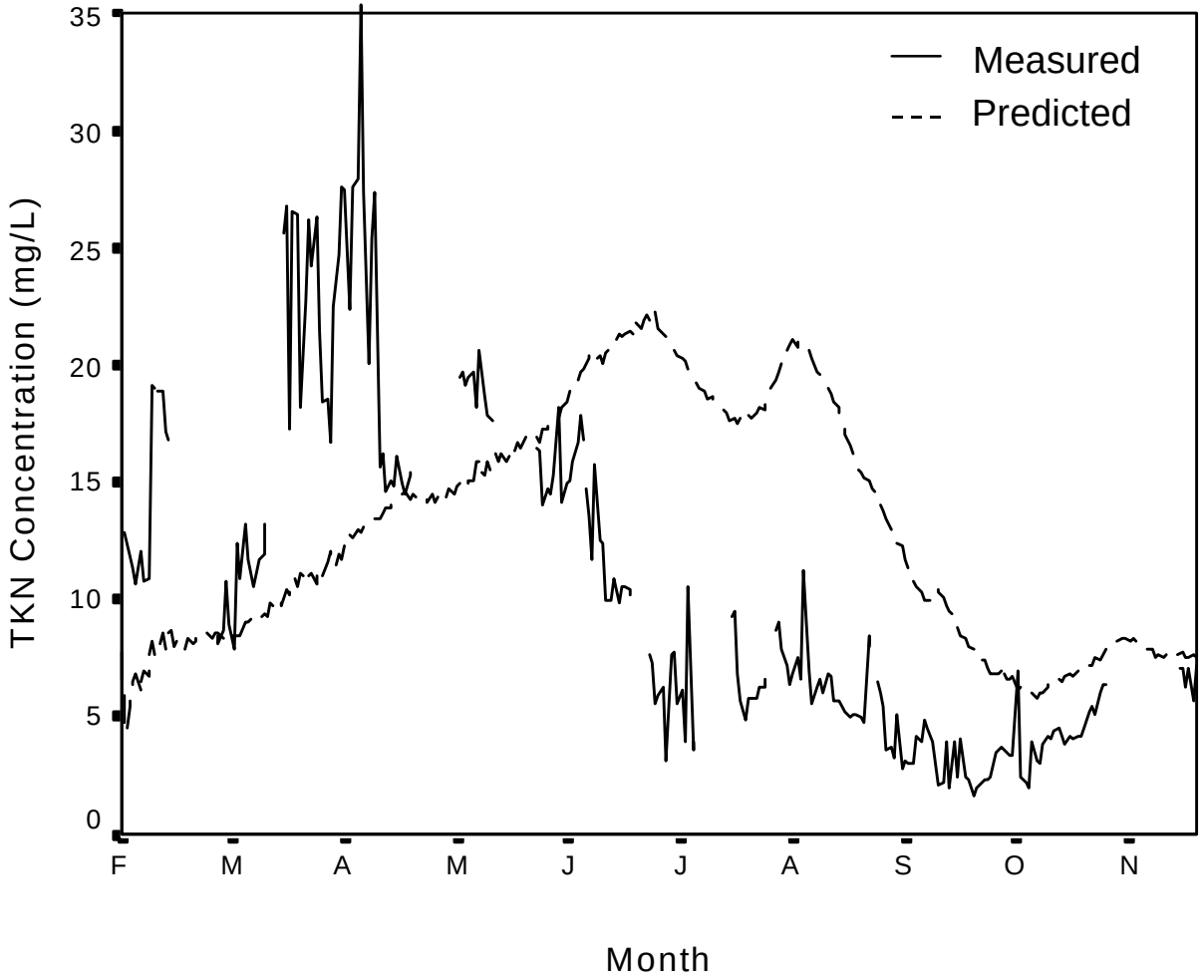


Figure 5-19. Comparison of measured and predicted total Kjeldahl nitrogen (TKN) concentrations for the calibration phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 8.8 mg L^{-1}. Note that TKN concentration is equal to the sum of the ammonia concentration and the organic nitrogen concentration.

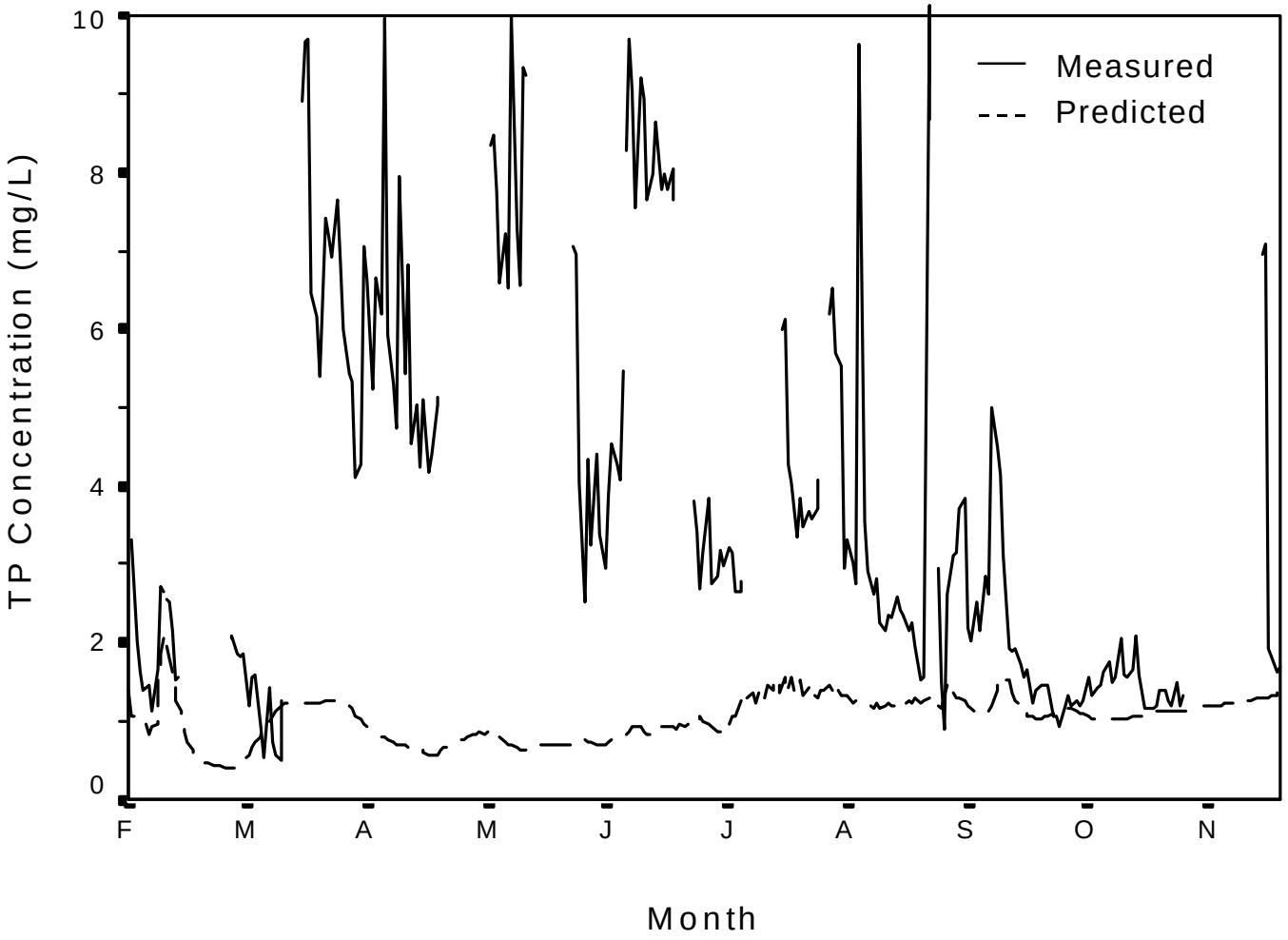


Figure 5-20. Comparison of measured and predicted total phosphorus (TP) concentrations for the calibration phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 3.7 mg L^{-1}. Note that TP concentration is equal to the sum of the orthophosphate concentration and the organic phosphorus concentration.

Next, the vegetation component was evaluated by assuring that C:N and C:P ratios were maintained during simulated plant growth and death. Figure 5-15 gives simulated plant shoot growth in terms of carbon, nitrogen, and phosphorus. Peak growth occurred in August at a carbon biomass value approximately 70 kg. This value, when divided over the wetland surface area, resulted in a carbon biomass per unit area of approximately 78 g m^{-2}. A photosynthesis rate constant of 1.1 g m^{-2} d^{-1} was selected because it was the lowest rate constant that would maintain plant growth without crashing due to extreme nutrient limitation. The resulting daily photosynthesis rate ranged from 0.1 to 1.0 g m^{-2}/ d^{-1} depending on the plant growth curve. Note that this value was used to simulate plant growth within the entire area of the simulated wetland cell. Carbon-to-nitrogen and carbon-to-phosphorus ratios for live shoots were 20 and 30, respectively, and these ratios were maintained throughout the growing season, as indicated in Figure 5-15, resulting in peak biomass values in August of 3.5 kg nitrogen and 2.3 kg phosphorus for the entire wetland area, or 3.9 g m^{-2} and 2.6 g m^{-2}, respectively.

Once the hydrology and vegetation components were calibrated based on depth and productivity outputs within an order of magnitude of measured and estimated, calibration focused on the comparison of simulated versus measured effluent inorganic nutrient concentrations. Simulation runs were performed while adjusting nitrification and denitrification rate constants until simulated ammonia and nitrate effluent concentrations were within an order of magnitude of measured data. Figures 5-16 and 5-17 show results for measured and predicted nitrate and ammonia concentrations, respectively. Results of the calibration simulations showed that the model underestimated both effluent ammonia and nitrate concentrations early in the simulation. However, RMSE values were considered acceptable at values of 7.4 and 0.9, respectively (Table 5-7). Nitrification rates ranged from 45 to 240 g d^{-1} for the entire wetland cell area, or 0.05 to 0.27 g m^{-2} d^{-1}. Denitrification rates ranged from 45 to 216 g

d^{-1} for the entire wetland cell area, or 0.05 to 0.24 g m^{-2} d^{-1}. For inorganic phosphorus, sorption and decomposition rate constants were adjusted until simulated effluent orthophosphate concentrations were within an order of magnitude of measured data. Figure 5-18 shows results for measured and predicted orthophosphate concentrations. The model greatly underestimated the effluent orthophosphate concentrations throughout the entire calibration simulation. However, the RMSE value was considered acceptable at a value of 3.1 (Table 5-7). The daily orthophosphate sorption rate ranged from 7 to 52 g d^{-1} for the entire wetland area, or 0.008 to 0.06 g m^{-2} d^{-1}. The daily sediment phosphorus decomposition rate ranged from 0 to 10 g d^{-1} for the entire wetland area, or from 0.0 to 0.01 g m^{-2} d^{-1}.

The final step in model calibration was the adjustment of sedimentation rates. To this aim, simulation runs were performed while adjusting the sedimentation rate constant until simulated total Kjeldahl nitrogen (TKN) and total phosphorus (TP) effluent concentrations were within an order of magnitude of measured data. Figures 5-19 and 5-20 show results for measured and predicted TKN and TP concentrations, respectively. Model calibration runs underestimated effluent TKN concentrations early in the simulation, while overestimating effluent TKN concentrations later in the simulation. Model calibration runs underestimated effluent TP concentrations throughout the entire simulation duration. However, RMSE values were considered acceptable at values of 8.8 and 3.7, respectively (Table 5-7). Net sedimentation rates in terms of carbon ranged from 1100 to 1200 g d^{-1} for the entire wetland area, or 1.2 to 1.3 g m^{-2} d^{-1}. Net sedimentation rates in terms of nitrogen ranged from 6 to 170 g d^{-1} for the entire wetland area, or 0.007 to 0.19 g m^{-2} d^{-1}. Net sedimentation rates in terms of phosphorus ranged from 6 to 77 g d^{-1} for the entire wetland area, or 0.007 to 0.085 g m^{-2} d^{-1}. Resulting maximum sediment carbon, nitrogen, and phosphorus concentrations for the final calibration simulation were 1600 mg L^{-1}, 4.7 mg L^{-1}, and 30 mg L^{-1}, respectively.

Model Validation

Table 5-7 gives root mean square error (RMSE) values for the validation simulation. Validation of the hydrology component resulted in a RMSE value of 0.096, which was considered acceptable as being within the measured data range. Figure 5-21 shows results from the hydrology validation considering simulated versus measured depth.

The dynamics of the vegetation component were validated with results shown in Figure 5-22. Because the initial conditions used for the validation simulation were taken from the calibration simulation, the resulting simulated vegetation behavior should be similar to the results of calibration. In fact, plant biomass peaked in August as in the calibration runs; however, plant shoot biomass peaked at a lower value compared to that of the calibration simulation. Lower plant growth can be attributed to the fact that measured data used as input for the validation simulation was taken from the wetland cell downstream to those input data for the calibration phase. Lower nutrient concentrations entering the downstream section of the wetland cell led to lower peak biomass in the validation phase. For example, in the validation simulation, plant shoot carbon biomass peaked at just above 60 kg for the entire wetland area, or at approximately 67 g m^{-2}, compared to 70 kg of carbon, or 78 g m^{-2}, during the calibration phase. Carbon-to-nitrogen and carbon-to-phosphorus ratios remained intact for shoot growth during the validation simulation. These results demonstrate the expected behavior of the plant growth simulation during the validation phase.

Figures 5-23 to 5-27 show the results of simulated versus measured effluent nutrient concentrations. During the validation phase, the model did an acceptable job of simulating effluent nutrient concentrations based on RMSE values (Table 5-7), with values of 6.1 for ammonia, 1.8 for orthophosphate, 5.9 for total Kjeldahl nitrogen, and 1.6 for total phosphorus. The simulated effluent nutrient concentrations were closer to measured concentrations in the validation phase than in the calibration phase, with the

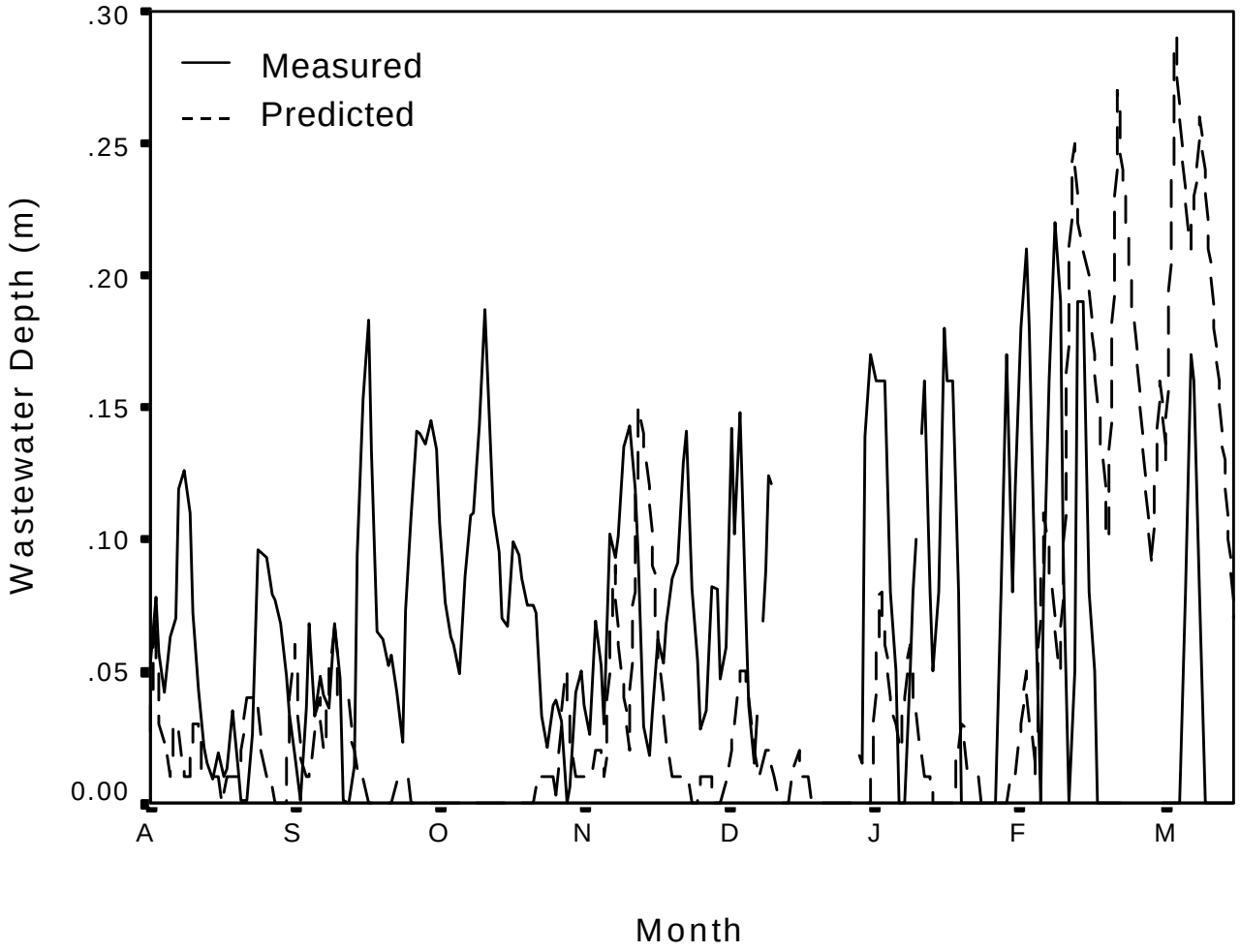


Figure 5-21. Comparison of measured and predicted wastewater depths for the calibration phase of the modeling effort. A wastewater depth of 0.00 m represents measured depth from a datum equivalent to the bottom of the wetland cell. The root mean square error (RMSE) value between measured and simulated data was 0.096 m.

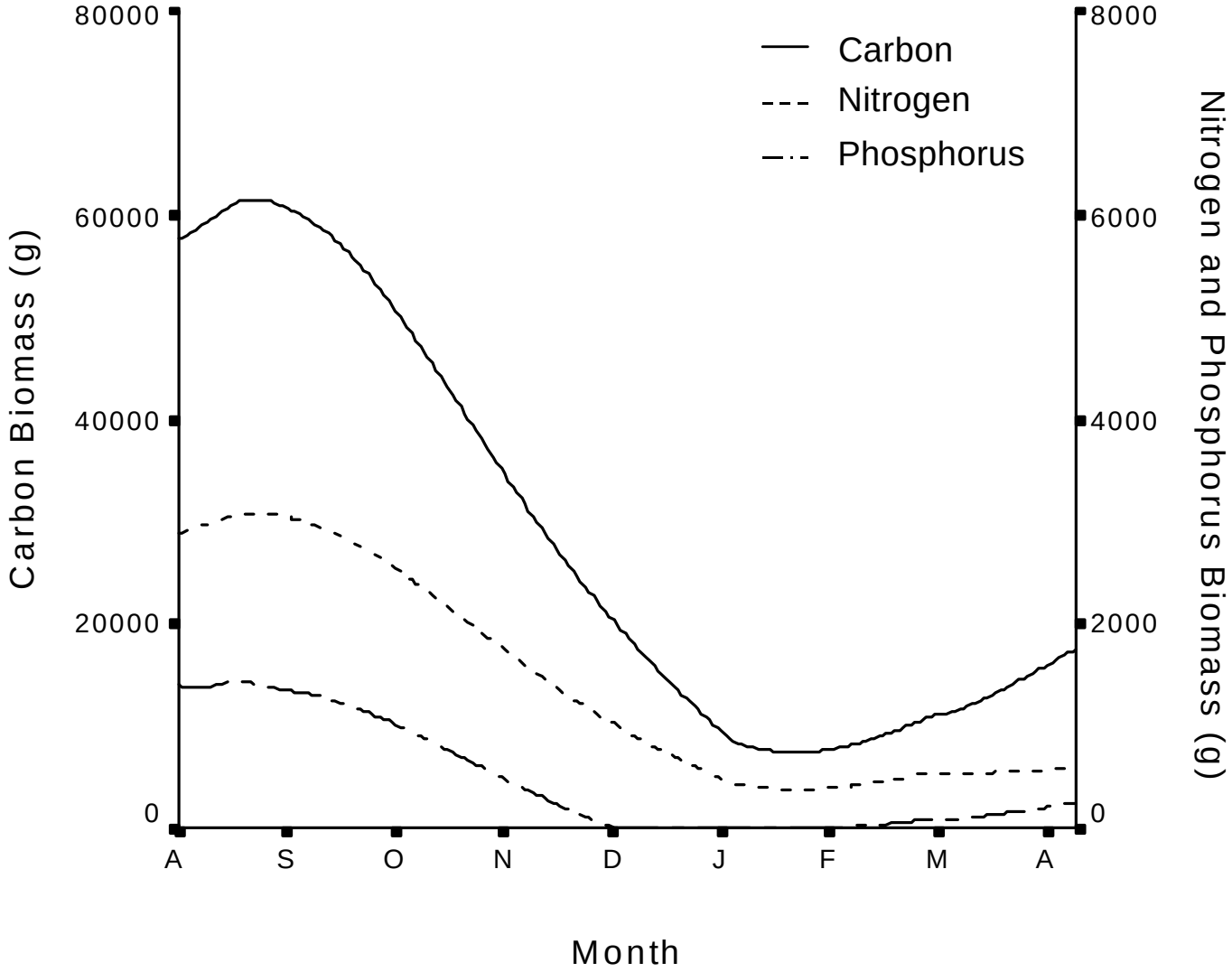


Figure 5-22. Results of vegetation simulation for the validation phase of the modeling effort, including carbon, nitrogen, and phosphorus biomass.

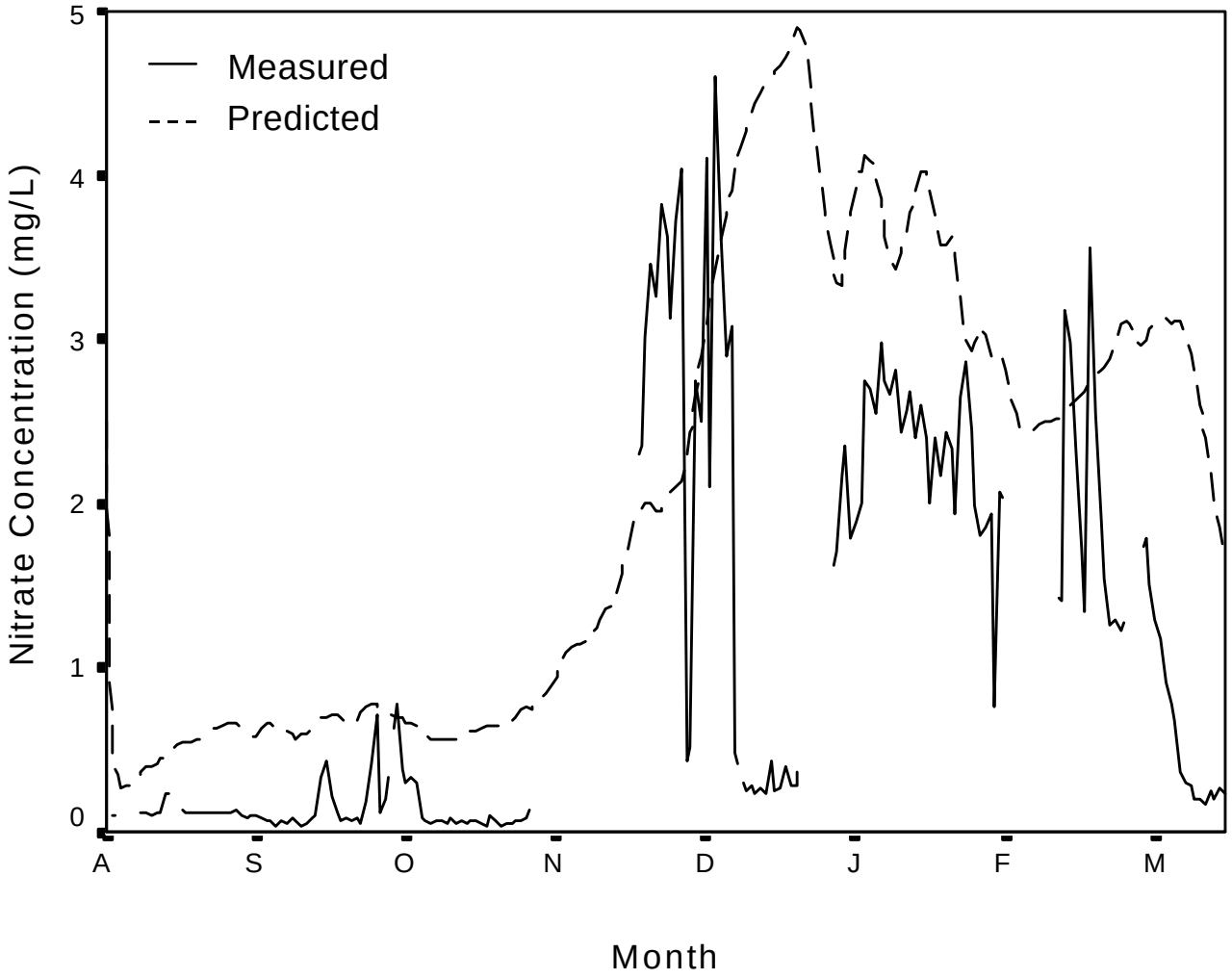


Figure 5-23. Comparison of measured and predicted nitrate concentrations for the validation phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 1.6 mg L^{-1}.

