MODELING OF AIRCRAFT DEICING FLUID INDUCED BIOCHEMICAL OXYGEN DEMAND IN SUBSURFACE-FLOW CONSTRUCTED TREATMENT WETLANDS

THESIS

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Abstract

Aircraft deicing is vital to safe operation in cold weather environments. Unfortunately, release of glycol-based aircraft deicing fluids (ADF) to waterways adjacent to airfields poses a significant environmental threat. The deicing fluids used at DoD airfields impart a high biochemical oxygen demand (BOD) when they enter waterways. The currently accepted conventional treatment is collection and transport of ADF-laden storm water to a publicly owned treatment works. The volume and BOD concentrations in the storm water often make this type of treatment impractical. Subsurface flow constructed treatment wetlands have been demonstrated to be effective in attenuating ADF-induced BOD. The models currently used to design and model these types of wetlands focus on simple input-output relationships and do not take underlying processes into account. This study explores the use of a system dynamics modeling method as the basis for a useful design and management tool. The model focuses on simulating storm water flow between defined sections of the wetland and microbial kinetics in each section. Microbial utilization of substrates leads to attenuation in well designed wetlands. The model exhibits the potential to be a useful tool for this and possibly other applications

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For all who proudly wear the Gear and Compass

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Bill McLaughlin

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MODELING OF AIRCRAFT DEICING FLUID INDUCED BIOCHEMICAL OXYGEN DEMAND IN SUBSURFACE-FLOW CONSTRUCTED TREATMENT WETLANDS

I. Introduction

Background

Deicing is necessary for safe air travel in cold climates. The importance of proper ice control was highlighted when a U. S. Air flight leaving New York's LaGuardia Airport crashed into Flushing Bay due to wing icing killing 27 people in March 1992 (National Transportation Safety Board, 1993). The Department of Defense (DoD) is not immune from this requirement. The military operates airfields across the world, many of which require deicing to be conducted if operations are to continue during cold weather. Regardless of the aircraft type being supported, the methods of deicing and the concerns that accompany it remain the same.

The most common method of deicing is to spray the aircraft with hot fluid that melts the ice adhering to the outer surface. The components of these fluids are usually water, additives, and glycol-based antifreeze. Despite the addition of thickeners to many of the formulations, as much as 80% of the fluid dispensed runs off of the aircraft during the deicing process (Rice *et al.*, 1997). The overspray results in large volumes of glycol entering the storm water system. If the contaminated water is not treated, the high biochemical oxygen demand (BOD) characteristic of glycol compounds will be transferred to receiving waters and can result in anoxic conditions, fish kills, and other undesirable effects on the environment (Corsi *et al.*, 2001).

Problem Statement

Currently, discharge of glycol-contaminated storm water to a publicly-owned treatment works (POTW), or on-installation federally-owned treatment works (FOTW) in the case of some DoD installations, is considered the “standard” treatment method (Naval Facilities Engineering Service Center, 2004). This solution can be troublesome due to the large volume and high BOD concentrations that can disrupt the normal operations of a POTW. In other cases, the effluent is released directly to a receiving body of water (Corsi, *et al.*, 2001). Other methods of on-site attenuation include the construction of aerated storage lagoons, biofilm reactors, or constructed wetland systems. Subsurface flow constructed treatment wetlands (SSFCTW) have been demonstrated as a viable method for removing pollutants from airfield storm water (Revitt *et al.*, 2001; Higgins and MacLean, 2002). Along with a lack of awareness of the technology, the absence of confidence-inspiring design and management tools for this type of wetland is likely a barrier to further adoption by DoD components.

Research Objectives

The overarching objective of this research will be to add to the body of knowledge to help promote understanding and facilitate more productive use of SSFCTW technology. One primary objective of this research that will not be explicitly investigated is to increase awareness of this technology with the Air Force environmental management community and the DoD at large. The Naval Facilities Engineering Service Center (2004) pilot study identified lack of awareness as a major obstacle to adoption.

Though there are other major hurdles that will be discussed later, no solutions will be found to these problems if the SSFCTW option is never put on the table. The more focused specific objectives are discussed below.

Three specific research objectives have been formulated to help guide this research effort: 1. Explore the use of a system dynamics approach to modeling subsurface flow constructed treatment wetland system. 2. Identify factors important to the performance of subsurface flow constructed treatment wetland systems, especially those being used to attenuate deicer-induced water quality issues. 3. Build a useful tool for design and management of constructed treatment wetland systems. All three of these objectives were pursued simultaneously as the modeling effort unfolded.