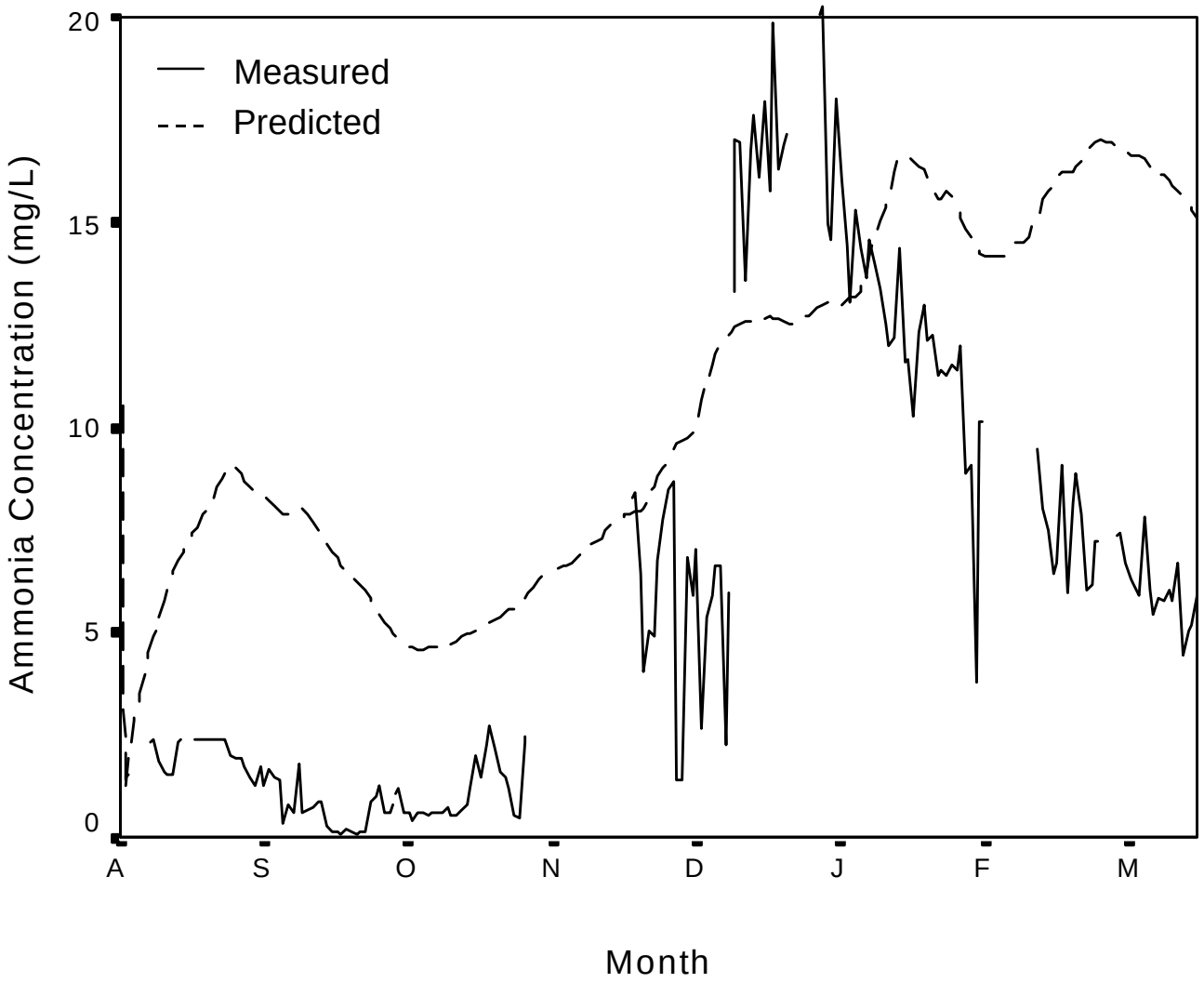


Figure 5-24. Comparison of measured and predicted ammonia concentrations for the validation phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 6.1 mg L^{-1}.

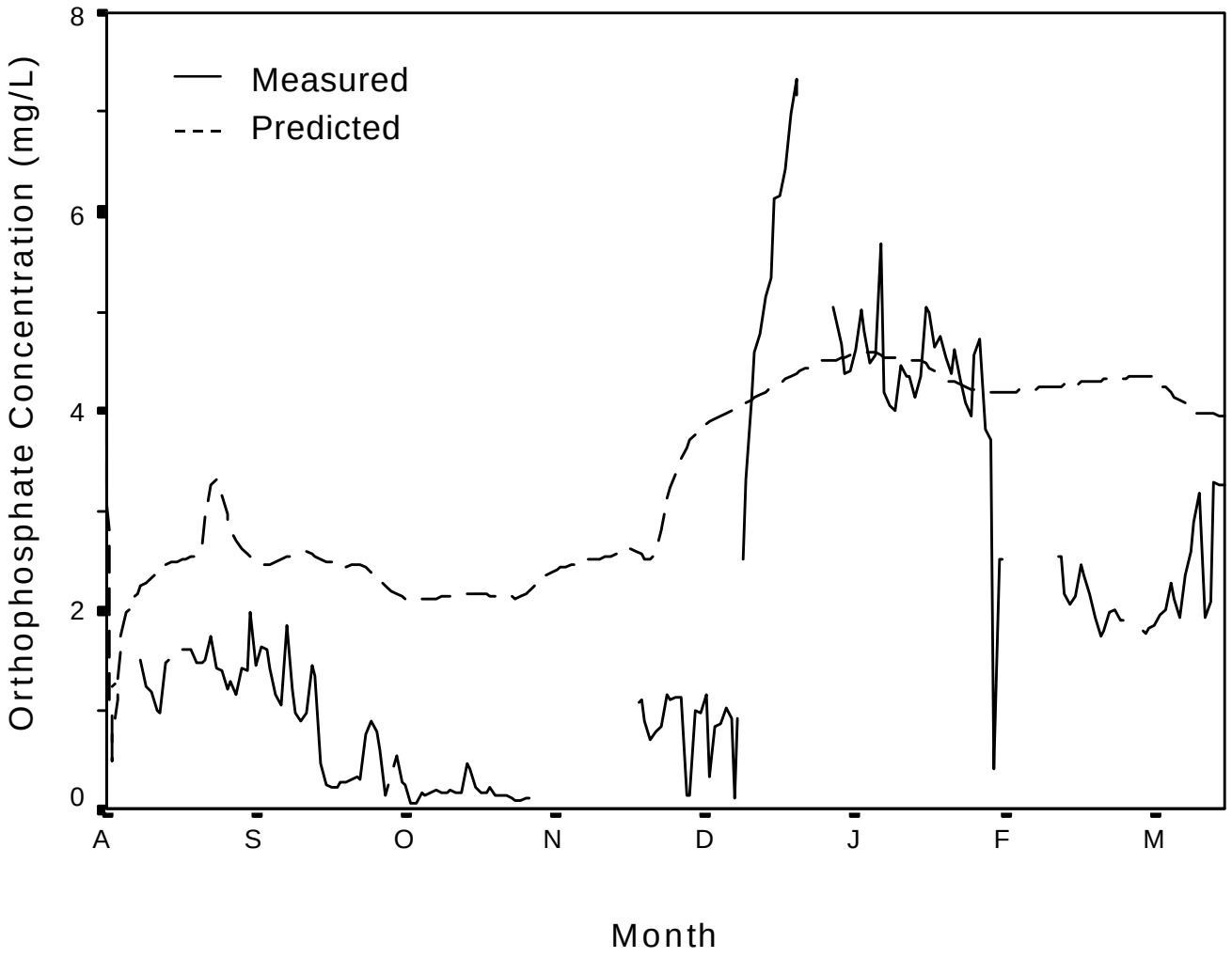


Figure 5-25. Comparison of measured and predicted orthophosphate concentrations for the validation phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 1.8 mg L^{-1}.

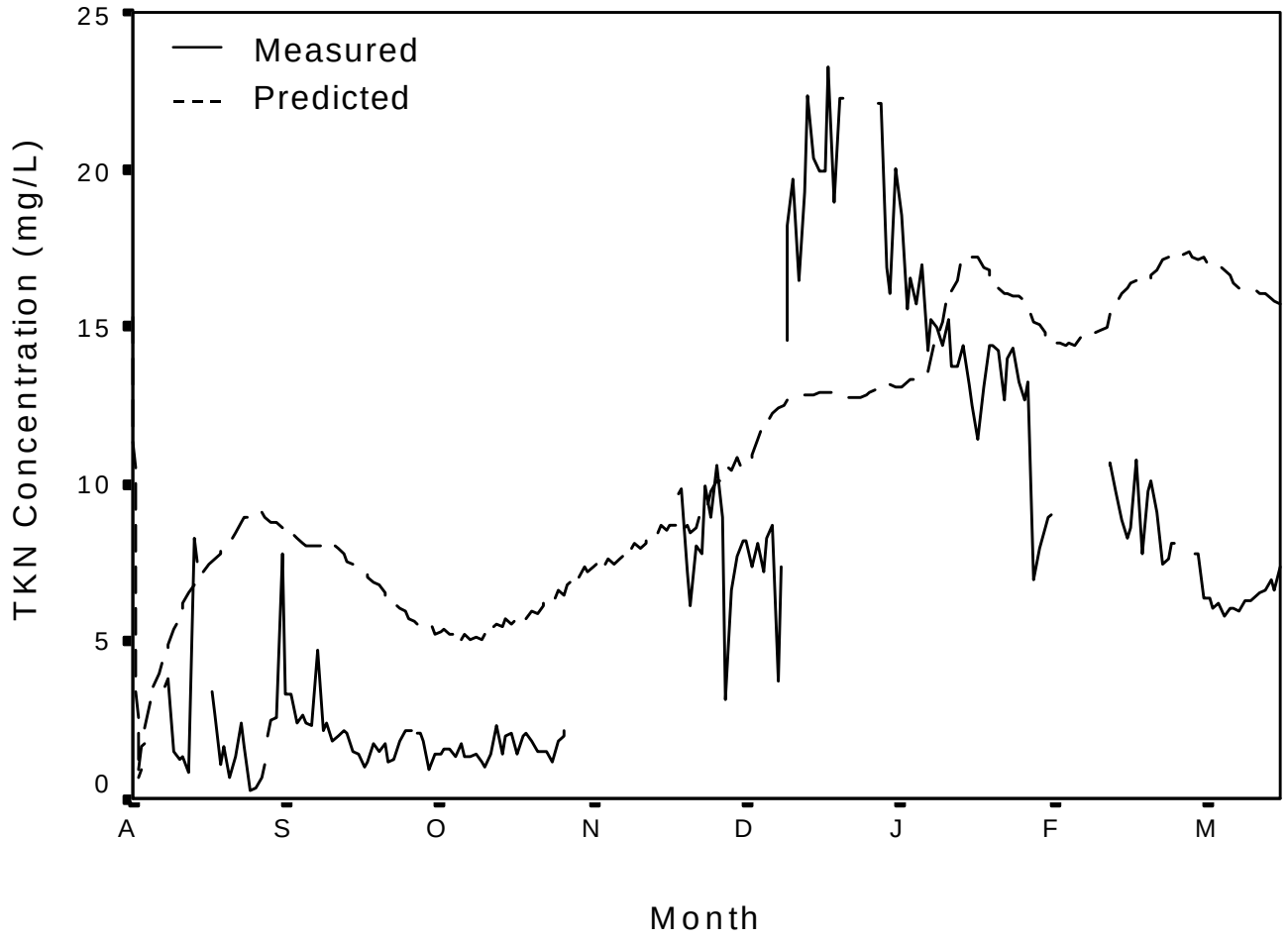


Figure 5-26. Comparison of measured and predicted total Kjeldahl nitrogen (TKN) concentrations for the validation phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 5.9 mg L^{-1}. Note that TKN concentration is equal to the sum of the ammonia concentration and the organic nitrogen concentration.

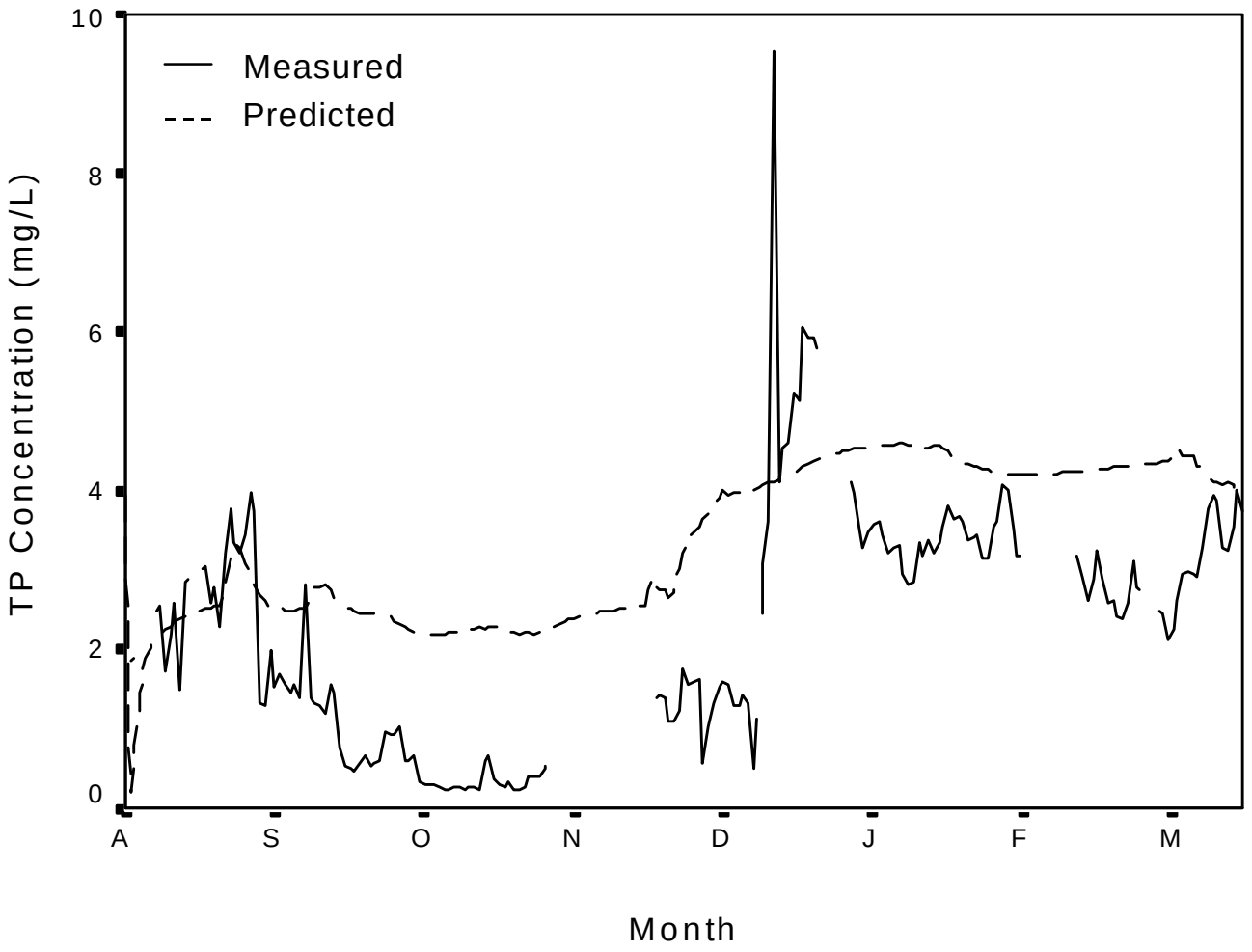


Figure 5-27. Comparison of measured and predicted total phosphorus (TP) concentrations for the validation phase of the modeling effort. The root mean square error (RMSE) value between measured and simulated data was 1.6 mg L^{-1}. Note that TP concentration is equal to the sum of the orthophosphate concentration and the organic phosphorus concentration.

exception of effluent nitrate concentrations, with a validation RMSE of 1.6 and a calibration RMSE of 0.9.

This modeling effort allowed for the exploration of nutrient partitioning within a constructed wastewater treatment wetland. Based on the nutrient model design, approximately 2 % of influent ammonia was taken up by plants, nearly 80 % was nitrified, and approximately 18 % left the wetland cell in effluent during calibration and validation simulations. Approximately 18 % of influent nitrate was taken up by plants, nearly 71 % was denitrified, and approximately 11 % left the wetland cell in effluent. Approximately 90 % of organic nitrogen was partitioned to sediment, while nearly 10 % left the cell in effluent. Note that these results only represent the first cell of the wetland system, which has a total of 4 cells in operation.

Approximately 45 % of the influent orthophosphate was taken up by plants, nearly 45 % was sorbed to sediment, and approximately 10 % left the cell in effluent. Approximately 94 % of organic phosphorus was partitioned to sediment, while nearly 6 % left the cell in effluent. Again, note that these results only represent the first cell of the wetland system, which has a total of 4 cells in operation.

Estimation of Rates for Wetland Processes

Seasonal evapotranspiration rates were verified during the calibration simulation. The resulting estimated daily rate ranged between 0.5 and 1.0 cm m^{-2}. The estimated daily evapotranspiration rate was considered to be between approximately 1.7 and 2.1 mm for a marsh system in Illinois (Konyha et al., 1995). As previously described, for 100 surface wetlands in North America, 1.00 cm d^{-1} is the 40^{th} percentile (Kadlec and Knight, 1996). Evapotranspiration losses approach a daily average of 0.50 cm d^{-1} in summer in the southern U. S.; consequently, more than half the daily added water may be lost to evapotranspiration under those circumstances (Kadlec and Knight, 1996). Wetland evapotranspiration has been estimated to be as low as 0.25 to 0.8 cm d^{-1} in

Nevada, where an arid climate prevails (Laczniak et al., 1999). Daily evapotranspiration rates for a 1.5 ha peatland in New York have been estimated to range from 13.6 to 40 $m^3 d^{-1}$, or 0.09 to 0.27 cm $m^{-2} d^{-1}$ (Drexler et al., 1999). Werner and Kadlec (2000) considered total maximum evapotranspiration for one day to be 0.3 cm in the stochastic simulation of treatment wetlands.

Parameter estimation through calibration and subsequent validation provided some insight into the rates at which biological processes responsible for wastewater treatment performance occur. Simulated plant growth resulted in peak biomass values of 67 to 78 g m^{-2}, 3.9 g m^{-2} and 2.6 g m^{-2} for carbon, nitrogen, and phosphorus, respectively. Researchers have summarized estimates of standing stock vegetative biomass to be 190 to 680 g m^{-2} for *Typha latifolia* and 90 to 150 g m^{-2} for *Scirpus americanus* in wetland plots in South Carolina (Heliotis and DeWitt, 1983). Also, summarized estimates of peak standing stock nitrogen and phosphorus biomass values have been reported to be 5.35 g m^{-2} and 0.77 g m^{-2} , respectively for *Typha*, and 1.66 g m^{-2} and 0.23 g m^{-2}, respectively for *Scirpus* (Heliotis, 1982; Heliotis and DeWitt, 1983). In nutrient studies of cattail (*Typha*) crops, percentages of shoot to root biomass range from 35% (winter) to 85% (summer) (Martín and Fernández, 1992). Plant nitrogen biomass of *Scirpus*, *Typha*, and *Juncus* wetland plant species ranged from 1.0 to 1.5% plant dry weight, while plant phosphorus biomass ranged from 0.2 to 0.4% plant dry weight (McJannet et al., 1995). Plant nitrogen biomass of *Typha* species ranged from 1.0% to 2.8% (shoots) and from 1.5% to 2.9% (roots and rhizomes) (Martín and Fernández, 1992).

Nitrification rates were estimated to range from 0.05 to 0.27 g $m^{-2} d^{-1}$ during the calibration phase of the modeling effort. Nitrification rates in general have been reported to range from 0.025 to 0.160 g $m^{-2} d^{-1}$ (U. S. EPA, 1985). Nitrification rates for wetland systems have been reported to be 2.8 to 3.4 nM $cm^{-3} h^{-1}$ (Howard-Williams and Downes, 1993). Nitrification rates for riparian wetlands have been estimated to be 0.08

to 0.10 g m^{-2} d^{-1} (Dorge, 1994). Also, the effects of temperature on nitrification rates are noteworthy. Ammonia removal and nitrification rates have been reported to decrease as much as 20% in model wetland systems where temperature was changed from 23 to 5 ^{o}C (Lee et al., 1999).

Denitrification were estimated to range from 0.05 to 0.24 g m^{-2} d^{-1} during the calibration phase of the modeling effort. Nitrate reductase activity has been reported to be three or four orders of magnitude higher for freshwater sediments than for overlying water (Jones, 1979). Denitrification rates in general have been reported to range from 0.002 to 0.100 m^{-2} d^{-1} (U. S. EPA, 1985). Denitrification rates of 0.12 g m^{-2} d^{-1} (sediment) to 0.48 g m^{-2} d^{-1} (litter) have been estimated in artificial shallow water systems (Weisner et al., 1994). DeLaune et al. (1996) have explored denitrification in bottomland hardwood wetlands; they reported estimates of nitrogen export from the water column of between 7.5 mg m^{-2} d^{-1} and 11.5 mg m^{-2} d^{-1}. Lusby et al. (1998) have reported on the comparison of nitrification and denitrification potentials in organic and sandy sediments with redox potential values ranging from -50 to +50 mV. The nitrification and denitrification potentials were much greater in the organic sediments (32 ± 49 and 165 ± 150 ng per gram sediment per day, respectively) than in the sandy sediments (-1 ± 3 and 2 ± 5 ng per gram sediment per day, respectively). Denitrifying potential was more than five times higher than nitrifying potential in the organic sediments. Denitrification rates have been estimated to range from 0.04 to 0.24 g m^{-2} d^{-1} using simulations considering the interaction and spatial distribution of wetland nitrogen processes (Martin and Reddy, 1997).

The phosphorus sorption rate was estimated to range from 0.008 to 0.06 g m^{-2} d^{-1} during the calibration phase of the modeling effort. The phosphorus decomposition rate was estimated to range from 0 to 0.01 g m^{-2} d^{-1}. Overall, a net gain in bound sediment phosphorus is often expected in aquatic systems (Canale, 1976; Emsley, 1980), and especially in constructed wetland systems (Mitsch and Reeder, 1991;

Cooke, 1992; Mitsch et al., 1995; U. S. EPA, 2000). Mitsch and Reeder (1991) have estimated phosphorus sedimentation rates to be as high as 0.01 to 0.04 g m^{-2} d^{-1}, with an estimated net phosphorus retention rate of 2.9 mg m^{-2} d^{-1}, in coastal freshwater wetlands. Cooke (1992) has reported estimated phosphorus deposition rates of up to 30 g m^{-2} d^{-1}. Mitsch et al. (1995) have reported phosphorus retention in constructed freshwater riparian marshes to range from 0.5 to 3 g m^{-2} yr^{-1}. Braskerud (2000) has reported overall phosphorus removal to be 0.05 to 0.2 g m^{-2} d^{-1} in wetlands receiving nonpoint source runoff.

Organic sedimentation rates in terms of carbon, nitrogen, and phosphorus were estimated to range from 1.2 to 1.3 g m^{-2} d^{-1}, from 0.007 to 0.19 g m^{-2} d^{-1}, and from 0.007 to 0.085 g m^{-2} d^{-1}, respectively, during the calibration phase of the modeling effort. Note that these rates did not include the contribution from vegetative biomass litter decay, as these processes were simulated separately.

Further Considerations

Many assumptions were made in the nutrient modeling effort of the Tignall Water Reclamation Facility. Efforts could be taken to improve modeling results by appropriately addressing these assumptions.

Hydrology component. Relationships between the resuspension of sediments and extreme hydrologic conditions, such as high flows and heavy rainfall, could be linked to increased phosphorus availability or outflow. Calibration simulation results in this study underestimated phosphorus concentrations in the water column and in wetland cell outflow. Also, the evapotranspiration flow of the hydrology component could be improved using more detailed and specific relationships, with potential rate equations being considered as functions of temperature, solar radiation, water levels, and/or relative humidity.

Vegetation component. Relationships between the carbon, nitrogen, and phosphorus dynamics within the model were dictated by the use of carbon-to-nitrogen and carbon-to-phosphorus ratios. These ratios for many of the ecologically pertinent components, such as the vegetation component, were held fixed for the duration of simulations. Because these ratios link the vegetation component to other flow processes of the model, these ratios should be further explored and adjusted. Variable nutrient ratios, particularly for the vegetation component, could be implemented to address seasonality in plant growth nutrient dynamics. More accurate estimations for these ratios are critical for model predictability of nutrient removal within the wetland treatment system. Also, varying plant growth characteristics by means of the plant growth curve, plant death curve, root growth curve, ammonia uptake fraction could be better representative of plant species, especially with respect to multiple plant species within a given wetland cell. Further relationships could be used for linking plant growth to temperature, solar radiation, and other climatological conditions.

Inorganic nutrients and water quality parameters. Assumptions concerning water quality parameter controls on microbial processes could be better estimated and evaluated. For example, relationships between dissolved oxygen concentrations and nitrification-denitrification could be further explored. Also, relationships between redox potential and microbial activity could be explored. Finally, relationships between these water quality parameters and depth could be incorporated into future simulations.

Further sensitivity analyses are necessary to fully evaluate the robustness of the nutrient modeling tool. By adjusting initial conditions and rate constants, as well as inputs such as influent concentrations, temperature, and rainfall data, the ability of the model to represent the wetland system under different scenarios can be evaluated. By exploring the degree of change in model behavior under changing conditions, the limitations under which the model maintains accuracy could be determined.

Conclusions

A biogeochemical and ecological model of a wetland incorporating the processes of nutrient dynamics was developed, calibrated, and validated using data acquired from monitoring a constructed treatment wetland. Simulation results aided in the quantitative determination of how, and at what rate, given biogeochemical and ecological processes affected the primary production, and subsequent treatment performance, of the constructed treatment wetland system. Rates for these processes were determined using the compartmentalized nutrient model. Simulated plant growth resulted in peak biomass values of 67 to 78 g m^{-2}, 3.9 g m^{-2} and 2.6 g m^{-2} for carbon, nitrogen, and phosphorus, respectively. Nitrification rates were estimated to range from 0.05 to 0.27 g m^{-2} d^{-1}. Denitrification were estimated to range from 0.05 to 0.24 g m^{-2} d^{-1}. The phosphorus sorption rate was estimated to range from 0.008 to 0.06 g m^{-2} d^{-1}. The phosphorus decomposition rate was estimated to range from 0 to 0.01 g m^{-2} d^{-1}. Organic sedimentation rates in terms of carbon, nitrogen, and phosphorus were estimated to range from 1.2 to 1.3 g m^{-2} d^{-1}, from 0.007 to 0.19 g m^{-2} d^{-1}, and from 0.007 to 0.085 g m^{-2} d^{-1}, respectively.

This modeling effort allowed for the exploration of nutrient partitioning within a constructed wastewater treatment wetland considering physical, chemical, and biological processes. On average, simulation results based on model design showed that approximately 2 % of influent ammonia was taken up by plants, nearly 80 % was nitrified, and approximately 18 % left the wetland cell in effluent. Approximately 18 % of influent nitrate was taken up by plants, nearly 71 % was denitrified, and approximately 11 % left the wetland cell via discharge. Approximately 90 % of organic nitrogen was partitioned to sediment, while nearly 10 % left the cell in effluent. Simulation results showed that approximately 45 % of the influent orthophosphate was taken up by plants, nearly 45 % was sorbed to sediment, and approximately 10 % left the

cell in effluent. Also, approximately 94 % of organic phosphorus was partitioned to sediment, while nearly 6 % left the cell via discharge.

The results of this modeling effort provided insight into the rates of physical, chemical, and biological processes for a wastewater treatment wetland in the Georgia Piedmont. The model also provides an opportunity to explore relationships between environmental conditions and these rate processes. In conclusion, the complexity of nutrient cycling within a constructed wastewater treatment wetland system can be better understood and evaluated with the modeling tool proposed in this chapter.

References

Braskerud, B. C. 2000. Measurement and modelling of phosphorus retention in small constructed wetlands treating agricultural non-point source pollution. 7th International Conference on Wetland Systems for Water Pollution Control, Nov. 11-16, Lake Buena Vista, FL, pp. 75-86.

Brix, H. 1993. Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL, pp. 9-22.

Brown, M. T. 1988. A simulation model of hydrology and nutrient dynamics in wetlands. *Comput. Environ. Urban Syst.*, 12(4): 221-237.

Canale, R. P. 1976. Modeling Biochemical Processes in Aquatic Ecosystems. Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Cooke, J. G. 1992. Phosphorus removal processes in a wetland after a decade of receiving a sewage effluent. *J. Environ. Qual*. 21:733-739.

Costanza, R., and F. H. Sklar. 1985. Articulation, accuracy, and effectiveness of mathematical models: a review of freshwater wetland applications. *Ecol. Model.* 27:45-68.

Davis, C. 2001. Personal communication. Tignall Water Reclamation Facility superintendent, Tignall, GA.

DeLaune, R. D., R. R. Boar, C. W. Lindau, and B. A. Kleiss. 1996. Denitrification in bottomland hardwood wetland soils of the Cache River. *Wetlands* 16:309-320.

Drexler, J. Z., B. L. Bedford, A. T. DeGaetano, and D. I. Siegel. 1999. Quantification of the water budget and nutrient loading in a small peatland. *J. Am. Wat. Res. Assoc.* 35:753-769.

Dorge, J. 1994. Modeling nitrogen transformations in freshwater wetlands - estimating nitrogen-retention and removal in natural wetlands in relation to their hydrology and nutrient loadings. *Ecol. Model.* 75:409-420.

Emsley, J. 1980. The phosphorus cycle. In: Hutzinger, O., Ed., The Handbook of Environmental Chemistry, Vol. 1, Part A, The Natural Environment and the Biogeochemical Cycles, Springer-Verlag, Berlin, p. 161.

Fennessy, M. S., C. C. Brueske, and W. J. Mitsch. 1994. Sediment deposition patterns in restored freshwater wetlands using sediment traps. *Ecological Engineering*, 3: 409-428.

Georgia Department of Natural Resources (GA DNR). 1995. Guidelines for Constructed Wetlands for Municipal Wastewater Treatment Facilities. Environmental Protection Division, Water Protection Branch, Atlanta, GA.

Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY.

Hammer, D. A. (Ed.). 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Lewis Publishers, Inc., Boca Raton, FL.

Hammer, D. A. 1992. Creating Freshwater Wetlands. Lewis Publishers, Boca Raton, FL.

Heliotis, F. D., and C. B. DeWitt. 1983. A conceptual model of nutrient cycling in wetlands used for wastewater treatment: a literature analysis. *Wetlands*, 3: 134-152.

High Performance Systems (HPS), Inc. 1989-1998. STELLA® Simulation Software.

Howard-Williams, C. 1985. Cycling and retention of nitrogen and phosphorus in wetlands: a theoretical and applied perspective. *Freshwater Biol.*, 15: 391-431.

Howard-Williams, C., and M. T. Downes. 1993. Nitrogen Cycling in Wetlands. In: Burt, T. P., A. L. Heathwaite, and S. T. Trudgill (Eds.), Nitrate: Processes, Patterns, and Management, John Wiley and Sons, New York, NY.

Johnston, C. A. 1993. Mechanisms of Wetland-Water Quality Interaction. In: Moshiri, G. A. (ed.), Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, pp. 293-299.

Jones, J. G. 1979. Microbial nitrate reduction in freshwater sediments. *J. Gen. Microbiol.* 115:27-35.

Jørgenson, S. E. 1988a. Modelling Eutrophication of Shallow Lakes. In: Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.), Wetland Modelling, Elsevier Publishers, Amsterdam, pp. 177-188.

Jørgenson, S. E. 1988b. Modelling of Wetlands. In: Marani, A. (Ed.), Advances in Environmental Modelling, Elsevier Publishers, Amsterdam, pp. 535-544.

Jørgenson, S. E. 1994. A general model of nitrogen removal by wetlands. In: Mitsch, W. J. (Ed.). Global Wetlands: Old World and New, Elsevier Publishers, New York, NY, pp. 575-583.

Jørgenson, S. E., L. Kamp-Nielson, and O. S. Jacobsen. 1975. A submodel for anaerobic mud-water exchange of phosphate. *Ecol. Model.* 1:133-146.

Jørgenson, S. E., C. C. Hoffmann, and W. J. Mitsch. 1988. Modelling Nutrient Retention by a Reedswamp and Wet Meadow in Denmark. In: Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.), Wetland Modelling, Elsevier Publishers, Amsterdam, pp. 133-151.

Kadlec, R. H. 1999. Chemical, physical, and biological cycles in treatment wetlands. *Wat. Sci. Tech.* 40:37-44.

Kadlec, R. H. 2000. The inadequacy of first-order treatment wetlands models. *Ecol Eng*., 15: 105-109.

Kadlec, R. H., and J. A. Kadlec. 1979. Wetlands and Water Quality. In: Grecian, P. E., J. R. Clark, and J. E. Clark (Eds.). 1979. Wetland Functions and Values: the State of Our Understanding. American Water Resources Association, Minneapolis, MN, pp. 436-456.

Kadlec, R. H., and D. E. Hammer. 1988. Modeling Nutrient Behavior in Wetlands. *Ecol. Modelling*, 40: 37-66.

Kadlec, R. H., and R. L. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL.

Klopatek, J. M. 1978. Nutrient Dynamics of Freshwater Riverine Marshes and the Role of Emergent Macrophytes. In: Good, R. E., D. F. Whigham, and R. L. Simpson (eds.). 1978. Freshwater Wetlands: Ecological Processes and Management Potential, Academic Press, New York, NY, pp. 195-216.

Koerselman, W., and A. F. M. Meuleman, 1996. The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. *J. Appl. Ecol.* 33:1441-1450.

Konyha, K. D., D. T. Shaw, and K. W. Weiler. 1995. Hydrologic design of a wetland: advantages of continuous modeling. *Ecological Engineering* 4:99-116.

Laczniak, R. J., DeMeo, G. A, Reiner, S. R., and LaRue-Smith, J., and W. E. Nylund. 1999. Estimates of Ground-Water Discharge as Determined From Measurements of Evapotranspiration, Ash Meadows Area, Nye County, Nevada Water-Resources Investigations Report 99-4079.

Lee, M. A., J. S. Stansbury, and T. C. Zhang. 1999. The effect of low temperatures on ammonia removal in a laboratory-scale constructed wetland. *Wat. Environ. Res.* 71:340-347.

Lusby, F. E., M. M. Gibbs, A. B. Cooper, and K. Thompson. 1998. Fate of groundwater ammonium in a lake edge wetland. *J. Environ. Qual.* 27:459-466.

Martín, I., and J. Fernández. 1992. Nutrient dynamics and growth of a cattail crop (Typha latifolia L.) developed in an effluent with high eutrophic potential-application to wastewater purification systems. *Biores. Technol.* 42:7-12.

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

McGill, W. B., H. W. Hunt, G. G. Woodmansee, and J. O. Reuss. 1979. PHOENIX, a model of the dynamics of carbon and nitrogen in grassland soils. In: Clark, F. E., and T. Rosswall (Eds.), Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies, and Management Impacts, *Ecol. Bull*. 33:49-115.

McJannet, P. A. Keddy, and F. R. Pick. 1995. Nitrogen and phosphorus tissue concentrations in 41 wetland plants: a comparison across habitats and functional groups. *Functional Ecol.* 9:231-238.

Metzker, K., and W. J. Mitsch. 1997. Modelling self-design of the aquatic community in a newly created freshwater wetland. *Ecol. Modelling,* 100: 61-68.

Mitsch, W. J. 1988. Productivity-Hydrology-Nutrient Models of Forested Wetlands. In: Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.), Wetland Modelling. Elsevier Publishers, Amsterdam, pp. 115-132.

Mitsch, W. J., J. W. Day, Jr., J. R. Taylor, and C. Madden. 1982. Models of North American Freshwater Wetlands-A Review. In: Proceedings of the SCOPE/UNEP International Scientific Workshop on Ecosystem Dynamics in Freshwater Wetlands and Shallow Water Bodies 2, 5-32.

Mitsch, W. J., M. Straškraha, and S. E. Jørgenson (Eds.). 1988. Wetland Modelling. Elsevier Publishers, Amsterdam.

Mitsch, W. J., and B. C. Reeder. 1991. Modelling nutrient retention of a freshwater coastal wetland: estimating the roles of primary productivity, sedimentation, resuspension and hydrology. *Ecol. Modelling*, 54: 151-187.

Mitsch, W.J., J. K. Cronk, X. Wu, R. W. Nairn, and D. L. Hey. 1995. Phosphorus retention in constructed freshwater riparian marshes. *Ecol. Applications* 5, 830-845.

Moshiri, G. A. (Ed.). 1993. Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL.

Morris, J. T., and W. B. Bowden. 1986. A mechanistic, numerical model of sedimentation, mineralization, and decomposition for marsh sediments. *Soil Sci. Soc. Am. J.* 50:96-105.

Qian, S. S., and K. H. Reckhow. 1998. Modeling phosphorus trapping in wetlands using nonparametric Bayesian regression. *Wat. Res.* 34:1745-1754.

Reddy, K. R., and D. A. Graetz. 1988. Carbon and Nitrogen Dynamics in Wetland Soils. In: Hook, D. D., et al., (Eds.), The Ecology and Management of Wetlands, Vol. 1: Ecology of Wetlands. Timber Press, Portland, OR., pp. 307-318.

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

Sheridan, J. M., R. G. Williams, L. S. Altier, R. R. Lowrance, W. C. Mills, D. L. Thomas. 1993. Hydrologic Modeling for Riparian Management. ASAE International Winter Meeting, December 14-17, Paper No. 932598.

Tilton, D. L., R. H. Kadlec, and C. J. Richardson (Eds.). 1976. Freshwater Wetlands and Sewage Effluent Disposal. The University of Michigan Press, Ann Arbor, MI.

U. S. Environmental Protection Agency. 1983. Phase I Report: Freshwater Wetlands for Wastewater Management. Office of Water , Washington, D. C. EPA 904/9-83-107.

U. S. Environmental Protection Agency. 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling, 2nd. ed. Environmental Research Laboratory, Office of Research and Development, Athens, GA. EPA/600/3-85/040.

U. S. Environmental Protection Agency. 1987. Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal. Office of Water , Washington, D. C. EPA/430/09-88-055.

U. S. Environmental Protection Agency. 1988. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. Office of Water , Washington, D. C. EPA/625/1-88/022.

U. S. Environmental Protection Agency. 2000. Constructed Wetlands Treatment of Municipal Wastewaters. National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH. EPA/625/R-99/010.

Valiela, I., and J. M. Teal. 1978. Nutrient Dynamics: Summary and Recommendations. In: Good, R. E., D. F. Whigham, and R. L. Simpson (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, NY, pp. 259-263.

Vargo, S. M., R. K. Neely, and S. M. Kirkwood. 1998. Emergent plant decomposition and sedimentation: response to sediments varying in texture, phosphorus content, and frequency of deposition. *Env. Exp. Botany* 40:43-58.

Vymazal, J. 1995. Algae and Element Cycling in Wetlands. Lewis Publishers, Boca Raton, FL.

Weisner, S. E. B., P. G. Erikkson, W. Granéli, and L. Leonardson. 1994. Influence of macrophytes on nitrate removal in wetlands. *Ambio* 23:363-366.

Werner, T. M., and R. H. Kadlec. 2000. Stochastic simulation of partially-mixed, event driven treatment wetlands. *Ecological Engineering* 14:253-267.

CHAPTER 6

CONCLUSIONS

Revisiting Objectives

The primary objective of this study was to better understand and estimate the processes that govern the fate and transport of nutrients through a constructed treatment wetland system in North Georgia. Specifically, the following questions were addressed:

1) What are the primary biological processes responsible for wastewater treatment in a constructed wetland system in north Georgia?

2) What are the microbial populations in a wetland system constructed for municipal wastewater treatment in north Georgia?

3) What is the role of wetland vegetation (intentionally planted and volunteer) on specific treatment processes?

4) How and at what rate is the decomposition of organic matter mediated by microorganisms in the constructed wetland system?

5) How and at what rate are the removal of nutrients mediated by microorganisms in the constructed wetland system?

6) What effects due seasonal fluctuations in parameters, such as temperature, have on 1) through 5) above?

7) What recommendations, if any, can be made on constructed wetland design, operations, and maintenance based on the answers to 1) through 6) above?

The major biogeochemical and ecological processes involved in treatment of wastewater with constructed wetlands included: 1) the uptake and assimilation of nutrients by vegetation; 2) the contribution of dead vegetative biomass to the organic content of sediment; 3) the microbial decomposition of vegetative organic material; 4) the microbial activity resulting in nitrification of ammonia-nitrogen and denitrification of nitrate-nitrogen; and 5) the physicohemical and microbial processes leading to the sorption and decomposition of phosphorus compounds. Biochemical transformations and the physical mass transport of nutrients provided the common unit of transfer between these five distinct but intertwined processes, and thus played an integral role in understanding and estimating nutrient fluxes.

Spatiotemporal Characterization of Treatment Wetland

The first step in understanding the internal physical, chemical, and biological processes that occur in a treatment wetland was to assess the spatial and seasonal variability of nutrients within the system. By monitoring a section of the constructed wetland over a two year period, relationships between water quality parameters and nutrients, solids, and biochemical oxygen demand (BOD) concentrations were determined. High inverse relationships between temperature and dissolved oxygen concentrations existed, while good positive correlations between dissolved oxygen concentration and redox potential were indicated over space and time. Also, high correlations between nutrient concentrations and solids concentrations were indicated in this study.

The spatial distribution of nutrients, solids, and BOD concentrations was explored, indicating that higher concentrations existed within more densely vegetated areas. Also, concentrations increased along the flow gradient of the vegetated area before decreasing, or in some cases not changing significantly, at the end of the vegetated area. The contribution of dead vegetative organic matter, increased filtration due to plant stems

and roots, and higher sedimentation from slowed flow due to vegetation resistance were considered to be responsible for higher nutrients, solids, and BOD concentrations in the vegetated area.

Seasonal patterns in nutrient concentrations demonstrated oscillations in ammonia and nitrate concentrations, with ammonia concentrations being high in the summer and low in the winter. The opposite was true for nitrate concentrations. This pattern was attributed to environmental conditions, including temperature, dissolved oxygen concentrations, and redox potential. Winter conditions (low temperature, high dissolved oxygen concentration, high redox potential), appeared to favor nitrification, while summer conditions (high temperature, low dissolved oxygen concentrations, low redox potential) favored denitrification. Seasonal patterns were not detected for other nutrients; however, broader distributions in summer months of nutrients and solids concentrations related to organic matter suggest that higher vegetative biomass may impact wastewater treatment performance by contributing high organic matter to the system during the peak of the growing season.

Identification of Microbial Populations

The exploration and characterization of microbial populations in the constructed wetland system provided information regarding the identification of Gram negative bacteria, and the functional role of these bacteria in wastewater treatment was assessed. Both obligate aerobic and facultative anaerobic bacteria were found to be present in the wetland system, indicating a range of aerobic and anaerobic conditions that exist in the wetland. Varying dissolved oxygen concentrations and redox potentials further indicated this range of conditions. Nitrifying bacteria, denitrifying bacteria, and nitrogen fixing bacteria were all present in the wetland.

Relationships between the types of bacteria and water quality parameters such as temperature, dissolved oxygen concentration, and redox potential were explored. Results

indicated that higher microbial activity occurred during the summer than in the winter. In the summer, when oxygen may be limited, there was a higher percentage of facultative anaerobic bacteria than in the winter. Also, a higher percentage of denitrifying bacteria were present in the summer than in the winter, reflecting anaerobic conditions because denitrification is known to be favorable under oxygen-limited conditions.

Relationships between the types of bacteria present in the system and solids, BOD, and nutrient concentrations were assessed. In the summer, solids concentrations were higher, indicating a higher presence of organic matter and, subsequently, anaerobic conditions. Also, BOD concentrations were higher in the summer, reflecting more anaerobic conditions. As previously discussed, facultative anaerobic bacteria and denitrifying bacteria were higher in the summer than in the winter. In the summer, both ammonia and nitrate concentrations were lower than in the winter, indicating higher nitrification and denitrification microbial activity in the summer. Ammonia concentrations were twice as high in winter than in summer, while nitrate concentrations were three times as high in winter than in summer. The results indicate favorable nitrification in the winter, and favorable denitrification in the summer.

Nutrient Modeling of Constructed Wetland

A biogeochemical and ecological model of a wetland incorporating the processes of nutrient dynamics was developed, calibrated, and validated using data acquired from monitoring a constructed treatment wetland. Simulation results aided in determining quantitatively how each of the five biogeochemical and ecological processes affected the primary production, and subsequent treatment performance, of the constructed treatment wetland system. Rates for these processes were determined using the compartmentalized nutrient model. Simulated plant growth resulted in peak biomass values of 67 to 78 g m^{-2}, 3.9 g m^{-2} and 2.6 g m^{-2} for carbon, nitrogen, and phosphorus, respectively. Nitrification rates were estimated to range from 0.05 to 0.27 g m^{-2} d^{-1}. Denitrification

were estimated to range from 0.05 to 0.24 g m^{-2} d^{-1}. The phosphorus sorption rate was estimated to range from 0.008 to 0.06 g m^{-2} d^{-1}. The phosphorus decomposition rate was estimated to range from 0 to 0.01 g m^{-2} d^{-1}. Organic sedimentation rates in terms of carbon, nitrogen, and phosphorus were estimated to range from 1.2 to 1.3 g m^{-2} d^{-1}, from 0.007 to 0.19 g m^{-2} d^{-1}, and from 0.007 to 0.085 g m^{-2} d^{-1}, respectively.

According to the nutrient model design, influent nitrogen was partitioned into certain components based on results demonstrated via calibration and validation simulations. Results showed that approximately 2 % of influent ammonia was taken up by plants, nearly 80 % was nitrified and subsequently denitrified, and approximately 18 % left the wetland cell in effluent. Approximately 18 % of influent nitrate was taken up by plants, nearly 71 % was denitrified, and approximately 11 % left the wetland cell in effluent. Approximately 90 % of organic nitrogen was partitioned to sediment, while nearly 10 % left the cell in effluent.

According to the nutrient model design, influent phosphorus was partitioned into certain components based on results demonstrated via calibration and validation simulations. Approximately 45 % of the influent orthophosphate was taken up by plants, nearly 45 % was sorbed to sediment, and approximately 10 % left the cell in effluent. Approximately 94 % of organic phosphorus was partitioned to sediment, while nearly 6 % left the cell in effluent.

Overall Recommendations

The research presented in this dissertation has led to possible recommendations regarding the design, operations, and maintenance of the Tignall Water Reclamation Facility. Further investigations and experiments should be considered to study the impact of these recommendations on treatment system performance, and benefit-cost relationships should be evaluated.

First of all, based on the high degree of organic content in wastewater, plant selection during the design process could be improved by choosing plant species that contribute less biomass to the system. For example, as discussed in Chapter 3, the contribution of *Zizaniopsis miliacea* (cutgrass) biomass to the system was high compared to that of *Schoenoplectus californicus* (bullrush). The recommendation would be to explore alternative species that contribute less biomass to the system, thus decreasing internal BOD, solids, and nutrient concentrations, and ultimately improving treatment performance.

Second, treatment performance may be improved by incorporating operational strategies that would increase oxygen concentrations in the summer. This strategy would encourage higher nitrification-denitrification rates, as discussed in Chapter 4, thus allowing for more nitrogen to leave the system as nitrogen gas.

Third, plant harvest may be incorporated into maintenance strategies in order to remove these sequestered nutrients from the system. This would be especially effective if plants such as *Z. miliacea*, which contributes high amounts of biomass to the system, have been planted. Nutrients would be removed from the system, and less biomass would be contributed to the system, thus lowering internal BOD, solids, and nutrient concentrations, and increasing treatment performance.

Finally, sediment and sludge removal could be incorporated as an operation and maintenance strategy for the system. As indicated in Chapter 5, simulation results indicated that most of the organic matter and inorganic phosphorus was partitioned into the sediment component. Sediment removal would remove organic matter and decrease BOD concentrations, resulting in higher oxygen availability, higher organic decomposition, and better BOD removal. Also, higher oxygen availability may improve nitrification, taking ammonia one step closer to being removed from the system as nitrogen gas. Sediment removal would remove inorganic phosphorus from the system. If the system were to continue to accumulate phosphorus, the sediment may eventually

become a source of phosphorus rather than a sink. Finally, sludge accumulation leads to short-circuiting within the wetland, resulting in decreased retention times and overall reduction in treatment performance.

Final Conclusions

The research presented in this dissertation includes water quality monitoring, laboratory analyses, and computer simulation modeling. These efforts were conducted in order to better understand the processes responsible for wastewater treatment using constructed wetlands. First-order design models cannot take into consideration the vast complexity of biogeochemical and ecological processes that occur in such systems as presented in this dissertation. The scope of this dissertation research only begins to uncover insights into assessing and evaluating this complexity. Further research efforts must be undertaken in order to incorporate the patterns and relationships resulting from this work into improving the future design of wastewater wetland treatment systems and incorporating effective strategies into the operations and maintenance of these systems.