Research Focus

The bulk of this effort focuses on the creation of an integrated microbial growth and decay model that is meant to simulate many of the underlying processes that lead to the degradation of high BOD levels in a SSFCTW. The modeling is accomplished using a system dynamics methodology and attempts to capture the natural feedback mechanisms important to behavior in the wetland. Inquiry and review of relevant literature are guided by the needs suggested from the modeling process. Attention is paid to certain externally controllable variables to build some practical utility into the model.

Research Approach

The research begins with a literature review focusing on previous studies of glycol treatment and degradation in natural environments. The review will also explore past wetland modeling efforts to ascertain the strengths and weakness of past approaches. Past system dynamics based efforts were of special interest to discover if there are structural elements and/or parameters that would be applicable to this model. Once an adequate model has been constructed and examined under steady-state conditions, the model will be subjected to real-world input data based on meteorological and aircraft deicing fluid (ADF) use data for Westover ARB, Chicopee Massachusetts. (Air Force Combat Climatology Center, 2008; Naval Facilities Engineering Service Center, 2004)

Assumptions and Limitations

As any model is necessarily a simplification of reality, there are several assumptions and limitations of both scope and applicability. Many of these may be restated as the portions of the methodology or results to which they apply are explained. Those mentioned in this section are intended to help shape the expectations of the reader as to the overall shape of the effort and identify the areas where the most robust modeling was undertaken.

The basic scope of the model focuses on the core processes that lead to and influence the attenuation of BOD in the wetland. These elements include the flow of storm water through the wetland, transport of substances with the storm water, utilizations of substances by biomass, and the kinetics of biomass growth. The model also includes structures that govern the input of storm water to the wetland, and the introduction of substance with the storm water and by wetland plants. These representations are more highly aggregated than the core processes and are meant to adequately represent an influence without precisely modeling that element's own internal dynamics.

Several assumptions concern the chosen unit of analysis for the model which is referred to at a wetland "cell". A cell represents a physical section of wetland extending a set length and the full width of the wetland. The cell is considered to be a completely mixed volume with uniform conditions throughout. All storm water flow occurs perpendicular to the dividing line between two adjacent cells.

Biomass types are aggregated into three broad categories based on affinity for oxygen and the type of substrate utilized for energy. Many contaminants, including glycol, are biodegraded in several steps by consortia of microbes (Zitomer *et al*., 2003). Though several species may be present, they are modeled as a single biomass. Also, other than methane, glycol and other BOD-inducing substances are collectively tracked as a mass of chemical oxygen demand (COD). Kinetic values related to COD as well as the relative COD of different substances were easier to find and handle collectively than BOD values. There are established relationships between BOD and COD published in the literature in the event that model output must be converted to BOD (Tchobanoglous and Burton, 1991).

The model also operates under an assumption of no temperature effect on the effectiveness of wetland treatment processes. This lack of a solid relationship has been reported in the literature, most notably by Kadlec and Knight (1996). An attempt was made to mechanistically explore the reasons for what seems to be a non-intuitive lack of relationship; however, the assumption was eventually accepted. Details of the temperature modeling attempt are provided.

A final limitation for this and any model is that outputs should not be considered to be exact by any means. A well calibrated model can be relied upon to give outputs that are close to values to be expected in practice. These values should be close enough to be used as a management or design tool as long as honest inputs are made. The true values in a model like this that strives to include underlying mechanisms is that it suggests more focused actions that can be undertaken to influence the state of the system. The actual COD output of the system is still a very important measure of effectiveness, but the model user must explore the other state variables and retain some subjective judgment if the full potential of the model is to be realized.

II. **Literature Review**

Glycol-Based Deicing Fluids

Glycols are alcohol-type compounds containing two hydroxyl (OH) groups on each molecule. Three specific glycols are commonly used as the major constituent of aircraft deicing and anti-icing fluids (ADF): ethylene glycol (EG), propylene glycol (PG), and diethylene glycol (DEG). These compounds are colorless, practically odorless, and completely miscible in water. Glycols also possess the property of depressing the freezing point of the water in which they are dissolved making them useful as an antifreeze or deicing agent. Of the three, EG and DEG are considered toxic chemicals. PG is actually used in applications that may result in human consumption and consequently has become a preferred component of ADF (Naval Facilities Engineering Service Center, 2004; Switzenbaum *et al*., 1999).