APPENDIX A

STELLA® MODEL EQUATIONS FOR FINAL CALIBRATION SIMULATION

State variable equations:

Ammonia_N(t) = Ammonia_N(t - dt) + (Inf_NH3 + Outflow_in_NH3 + N_fixing - Nitrification - Root_Uptake_NH4 - Outflow_NH3) * dt

INIT Ammonia_N = 300
DOCUMENT: (grams)

Inf_NH3 = Influent_NH3_Conc*Influent
DOCUMENT: (grams per day)

Outflow_in_NH3 = Outflow_NH3
DOCUMENT: (grams per day)

N_fixing = MAF*k_N_fixers*Sediment_N
DOCUMENT: (grams per day)

Nitrification = ((kNit*Ammonia_N))*DOF_Nit
DOCUMENT: (grams per day)

Root_Uptake_NH4 =
IF(Root_Growth_C/CNRoot*NH3_Uptake_Fraction<Ammonia_N)
THEN(Root_Growth_C/CNRoot*NH3_Uptake_Fraction)
ELSE(0)
DOCUMENT: (grams per day)

Outflow_NH3 = Ammonia_N/OUTFLOW
DOCUMENT: (grams per day)

Available_P(t) = Available_P(t - dt) + (Inf_orthoP + Decomp_P + Outflow_in_orthoP - Root_Uptake_P - Outflow_orthoP - Sorbed_P) * dt

INIT Available_P = 100
DOCUMENT: (grams)

Inf_orthoP = Influent_ortho_P_Conc*Influent
DOCUMENT: (grams per day)

Decomp_P = k_decomp_P*Sediment_P*MAF
DOCUMENT: (grams per day)

Outflow_in_orthoP = Outflow_orthoP
DOCUMENT: (grams per day)

```
        Root_Uptake_P = IF(Root_Growth_C/CPRoot<Available_P)
        THEN(Root_Growth_C/CPRoot)
        ELSE(0)
        DOCUMENT:  (grams per day)

        Outflow_orthoP = Available_P/OUTFLOW
        DOCUMENT:  (grams per day)

        Sorbed_P = k_sorb_P*Available_P

Litter_C(t) = Litter_C(t - dt) + (Dead_Litter_C + Root_Litter_C - Litter_Sediment_C)*dt

INIT Litter_C = 20
DOCUMENT:  (grams)

        Dead_Litter_C = IF(Standing_Dead_C*Kd>Standing_Dead_C)
        THEN(Standing_Dead_C*Kd)
        ELSE(Standing_Dead_C)


        Root_Litter_C = Kr*Plant_Death_Curve*Live_Root_C
        DOCUMENT:  (grams per day)

        Litter_Sediment_C = Litter_C*K_litter
        DOCUMENT:  (grams per day)

Litter_N(t) = Litter_N(t - dt)+(Dead_Litter_N + Root_Litter_N - Litter_Sediment_N)* dt

INIT Litter_N = 1
DOCUMENT:  (grams)

        Dead_Litter_N = Dead_Litter_C/CNDead
        DOCUMENT:  (grams per day)

        Root_Litter_N = IF((Root_Litter_C/CNRoot<Live_Root_N)
                        AND(Root_Shoot_N<Live_Root_N))
                        THEN(Root_Litter_C/CNRoot)
                        ELSE(0)
        DOCUMENT:  (grams per day)

        Litter_Sediment_N = Litter_Sediment_C/CNLitter
        DOCUMENT:  (grams per day)
```

```
Litter_P(t) = Litter_P(t - dt) + (Dead_Litter_P + Root_Litter_P - Litter_Sediment_P) * dt

INIT Litter_P = 3
DOCUMENT:  (grams)

        Dead_Litter_P = IF(Dead_Litter_C/CPDead<Standing_Dead__P)
                        THEN(Dead_Litter_C/CPDead)
                        ELSE(Standing_Dead__P)
        DOCUMENT:  (grams per day)

        Root_Litter_P = IF(PHOTO_C/CPRoot+Root_Litter_C/CPRoot<Live_Root_P)
                        THEN(Root_Litter_C/CPRoot)
                        ELSE(Live_Root_P-PHOTO_C/CPRoot)
        DOCUMENT:  (grams per day)

        Litter_Sediment_P = Litter_Sediment_C/CPLitter
        DOCUMENT:  (grams per day)

Live_Root_C(t) = Live_Root_C(t - dt) + (Root_Growth_C - Root_Litter_C) * dt

INIT Live_Root_C = 250
DOCUMENT:  (grams)

        Root_Growth_C = PHOTO_C*Root_Fraction
        DOCUMENT:  (grams per day)

        Root_Litter_C = Kr*Plant_Death_Curve*Live_Root_C
        DOCUMENT:  (grams per day)

Live_Root_N(t) = Live_Root_N(t - dt) + (Root_Uptake_NH4 + Root_Uptake_NO3 -
                 Root_Shoot_N - Root_Litter_N) * dt

INIT Live_Root_N = 100
DOCUMENT:  (grams)

        Root_Uptake_NH4 =
                IF(Root_Growth_C/CNRoot*NH3_Uptake_Fraction<Ammonia_N)
                THEN(Root_Growth_C/CNRoot*NH3_Uptake_Fraction)
                ELSE(0)
        DOCUMENT:  (grams per day)
```

```
        Root_Uptake_NO3 =
                IF(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction)<Nitrate_N)
                THEN(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction))
                ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Shoot_N = IF(PHOTO_C/CNShoot<Live_Root_N)
                          THEN(PHOTO_C/CNShoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Litter_N = IF((Root_Litter_C/CNRoot<Live_Root_N)
                         AND(Root_Shoot_N<Live_Root_N))
                         THEN(Root_Litter_C/CNRoot)
                         ELSE(0)
        DOCUMENT:  (grams per day)

Live_Root_P(t) = Live_Root_P(t - dt) + (Root_Uptake_P - Root_Shoot_P -
                    Root_Litter_P) * dt

INIT Live_Root_P = 100
DOCUMENT:  (grams)

        Root_Uptake_P = IF(Root_Growth_C/CPRoot<Available_P)
                          THEN(Root_Growth_C/CPRoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Shoot_P = IF(PHOTO_C/CPShoot<Live_Root_P)
                          THEN(PHOTO_C/CPShoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Litter_P = IF(PHOTO_C/CPRoot+Root_Litter_C/CPRoot<Live_Root_P)
                          THEN(Root_Litter_C/CPRoot)
                          ELSE(Live_Root_P-PHOTO_C/CPRoot)
        DOCUMENT:  (grams per day)


Live_Shoot_C(t) = Live_Shoot_C(t - dt) + (PHOTO_C - Shoot_C) * dt

INIT Live_Shoot_C = 50
DOCUMENT:  (grams)
```

```
        PHOTO_C = (IF(Kp*Plant_Growth_Curve/CNShoot>Live_Root_N)
                        THEN(Live_Root_N*CNShoot)
                        ELSE(IF(Kp*Plant_Growth_Curve/CPShoot>Live_Root_P)
                        THEN(Live_Root_P*CPShoot)
                        ELSE(Kp*Plant_Growth_Curve)))
        DOCUMENT:  (grams per day)

        Shoot_C = Ks*Plant_Death_Curve*Live_Shoot_C
        DOCUMENT:  (grams per day)

Live_Shoot_N(t) = Live_Shoot_N(t - dt) + (Root_Shoot_N - Shoot_N) * dt

INIT Live_Shoot_N = 10
DOCUMENT:  (grams)

        Root_Shoot_N = IF(PHOTO_C/CNShoot<Live_Root_N)
                          THEN(PHOTO_C/CNShoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Shoot_N = Shoot_C/CNShoot
        DOCUMENT:  (grams per day)

Live_Shoot_P(t) = Live_Shoot_P(t - dt) + (Root_Shoot_P - Shoot_P) * dt

INIT Live_Shoot_P = 5
DOCUMENT:  (grams)

        Root_Shoot_P = IF(PHOTO_C/CPShoot<Live_Root_P)
                          THEN(PHOTO_C/CPShoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Shoot_P = Shoot_C/CPShoot
        DOCUMENT:  (grams per day)



Nitrate_N(t) = Nitrate_N(t - dt) + (Nitrification + Inf_NO3 + Outflow_in_NO3 -
                Denitrification - Root_Uptake_NO3 - Outflow_NO3) * dt

INIT Nitrate_N = 300
DOCUMENT:  (grams)
```

```
        Nitrification = ((kNit*Ammonia_N))*DOF_Nit
        DOCUMENT:  (grams per day)

        Inf_NO3 = Influent_NO3_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_NO3 = Outflow_NO3
        DOCUMENT:  (grams per day)

        Denitrification = (kDeNit*Nitrate_N)*DOF_Denit
        DOCUMENT:  (grams per day)

        Root_Uptake_NO3 =
                IF(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction)<Nitrate_N)
                THEN(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction))
                ELSE(0)
        DOCUMENT:  (grams per day)

        Outflow_NO3 = Nitrate_N/OUTFLOW
        DOCUMENT:  (grams per day)

Organic_C(t) = Organic_C(t - dt) + (Inflow_C + Outflow_in_C - Outflow_C -
                Water_Sediment_C) * dt

INIT Organic_C = 1000
DOCUMENT:  (grams)

        Inflow_C = INFLUENT_C_CONC*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_C = Outflow_C
        DOCUMENT:  (grams per day)

        Outflow_C = Organic_C/OUTFLOW
        DOCUMENT:  (grams per day)

        Water_Sediment_C = IF(Ksed*SF<Organic_C)
        THEN(Ksed*SF)
        ELSE(0)
        DOCUMENT:  (grams per day)
```

```
Organic_N(t) = Organic_N(t - dt) + (Inflow_Organic_N + Outflow_in_N -
                Water_Sediment_N - Outflow_N) * dt

INIT Organic_N = 300
DOCUMENT:  (grams)

        Inflow_Organic_N = Inf_Org_N_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_N = Outflow_N
        DOCUMENT:  (grams per day)

        Water_Sediment_N = Water_Sediment_C/CNOrganic
        DOCUMENT:  (grams per day)

        Outflow_N = Organic_N/OUTFLOW
        DOCUMENT:  (grams per day)

Organic_P(t) = Organic_P(t - dt) + (Inflow_P + Outflow_in_P - Water_Sediment_P -
                Outflow_P) * dt

INIT Organic_P = 100
DOCUMENT:  (grams)

        Inflow_P = Inf_Org_P_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_P = Outflow_in*Effluent_Org_P_Conc
        DOCUMENT:  (grams per day)

        Water_Sediment_P = Water_Sediment_C/CPOrganic
        DOCUMENT:  (grams per day)

        Outflow_P = Organic_P/OUTFLOW
        DOCUMENT:  (grams per day)



Sediment_C(t) = Sediment_C(t - dt) + (Litter_Sediment_C + Water_Sediment_C -
                Sediment_CO2) * dt

INIT Sediment_C = 10
DOCUMENT:  (grams)
```

```
        Litter_Sediment_C = Litter_C*K_litter
        DOCUMENT:  (grams per day)

        Water_Sediment_C = IF(Ksed*SF<Organic_C)
                               THEN(Ksed*SF)
                                ELSE(0)
        DOCUMENT:  (grams per day)

        Sediment_CO2 = MAF*K_CO2*Sediment_C
        DOCUMENT:  (grams per day)

Sediment_N(t) = Sediment_N(t - dt) + (Water_Sediment_N + Litter_Sediment_N -
                N_fixing) * dt

INIT Sediment_N = 1
DOCUMENT:  (grams)

        Water_Sediment_N = Water_Sediment_C/CNOrganic
        DOCUMENT:  (grams per day)

        Litter_Sediment_N = Litter_Sediment_C/CNLitter
        DOCUMENT:  (grams per day)

        N_fixing = MAF*k_N_fixers*Sediment_N
        DOCUMENT:  (grams per day)

Sediment_P(t) = Sediment_P(t - dt) + (Litter_Sediment_P + Water_Sediment_P +
                Sorbed_P - Decomp_P) * dt

INIT Sediment_P = 2
DOCUMENT:  (grams)

        Litter_Sediment_P = Litter_Sediment_C/CPLitter
        DOCUMENT:  (grams per day)

        Water_Sediment_P = Water_Sediment_C/CPOrganic
        DOCUMENT:  (grams per day)

        Sorbed_P = k_sorb_P*Available_P
        DOCUMENT:  (grams per day)

        Decomp_P = k_decomp_P*Sediment_P*MAF
        DOCUMENT:  (grams per day)
```

```
Sediment_Volume(t) = Sediment_Volume(t - dt) + (Sediment_Inflow -
                     Sediment_Outflow) * dt

INIT Sediment_Volume = Bottom_Area*INITIAL_SED_DEPTH
DOCUMENT:  (cubic meters)

    Sediment_Inflow=(Litter_Sediment_C+Litter_Sediment_N+Litter_Sediment_P+
                     Water_Sediment_C+Water_Sediment_N+Water_Sediment_P)*
                     Sediment_density
    DOCUMENT:  (cubic meters per day)

    Sediment_Outflow = 0
    DOCUMENT:  (cubic meters per day)

Standing_Dead_C(t) = Standing_Dead_C(t - dt) + (Shoot_C - Dead_Litter_C) * dt

INIT Standing_Dead_C = 100
DOCUMENT:  (grams)

    Shoot_C = Ks*Plant_Death_Curve*Live_Shoot_C
    DOCUMENT:  (grams per day)

    Dead_Litter_C = IF(Standing_Dead_C*Kd>Standing_Dead_C)
                    THEN(Standing_Dead_C*Kd)
                    ELSE(Standing_Dead_C)
    DOCUMENT:  (grams per day)

Standing_Dead_N(t) = Standing_Dead_N(t - dt) + (Shoot_N - Dead_Litter_N) * dt

INIT Standing_Dead_N = 2
DOCUMENT:  (grams)

    Shoot_N = Shoot_C/CNShoot
    DOCUMENT:  (grams per day)

    Dead_Litter_N = Dead_Litter_C/CNDead
    DOCUMENT:  (grams per day)

Standing_Dead__P(t) = Standing_Dead__P(t - dt) + (Shoot_P - Dead_Litter_P) * dt

INIT Standing_Dead__P = 1
DOCUMENT:  (grams)
```

```
        Shoot_P = Shoot_C/CPShoot
        DOCUMENT:  (grams per day)

        Dead_Litter_P = IF(Dead_Litter_C/CPDead<Standing_Dead__P)
                          THEN(Dead_Litter_C/CPDead)
                          ELSE(Standing_Dead__P)
        DOCUMENT:  (grams per day)

WW_volume(t) = WW_volume(t - dt) + (Precip + Influent + Outflow_in - ET -
                    OUTFLOW) * dt

INIT WW_volume = Bottom_Area*INITIAL_WW_DEPTH
DOCUMENT:  (cubic meters)

        Precip = ACTUAL_PRECIP*0.0254*Surface_area
        DOCUMENT:  (cubic meters per day)

        Influent = INFLOW*flow_divider
        DOCUMENT:  (cubic meters per day)

        Outflow_in = IF ((RECIRCULATE=1)
                        AND ((YEARDAY<=RECIRC_START)
                        OR(YEARDAY>RECIRC_END)))
                        THEN (0)
                        ELSE (OUTFLOW*.2)
        DOCUMENT:  (cubic meters per day)

        OUTFLOW = Influent
        DOCUMENT:  (cubic meters per day)
```

Rate constants and parameter equations:

```
Bottom_Area = LENGTH*BOTTOM_WIDTH
DOCUMENT:  (square meters)

BOTTOM_WIDTH = 18
DOCUMENT:  (meters)

Cell_volume = ((LENGTH*BOTTOM_WIDTH)+(LENGTH-2*MAX_DEPTH*SLOPE)
                *(BOTTOM_WIDTH-2*MAX_DEPTH*SLOPE)+4*(LENGTH-
                MAX_DEPTH*SLOPE)*(BOTTOM_WIDTH-MAX_DEPTH*
                SLOPE)*MAX_DEPTH)/6
DOCUMENT:  (cubic meters)
```

```
CNDead = 100

CNLitter = 10

CNOrganic = Organic_C/Organic_N

CNRoot = 5

CNShoot = 20

CN_Sediment = Sediment_C/Sediment_N

CPDead = 100

CPLitter = Litter_C/Litter_P

CPOrganic = Organic_C/Organic_P

CPRoot = 10

CPSediment = Sediment_C/Sediment_P

CPShoot = 30

Effluent_C_Conc = IF(OUTFLOW>0)
                  THEN(Outflow_C/OUTFLOW)
                  ELSE(0)
DOCUMENT:  (milligrams per liter)

Effluent_NH3_Conc = IF(OUTFLOW>0)
                    THEN(Outflow_NH3/OUTFLOW)
                    ELSE(0)
DOCUMENT:  (milligrams per liter)

Effluent_NO3_Conc = IF(OUTFLOW>0)
                    THEN(Outflow_NO3/OUTFLOW)
                    ELSE(0)
DOCUMENT:  (milligrams per liter)

Effluent_Org_P_Conc = IF(OUTFLOW>0)
                      THEN(Outflow_P/OUTFLOW)
                      ELSE(0)
DOCUMENT:  (milligrams per liter)
```

```
Effluent_TKN_Conc = Effluent_NH3_Conc+Effluent_Org_N_Conc
DOCUMENT:  (milligrams per liter)

Effluent_TP_Conc = Effuent_OrthoP_Conc+Effluent_Org_P_Conc
DOCUMENT:  (milligrams per liter)

Effluent__Org_N_Conc = IF(OUTFLOW>0)
                         THEN(Outflow_N/OUTFLOW)
                         ELSE(0)
DOCUMENT:  (milligrams per liter)

Effuent_OrthoP_Conc = IF(OUTFLOW>0)
                        THEN(Outflow_orthoP/OUTFLOW)
                        ELSE(0)
DOCUMENT:  (milligrams per liter)

ET = kET*ETF*Surface_area
DOCUMENT:  (cubic meters per day)

INFLUENT_C_CONC = 100
DOCUMENT:  (milligrams per liter)

INITIAL_DAY = 50

INITIAL_SED_DEPTH = .30
DOCUMENT:  (meters)

INITIAL_WW_DEPTH = .08
DOCUMENT:  (meters)

K_CO2 = .001
DOCUMENT:  (per day)

Kd = .02
DOCUMENT:  (per day)

kDeNit = .5
DOCUMENT:  (per day)

kET = .005
DOCUMENT:  (meters per day)

kNit = .07
DOCUMENT:  (per day)
```

Kp = 1.1
DOCUMENT: (grams per day)

Kr = .01
DOCUMENT: (per day)

Ks = .1
DOCUMENT: (per day)

Ksed = 5
DOCUMENT: (per day)

k_decomp_P = .001
DOCUMENT: (per day)
K_litter = .05
DOCUMENT: (per day)

k_N_fixers = .05
DOCUMENT: (per day)

k_sorb_P = .0002
DOCUMENT: (per day)

LENGTH = 50
DOCUMENT: (meters)

Live_Shoot_Biomass = Live_Shoot_C + Live_Shoot_N + Live_Shoot_P
DOCUMENT: (grams)

MAX_DEPTH = 2
DOCUMENT: (meters)

NH3_Conc = Ammonia_N/Total_Volume
DOCUMENT: (milligrams per liter)

NH3_Uptake_Fraction = .1

NO3_Conc = Nitrate_N/Total_Volume
DOCUMENT: (milligrams per liter)

number_of_cells = 1

Org_C_Conc = Organic_C/WW_volume
DOCUMENT: (milligrams per liter)

Org_N_Conc = Organic_N/WW_volume
DOCUMENT: (milligrams per liter)

Org_P_Conc = Organic_P/WW_volume
DOCUMENT: (milligrams per liter)

Ortho_P_Conc = Available_P/Total_Volume
DOCUMENT: (milligrams per liter)

RECIRCULATE = 1

RECIRC_END = 200
DOCUMENT: (days)

RECIRC_START = 100
DOCUMENT: (days)

Retention_time = WW_volume*Porosity/((Influent+OUTFLOW)/2)
DOCUMENT: (days)

Sediment_density = 100
DOCUMENT: (grams per cubic meter)

Sediment_Depth = Sediment_Volume/Bottom_Area
DOCUMENT: (meters)

Sed_C_Conc = Sediment_C/Sediment_Volume
DOCUMENT: (milligrams per liter)

Sed_N_Conc = Sediment_N/Sediment_Volume
DOCUMENT: (milligrams per liter)

Sed_P_Conc = Sediment_P/Sediment_Volume
DOCUMENT: (milligrams per liter)

SLOPE = 3

Surface_area = top_width*LENGTH*number_of_cells
DOCUMENT: (square meters)

TKN_Conc = NH3_Conc+Org_N_Conc
DOCUMENT: (milligrams per liter)

top_width = bottom_width+(2*WW_Depth/SLOPE)
DOCUMENT: (meters)

Total_Depth = WW_Depth+Sediment_Depth
DOCUMENT: (meters)

Total_Volume = WW_volume+Sediment_Volume
DOCUMENT: (cubic meters)

TP_Conc = Ortho_P_Conc+Org_P_Conc
DOCUMENT: (milligrams per liter)

WW_Depth = WW_volume/Bottom_Area
DOCUMENT: (meters)

YEARDAY = IF(INITIAL_DAY+TIME>365)
THEN(INITIAL_DAY+TIME-365)
ELSE(INITIAL_DAY+TIME)

ACTUAL_PRECIP = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.4), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.25), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.07), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.065), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 1.09), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.2), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.5), (44.0, 0.1), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.2), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.25), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.25), (66.0, 0.1), (67.0, 0.00), (68.0, 0.00), (69.0, 0.2), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.6), (75.0, 0.00), (76.0, 0.00), (77.0, 0.00), (78.0, 0.00), (79.0, 0.00), (80.0, 0.00), (81.0, 0.00), (82.0, 0.00), (83.0, 0.00), (84.0, 0.15), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.75), (97.0, 0.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 0.00), (102, 0.00), (103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.00), (109, 0.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.6), (118, 0.00), (119, 0.00), (120, 0.00), (121, 0.18), (122, 0.4), (123, 0.35), (124, 0.00), (125, 0.00), (126, 0.00), (127, 0.00), (128, 1.60), (129, 0.25), (130, 0.1), (131, 0.4), (132, 0.00), (133, 0.00), (134, 0.00), (135, 0.00), (136, 0.00), (137, 0.00), (138, 0.00), (139, 0.16), (140, 0.00), (141, 0.00), (142, 0.00), (143, 0.6), (144, 0.00), (145, 0.00), (146, 0.00), (147, 0.00), (148, 0.00), (149, 0.00), (150, 0.00), (151, 0.00), (152, 0.00), (153, 0.00), (154, 0.00), (155, 0.7), (156, 0.2), (157, 0.00), (158, 0.00), (159, 0.00), (160, 0.00), (161, 0.00), (162, 0.00), (163, 0.55), (164, 1.00), (165, 0.65), (166, 0.9), (167, 0.3), (168, 0.00), (169, 0.00), (170, 0.00), (171, 0.00), (172, 0.00), (173, 0.00), (174, 0.2), (175, 0.00), (176, 0.00), (177, 0.00), (178, 0.00), (179, 0.00), (180, 0.00), (181, 0.00), (182, 0.00), (183, 0.00), (184, 0.5), (185, 0.00), (186, 0.00), (187, 0.00), (188, 0.55), (189, 0.00), (190, 0.00), (191, 0.00), (192, 0.00), (193, 0.00), (194, 0.00), (195, 0.15), (196, 0.00), (197,

0.00), (198, 0.4), (199, 0.5), (200, 0.35), (201, 0.2), (202, 0.00), (203, 0.00), (204, 0.00), (205, 0.00), (206, 0.00), (207, 0.00), (208, 1.00), (209, 0.00), (210, 0.00), (211, 0.00), (212, 0.00), (213, 0.725), (214, 0.00), (215, 0.1), (216, 1.00), (217, 0.00), (218, 0.15), (219, 0.6), (220, 0.00), (221, 0.00), (222, 0.00), (223, 0.00), (224, 0.00), (225, 0.00), (226, 0.00), (227, 0.00), (228, 0.00), (229, 0.00), (230, 0.15), (231, 0.00), (232, 0.00), (233, 0.00), (234, 0.00), (235, 0.00), (236, 0.00), (237, 0.00), (238, 0.00), (239, 0.00), (240, 0.00), (241, 0.00), (242, 0.00), (243, 0.00), (244, 0.00), (245, 0.00), (246, 0.00), (247, 0.00), (248, 0.00), (249, 0.00), (250, 0.00), (251, 0.00), (252, 0.00), (253, 0.00), (254, 0.00), (255, 0.00), (256, 0.00), (257, 0.00), (258, 0.00), (259, 0.1), (260, 0.00), (261, 0.05), (262, 0.00), (263, 0.00), (264, 0.8), (265, 0.00), (266, 0.00), (267, 0.00), (268, 0.00), (269, 0.25), (270, 0.00), (271, 0.3), (272, 0.05), (273, 0.00), (274, 0.2), (275, 0.00), (276, 0.00), (277, 0.00), (278, 0.00), (279, 0.5), (280, 0.4), (281, 0.00), (282, 0.00), (283, 0.00), (284, 0.00), (285, 0.00), (286, 0.00), (287, 0.00), (288, 0.2), (289, 0.00), (290, 0.00)
DOCUMENT: (inches)

Dissolved_Oxygen_Conc = GRAPH(TIME)
(0.00, 2.20), (1.00, 2.20), (2.00, 2.35), (3.00, 2.35), (4.00, 1.65), (5.00, 1.70), (6.00, 1.80), (7.00, 1.55), (8.00, 1.70), (9.00, 1.50), (10.0, 1.10), (11.0, 0.7), (12.0, 0.7), (13.0, 0.7), (14.0, 0.7), (15.0, 0.7), (16.0, 0.65), (17.0, 0.65), (18.0, 0.65), (19.0, 0.65), (20.0, 0.2), (21.0, 0.5), (22.0, 0.45), (23.0, 1.95), (24.0, 2.35), (25.0, 2.15), (26.0, 2.60), (27.0, 2.00), (28.0, 2.05), (29.0, 2.55), (30.0, 3.95), (31.0, 4.75), (32.0, 4.15), (33.0, 4.05), (34.0, 4.10), (35.0, 4.15), (36.0, 4.30), (37.0, 5.00), (38.0, 5.20), (39.0, 0.25), (40.0, 0.25), (41.0, 0.75), (42.0, 0.6), (43.0, 0.6), (44.0, 0.85), (45.0, 2.20), (46.0, 2.70), (47.0, 2.70), (48.0, 2.70), (49.0, 3.95), (50.0, 3.20), (51.0, 2.85), (52.0, 2.80), (53.0, 2.70), (54.0, 3.45), (55.0, 3.35), (56.0, 3.20), (57.0, 2.35), (58.0, 2.35), (59.0, 2.35), (60.0, 2.20), (61.0, 2.05), (62.0, 2.25), (63.0, 2.45), (64.0, 2.50), (65.0, 2.55), (66.0, 2.55), (67.0, 2.45), (68.0, 2.40), (69.0, 2.45), (70.0, 2.45), (71.0, 2.40), (72.0, 2.35), (73.0, 2.10), (74.0, 2.20), (75.0, 2.65), (76.0, 2.70), (77.0, 2.65), (78.0, 3.40), (79.0, 3.25), (80.0, 3.75), (81.0, 3.35), (82.0, 3.70), (83.0, 3.45), (84.0, 3.80), (85.0, 4.05), (86.0, 4.60), (87.0, 4.45), (88.0, 4.40), (89.0, 3.80), (90.0, 4.05), (91.0, 4.05), (92.0, 4.35), (93.0, 4.35), (94.0, 4.40), (95.0, 4.00), (96.0, 3.90), (97.0, 3.90), (98.0, 3.45), (99.0, 3.85), (100, 4.10), (101, 4.05), (102, 4.10), (103, 4.00), (104, 3.85), (105, 3.85), (106, 4.10), (107, 4.30), (108, 4.10), (109, 4.40), (110, 4.10), (111, 3.95), (112, 3.75), (113, 3.60), (114, 3.50), (115, 3.40), (116, 3.40), (117, 3.45), (118, 3.75), (119, 3.60), (120, 3.35), (121, 3.65), (122, 3.60), (123, 3.45), (124, 3.40), (125, 3.40), (126, 3.35), (127, 3.25), (128, 3.15), (129, 3.30), (130, 3.30), (131, 3.45), (132, 3.20), (133, 3.25), (134, 3.15), (135, 3.20), (136, 3.05), (137, 2.85), (138, 2.70), (139, 2.80), (140, 2.65), (141, 2.50), (142, 2.30), (143, 2.00), (144, 2.60), (145, 2.90), (146, 2.90), (147, 3.05), (148, 2.25), (149, 2.30), (150, 2.35), (151, 2.15), (152, 1.70), (153, 1.75), (154, 1.75), (155, 1.75), (156, 1.90), (157, 1.90), (158, 1.60), (159, 2.05), (160, 1.40), (161, 1.35), (162, 1.40), (163, 1.65), (164, 1.70), (165, 1.75), (166, 2.10), (167, 1.85), (168, 1.70), (169, 1.35), (170, 1.35), (171, 1.65), (172, 1.70), (173, 2.10), (174, 1.45), (175, 1.65), (176, 1.90), (177, 1.95), (178, 1.95), (179, 1.75), (180, 1.75), (181, 1.60), (182, 1.60), (183, 1.75), (184, 1.80), (185, 1.85), (186, 1.80), (187, 1.75), (188, 1.80), (189, 1.80), (190, 1.80), (191, 1.80), (192, 1.85), (193, 1.85), (194, 1.90), (195, 1.90), (196, 1.85), (197, 1.75), (198, 2.00), (199, 1.95), (200, 2.25), (201, 2.15), (202, 2.10),

(203, 1.80), (204, 1.75), (205, 1.80), (206, 1.80), (207, 1.70), (208, 1.55), (209, 1.65), (210, 1.90), (211, 1.90), (212, 2.00), (213, 1.75), (214, 1.95), (215, 2.15), (216, 1.60), (217, 1.65), (218, 1.55), (219, 1.65), (220, 1.80), (221, 1.70), (222, 1.70), (223, 1.60), (224, 1.50), (225, 1.25), (226, 1.10), (227, 1.05), (228, 0.95), (229, 1.00), (230, 1.15), (231, 1.25), (232, 1.40), (233, 1.40), (234, 1.70), (235, 1.40), (236, 1.50), (237, 1.30), (238, 1.35), (239, 1.40), (240, 1.25), (241, 1.20), (242, 1.15), (243, 1.15), (244, 1.10), (245, 1.00), (246, 1.00), (247, 1.20), (248, 1.25), (249, 1.20), (250, 1.00), (251, 1.05), (252, 0.9), (253, 0.95), (254, 0.75), (255, 0.9), (256, 0.75), (257, 0.8), (258, 0.85), (259, 0.7), (260, 0.7), (261, 0.95), (262, 0.95), (263, 1.25), (264, 1.30), (265, 0.95), (266, 0.9), (267, 1.00), (268, 1.40), (269, 1.35), (270, 1.15), (271, 1.25), (272, 1.60), (273, 2.05), (274, 2.30), (275, 2.20), (276, 2.10), (277, 2.00), (278, 1.80), (279, 1.75), (280, 1.75), (281, 1.80), (282, 1.75), (283, 1.75), (284, 1.65), (285, 1.75), (286, 1.90), (287, 1.90), (288, 1.85), (289, 2.00), (290, 2.05)
DOCUMENT: (milligrams per liter)

DOF_Denit = GRAPH(Dissolved_Oxygen_Conc)
(0.00, 1.00), (0.5, 0.9), (1.00, 0.8), (1.50, 0.7), (2.00, 0.6), (2.50, 0.5), (3.00, 0.4), (3.50, 0.3), (4.00, 0.2), (4.50, 0.1), (5.00, 0.00)

DOF_Nit = GRAPH(Dissolved_Oxygen_Conc)
(0.00, 0.00), (0.5, 0.1), (1.00, 0.2), (1.50, 0.3), (2.00, 0.4), (2.50, 0.5), (3.00, 0.6), (3.50, 0.7), (4.00, 0.8), (4.50, 0.9), (5.00, 1.00)

ETF = GRAPH(YEARDAY)
(0.00, 0.5), (33.2, 0.5), (66.4, 0.625), (99.5, 0.75), (133, 0.875), (166, 1.00), (199, 1.00), (232, 1.00), (265, 0.875), (299, 0.75), (332, 0.625), (365, 0.5)

INFLOW = GRAPH(YEARDAY)
(0.00, 68.5), (33.2, 95.4), (66.4, 84.8), (99.5, 46.6), (133, 87.1), (166, 50.0), (199, 50.0), (232, 50.0), (265, 50.0), (299, 79.0), (332, 110), (365, 65.1)
DOCUMENT: (cubic meters per day)

Influent_NH3_Conc = GRAPH(TIME)
(0.00, 8.59), (1.00, 8.57), (2.00, 8.48), (3.00, 7.94), (4.00, 7.82), (5.00, 7.82), (6.00, 7.70), (7.00, 8.30), (8.00, 8.30), (9.00, 8.89), (10.0, 8.26), (11.0, 7.67), (12.0, 7.04), (13.0, 6.69), (14.0, 6.25), (15.0, 7.50), (16.0, 7.50), (17.0, 7.50), (18.0, 7.50), (19.0, 7.50), (20.0, 7.50), (21.0, 7.50), (22.0, 7.50), (23.0, 7.50), (24.0, 7.50), (25.0, 7.50), (26.0, 7.50), (27.0, 8.88), (28.0, 9.02), (29.0, 8.17), (30.0, 8.38), (31.0, 10.1), (32.0, 8.72), (33.0, 7.81), (34.0, 8.40), (35.0, 8.55), (36.0, 7.27), (37.0, 6.12), (38.0, 9.00), (39.0, 9.00), (40.0, 9.00), (41.0, 9.00), (42.0, 9.00), (43.0, 9.00), (44.0, 9.00), (45.0, 9.00), (46.0, 9.00), (47.0, 9.00), (48.0, 9.00), (49.0, 9.00), (50.0, 9.00), (51.0, 9.00), (52.0, 9.00), (53.0, 12.5), (54.0, 13.7), (55.0, 12.5), (56.0, 13.6), (57.0, 14.2), (58.0, 13.9), (59.0, 13.5), (60.0, 14.7), (61.0, 14.3), (62.0, 14.6), (63.0, 15.1), (64.0, 15.4), (65.0, 14.8), (66.0, 14.5), (67.0, 15.3), (68.0, 15.1), (69.0, 14.8), (70.0, 16.9), (71.0, 16.6), (72.0, 15.8), (73.0, 13.0), (74.0, 12.1), (75.0, 8.96), (76.0, 9.73), (77.0, 9.40), (78.0, 9.40), (79.0, 9.40), (80.0, 9.40), (81.0, 9.40), (82.0, 9.40), (83.0, 9.40),

(84.0, 9.40), (85.0, 9.10), (86.0, 10.4), (87.0, 11.4), (88.0, 13.0), (89.0, 11.5), (90.0, 9.89), (91.0, 7.76), (92.0, 7.48), (93.0, 8.35), (94.0, 9.21), (95.0, 8.41), (96.0, 7.70), (97.0, 6.98), (98.0, 10.0), (99.0, 10.0), (100, 10.0), (101, 10.0), (102, 10.0), (103, 10.0), (104, 10.0), (105, 10.0), (106, 10.0), (107, 10.0), (108, 10.0), (109, 10.0), (110, 10.0), (111, 13.4), (112, 14.7), (113, 13.0), (114, 10.8), (115, 11.6), (116, 10.1), (117, 13.6), (118, 11.1), (119, 11.7), (120, 11.6), (121, 12.2), (122, 10.1), (123, 9.80), (124, 9.64), (125, 8.24), (126, 9.10), (127, 8.03), (128, 10.8), (129, 8.56), (130, 8.03), (131, 8.66), (132, 7.84), (133, 6.37), (134, 6.65), (135, 6.65), (136, 8.20), (137, 8.20), (138, 8.20), (139, 8.20), (140, 8.20), (141, 9.87), (142, 4.36), (143, 3.33), (144, 5.79), (145, 5.56), (146, 4.34), (147, 6.62), (148, 5.99), (149, 6.20), (150, 6.20), (151, 6.20), (152, 6.20), (153, 6.20), (154, 6.20), (155, 6.20), (156, 6.20), (157, 6.20), (158, 6.20), (159, 6.20), (160, 6.32), (161, 6.56), (162, 5.43), (163, 5.45), (164, 8.39), (165, 4.87), (166, 3.96), (167, 4.08), (168, 7.10), (169, 4.60), (170, 3.93), (171, 4.21), (172, 8.00), (173, 8.00), (174, 8.00), (175, 8.00), (176, 11.9), (177, 12.3), (178, 10.2), (179, 10.9), (180, 7.10), (181, 7.70), (182, 7.70), (183, 8.59), (184, 6.00), (185, 6.00), (186, 6.00), (187, 6.00), (188, 6.00), (189, 6.00), (190, 6.00), (191, 6.00), (192, 3.10), (193, 3.36), (194, 3.20), (195, 3.31), (196, 2.89), (197, 3.23), (198, 3.69), (199, 3.40), (200, 3.71), (201, 4.18), (202, 3.77), (203, 3.30), (204, 3.23), (205, 3.13), (206, 3.19), (207, 2.72), (208, 2.76), (209, 2.41), (210, 2.82), (211, 2.35), (212, 2.47), (213, 2.04), (214, 1.99), (215, 1.89), (216, 1.77), (217, 3.36), (218, 4.09), (219, 1.94), (220, 2.18), (221, 1.34), (222, 0.919), (223, 0.82), (224, 0.734), (225, 0.937), (226, 0.797), (227, 1.05), (228, 0.531), (229, 0.891), (230, 0.889), (231, 0.951), (232, 1.56), (233, 0.94), (234, 1.30), (235, 1.30), (236, 1.67), (237, 1.36), (238, 1.45), (239, 1.45), (240, 1.65), (241, 1.40), (242, 2.26), (243, 1.79), (244, 1.82), (245, 1.85), (246, 1.95), (247, 2.22), (248, 2.78), (249, 2.75), (250, 2.62), (251, 2.88), (252, 2.99), (253, 3.19), (254, 3.13), (255, 3.20), (256, 3.28), (257, 3.34), (258, 3.85), (259, 3.77), (260, 3.80), (261, 3.96), (262, 4.47), (263, 4.47), (264, 5.30), (265, 5.30), (266, 5.30), (267, 5.30), (268, 5.30), (269, 5.30), (270, 5.30), (271, 5.30), (272, 5.30), (273, 5.30), (274, 5.30), (275, 5.30), (276, 5.30), (277, 5.30), (278, 5.30), (279, 5.30), (280, 5.30), (281, 5.30), (282, 5.30), (283, 5.30), (284, 5.30), (285, 5.30), (286, 5.30), (287, 5.30), (288, 6.00), (289, 6.50), (290, 7.42), (291, 7.62)
DOCUMENT: (milligrams per liter)

Influent_NO3_Conc = GRAPH(TIME)
(0.00, 2.79), (1.00, 2.88), (2.00, 2.96), (3.00, 3.16), (4.00, 2.95), (5.00, 2.76), (6.00, 2.79), (7.00, 2.50), (8.00, 2.50), (9.00, 2.30), (10.0, 2.61), (11.0, 2.80), (12.0, 2.40), (13.0, 2.52), (14.0, 2.69), (15.0, 2.60), (16.0, 2.60), (17.0, 2.60), (18.0, 2.60), (19.0, 2.60), (20.0, 2.60), (21.0, 2.60), (22.0, 2.60), (23.0, 2.60), (24.0, 2.60), (25.0, 2.60), (26.0, 2.60), (27.0, 2.53), (28.0, 2.78), (29.0, 2.77), (30.0, 2.57), (31.0, 2.42), (32.0, 2.62), (33.0, 2.56), (34.0, 2.01), (35.0, 2.23), (36.0, 1.50), (37.0, 1.77), (38.0, 1.65), (39.0, 1.65), (40.0, 1.65), (41.0, 1.65), (42.0, 1.65), (43.0, 1.65), (44.0, 1.65), (45.0, 1.65), (46.0, 1.65), (47.0, 1.65), (48.0, 1.65), (49.0, 1.65), (50.0, 1.65), (51.0, 1.65), (52.0, 1.65), (53.0, 1.47), (54.0, 1.44), (55.0, 1.56), (56.0, 1.50), (57.0, 1.54), (58.0, 1.63), (59.0, 1.35), (60.0, 1.44), (61.0, 1.58), (62.0, 1.00), (63.0, 0.449), (64.0, 2.47), (65.0, 3.52), (66.0, 2.94), (67.0, 2.05), (68.0, 2.99), (69.0, 2.63), (70.0, 2.81), (71.0, 2.04), (72.0, 2.26), (73.0, 3.87), (74.0, 3.84), (75.0, 3.54), (76.0, 3.03), (77.0, 2.00), (78.0, 2.00), (79.0, 2.00), (80.0, 2.00), (81.0, 2.00), (82.0, 2.00), (83.0,

2.00), (84.0, 2.00), (85.0, 1.10), (86.0, 1.23), (87.0, 1.09), (88.0, 0.821), (89.0, 1.20), (90.0, 1.41), (91.0, 2.11), (92.0, 2.35), (93.0, 2.84), (94.0, 2.60), (95.0, 2.69), (96.0, 2.71), (97.0, 2.93), (98.0, 1.60), (99.0, 1.60), (100, 1.60), (101, 1.60), (102, 1.60), (103, 1.60), (104, 1.60), (105, 1.60), (106, 1.60), (107, 1.60), (108, 1.60), (109, 1.60), (110, 1.60), (111, 0.288), (112, 0.228), (113, 0.322), (114, 0.397), (115, 0.368), (116, 0.387), (117, 0.085), (118, 0.37), (119, 0.341), (120, 0.331), (121, 0.328), (122, 0.325), (123, 0.35), (124, 0.376), (125, 0.476), (126, 0.428), (127, 0.496), (128, 0.232), (129, 0.505), (130, 0.506), (131, 0.57), (132, 0.596), (133, 0.649), (134, 0.66), (135, 0.854), (136, 0.88), (137, 0.88), (138, 0.88), (139, 0.88), (140, 0.88), (141, 0.911), (142, 1.05), (143, 1.17), (144, 0.883), (145, 0.904), (146, 0.815), (147, 0.483), (148, 0.535), (149, 0.3), (150, 0.3), (151, 0.3), (152, 0.3), (153, 0.3), (154, 0.3), (155, 0.3), (156, 0.3), (157, 0.3), (158, 0.3), (159, 0.3), (160, 0.152), (161, 0.123), (162, 0.251), (163, 0.314), (164, 0.239), (165, 0.365), (166, 0.556), (167, 0.726), (168, 0.47), (169, 0.839), (170, 0.982), (171, 0.984), (172, 0.7), (173, 0.7), (174, 0.7), (175, 0.7), (176, 0.391), (177, 0.173), (178, 0.465), (179, 0.389), (180, 0.689), (181, 0.55), (182, 0.55), (183, 0.47), (184, 0.9), (185, 0.9), (186, 0.9), (187, 0.9), (188, 0.9), (189, 0.9), (190, 0.9), (191, 0.9), (192, 1.30), (193, 1.89), (194, 1.46), (195, 1.93), (196, 1.47), (197, 1.74), (198, 1.70), (199, 1.98), (200, 2.28), (201, 1.72), (202, 1.78), (203, 1.80), (204, 1.85), (205, 1.99), (206, 2.14), (207, 1.55), (208, 1.70), (209, 1.68), (210, 1.71), (211, 2.34), (212, 2.34), (213, 2.38), (214, 2.21), (215, 1.92), (216, 1.86), (217, 0.475), (218, 0.12), (219, 0.238), (220, 0.248), (221, 1.08), (222, 1.51), (223, 2.20), (224, 1.90), (225, 3.61), (226, 3.26), (227, 3.55), (228, 2.91), (229, 2.98), (230, 3.57), (231, 3.97), (232, 5.16), (233, 6.43), (234, 5.20), (235, 5.20), (236, 4.08), (237, 5.31), (238, 4.93), (239, 6.24), (240, 6.10), (241, 5.40), (242, 3.99), (243, 3.78), (244, 4.38), (245, 4.34), (246, 4.25), (247, 4.33), (248, 4.79), (249, 3.76), (250, 4.62), (251, 4.95), (252, 4.44), (253, 4.42), (254, 4.41), (255, 4.83), (256, 4.59), (257, 3.37), (258, 3.06), (259, 3.67), (260, 4.31), (261, 4.40), (262, 4.16), (263, 3.56), (264, 3.90), (265, 3.90), (266, 3.90), (267, 3.90), (268, 3.90), (269, 3.90), (270, 3.90), (271, 3.90), (272, 3.90), (273, 3.90), (274, 3.90), (275, 3.90), (276, 3.90), (277, 3.90), (278, 3.90), (279, 3.90), (280, 3.90), (281, 3.90), (282, 3.90), (283, 3.90), (284, 3.90), (285, 3.90), (286, 3.90), (287, 3.90), (288, 4.23), (289, 4.84), (290, 4.77), (291, 4.83)
DOCUMENT: (milligrams per liter)

Influent_ortho_P_Conc = GRAPH(TIME)
(0.00, 2.67), (1.00, 2.98), (2.00, 2.37), (3.00, 2.92), (4.00, 2.77), (5.00, 2.78), (6.00, 2.40), (7.00, 21.0), (8.00, 2.10), (9.00, 1.75), (10.0, 3.21), (11.0, 2.04), (12.0, 1.91), (13.0, 1.49), (14.0, 1.65), (15.0, 2.30), (16.0, 2.30), (17.0, 2.30), (18.0, 2.30), (19.0, 2.30), (20.0, 2.30), (21.0, 2.30), (22.0, 2.30), (23.0, 2.30), (24.0, 2.30), (25.0, 2.30), (26.0, 2.30), (27.0, 3.05), (28.0, 3.33), (29.0, 3.69), (30.0, 4.06), (31.0, 4.02), (32.0, 4.04), (33.0, 4.57), (34.0, 5.03), (35.0, 5.15), (36.0, 5.08), (37.0, 5.30), (38.0, 4.40), (39.0, 4.40), (40.0, 4.40), (41.0, 4.40), (42.0, 4.40), (43.0, 4.40), (44.0, 4.40), (45.0, 4.40), (46.0, 4.40), (47.0, 4.40), (48.0, 4.40), (49.0, 4.40), (50.0, 4.40), (51.0, 4.40), (52.0, 4.40), (53.0, 3.55), (54.0, 3.75), (55.0, 2.78), (56.0, 2.76), (57.0, 2.65), (58.0, 2.55), (59.0, 2.73), (60.0, 2.66), (61.0, 2.52), (62.0, 2.40), (63.0, 2.25), (64.0, 2.31), (65.0, 2.18), (66.0, 2.19), (67.0, 2.26), (68.0, 2.18), (69.0, 2.02), (70.0, 2.42), (71.0, 2.22), (72.0, 1.79), (73.0, 1.66), (74.0, 1.53), (75.0, 1.88), (76.0, 2.15), (77.0, 2.40), (78.0, 2.40), (79.0, 2.40), (80.0, 2.40), (81.0, 2.40), (82.0, 2.40), (83.0, 2.40),

(84.0, 2.40), (85.0, 2.73), (86.0, 2.66), (87.0, 2.72), (88.0, 2.91), (89.0, 2.92), (90.0, 2.94), (91.0, 2.06), (92.0, 1.91), (93.0, 2.01), (94.0, 2.09), (95.0, 1.92), (96.0, 1.98), (97.0, 1.93), (98.0, 2.30), (99.0, 2.30), (100, 2.30), (101, 2.30), (102, 2.30), (103, 2.30), (104, 2.30), (105, 2.30), (106, 2.30), (107, 2.30), (108, 2.30), (109, 2.30), (110, 2.30), (111, 2.73), (112, 2.62), (113, 2.36), (114, 2.30), (115, 2.16), (116, 2.32), (117, 2.52), (118, 2.25), (119, 2.42), (120, 2.65), (121, 2.76), (122, 2.42), (123, 3.20), (124, 3.99), (125, 3.46), (126, 3.35), (127, 2.65), (128, 2.49), (129, 2.57), (130, 3.08), (131, 2.87), (132, 2.83), (133, 2.93), (134, 2.75), (135, 2.34), (136, 2.90), (137, 2.90), (138, 2.90), (139, 2.90), (140, 2.90), (141, 3.61), (142, 3.14), (143, 2.23), (144, 2.83), (145, 2.63), (146, 2.17), (147, 2.58), (148, 2.44), (149, 2.65), (150, 2.65), (151, 2.65), (152, 2.65), (153, 2.65), (154, 2.65), (155, 2.65), (156, 2.65), (157, 2.65), (158, 2.65), (159, 2.65), (160, 2.94), (161, 2.60), (162, 2.06), (163, 2.08), (164, 2.31), (165, 2.07), (166, 2.09), (167, 2.13), (168, 2.68), (169, 2.52), (170, 2.42), (171, 2.54), (172, 3.00), (173, 3.00), (174, 3.00), (175, 3.00), (176, 3.50), (177, 3.31), (178, 2.92), (179, 2.97), (180, 2.54), (181, 2.60), (182, 2.60), (183, 2.76), (184, 2.50), (185, 2.50), (186, 2.50), (187, 2.50), (188, 2.50), (189, 2.50), (190, 2.50), (191, 2.50), (192, 2.24), (193, 2.50), (194, 2.36), (195, 2.46), (196, 2.40), (197, 2.26), (198, 1.99), (199, 1.93), (200, 1.81), (201, 1.78), (202, 1.81), (203, 1.78), (204, 1.77), (205, 1.74), (206, 1.81), (207, 2.42), (208, 2.59), (209, 2.13), (210, 2.14), (211, 1.90), (212, 1.81), (213, 1.68), (214, 1.75), (215, 1.79), (216, 1.91), (217, 3.97), (218, 5.94), (219, 1.80), (220, 3.50), (221, 1.64), (222, 1.17), (223, 0.966), (224, 1.08), (225, 1.39), (226, 1.44), (227, 1.37), (228, 1.09), (229, 1.38), (230, 1.44), (231, 1.51), (232, 1.58), (233, 1.69), (234, 1.90), (235, 1.90), (236, 2.13), (237, 1.53), (238, 1.48), (239, 1.55), (240, 1.50), (241, 1.25), (242, 1.25), (243, 1.34), (244, 1.22), (245, 1.27), (246, 1.33), (247, 1.32), (248, 1.39), (249, 1.48), (250, 1.49), (251, 1.57), (252, 1.55), (253, 1.56), (254, 1.60), (255, 1.56), (256, 1.48), (257, 1.21), (258, 2.28), (259, 1.61), (260, 1.53), (261, 1.47), (262, 1.45), (263, 1.36), (264, 1.50), (265, 1.50), (266, 1.50), (267, 1.50), (268, 1.50), (269, 1.50), (270, 1.50), (271, 1.50), (272, 1.50), (273, 1.50), (274, 1.50), (275, 1.50), (276, 1.50), (277, 1.50), (278, 1.50), (279, 1.50), (280, 1.50), (281, 1.50), (282, 1.50), (283, 1.50), (284, 1.50), (285, 1.50), (286, 1.50), (287, 1.50), (288, 1.69), (289, 1.40), (290, 1.35), (291, 1.35)
DOCUMENT: (milligrams per liter)

Inf_Org_N_Conc = GRAPH(TIME)
(0.00, 8.57), (1.00, 8.71), (2.00, 6.79), (3.00, 10.5), (4.00, 8.32), (5.00, 10.0), (6.00, 17.8), (7.00, 11.7), (8.00, 11.7), (9.00, 5.95), (10.0, 9.74), (11.0, 7.34), (12.0, 6.30), (13.0, 5.74), (14.0, 3.67), (15.0, 3.10), (16.0, 3.10), (17.0, 3.10), (18.0, 3.10), (19.0, 3.10), (20.0, 3.10), (21.0, 3.10), (22.0, 3.10), (23.0, 3.10), (24.0, 3.10), (25.0, 3.10), (26.0, 3.10), (27.0, 2.49), (28.0, 2.02), (29.0, 2.09), (30.0, 2.09), (31.0, 2.43), (32.0, 2.53), (33.0, 3.61), (34.0, 2.57), (35.0, 2.47), (36.0, 2.71), (37.0, 3.00), (38.0, 7.00), (39.0, 7.00), (40.0, 7.00), (41.0, 7.00), (42.0, 7.00), (43.0, 7.00), (44.0, 7.00), (45.0, 7.00), (46.0, 7.00), (47.0, 7.00), (48.0, 7.00), (49.0, 7.00), (50.0, 7.00), (51.0, 7.00), (52.0, 7.00), (53.0, 8.30), (54.0, 9.03), (55.0, 3.89), (56.0, 1.26), (57.0, 3.51), (58.0, 4.03), (59.0, 7.85), (60.0, 5.86), (61.0, 0.496), (62.0, 1.20), (63.0, 1.76), (64.0, 2.94), (65.0, 1.34), (66.0, 2.19), (67.0, 1.51), (68.0, 3.24), (69.0, 3.94), (70.0, 0.639), (71.0, 2.16), (72.0, 2.35), (73.0, 5.24), (74.0, 5.51), (75.0, 2.88), (76.0, 2.84), (77.0, 4.60), (78.0, 4.60), (79.0, 4.60), (80.0, 4.60), (81.0, 4.60), (82.0, 4.60),

(83.0, 4.60), (84.0, 4.60), (85.0, 6.34), (86.0, 3.71), (87.0, 3.50), (88.0, 3.90), (89.0, 4.30), (90.0, 4.67), (91.0, 4.58), (92.0, 4.32), (93.0, 18.0), (94.0, 8.55), (95.0, 4.57), (96.0, 5.13), (97.0, 4.97), (98.0, 4.30), (99.0, 4.30), (100, 4.30), (101, 4.30), (102, 4.30), (103, 4.30), (104, 4.30), (105, 4.30), (106, 4.30), (107, 4.30), (108, 4.30), (109, 4.30), (110, 4.30), (111, 3.39), (112, 1.03), (113, 2.16), (114, 1.59), (115, 2.31), (116, 1.89), (117, 4.01), (118, 1.80), (119, 2.36), (120, 2.52), (121, 1.90), (122, 2.88), (123, 5.20), (124, 7.38), (125, 3.63), (126, 5.37), (127, 3.60), (128, 3.78), (129, 3.57), (130, 4.67), (131, 4.90), (132, 3.57), (133, 4.52), (134, 4.55), (135, 4.62), (136, 5.80), (137, 5.80), (138, 5.80), (139, 5.80), (140, 5.80), (141, 6.51), (142, 5.86), (143, 2.33), (144, 1.28), (145, 1.04), (146, 0.997), (147, 0.73), (148, 1.30), (149, 2.30), (150, 2.30), (151, 2.30), (152, 2.30), (153, 2.30), (154, 2.30), (155, 2.30), (156, 2.30), (157, 2.30), (158, 2.30), (159, 2.30), (160, 3.66), (161, 2.35), (162, 2.66), (163, 2.51), (164, 2.39), (165, 2.35), (166, 2.51), (167, 2.19), (168, 1.70), (169, 2.58), (170, 2.40), (171, 2.49), (172, 3.00), (173, 3.00), (174, 3.00), (175, 3.00), (176, 5.80), (177, 5.18), (178, 2.79), (179, 3.82), (180, 4.23), (181, 3.58), (182, 3.58), (183, 2.65), (184, 1.50), (185, 1.50), (186, 1.50), (187, 1.50), (188, 1.50), (189, 1.50), (190, 1.50), (191, 1.50), (192, 1.15), (193, 0.853), (194, 1.10), (195, 1.11), (196, 1.65), (197, -0.277), (198, 1.53), (199, 1.99), (200, 1.87), (201, 1.84), (202, 2.23), (203, 1.92), (204, 2.39), (205, 1.99), (206, 1.93), (207, 2.27), (208, 3.18), (209, 3.11), (210, 1.85), (211, 0.602), (212, 0.083), (213, 0.209), (214, 1.33), (215, 0.361), (216, 0.311), (217, 1.10), (218, 4.60), (219, 0.653), (220, 0.212), (221, 1.05), (222, 1.01), (223, 0.87), (224, 1.12), (225, 1.25), (226, 1.38), (227, 0.709), (228, 1.25), (229, 4.00), (230, 1.19), (231, 0.47), (232, 3.54), (233, 0.575), (234, 4.70), (235, 4.70), (236, 9.46), (237, 4.64), (238, 4.22), (239, 4.59), (240, 3.64), (241, 0.789), (242, 3.00), (243, 3.27), (244, 0.507), (245, 0.423), (246, 0.457), (247, 3.04), (248, 3.41), (249, 3.34), (250, 2.98), (251, 2.41), (252, 2.18), (253, 1.89), (254, 2.12), (255, 1.95), (256, 2.28), (257, 2.47), (258, 2.46), (259, 2.27), (260, 2.50), (261, 2.59), (262, 2.63), (263, 2.31), (264, 2.30), (265, 2.30), (266, 2.30), (267, 2.30), (268, 2.30), (269, 2.30), (270, 2.30), (271, 2.30), (272, 2.30), (273, 2.30), (274, 2.30), (275, 2.30), (276, 2.30), (277, 2.30), (278, 2.30), (279, 2.30), (280, 2.30), (281, 2.30), (282, 2.30), (283, 2.30), (284, 2.30), (285, 2.30), (286, 2.30), (287, 2.30), (288, 2.41), (289, 3.15), (290, 2.18), (291, 2.07)
DOCUMENT: (milligrams per liter)

Inf_Org_P_Conc = GRAPH(TIME)
(0.00, 1.38), (1.00, 1.11), (2.00, 0.709), (3.00, 1.69), (4.00, 1.60), (5.00, 1.76), (6.00, 6.12), (7.00, 0.00), (8.00, 2.90), (9.00, 0.634), (10.0, 1.29), (11.0, 0.674), (12.0, 0.575), (13.0, 0.321), (14.0, 0.336), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.111), (76.0, 0.255), (77.0, 0.4), (78.0, 0.4), (79.0, 0.4), (80.0, 0.4), (81.0, 0.4), (82.0,

0.4), (83.0, 0.4), (84.0, 0.4), (85.0, 0.521), (86.0, 0.749), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.094), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.2), (99.0, 0.2), (100, 0.2), (101, 0.2), (102, 0.2), (103, 0.2), (104, 0.2), (105, 0.2), (106, 0.2), (107, 0.2), (108, 0.2), (109, 0.2), (110, 0.2), (111, 0.634), (112, 0.36), (113, 0.271), (114, 0.02), (115, 0.398), (116, 0.00), (117, 0.429), (118, 0.501), (119, 0.387), (120, 0.423), (121, 0.395), (122, 0.626), (123, 0.3), (124, 0.00), (125, 0.00), (126, 0.00), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.673), (131, 0.817), (132, 0.528), (133, 0.645), (134, 0.419), (135, 0.584), (136, 0.7), (137, 0.7), (138, 0.7), (139, 0.7), (140, 0.7), (141, 0.309), (142, 0.846), (143, 0.463), (144, 0.12), (145, 0.167), (146, 0.234), (147, 0.27), (148, 0.00), (149, 2.55), (150, 2.55), (151, 2.55), (152, 2.55), (153, 2.55), (154, 2.55), (155, 2.55), (156, 2.55), (157, 2.55), (158, 2.55), (159, 2.55), (160, 4.18), (161, 3.33), (162, 3.31), (163, 3.20), (164, 3.27), (165, 3.08), (166, 2.90), (167, 2.74), (168, 2.42), (169, 2.36), (170, 2.31), (171, 2.21), (172, 1.70), (173, 1.70), (174, 1.70), (175, 1.70), (176, 1.18), (177, 0.776), (178, 0.401), (179, 0.523), (180, 0.684), (181, 0.7), (182, 0.7), (183, 0.713), (184, 0.7), (185, 0.7), (186, 0.7), (187, 0.7), (188, 0.7), (189, 0.7), (190, 0.7), (191, 0.7), (192, 0.803), (193, 0.641), (194, 1.15), (195, 0.842), (196, 1.06), (197, 0.994), (198, 1.24), (199, 1.32), (200, 1.31), (201, 1.53), (202, 0.00), (203, 1.54), (204, 4.90), (205, 2.01), (206, 2.51), (207, 0.254), (208, 0.00), (209, 0.129), (210, 0.00), (211, 0.00), (212, 0.00), (213, 0.056), (214, 0.06), (215, 0.092), (216, 0.121), (217, 0.121), (218, 0.00), (219, 2.22), (220, 0.00), (221, 0.11), (222, 0.024), (223, 0.06), (224, 0.058), (225, 0.00), (226, 0.00), (227, 0.093), (228, 0.111), (229, 0.309), (230, 0.94), (231, 0.328), (232, 0.159), (233, 0.071), (234, 0.2), (235, 0.2), (236, 0.358), (237, 0.011), (238, 0.00), (239, 0.00), (240, 0.00), (241, 0.00), (242, 0.00), (243, 0.157), (244, 0.014), (245, 0.00), (246, 0.00), (247, 0.11), (248, 0.00), (249, 0.00), (250, 0.00), (251, 0.00), (252, 0.00), (253, 0.00), (254, 0.00), (255, 0.00), (256, 0.00), (257, 0.00), (258, 0.048), (259, 0.00), (260, 0.00), (261, 0.00), (262, 0.00), (263, 0.00), (264, 0.1), (265, 0.1), (266, 0.1), (267, 0.1), (268, 0.1), (269, 0.1), (270, 0.1), (271, 0.1), (272, 0.1), (273, 0.1), (274, 0.1), (275, 0.1), (276, 0.1), (277, 0.1), (278, 0.1), (279, 0.1), (280, 0.1), (281, 0.1), (282, 0.1), (283, 0.1), (284, 0.1), (285, 0.1), (286, 0.1), (287, 0.1), (288, 0.263), (289, 0.4), (290, 0.335), (291, 0.436)
DOCUMENT: (milligrams per liter)

MAF = GRAPH(WATER_TEMP)
(-20.0, 0.8), (-17.2, 0.8), (-14.5, 0.8), (-11.7, 0.8), (-8.95, 0.8), (-6.19, 0.8), (-3.43, 0.8), (-0.667, 0.8), (2.10, 0.8), (4.86, 1.00), (7.62, 1.00), (10.4, 1.00), (13.1, 1.00), (15.9, 1.00), (18.7, 1.00), (21.4, 1.00), (24.2, 1.00), (27.0, 1.00), (29.7, 1.00), (32.5, 1.00), (35.2, 1.00), (38.0, 1.00)

Plant_Death_Curve = GRAPH(YEARDAY)
(0.00, 0.3), (33.2, 0.2), (66.4, 0.1), (99.5, 0.1), (133, 0.1), (166, 0.1), (199, 0.1), (232, 0.1), (265, 0.2), (299, 0.3), (332, 0.4), (365, 0.5)

Plant_Growth_Curve = GRAPH(YEARDAY)
(0.00, 0.1), (33.2, 0.3), (66.4, 0.4), (99.5, 0.5), (133, 0.7), (166, 0.9), (199, 1.00), (232, 1.00), (265, 0.8), (299, 0.5), (332, 0.2), (365, 0.1)

Porosity = GRAPH(Live_Shoot_Biomass)
(0.00, 1.00), (1000, 0.95), (2000, 0.9), (3000, 0.85), (4000, 0.8), (5000, 0.75), (6000, 0.7), (7000, 0.65), (8000, 0.6), (9000, 0.55), (10000, 0.5)

Root_Fraction = GRAPH(YEARDAY)
(0.00, 0.7), (33.2, 0.6), (66.4, 0.5), (99.5, 0.4), (133, 0.3), (166, 0.3), (199, 0.3), (232, 0.3), (265, 0.3), (299, 0.4), (332, 0.5), (365, 0.7)

SF = GRAPH(YEARDAY)
(0.00, 0.3), (30.4, 0.8), (60.8, 1.00), (91.3, 1.00), (122, 1.00), (152, 1.00), (183, 1.00), (213, 1.00), (243, 1.00), (274, 1.00), (304, 1.00), (335, 1.00), (365, 0.8)
DOCUMENT: (grams per day)

WATER_TEMP = GRAPH(TIME)
(0.00, 15.8), (1.00, 14.6), (2.00, 14.1), (3.00, 14.1), (4.00, 13.9), (5.00, 14.4), (6.00, 16.5), (7.00, 16.7), (8.00, 14.8), (9.00, 17.1), (10.0, 16.1), (11.0, 17.5), (12.0, 17.5), (13.0, 17.5), (14.0, 17.5), (15.0, 17.5), (16.0, 17.5), (17.0, 17.5), (18.0, 17.5), (19.0, 17.5), (20.0, 18.7), (21.0, 17.6), (22.0, 16.5), (23.0, 17.5), (24.0, 16.7), (25.0, 16.2), (26.0, 15.5), (27.0, 18.3), (28.0, 15.4), (29.0, 13.5), (30.0, 15.2), (31.0, 15.2), (32.0, 16.7), (33.0, 16.7), (34.0, 17.2), (35.0, 17.3), (36.0, 17.8), (37.0, 16.0), (38.0, 16.6), (39.0, 16.6), (40.0, 16.6), (41.0, 17.2), (42.0, 17.8), (43.0, 16.6), (44.0, 18.6), (45.0, 17.9), (46.0, 16.2), (47.0, 17.1), (48.0, 17.8), (49.0, 17.2), (50.0, 15.5), (51.0, 15.9), (52.0, 16.9), (53.0, 17.4), (54.0, 17.0), (55.0, 14.4), (56.0, 15.5), (57.0, 16.8), (58.0, 17.3), (59.0, 17.2), (60.0, 17.8), (61.0, 18.3), (62.0, 18.5), (63.0, 17.6), (64.0, 16.9), (65.0, 16.8), (66.0, 16.7), (67.0, 17.4), (68.0, 17.3), (69.0, 17.6), (70.0, 17.8), (71.0, 17.9), (72.0, 18.3), (73.0, 19.0), (74.0, 20.4), (75.0, 20.4), (76.0, 21.1), (77.0, 22.2), (78.0, 22.0), (79.0, 21.7), (80.0, 21.8), (81.0, 21.9), (82.0, 22.2), (83.0, 22.7), (84.0, 22.7), (85.0, 23.1), (86.0, 22.1), (87.0, 21.9), (88.0, 21.3), (89.0, 22.8), (90.0, 23.4), (91.0, 23.3), (92.0, 22.8), (93.0, 23.8), (94.0, 22.8), (95.0, 23.8), (96.0, 24.4), (97.0, 24.6), (98.0, 25.1), (99.0, 24.4), (100, 23.9), (101, 23.7), (102, 23.6), (103, 23.6), (104, 23.9), (105, 24.5), (106, 24.2), (107, 23.9), (108, 24.0), (109, 22.9), (110, 23.0), (111, 23.3), (112, 23.8), (113, 24.3), (114, 24.9), (115, 25.2), (116, 25.7), (117, 25.6), (118, 26.0), (119, 26.2), (120, 26.6), (121, 26.3), (122, 26.3), (123, 26.3), (124, 25.8), (125, 25.8), (126, 25.7), (127, 25.8), (128, 25.8), (129, 25.4), (130, 25.9), (131, 25.7), (132, 26.7), (133, 26.3), (134, 25.9), (135, 25.9), (136, 26.4), (137, 26.8), (138, 27.1), (139, 27.4), (140, 27.2), (141, 27.4), (142, 27.5), (143, 27.4), (144, 27.6), (145, 27.8), (146, 28.4), (147, 27.8), (148, 27.5), (149, 27.3), (150, 26.1), (151, 26.1), (152, 25.7), (153, 25.7), (154, 25.7), (155, 25.7), (156, 25.7), (157, 25.7), (158, 25.5), (159, 26.1), (160, 26.1), (161, 26.2), (162, 26.5), (163, 26.1), (164, 26.1), (165, 25.5), (166, 25.7), (167, 25.7), (168, 26.1), (169, 26.2), (170, 26.8), (171, 27.2), (172, 27.3), (173, 26.9), (174, 27.0), (175, 27.0), (176, 26.6), (177, 26.4), (178, 25.9), (179, 26.6), (180, 27.0), (181, 27.2), (182, 27.6), (183, 26.8), (184, 26.1), (185, 25.6), (186, 25.8), (187, 25.7), (188, 26.3), (189, 26.3), (190, 25.8), (191, 25.9), (192, 25.9), (193, 25.6), (194, 25.1), (195, 25.4), (196, 25.7), (197, 25.8), (198, 25.9), (199, 25.4), (200, 24.2), (201, 22.5), (202, 22.5), (203, 23.1), (204, 23.1), (205, 23.2), (206, 23.7), (207, 23.6), (208, 24.4), (209, 24.7), (210, 23.7), (211, 21.6), (212, 20.7), (213, 21.3), (214, 22.2), (215, 22.1), (216, 22.2),

(217, 24.2), (218, 25.9), (219, 25.8), (220, 22.7), (221, 21.5), (222, 19.8), (223, 18.8), (224, 19.5), (225, 20.8), (226, 21.0), (227, 21.5), (228, 22.0), (229, 21.7), (230, 21.7), (231, 21.7), (232, 21.0), (233, 18.4), (234, 17.4), (235, 17.2), (236, 17.1), (237, 17.0), (238, 16.9), (239, 16.8), (240, 17.1), (241, 17.4), (242, 17.9), (243, 18.1), (244, 18.5), (245, 18.5), (246, 18.7), (247, 18.8), (248, 18.4), (249, 18.7), (250, 18.6), (251, 18.4), (252, 18.7), (253, 18.6), (254, 18.1), (255, 17.6), (256, 17.5), (257, 17.8), (258, 18.0), (259, 17.7), (260, 17.9), (261, 17.1), (262, 17.3), (263, 17.8), (264, 18.2), (265, 17.8), (266, 16.2), (267, 15.2), (268, 14.9), (269, 15.2), (270, 14.0), (271, 13.4), (272, 13.6), (273, 12.7), (274, 11.9), (275, 11.5), (276, 10.7), (277, 9.61), (278, 9.89), (279, 10.4), (280, 10.4), (281, 11.0), (282, 11.0), (283, 11.0), (284, 11.0), (285, 11.0), (286, 11.0), (287, 11.0), (288, 11.0), (289, 11.0), (290, 11.0)
DOCUMENT: (degrees Celsius)

APPENDIX B

STELLA® MODEL EQUATIONS FOR FINAL VALIDATION SIMULATION

State variable equations:

```
Ammonia_N(t) = Ammonia_N(t - dt) + (Inf_NH3 + Outflow_in_NH3 + N_fixing -
                    Nitrification - Root_Uptake_NH4 - Outflow_NH3) * dt

INIT Ammonia_N = 102
DOCUMENT:  (grams)

        Inf_NH3 = Influent_NH3_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_NH3 = Outflow_NH3
        DOCUMENT:  (grams per day)

        N_fixing = MAF*k_N_fixers*Sediment_N
        DOCUMENT:  (grams per day)

        Nitrification = ((kNit*Ammonia_N))*DOF_Nit
        DOCUMENT:  (grams per day)

        Root_Uptake_NH4 =
                IF(Root_Growth_C/CNRoot*NH3_Uptake_Fraction<Ammonia_N)
                THEN(Root_Growth_C/CNRoot*NH3_Uptake_Fraction)
                ELSE(0)
        DOCUMENT:  (grams per day)

        Outflow_NH3 = Ammonia_N/OUTFLOW
        DOCUMENT:  (grams per day)


Available_P(t) = Available_P(t - dt) + (Inf_orthoP + Decomp_P + Outflow_in_orthoP -
                    Root_Uptake_P - Outflow_orthoP - Sorbed_P) * dt

INIT Available_P = 28
DOCUMENT:  (grams)

        Inf_orthoP = Influent_ortho_P_Conc*Influent
        DOCUMENT:  (grams per day)

        Decomp_P = k_decomp_P*Sediment_P*MAF
        DOCUMENT:  (grams per day)
```

Outflow_in_orthoP = Outflow_orthoP
DOCUMENT: (grams per day)

Root_Uptake_P = IF(Root_Growth_C/CPRoot<Available_P)
THEN(Root_Growth_C/CPRoot)
ELSE(0)
DOCUMENT: (grams per day)

Outflow_orthoP = Available_P/OUTFLOW
DOCUMENT: (grams per day)

Sorbed_P = k_sorb_P*Available_P

Litter_C(t) = Litter_C(t - dt) + (Dead_Litter_C + Root_Litter_C - Litter_Sediment_C)*dt

INIT Litter_C = 24750
DOCUMENT: (grams)

Dead_Litter_C = IF(Standing_Dead_C*Kd>Standing_Dead_C)
THEN(Standing_Dead_C*Kd)
ELSE(Standing_Dead_C)

Root_Litter_C = Kr*Plant_Death_Curve*Live_Root_C
DOCUMENT: (grams per day)

Litter_Sediment_C = Litter_C*K_litter
DOCUMENT: (grams per day)

Litter_N(t) = Litter_N(t - dt)+(Dead_Litter_N + Root_Litter_N - Litter_Sediment_N)* dt

INIT Litter_N = 39
DOCUMENT: (grams)

Dead_Litter_N = Dead_Litter_C/CNDead
DOCUMENT: (grams per day)

Root_Litter_N = IF((Root_Litter_C/CNRoot<Live_Root_N)
AND(Root_Shoot_N<Live_Root_N))
THEN(Root_Litter_C/CNRoot)
ELSE(0)
DOCUMENT: (grams per day)

```
        Litter_Sediment_N = Litter_Sediment_C/CNLitter
        DOCUMENT:  (grams per day)

Litter_P(t) = Litter_P(t - dt) + (Dead_Litter_P + Root_Litter_P - Litter_Sediment_P) * dt

INIT Litter_P = 763
DOCUMENT:  (grams)

        Dead_Litter_P = IF(Dead_Litter_C/CPDead<Standing_Dead__P)
                        THEN(Dead_Litter_C/CPDead)
                        ELSE(Standing_Dead__P)
        DOCUMENT:  (grams per day)

        Root_Litter_P = IF(PHOTO_C/CPRoot+Root_Litter_C/CPRoot<Live_Root_P)
                        THEN(Root_Litter_C/CPRoot)
                        ELSE(Live_Root_P-PHOTO_C/CPRoot)
        DOCUMENT:  (grams per day)

        Litter_Sediment_P = Litter_Sediment_C/CPLitter
        DOCUMENT:  (grams per day)

Live_Root_C(t) = Live_Root_C(t - dt) + (Root_Growth_C - Root_Litter_C) * dt

INIT Live_Root_C = 54285
DOCUMENT:  (grams)

        Root_Growth_C = PHOTO_C*Root_Fraction
        DOCUMENT:  (grams per day)

        Root_Litter_C = Kr*Plant_Death_Curve*Live_Root_C
        DOCUMENT:  (grams per day)

Live_Root_N(t) = Live_Root_N(t - dt) + (Root_Uptake_NH4 + Root_Uptake_NO3 -
                 Root_Shoot_N - Root_Litter_N) * dt

INIT Live_Root_N = 2450
DOCUMENT:  (grams)

        Root_Uptake_NH4 =
                IF(Root_Growth_C/CNRoot*NH3_Uptake_Fraction<Ammonia_N)
                THEN(Root_Growth_C/CNRoot*NH3_Uptake_Fraction)
                ELSE(0)
        DOCUMENT:  (grams per day)
```

```
        Root_Uptake_NO3 =
                IF(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction)<Nitrate_N)
                THEN(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction))
                ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Shoot_N = IF(PHOTO_C/CNShoot<Live_Root_N)
                          THEN(PHOTO_C/CNShoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Litter_N = IF((Root_Litter_C/CNRoot<Live_Root_N)
                         AND(Root_Shoot_N<Live_Root_N))
                         THEN(Root_Litter_C/CNRoot)
                         ELSE(0)
        DOCUMENT:  (grams per day)

Live_Root_P(t) = Live_Root_P(t - dt) + (Root_Uptake_P - Root_Shoot_P -
                 Root_Litter_P) * dt

INIT Live_Root_P = 25
DOCUMENT:  (grams)

        Root_Uptake_P = IF(Root_Growth_C/CPRoot<Available_P)
                          THEN(Root_Growth_C/CPRoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Shoot_P = IF(PHOTO_C/CPShoot<Live_Root_P)
                          THEN(PHOTO_C/CPShoot)
                          ELSE(0)
        DOCUMENT:  (grams per day)

        Root_Litter_P = IF(PHOTO_C/CPRoot+Root_Litter_C/CPRoot<Live_Root_P)
                         THEN(Root_Litter_C/CPRoot)
                         ELSE(Live_Root_P-PHOTO_C/CPRoot)
        DOCUMENT:  (grams per day)

Live_Shoot_C(t) = Live_Shoot_C(t - dt) + (PHOTO_C - Shoot_C) * dt

INIT Live_Shoot_C = 57670
DOCUMENT:  (grams)
```

```
        PHOTO_C = (IF(Kp*Plant_Growth_Curve/CNShoot>Live_Root_N)
                        THEN(Live_Root_N*CNShoot)
                        ELSE(IF(Kp*Plant_Growth_Curve/CPShoot>Live_Root_P)
                        THEN(Live_Root_P*CPShoot)
                        ELSE(Kp*Plant_Growth_Curve)))
        DOCUMENT:  (grams per day)

        Shoot_C = Ks*Plant_Death_Curve*Live_Shoot_C
        DOCUMENT:  (grams per day)

Live_Shoot_N(t) = Live_Shoot_N(t - dt) + (Root_Shoot_N - Shoot_N) * dt

INIT Live_Shoot_N = 2890
DOCUMENT:  (grams)

        Root_Shoot_N = IF(PHOTO_C/CNShoot<Live_Root_N)
                        THEN(PHOTO_C/CNShoot)
                        ELSE(0)
        DOCUMENT:  (grams per day)

        Shoot_N = Shoot_C/CNShoot
        DOCUMENT:  (grams per day)

Live_Shoot_P(t) = Live_Shoot_P(t - dt) + (Root_Shoot_P - Shoot_P) * dt

INIT Live_Shoot_P = 1407
DOCUMENT:  (grams)

        Root_Shoot_P = IF(PHOTO_C/CPShoot<Live_Root_P)
                        THEN(PHOTO_C/CPShoot)
                        ELSE(0)
        DOCUMENT:  (grams per day)

        Shoot_P = Shoot_C/CPShoot
        DOCUMENT:  (grams per day)

Nitrate_N(t) = Nitrate_N(t - dt) + (Nitrification + Inf_NO3 + Outflow_in_NO3 -
                Denitrification - Root_Uptake_NO3 - Outflow_NO3) * dt

INIT Nitrate_N = 110
DOCUMENT:  (grams)
```

```
        Nitrification = ((kNit*Ammonia_N))*DOF_Nit
        DOCUMENT:  (grams per day)

        Inf_NO3 = Influent_NO3_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_NO3 = Outflow_NO3
        DOCUMENT:  (grams per day)

        Denitrification = (kDeNit*Nitrate_N)*DOF_Denit
        DOCUMENT:  (grams per day)

        Root_Uptake_NO3 =
                IF(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction)<Nitrate_N)
                THEN(Root_Growth_C/CNRoot*(1-NH3_Uptake_Fraction))
                ELSE(0)
        DOCUMENT:  (grams per day)

        Outflow_NO3 = Nitrate_N/OUTFLOW
        DOCUMENT:  (grams per day)

Organic_C(t) = Organic_C(t - dt) + (Inflow_C + Outflow_in_C - Outflow_C -
                Water_Sediment_C) * dt

INIT Organic_C = 1390
DOCUMENT:  (grams)

        Inflow_C = INFLUENT_C_CONC*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_C = Outflow_C
        DOCUMENT:  (grams per day)

        Outflow_C = Organic_C/OUTFLOW
        DOCUMENT:  (grams per day)

        Water_Sediment_C = IF(Ksed*SF<Organic_C)
        THEN(Ksed*SF)
        ELSE(0)
        DOCUMENT:  (grams per day)
```

```
Organic_N(t) = Organic_N(t - dt) + (Inflow_Organic_N + Outflow_in_N -
                Water_Sediment_N - Outflow_N) * dt

INIT Organic_N = 15.25
DOCUMENT:  (grams)

        Inflow_Organic_N = Inf_Org_N_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_N = Outflow_N
        DOCUMENT:  (grams per day)

        Water_Sediment_N = Water_Sediment_C/CNOrganic
        DOCUMENT:  (grams per day)

        Outflow_N = Organic_N/OUTFLOW
        DOCUMENT:  (grams per day)

Organic_P(t) = Organic_P(t - dt) + (Inflow_P + Outflow_in_P - Water_Sediment_P -
                Outflow_P) * dt

INIT Organic_P = 1
DOCUMENT:  (grams)

        Inflow_P = Inf_Org_P_Conc*Influent
        DOCUMENT:  (grams per day)

        Outflow_in_P = Outflow_in*Effluent_Org_P_Conc
        DOCUMENT:  (grams per day)

        Water_Sediment_P = Water_Sediment_C/CPOrganic
        DOCUMENT:  (grams per day)

        Outflow_P = Organic_P/OUTFLOW
        DOCUMENT:  (grams per day)

Sediment_C(t) = Sediment_C(t - dt) + (Litter_Sediment_C + Water_Sediment_C -
                 Sediment_CO2) * dt

INIT Sediment_C = 357000
DOCUMENT:  (grams)
```

Litter_Sediment_C = Litter_C*K_litter
DOCUMENT: (grams per day)

Water_Sediment_C = IF(Ksed*SF<Organic_C)
THEN(Ksed*SF)
ELSE(0)
DOCUMENT: (grams per day)

Sediment_CO2 = MAF*K_CO2*Sediment_C
DOCUMENT: (grams per day)

Sediment_N(t) = Sediment_N(t - dt) + (Water_Sediment_N + Litter_Sediment_N - N_fixing) * dt

INIT Sediment_N = 970
DOCUMENT: (grams)

Water_Sediment_N = Water_Sediment_C/CNOrganic
DOCUMENT: (grams per day)

Litter_Sediment_N = Litter_Sediment_C/CNLitter
DOCUMENT: (grams per day)

N_fixing = MAF*k_N_fixers*Sediment_N
DOCUMENT: (grams per day)

Sediment_P(t) = Sediment_P(t - dt) + (Litter_Sediment_P + Water_Sediment_P + Sorbed_P - Decomp_P) * dt

INIT Sediment_P = 7108
DOCUMENT: (grams)

Litter_Sediment_P = Litter_Sediment_C/CPLitter
DOCUMENT: (grams per day)

Water_Sediment_P = Water_Sediment_C/CPOrganic
DOCUMENT: (grams per day)

Sorbed_P = k_sorb_P*Available_P
DOCUMENT: (grams per day)

Decomp_P = k_decomp_P*Sediment_P*MAF
DOCUMENT: (grams per day)

```
Sediment_Volume(t) = Sediment_Volume(t - dt) + (Sediment_Inflow -
                     Sediment_Outflow) * dt

INIT Sediment_Volume = Bottom_Area*INITIAL_SED_DEPTH
DOCUMENT:  (cubic meters)

    Sediment_Inflow=(Litter_Sediment_C+Litter_Sediment_N+Litter_Sediment_P+
                     Water_Sediment_C+Water_Sediment_N+Water_Sediment_P)*
                     Sediment_density
    DOCUMENT:  (cubic meters per day)

    Sediment_Outflow = 0
    DOCUMENT:  (cubic meters per day)

Standing_Dead_C(t) = Standing_Dead_C(t - dt) + (Shoot_C - Dead_Litter_C) * dt

INIT Standing_Dead_C = 1350
DOCUMENT:  (grams)

    Shoot_C = Ks*Plant_Death_Curve*Live_Shoot_C
    DOCUMENT:  (grams per day)

    Dead_Litter_C = IF(Standing_Dead_C*Kd>Standing_Dead_C)
                    THEN(Standing_Dead_C*Kd)
                    ELSE(Standing_Dead_C)
    DOCUMENT:  (grams per day)

Standing_Dead_N(t) = Standing_Dead_N(t - dt) + (Shoot_N - Dead_Litter_N) * dt

INIT Standing_Dead_N = 4475
DOCUMENT:  (grams)

    Shoot_N = Shoot_C/CNShoot
    DOCUMENT:  (grams per day)

    Dead_Litter_N = Dead_Litter_C/CNDead
    DOCUMENT:  (grams per day)

Standing_Dead__P(t) = Standing_Dead__P(t - dt) + (Shoot_P - Dead_Litter_P) * dt

INIT Standing_Dead__P = 45
DOCUMENT:  (grams)
```

```
        Shoot_P = Shoot_C/CPShoot
        DOCUMENT:  (grams per day)

        Dead_Litter_P = IF(Dead_Litter_C/CPDead<Standing_Dead__P)
                          THEN(Dead_Litter_C/CPDead)
                          ELSE(Standing_Dead__P)
        DOCUMENT:  (grams per day)

WW_volume(t) = WW_volume(t - dt) + (Precip + Influent + Outflow_in - ET -
                    OUTFLOW) * dt

INIT WW_volume = Bottom_Area*INITIAL_WW_DEPTH
DOCUMENT:  (cubic meters)

        Precip = ACTUAL_PRECIP*0.0254*Surface_area
        DOCUMENT:  (cubic meters per day)

        Influent = INFLOW*flow_divider
        DOCUMENT:  (cubic meters per day)

        Outflow_in = IF ((RECIRCULATE=1)
                        AND ((YEARDAY<=RECIRC_START)
                        OR(YEARDAY>RECIRC_END)))
                        THEN (0)
                        ELSE (OUTFLOW*.2)
        DOCUMENT:  (cubic meters per day)

        OUTFLOW = Influent
        DOCUMENT:  (cubic meters per day)
```

Rate constants and parameter equations:

```
Bottom_Area = LENGTH*BOTTOM_WIDTH
DOCUMENT:  (square meters)

BOTTOM_WIDTH = 18
DOCUMENT:  (meters)
```

```
Cell_volume = ((LENGTH*BOTTOM_WIDTH)+(LENGTH-2*MAX_DEPTH*SLOPE)
              *(BOTTOM_WIDTH-2*MAX_DEPTH*SLOPE)+4*(LENGTH-
              MAX_DEPTH*SLOPE)*(BOTTOM_WIDTH-MAX_DEPTH*
              SLOPE)*MAX_DEPTH)/6
DOCUMENT:  (cubic meters)

CNDead = 100

CNLitter = 10

CNOrganic = Organic_C/Organic_N

CNRoot = 5

CNShoot = 20

CN_Sediment = Sediment_C/Sediment_N

CPDead = 100

CPLitter = Litter_C/Litter_P

CPOrganic = Organic_C/Organic_P

CPRoot = 10

CPSediment = Sediment_C/Sediment_P

CPShoot = 30

Effluent_C_Conc = IF(OUTFLOW>0)
                  THEN(Outflow_C/OUTFLOW)
                  ELSE(0)
DOCUMENT:  (milligrams per liter)

Effluent_NH3_Conc = IF(OUTFLOW>0)
                    THEN(Outflow_NH3/OUTFLOW)
                    ELSE(0)
DOCUMENT:  (milligrams per liter)
```

```
Effluent_NO3_Conc = IF(OUTFLOW>0)
                    THEN(Outflow_NO3/OUTFLOW)
                    ELSE(0)
DOCUMENT:  (milligrams per liter)

Effluent_Org_P_Conc = IF(OUTFLOW>0)
                      THEN(Outflow_P/OUTFLOW)
                      ELSE(0)
DOCUMENT:  (milligrams per liter)

Effluent_TKN_Conc = Effluent_NH3_Conc+Effluent_Org_N_Conc
DOCUMENT:  (milligrams per liter)

Effluent_TP_Conc = Effuent_OrthoP_Conc+Effluent_Org_P_Conc
DOCUMENT:  (milligrams per liter)

Effluent__Org_N_Conc = IF(OUTFLOW>0)
                       THEN(Outflow_N/OUTFLOW)
                       ELSE(0)
DOCUMENT:  (milligrams per liter)

Effuent_OrthoP_Conc = IF(OUTFLOW>0)
                      THEN(Outflow_orthoP/OUTFLOW)
                      ELSE(0)
DOCUMENT:  (milligrams per liter)

ET = kET*ETF*Surface_area
DOCUMENT:  (cubic meters per day)

INFLUENT_C_CONC = 100
DOCUMENT:  (milligrams per liter)

INITIAL_DAY = 227

INITIAL_SED_DEPTH = .34
DOCUMENT:  (meters)

INITIAL_WW_DEPTH = .02
DOCUMENT:  (meters)
```

K_CO2 = .001
DOCUMENT: (per day)

Kd = .02
DOCUMENT: (per day)

kDeNit = .5
DOCUMENT: (per day)

kET = .005
DOCUMENT: (meters per day)

kNit = .07
DOCUMENT: (per day)

Kp = 1.1
DOCUMENT: (grams per day)

Kr = .01
DOCUMENT: (per day)

Ks = .1
DOCUMENT: (per day)

Ksed = 5
DOCUMENT: (per day)

k_decomp_P = .001
DOCUMENT: (per day)

K_litter = .05
DOCUMENT: (per day)

k_N_fixers = .05
DOCUMENT: (per day)

k_sorb_P = .0002
DOCUMENT: (per day)

LENGTH = 50
DOCUMENT: (meters)

Live_Shoot_Biomass = Live_Shoot_C + Live_Shoot_N + Live_Shoot_P
DOCUMENT: (grams)

MAX_DEPTH = 2
DOCUMENT: (meters)

NH3_Conc = Ammonia_N/Total_Volume
DOCUMENT: (milligrams per liter)

NH3_Uptake_Fraction = .1

NO3_Conc = Nitrate_N/Total_Volume
DOCUMENT: (milligrams per liter)

number_of_cells = 1

Org_C_Conc = Organic_C/WW_volume
DOCUMENT: (milligrams per liter)

Org_N_Conc = Organic_N/WW_volume
DOCUMENT: (milligrams per liter)

Org_P_Conc = Organic_P/WW_volume
DOCUMENT: (milligrams per liter)

Ortho_P_Conc = Available_P/Total_Volume
DOCUMENT: (milligrams per liter)

RECIRCULATE = 1

RECIRC_END = 200
DOCUMENT: (days)

RECIRC_START = 100
DOCUMENT: (days)

Retention_time = WW_volume*Porosity/((Influent+OUTFLOW)/2)
DOCUMENT: (days)

Sediment_density = 100
DOCUMENT: (grams per cubic meter)

Sediment_Depth = Sediment_Volume/Bottom_Area
DOCUMENT: (meters)

Sed_C_Conc = Sediment_C/Sediment_Volume
DOCUMENT: (milligrams per liter)

Sed_N_Conc = Sediment_N/Sediment_Volume
DOCUMENT: (milligrams per liter)

Sed_P_Conc = Sediment_P/Sediment_Volume
DOCUMENT: (milligrams per liter)

SLOPE = 3

Surface_area = top_width*LENGTH*number_of_cells
DOCUMENT: (square meters)

TKN_Conc = NH3_Conc+Org_N_Conc
DOCUMENT: (milligrams per liter)

top_width = bottom_width+(2*WW_Depth/SLOPE)
DOCUMENT: (meters)

Total_Depth = WW_Depth+Sediment_Depth
DOCUMENT: (meters)

Total_Volume = WW_volume+Sediment_Volume
DOCUMENT: (cubic meters)

TP_Conc = Ortho_P_Conc+Org_P_Conc
DOCUMENT: (milligrams per liter)

WW_Depth = WW_volume/Bottom_Area
DOCUMENT: (meters)

YEARDAY = IF(INITIAL_DAY+TIME>365)
THEN(INITIAL_DAY+TIME-365)
ELSE(INITIAL_DAY+TIME)

ACTUAL_PRECIP = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.5), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.55), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.15), (16.0, 0.00), (17.0, 0.00), (18.0, 0.4), (19.0, 0.5), (20.0, 0.35),

(21.0, 0.2), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 1.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.725), (34.0, 0.00), (35.0, 0.1), (36.0, 1.00), (37.0, 0.00), (38.0, 0.15), (39.0, 0.6), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.15), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.00), (76.0, 0.00), (77.0, 0.00), (78.0, 0.00), (79.0, 0.1), (80.0, 0.00), (81.0, 0.05), (82.0, 0.00), (83.0, 0.00), (84.0, 0.8), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.25), (90.0, 0.00), (91.0, 0.3), (92.0, 0.05), (93.0, 0.00), (94.0, 1.20), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.00), (99.0, 1.50), (100, 0.4), (101, 0.00), (102, 0.00), (103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.2), (109, 0.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.2), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.00), (118, 0.25), (119, 0.1), (120, 0.4), (121, 0.5), (122, 0.00), (123, 0.15), (124, 0.00), (125, 0.00), (126, 0.3), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.00), (131, 0.00), (132, 0.2), (133, 0.2), (134, 0.00), (135, 0.00), (136, 0.00), (137, 0.00), (138, 0.00), (139, 0.00), (140, 0.00), (141, 0.00), (142, 0.00), (143, 0.00), (144, 0.00), (145, 0.00), (146, 0.00), (147, 0.00), (148, 0.00), (149, 1.05), (150, 0.00), (151, 0.00), (152, 0.1), (153, 0.00), (154, 0.1), (155, 0.75), (156, 0.00), (157, 0.00), (158, 0.00), (159, 0.00), (160, 0.00), (161, 0.00), (162, 0.00), (163, 0.00), (164, 0.00), (165, 0.00), (166, 0.5), (167, 0.00), (168, 0.00), (169, 0.05), (170, 0.00), (171, 0.00), (172, 0.00), (173, 0.00), (174, 0.00), (175, 0.00), (176, 0.00), (177, 0.1), (178, 0.00), (179, 0.7), (180, 0.00), (181, 0.05), (182, 0.00), (183, 1.35), (184, 0.00), (185, 0.00), (186, 0.00), (187, 0.00), (188, 1.30), (189, 1.30), (190, 0.00), (191, 0.00), (192, 0.2), (193, 0.00), (194, 0.00), (195, 0.00), (196, 0.00), (197, 0.00), (198, 2.10), (199, 0.00), (200, 0.00), (201, 0.00), (202, 0.00), (203, 0.00), (204, 0.00), (205, 0.00), (206, 0.00), (207, 1.15), (208, 0.00), (209, 0.00), (210, 2.00), (211, 0.00), (212, 0.00), (213, 0.00), (214, 0.00), (215, 1.00), (216, 0.1), (217, 0.00), (218, 0.00), (219, 0.00), (220, 0.00), (221, 0.00), (222, 0.00), (223, 0.00), (224, 0.00), (225, 0.00), (226, 0.00)
DOCUMENT: (inches)

Dissolved_Oxygen_Conc = GRAPH(TIME)
(0.00, 3.10), (1.00, 3.05), (2.00, 2.75), (3.00, 2.75), (4.00, 2.75), (5.00, 3.05), (6.00, 2.90), (7.00, 2.85), (8.00, 2.85), (9.00, 2.70), (10.0, 2.55), (11.0, 2.60), (12.0, 2.55), (13.0, 2.50), (14.0, 2.35), (15.0, 2.25), (16.0, 1.90), (17.0, 1.75), (18.0, 1.80), (19.0, 1.70), (20.0, 1.95), (21.0, 1.95), (22.0, 1.95), (23.0, 1.80), (24.0, 1.60), (25.0, 1.45), (26.0, 1.45), (27.0, 1.35), (28.0, 1.30), (29.0, 1.20), (30.0, 1.30), (31.0, 1.35), (32.0, 1.45), (33.0, 1.35), (34.0, 1.25), (35.0, 1.15), (36.0, 1.10), (37.0, 1.10), (38.0, 0.95), (39.0, 1.00), (40.0, 1.10), (41.0, 1.20), (42.0, 1.25), (43.0, 1.25), (44.0, 1.10), (45.0, 0.65), (46.0, 0.55), (47.0, 0.6), (48.0, 0.55), (49.0, 0.65), (50.0, 0.7), (51.0, 0.85), (52.0, 0.95), (53.0, 1.10), (54.0, 1.25), (55.0, 1.00), (56.0, 1.10), (57.0, 1.00), (58.0, 1.00), (59.0, 1.05), (60.0, 0.95), (61.0, 0.9), (62.0, 0.85), (63.0, 0.9), (64.0, 0.8), (65.0, 0.75), (66.0, 0.75), (67.0, 0.8), (68.0, 0.85), (69.0, 0.9),

(70.0, 0.75), (71.0, 0.8), (72.0, 0.65), (73.0, 0.65), (74.0, 0.5), (75.0, 0.65), (76.0, 0.6), (77.0, 0.65), (78.0, 0.5), (79.0, 0.4), (80.0, 0.4), (81.0, 0.65), (82.0, 0.55), (83.0, 0.5), (84.0, 0.45), (85.0, 0.6), (86.0, 0.75), (87.0, 0.85), (88.0, 0.75), (89.0, 0.6), (90.0, 0.9), (91.0, 0.85), (92.0, 0.55), (93.0, 0.5), (94.0, 0.5), (95.0, 0.4), (96.0, 0.5), (97.0, 0.5), (98.0, 0.3), (99.0, 0.35), (100, 0.25), (101, 0.35), (102, 0.25), (103, 0.2), (104, 0.1), (105, 0.2), (106, 0.35), (107, 0.4), (108, 0.5), (109, 0.8), (110, 0.65), (111, 0.65), (112, 0.7), (113, 0.65), (114, 0.55), (115, 0.7), (116, 0.55), (117, 0.8), (118, 1.75), (119, 0.45), (120, 0.25), (121, 0.45), (122, 0.45), (123, 0.3), (124, 0.3), (125, 0.3), (126, 0.3), (127, 0.4), (128, 0.4), (129, 0.4), (130, 0.4), (131, 0.4), (132, 0.4), (133, 0.4), (134, 0.4), (135, 0.4), (136, 0.45), (137, 0.45), (138, 0.45), (139, 0.55), (140, 0.55), (141, 0.6), (142, 0.65), (143, 0.65), (144, 0.75), (145, 0.7), (146, 0.55), (147, 0.2), (148, 0.2), (149, 0.25), (150, 0.25), (151, 0.25), (152, 0.3), (153, 0.2), (154, 0.15), (155, 0.15), (156, 0.15), (157, 0.1), (158, 0.05), (159, 0.1), (160, 0.2), (161, 0.1), (162, 0.1), (163, 0.05), (164, 0.05), (165, 0.15), (166, 0.1), (167, 0.05), (168, 0.05), (169, 0.05), (170, 0.35), (171, 0.1), (172, 0.05), (173, 0.05), (174, 0.05), (175, 0.05), (176, 0.05), (177, 0.05), (178, 0.05), (179, 0.05), (180, 0.05), (181, 0.1), (182, 0.15), (183, 0.05), (184, 0.05), (185, 0.1), (186, 0.1), (187, 0.1), (188, 0.1), (189, 0.1), (190, 0.15), (191, 0.15), (192, 0.15), (193, 0.15), (194, 0.15), (195, 0.15), (196, 0.4), (197, 0.2), (198, 0.15), (199, 0.15), (200, 0.15), (201, 0.15), (202, 0.15), (203, 0.15), (204, 0.2), (205, 0.2), (206, 0.2), (207, 0.2), (208, 0.2), (209, 0.2), (210, 0.2), (211, 0.2), (212, 0.2), (213, 0.2), (214, 0.2), (215, 0.2), (216, 0.2), (217, 0.25), (218, 0.4), (219, 0.55), (220, 0.6), (221, 0.6), (222, 0.65), (223, 0.65), (224, 0.5), (225, 0.5), (226, 0.4)
DOCUMENT: (milligrams per liter)

DOF_Denit = GRAPH(Dissolved_Oxygen_Conc)
(0.00, 1.00), (0.5, 0.9), (1.00, 0.8), (1.50, 0.7), (2.00, 0.6), (2.50, 0.5), (3.00, 0.4), (3.50, 0.3), (4.00, 0.2), (4.50, 0.1), (5.00, 0.00)

DOF_Nit = GRAPH(Dissolved_Oxygen_Conc)
(0.00, 0.00), (0.5, 0.1), (1.00, 0.2), (1.50, 0.3), (2.00, 0.4), (2.50, 0.5), (3.00, 0.6), (3.50, 0.7), (4.00, 0.8), (4.50, 0.9), (5.00, 1.00)

ETF = GRAPH(YEARDAY)
(0.00, 0.5), (33.2, 0.5), (66.4, 0.625), (99.5, 0.75), (133, 0.875), (166, 1.00), (199, 1.00), (232, 1.00), (265, 0.875), (299, 0.75), (332, 0.625), (365, 0.5)

INFLOW = GRAPH(YEARDAY)
(0.00, 68.5), (33.2, 95.4), (66.4, 84.8), (99.5, 46.6), (133, 87.1), (166, 50.0), (199, 50.0), (232, 50.0), (265, 50.0), (299, 79.0), (332, 110), (365, 65.1)
DOCUMENT: (cubic meters per day)

Influent_NH3_Conc = GRAPH(TIME)
(0.00, 6.11), (1.00, 6.35), (2.00, 10.4), (3.00, 6.01), (4.00, 4.96), (5.00, 5.66), (6.00, 5.54), (7.00, 5.53), (8.00, 5.71), (9.00, 6.52), (10.0, 5.26), (11.0, 5.26), (12.0, 4.43), (13.0, 6.23), (14.0, 4.50), (15.0, 4.84), (16.0, 7.12), (17.0, 4.31), (18.0, 4.31), (19.0, 9.03), (20.0, 7.00), (21.0, 7.00), (22.0, 5.67), (23.0, 4.24), (24.0, 2.37), (25.0, 2.37), (26.0, 2.80), (27.0, 2.80), (28.0, 2.80), (29.0, 3.48), (30.0, 3.24), (31.0, 3.01), (32.0, 3.08), (33.0, 3.29), (34.0, 3.59), (35.0, 3.83), (36.0, 3.80), (37.0, 3.88), (38.0, 2.00), (39.0, 1.96), (40.0, 1.81), (41.0, 2.22), (42.0, 2.12), (43.0, 2.13), (44.0, 1.56), (45.0, 1.29), (46.0, 1.49), (47.0, 1.44), (48.0, 1.75), (49.0, 2.15), (50.0, 1.92), (51.0, 1.26), (52.0, 1.29), (53.0, 1.32), (54.0, 1.29), (55.0, 1.06), (56.0, 1.02), (57.0, 1.09), (58.0, 1.04), (59.0, 1.09), (60.0, 1.17), (61.0, 1.17), (62.0, 1.41), (63.0, 1.53), (64.0, 1.24), (65.0, 1.17), (66.0, 1.35), (67.0, 1.44), (68.0, 1.62), (69.0, 1.68), (70.0, 2.28), (71.0, 2.02), (72.0, 1.88), (73.0, 1.89), (74.0, 2.01), (75.0, 1.58), (76.0, 1.82), (77.0, 1.71), (78.0, 1.99), (79.0, 1.81), (80.0, 1.87), (81.0, 1.52), (82.0, 2.71), (83.0, 2.75), (84.0, 3.50), (85.0, 3.50), (86.0, 3.50), (87.0, 3.50), (88.0, 3.50), (89.0, 3.50), (90.0, 3.50), (91.0, 3.50), (92.0, 3.50), (93.0, 3.50), (94.0, 3.50), (95.0, 3.50), (96.0, 3.50), (97.0, 3.50), (98.0, 3.50), (99.0, 3.50), (100, 3.50), (101, 3.50), (102, 3.50), (103, 3.50), (104, 4.36), (105, 5.00), (106, 4.68), (107, 5.00), (108, 5.67), (109, 7.11), (110, 9.05), (111, 8.50), (112, 8.50), (113, 8.50), (114, 8.50), (115, 8.50), (116, 8.50), (117, 8.50), (118, 7.94), (119, 13.5), (120, 13.5), (121, 13.5), (122, 13.5), (123, 13.5), (124, 13.5), (125, 13.5), (126, 13.5), (127, 13.5), (128, 13.5), (129, 13.5), (130, 13.5), (131, 13.5), (132, 13.5), (133, 13.5), (134, 13.5), (135, 13.5), (136, 13.5), (137, 13.5), (138, 13.5), (139, 13.5), (140, 13.5), (141, 13.5), (142, 13.5), (143, 13.5), (144, 13.5), (145, 13.5), (146, 13.5), (147, 13.5), (148, 13.5), (149, 13.5), (150, 13.5), (151, 13.5), (152, 13.5), (153, 13.5), (154, 19.4), (155, 18.7), (156, 19.0), (157, 17.5), (158, 20.5), (159, 20.5), (160, 24.5), (161, 23.1), (162, 18.5), (163, 19.3), (164, 15.1), (165, 15.1), (166, 13.7), (167, 14.5), (168, 12.4), (169, 12.3), (170, 15.0), (171, 17.5), (172, 12.2), (173, 12.5), (174, 11.7), (175, 11.7), (176, 11.7), (177, 11.7), (178, 11.7), (179, 11.7), (180, 11.7), (181, 11.7), (182, 11.7), (183, 11.7), (184, 11.7), (185, 11.7), (186, 11.7), (187, 11.7), (188, 11.7), (189, 11.7), (190, 11.7), (191, 11.7), (192, 11.7), (193, 11.7), (194, 11.7), (195, 11.7), (196, 11.7), (197, 11.7), (198, 11.7), (199, 11.7), (200, 11.7), (201, 11.7), (202, 11.7), (203, 11.7), (204, 11.7), (205, 11.7), (206, 11.7), (207, 11.7), (208, 11.7), (209, 10.9), (210, 10.8), (211, 7.68), (212, 8.54), (213, 7.45), (214, 6.80), (215, 8.59), (216, 8.75), (217, 6.65), (218, 6.15), (219, 6.36), (220, 6.42), (221, 6.37), (222, 6.40), (223, 6.40), (224, 6.40), (225, 6.40), (226, 6.45)
DOCUMENT: (milligrams per liter)

Influent_NO3_Conc = GRAPH(TIME)
(0.00, 1.11), (1.00, 1.15), (2.00, 0.986), (3.00, 1.09), (4.00, 0.853), (5.00, 0.854), (6.00, 0.879), (7.00, 1.09), (8.00, 0.943), (9.00, 0.917), (10.0, 0.907), (11.0, 0.935), (12.0, 0.853), (13.0, 1.08), (14.0, 1.03), (15.0, 0.889), (16.0, 0.917), (17.0, 0.964), (18.0, 0.89), (19.0, 0.865), (20.0, 0.7), (21.0, 0.7), (22.0, 0.585), (23.0, 0.736), (24.0, 0.78), (25.0, 0.79), (26.0, 0.6), (27.0, 0.6), (28.0, 0.6), (29.0, 0.438), (30.0, 0.568), (31.0, 0.994), (32.0, 0.895), (33.0, 0.936), (34.0, 1.19), (35.0, 1.45), (36.0, 1.27), (37.0, 1.12), (38.0, 0.925),

(39.0, 0.429), (40.0, 0.703), (41.0, 1.08), (42.0, 1.44), (43.0, 1.65), (44.0, 2.25), (45.0, 2.25), (46.0, 1.96), (47.0, 1.61), (48.0, 1.68), (49.0, 1.81), (50.0, 2.47), (51.0, 2.32), (52.0, 2.61), (53.0, 2.37), (54.0, 2.14), (55.0, 2.25), (56.0, 2.38), (57.0, 2.36), (58.0, 2.52), (59.0, 2.36), (60.0, 2.47), (61.0, 2.47), (62.0, 1.85), (63.0, 1.50), (64.0, 1.42), (65.0, 1.64), (66.0, 1.52), (67.0, 1.59), (68.0, 1.38), (69.0, 1.47), (70.0, 1.40), (71.0, 1.44), (72.0, 1.79), (73.0, 1.53), (74.0, 1.67), (75.0, 1.87), (76.0, 1.75), (77.0, 1.84), (78.0, 1.72), (79.0, 1.86), (80.0, 1.62), (81.0, 1.91), (82.0, 2.41), (83.0, 1.91), (84.0, 1.91), (85.0, 1.91), (86.0, 1.91), (87.0, 1.91), (88.0, 1.91), (89.0, 1.91), (90.0, 1.91), (91.0, 1.91), (92.0, 1.91), (93.0, 1.91), (94.0, 1.91), (95.0, 1.91), (96.0, 1.91), (97.0, 1.91), (98.0, 1.91), (99.0, 1.91), (100, 1.91), (101, 1.91), (102, 1.91), (103, 1.91), (104, 1.92), (105, 2.59), (106, 1.96), (107, 1.98), (108, 2.07), (109, 2.09), (110, 1.51), (111, 1.80), (112, 1.80), (113, 1.80), (114, 1.80), (115, 1.80), (116, 1.80), (117, 1.80), (118, 2.12), (119, 1.50), (120, 1.50), (121, 1.50), (122, 1.50), (123, 1.50), (124, 1.50), (125, 1.50), (126, 1.50), (127, 1.50), (128, 1.50), (129, 1.50), (130, 1.50), (131, 1.50), (132, 1.50), (133, 1.50), (134, 1.50), (135, 1.50), (136, 1.50), (137, 1.50), (138, 1.50), (139, 1.50), (140, 1.50), (141, 1.50), (142, 1.50), (143, 1.50), (144, 1.50), (145, 1.50), (146, 1.50), (147, 1.50), (148, 1.50), (149, 1.50), (150, 1.50), (151, 1.50), (152, 1.50), (153, 1.50), (154, 0.952), (155, 0.853), (156, 0.82), (157, 0.866), (158, 1.00), (159, 1.00), (160, 1.20), (161, 1.24), (162, 1.50), (163, 1.70), (164, 2.48), (165, 2.54), (166, 2.59), (167, 2.33), (168, 2.30), (169, 2.49), (170, 2.40), (171, 2.33), (172, 2.86), (173, 3.01), (174, 2.50), (175, 2.50), (176, 2.50), (177, 2.50), (178, 2.50), (179, 2.50), (180, 2.50), (181, 2.50), (182, 2.50), (183, 2.50), (184, 2.50), (185, 2.50), (186, 2.50), (187, 2.50), (188, 2.50), (189, 2.50), (190, 2.50), (191, 2.50), (192, 2.50), (193, 2.50), (194, 2.50), (195, 2.50), (196, 2.50), (197, 2.50), (198, 2.50), (199, 2.50), (200, 2.50), (201, 2.50), (202, 2.50), (203, 2.50), (204, 2.50), (205, 2.50), (206, 2.50), (207, 2.50), (208, 2.50), (209, 1.96), (210, 2.98), (211, 3.51), (212, 3.09), (213, 3.67), (214, 3.99), (215, 3.79), (216, 3.62), (217, 3.82), (218, 4.03), (219, 3.78), (220, 3.72), (221, 3.90), (222, 3.10), (223, 3.10), (224, 3.10), (225, 3.10), (226, 2.42)
DOCUMENT: (milligrams per liter)

Influent_Ortho_P_Conc = GRAPH(TIME)
(0.00, 3.25), (1.00, 5.62), (2.00, 9.69), (3.00, 4.13), (4.00, 3.44), (5.00, 3.96), (6.00, 3.76), (7.00, 3.45), (8.00, 3.57), (9.00, 3.88), (10.0, 3.73), (11.0, 3.98), (12.0, 3.63), (13.0, 3.65), (14.0, 3.45), (15.0, 3.81), (16.0, 3.55), (17.0, 3.56), (18.0, 3.19), (19.0, 10.9), (20.0, 7.00), (21.0, 7.00), (22.0, 2.99), (23.0, 2.24), (24.0, 1.95), (25.0, 2.26), (26.0, 2.35), (27.0, 2.35), (28.0, 2.35), (29.0, 2.49), (30.0, 2.31), (31.0, 2.26), (32.0, 2.66), (33.0, 2.82), (34.0, 2.87), (35.0, 2.83), (36.0, 2.81), (37.0, 2.83), (38.0, 2.84), (39.0, 2.87), (40.0, 2.25), (41.0, 2.09), (42.0, 2.14), (43.0, 2.09), (44.0, 2.01), (45.0, 2.05), (46.0, 1.74), (47.0, 2.16), (48.0, 2.28), (49.0, 2.29), (50.0, 2.34), (51.0, 1.51), (52.0, 1.49), (53.0, 1.23), (54.0, 0.905), (55.0, 0.944), (56.0, 0.846), (57.0, 0.878), (58.0, 0.873), (59.0, 0.881), (60.0, 0.906), (61.0, 0.894), (62.0, 1.08), (63.0, 1.02), (64.0, 1.04), (65.0, 1.15), (66.0, 1.21), (67.0, 1.09), (68.0, 1.18), (69.0, 1.11), (70.0, 1.17), (71.0, 1.16), (72.0, 1.24), (73.0, 1.20), (74.0, 0.822), (75.0, 0.917), (76.0, 0.865), (77.0, 0.912), (78.0, 1.05), (79.0, 0.941), (80.0, 0.936), (81.0, 0.631), (82.0, 1.00), (83.0, 0.994), (84.0, 1.80), (85.0, 1.80), (86.0, 1.80),

(87.0, 1.80), (88.0, 1.80), (89.0, 1.80), (90.0, 1.80), (91.0, 1.80), (92.0, 1.80), (93.0, 1.80), (94.0, 1.80), (95.0, 1.80), (96.0, 1.80), (97.0, 1.80), (98.0, 1.80), (99.0, 1.80), (100, 1.80), (101, 1.80), (102, 1.80), (103, 1.80), (104, 2.67), (105, 1.34), (106, 1.13), (107, 1.07), (108, 1.04), (109, 1.63), (110, 5.25), (111, 5.30), (112, 5.30), (113, 5.30), (114, 5.30), (115, 5.30), (116, 5.30), (117, 5.30), (118, 5.31), (119, 4.90), (120, 4.90), (121, 4.90), (122, 4.90), (123, 4.90), (124, 4.90), (125, 4.90), (126, 4.90), (127, 4.90), (128, 4.90), (129, 4.90), (130, 4.90), (131, 4.90), (132, 4.90), (133, 4.90), (134, 4.90), (135, 4.90), (136, 4.90), (137, 4.90), (138, 4.90), (139, 4.90), (140, 4.90), (141, 4.90), (142, 4.90), (143, 4.90), (144, 4.90), (145, 4.90), (146, 4.90), (147, 4.90), (148, 4.90), (149, 4.90), (150, 4.90), (151, 4.90), (152, 4.90), (153, 4.90), (154, 4.64), (155, 4.31), (156, 4.65), (157, 4.47), (158, 4.50), (159, 4.50), (160, 4.53), (161, 4.54), (162, 4.38), (163, 4.05), (164, 3.52), (165, 3.43), (166, 3.47), (167, 3.57), (168, 3.68), (169, 3.64), (170, 3.40), (171, 3.14), (172, 3.42), (173, 3.49), (174, 3.30), (175, 3.30), (176, 3.30), (177, 3.30), (178, 3.30), (179, 3.30), (180, 3.30), (181, 3.30), (182, 3.30), (183, 3.30), (184, 3.30), (185, 3.30), (186, 3.30), (187, 3.30), (188, 3.30), (189, 3.30), (190, 3.30), (191, 3.30), (192, 3.30), (193, 3.30), (194, 3.30), (195, 3.30), (196, 3.30), (197, 3.30), (198, 3.30), (199, 3.30), (200, 3.30), (201, 3.30), (202, 3.30), (203, 3.30), (204, 3.30), (205, 3.30), (206, 3.30), (207, 3.30), (208, 3.30), (209, 3.09), (210, 2.47), (211, 2.02), (212, 1.98), (213, 2.11), (214, 1.94), (215, 1.98), (216, 1.75), (217, 1.20), (218, 1.79), (219, 1.71), (220, 2.01), (221, 1.69), (222, 1.55), (223, 1.55), (224, 1.55), (225, 1.55), (226, 1.38)
DOCUMENT: (milligrams per liter)

Inf_Org_N_Conc = GRAPH(TIME)
(0.00, 1.43), (1.00, 0.275), (2.00, 0.75), (3.00, 0.933), (4.00, 0.657), (5.00, 0.56), (6.00, 1.06), (7.00, 0.478), (8.00, 1.09), (9.00, 0.179), (10.0, 0.431), (11.0, 0.403), (12.0, 0.973), (13.0, 0.00), (14.0, 0.511), (15.0, 0.276), (16.0, 0.00), (17.0, 0.673), (18.0, 0.464), (19.0, 0.00), (20.0, 0.2), (21.0, 0.2), (22.0, 0.375), (23.0, 1.20), (24.0, 1.26), (25.0, 0.834), (26.0, 1.43), (27.0, 0.392), (28.0, 2.32), (29.0, 0.00), (30.0, 0.00), (31.0, 0.001), (32.0, 0.00), (33.0, 0.859), (34.0, 0.392), (35.0, 1.09), (36.0, 0.733), (37.0, 0.065), (38.0, 0.994), (39.0, 0.118), (40.0, 0.393), (41.0, 1.70), (42.0, 0.00), (43.0, 1.77), (44.0, 0.894), (45.0, 2.78), (46.0, 0.954), (47.0, 0.897), (48.0, 0.00), (49.0, 0.00), (50.0, 0.197), (51.0, 1.07), (52.0, 0.985), (53.0, 1.13), (54.0, 2.15), (55.0, 2.50), (56.0, 2.71), (57.0, 2.37), (58.0, 2.27), (59.0, 2.22), (60.0, 5.75), (61.0, 1.22), (62.0, 0.841), (63.0, 0.471), (64.0, 2.69), (65.0, 1.99), (66.0, 1.67), (67.0, 2.42), (68.0, 2.54), (69.0, 2.39), (70.0, 2.13), (71.0, 2.55), (72.0, 2.32), (73.0, 1.93), (74.0, 2.18), (75.0, 2.43), (76.0, 2.38), (77.0, 2.48), (78.0, 2.58), (79.0, 3.43), (80.0, 3.53), (81.0, 3.60), (82.0, 3.36), (83.0, 3.65), (84.0, 3.20), (85.0, 3.20), (86.0, 3.20), (87.0, 3.20), (88.0, 3.20), (89.0, 3.20), (90.0, 3.20), (91.0, 3.20), (92.0, 3.20), (93.0, 3.20), (94.0, 3.20), (95.0, 3.20), (96.0, 3.20), (97.0, 3.20), (98.0, 3.20), (99.0, 3.20), (100, 3.20), (101, 3.20), (102, 3.20), (103, 3.20), (104, 2.70), (105, 1.21), (106, 2.43), (107, 0.694), (108, 1.52), (109, 1.18), (110, 5.86), (111, 4.00), (112, 4.00), (113, 4.00), (114, 4.00), (115, 4.00), (116, 4.00), (117, 4.00), (118, 2.04), (119, 1.00), (120, 1.00), (121, 1.00), (122, 1.00), (123, 1.00), (124, 1.00), (125, 1.00), (126, 1.00), (127, 1.00), (128, 1.00), (129, 1.00), (130, 1.00), (131, 1.00), (132, 1.00), (133, 1.00), (134, 1.00), (135,

1.00), (136, 1.00), (137, 1.00), (138, 1.00), (139, 1.00), (140, 1.00), (141, 1.00), (142, 1.00), (143, 1.00), (144, 1.00), (145, 1.00), (146, 1.00), (147, 1.00), (148, 1.00), (149, 1.00), (150, 1.00), (151, 1.00), (152, 1.00), (153, 1.00), (154, 0.00), (155, 0.607), (156, 2.99), (157, 4.53), (158, 4.00), (159, 4.00), (160, 2.67), (161, 3.77), (162, 1.32), (163, 2.94), (164, 3.96), (165, 1.18), (166, 0.686), (167, 0.034), (168, 2.10), (169, 4.02), (170, 1.80), (171, 0.00), (172, 0.00), (173, 0.833), (174, 1.30), (175, 1.30), (176, 1.30), (177, 1.30), (178, 1.30), (179, 1.30), (180, 1.30), (181, 1.30), (182, 1.30), (183, 1.30), (184, 1.30), (185, 1.30), (186, 1.30), (187, 1.30), (188, 1.30), (189, 1.30), (190, 1.30), (191, 1.30), (192, 1.30), (193, 1.30), (194, 1.30), (195, 1.30), (196, 1.30), (197, 1.30), (198, 1.30), (199, 1.30), (200, 1.30), (201, 1.30), (202, 1.30), (203, 1.30), (204, 1.30), (205, 1.30), (206, 1.30), (207, 1.30), (208, 1.30), (209, 1.76), (210, 0.00), (211, 0.546), (212, 0.00), (213, 0.077), (214, 0.00), (215, 0.00), (216, 0.117), (217, 0.00), (218, 3.18), (219, 1.87), (220, 1.87), (221, 1.41), (222, 1.70), (223, 1.70), (224, 1.70), (225, 1.70), (226, 2.02)
DOCUMENT: (milligrams per liter)

Inf_Org_P_Conc = GRAPH(TIME)
(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.671), (25.0, 0.475), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 1.36), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 2.19), (37.0, 1.68), (38.0, 1.29), (39.0, 0.232), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.296), (55.0, 0.365), (56.0, 0.34), (57.0, 0.393), (58.0, 0.308), (59.0, 0.386), (60.0, 0.66), (61.0, 0.433), (62.0, 0.339), (63.0, 0.455), (64.0, 0.575), (65.0, 0.602), (66.0, 0.283), (67.0, 0.472), (68.0, 0.861), (69.0, 0.469), (70.0, 0.375), (71.0, 0.507), (72.0, 0.843), (73.0, 0.371), (74.0, 0.332), (75.0, 0.258), (76.0, 0.293), (77.0, 0.276), (78.0, 0.355), (79.0, 0.446), (80.0, 0.316), (81.0, 0.568), (82.0, 0.472), (83.0, 0.195), (84.0, 0.00), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 0.00), (102, 0.00), (103, 0.00), (104, 4.41), (105, 0.578), (106, 0.694), (107, 0.548), (108, 0.659), (109, 1.43), (110, 4.22), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.00), (118, 2.19), (119, 0.00), (120, 0.00), (121, 0.00), (122, 0.00), (123, 0.00), (124, 0.00), (125, 0.00), (126, 0.00), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.00), (131, 0.00), (132, 0.00), (133, 0.00), (134, 0.00), (135, 0.00), (136, 0.00), (137, 0.00), (138, 0.00), (139, 0.00), (140, 0.00), (141, 0.00), (142, 0.00), (143, 0.00), (144, 0.00), (145, 0.00), (146, 0.00), (147, 0.00), (148, 0.00), (149, 0.00), (150, 0.00), (151, 0.00), (152, 0.00), (153, 0.00), (154, 0.466), (155, 0.498), (156, 0.352), (157, 0.223), (158, 0.00), (159, 0.00), (160, 0.365), (161, 0.286), (162, 0.278), (163, 0.243), (164, 0.053), (165, 0.002), (166, 0.086), (167, 0.215), (168, 0.05), (169, 0.00), (170, 0.00), (171, 0.455), (172, 0.081), (173, 0.22), (174, 0.00), (175,

0.00), (176, 0.00), (177, 0.00), (178, 0.00), (179, 0.00), (180, 0.00), (181, 0.00), (182, 0.00), (183, 0.00), (184, 0.00), (185, 0.00), (186, 0.00), (187, 0.00), (188, 0.00), (189, 0.00), (190, 0.00), (191, 0.00), (192, 0.00), (193, 0.00), (194, 0.00), (195, 0.00), (196, 0.00), (197, 0.00), (198, 0.00), (199, 0.00), (200, 0.00), (201, 0.00), (202, 0.00), (203, 0.00), (204, 0.00), (205, 0.00), (206, 0.00), (207, 0.00), (208, 0.00), (209, 1.95), (210, 1.43), (211, 1.25), (212, 1.50), (213, 1.13), (214, 0.812), (215, 0.00), (216, 0.00), (217, 0.36), (218, 0.895), (219, 0.573), (220, 0.555), (221, 0.138), (222, 0.00), (223, 0.00), (224, 0.00), (225, 0.00), (226, 0.9)
DOCUMENT: (milligrams per liter)

MAF = GRAPH(WATER_TEMP)
(-20.0, 0.8), (-17.2, 0.8), (-14.5, 0.8), (-11.7, 0.8), (-8.95, 0.8), (-6.19, 0.8), (-3.43, 0.8), (-0.667, 0.8), (2.10, 0.8), (4.86, 1.00), (7.62, 1.00), (10.4, 1.00), (13.1, 1.00), (15.9, 1.00), (18.7, 1.00), (21.4, 1.00), (24.2, 1.00), (27.0, 1.00), (29.7, 1.00), (32.5, 1.00), (35.2, 1.00), (38.0, 1.00)

Plant_Death_Curve = GRAPH(YEARDAY)
(0.00, 0.3), (33.2, 0.2), (66.4, 0.1), (99.5, 0.1), (133, 0.1), (166, 0.1), (199, 0.1), (232, 0.1), (265, 0.2), (299, 0.3), (332, 0.4), (365, 0.5)

Plant_Growth_Curve = GRAPH(YEARDAY)
(0.00, 0.1), (33.2, 0.3), (66.4, 0.4), (99.5, 0.5), (133, 0.7), (166, 0.9), (199, 1.00), (232, 1.00), (265, 0.8), (299, 0.5), (332, 0.2), (365, 0.1)

Porosity = GRAPH(Live_Shoot_Biomass)
(0.00, 1.00), (1000, 0.95), (2000, 0.9), (3000, 0.85), (4000, 0.8), (5000, 0.75), (6000, 0.7), (7000, 0.65), (8000, 0.6), (9000, 0.55), (10000, 0.5)

Root_Fraction = GRAPH(YEARDAY)
(0.00, 0.7), (33.2, 0.6), (66.4, 0.5), (99.5, 0.4), (133, 0.3), (166, 0.3), (199, 0.3), (232, 0.3), (265, 0.3), (299, 0.4), (332, 0.5), (365, 0.7)

SF = GRAPH(YEARDAY)
(0.00, 0.3), (30.4, 0.8), (60.8, 1.00), (91.3, 1.00), (122, 1.00), (152, 1.00), (183, 1.00), (213, 1.00), (243, 1.00), (274, 1.00), (304, 1.00), (335, 1.00), (365, 0.8)
DOCUMENT: (grams per day)

WATER_TEMP = GRAPH(TIME)
(0.00, 23.9), (0.934, 24.6), (1.87, 24.7), (2.80, 24.6), (3.74, 24.0), (4.67, 23.2), (5.60, 23.0), (6.54, 23.3), (7.47, 23.6), (8.40, 23.7), (9.34, 23.7), (10.3, 23.4), (11.2, 23.5), (12.1, 23.2), (13.1, 23.1), (14.0, 23.1), (14.9, 23.4), (15.9, 23.7), (16.8, 23.7), (17.7, 23.6), (18.7, 22.6), (19.6, 21.4), (20.5, 21.5), (21.5, 22.1), (22.4, 22.2), (23.3, 22.3), (24.3, 22.4), (25.2, 22.4), (26.1, 22.7), (27.1, 22.9), (28.0, 22.8), (29.0, 21.6), (29.9, 20.3), (30.8, 20.5), (31.8,

21.2), (32.7, 21.4), (33.6, 21.4), (34.6, 21.7), (35.5, 22.6), (36.4, 22.6), (37.4, 22.5), (38.3, 20.3), (39.2, 19.8), (40.2, 19.4), (41.1, 19.3), (42.0, 19.8), (43.0, 19.9), (43.9, 20.2), (44.8, 20.4), (45.8, 20.6), (46.7, 20.6), (47.6, 20.4), (48.6, 20.1), (49.5, 18.6), (50.4, 17.0), (51.4, 16.2), (52.3, 15.9), (53.2, 15.9), (54.2, 15.9), (55.1, 15.9), (56.0, 16.1), (57.0, 16.4), (57.9, 16.8), (58.8, 17.0), (59.8, 17.3), (60.7, 17.3), (61.6, 17.3), (62.6, 17.4), (63.5, 17.4), (64.4, 17.2), (65.4, 17.2), (66.3, 17.2), (67.2, 17.3), (68.2, 17.3), (69.1, 17.2), (70.0, 16.6), (71.0, 16.2), (71.9, 16.4), (72.8, 16.8), (73.8, 16.8), (74.7, 16.9), (75.6, 16.8), (76.6, 16.5), (77.5, 17.0), (78.4, 17.5), (79.4, 17.5), (80.3, 16.5), (81.2, 15.1), (82.2, 14.7), (83.1, 14.7), (84.0, 14.5), (85.0, 13.6), (85.9, 13.5), (86.9, 13.4), (87.8, 12.4), (88.7, 11.7), (89.7, 11.6), (90.6, 10.6), (91.5, 10.4), (92.5, 10.9), (93.4, 10.9), (94.3, 11.2), (95.3, 11.1), (96.2, 10.9), (97.1, 10.6), (98.1, 10.4), (99.0, 9.72), (99.9, 9.89), (101, 9.61), (102, 8.28), (103, 7.89), (104, 7.72), (105, 8.00), (106, 8.22), (106, 8.11), (107, 8.28), (108, 8.72), (109, 9.50), (110, 9.00), (111, 8.39), (112, 9.00), (113, 9.11), (114, 9.50), (115, 8.61), (116, 7.61), (117, 7.11), (118, 6.11), (119, 5.90), (120, 5.90), (120, 5.90), (121, 5.90), (122, 5.90), (123, 5.90), (124, 5.90), (125, 5.90), (126, 5.90), (127, 5.90), (128, 5.90), (129, 5.90), (130, 5.90), (131, 5.90), (132, 5.90), (133, 5.90), (134, 5.90), (134, 5.90), (135, 5.78), (136, 5.39), (137, 5.28), (138, 6.00), (139, 6.22), (140, 7.28), (141, 8.61), (142, 8.50), (143, 8.78), (144, 8.89), (145, 10.2), (146, 10.3), (147, 8.00), (148, 6.78), (148, 6.72), (149, 6.89), (150, 6.78), (151, 6.50), (152, 7.89), (153, 7.61), (154, 8.39), (155, 9.72), (156, 9.89), (157, 9.78), (158, 9.22), (159, 8.72), (160, 8.89), (161, 8.89), (162, 8.72), (162, 9.00), (163, 9.61), (164, 10.7), (165, 11.5), (166, 11.2), (167, 10.2), (168, 9.61), (169, 10.8), (170, 11.8), (171, 12.8), (172, 12.9), (173, 12.3), (174, 10.7), (175, 10.7), (176, 12.2), (177, 12.1), (177, 10.9), (178, 10.9), (179, 12.4), (180, 13.0), (181, 12.9), (182, 13.0), (183, 12.9), (184, 12.8), (185, 12.4), (186, 12.6), (187, 12.6), (188, 12.6), (189, 12.6), (190, 12.6), (191, 12.6), (191, 12.6), (192, 12.6), (193, 12.6), (194, 12.8), (195, 12.8), (196, 12.3), (197, 12.3), (198, 12.4), (199, 12.4), (200, 12.2), (201, 11.7), (202, 10.8), (203, 11.7), (204, 12.0), (205, 12.3), (205, 13.0), (206, 12.8), (207, 11.6), (208, 11.3), (209, 11.2), (210, 11.7), (211, 12.6), (212, 12.6), (213, 12.3), (214, 12.1), (215, 13.4), (216, 13.6), (217, 14.4), (218, 15.4), (219, 16.0), (219, 16.8), (220, 17.3), (221, 17.9), (222, 18.0), (223, 18.4), (224, 18.6), (225, 18.4), (226, 18.0)
DOCUMENT: (degrees Celsius)