All three compounds possess a high oxygen demand when they reach receiving waters. The chemical oxygen demand (COD) of EG and PG is 1.29 and 1.68 milligrams per liter respectively for each 1 milligram per liter of glycol concentration (Safferman *et al*., 1998). This high demand becomes significant when one considers that between 500 and 1000 gallons of ADF may be needed to deice a single large commercial aircraft (Switzenbaum *et al*., 1999). Concentrations from 70 to 75,000 milligrams per liter have been reported in surface waters near commercial airports (Rice *et al*., 1997). Assuming that the less toxic PG is employed and using the COD to ultimate BOD reduction factor of 0.94 reported by Safferman *et al*. (1998) these concentrations translate to a BOD ranging from 110.5 to 118,440 milligrams per liter. Backer *et al*. (1994) put this situation in perspective when they stated that deicing one commercial aircraft produces a pollution load equal to that of the wastewater produced daily by roughly 5000 people.

Research has demonstrated that glycols are readily biodegradable in the environment and that they are not thought to persist or accumulate (Bausmith and Neufeld, 1999; Klecka *et al*., 1993; Pitter, 1976). As part of a study conducted by Corsi *et al*. (2001) a controlled release of PG-based aircraft deicer was performed at General Mitchell International Airport near Milwaukee, WI. PG concentrations were found to drop as the plume flowed downstream at a rate higher than could be explained by dilution from tributaries between stations. This result suggests that natural biological processes are capable of breaking down glycol molecules. Laboratory tests conducted in liquid media demonstrate that removal of glycol from solution is achieved by microbial digestion, and not simply sorption to particles, though that may be a mechanism with a nontrivial effect in a SSFCTW context (Scow and Hutson, 1992; Pitter, 1976).

Current deicing procedures consist of spraying a waiting aircraft with a heated mixture of ADF and water. The heat melts ice away from the wings, and the remaining glycol prevents new ice from forming. FAA regulation in place since the 1992 LaGuardia crash mandate that undiluted commercial Type-1 ADF contain at least 80 percent pure glycol, the balance being made up of water, thickeners, anti-corrosives, and other minor constituents (Switzenbaum *et al*., 1999). The pure ADF is then mixed with water before application in a proportion that is meant to provide adequate buffer for temperature drops and holdover time prior to takeoff. Though mixtures of half ADF and half water may be used, the typical mixture employed at Westover ARB was 70 to 80 percent ADF. (Naval Facilities Engineering Service Center, 2004; Switzenbaum *et al*.,

1999) Compressed hot air and manual deicing have been used in some instances to reduce the amount of ADF used on a given aircraft; however, 80 percent of the applied fluid is likely to end up running off the aircraft and onto the ground (Naval Facilities Engineering Service Center, 2004; Switzenbaum *et al*., 1999; Rice *et al*., 1997). Recycling is an option, but is not always feasible due to the quality and quantity of ADF-containing runoff and expense of processing for reuse (Backer *et al*., 1994).

Though there are some concerns with the toxicity of ADF constituents, there is wide consensus in the literature that the major threat posed by ADF-contaminated runoff is the high BOD of glycols (Jaesche *et al*., 2006; Naval Facilities Engineering Service Center, 2004; Corsi *et al*. 2001; Revitt *et al*. 2001; Chong *et al*. 1999; Switzenbaum *et al*., 1999; Safferman *et al*. 1998; Rice *et al*., 1997; Backer *et al*. 1994). Since ADF-containing runoff must eventually be returned to the environment, something must be done to attenuate the high BOD and prevent oxygen depletion in receiving waters. Options include release to a publicly-owned treatment works, aeration beds, fixed film, fluidized bed, and other bioreactors, processing through constructed wetlands, and other options (Naval Facilities Engineering Command, 2004). This research will focus on the last stated solution, specifically the treatment of ADF using a sub-surface flow constructed wetland.

Constructed Treatment Wetlands

Constructed treatment wetlands (CTWs) have been used for many years to harness natural processes in the treatment of contaminated wastewaters. CTWs provide treatment will little or no human intervention and/or energy input, making them a cost effective attenuation method in many situations. Natural wetlands have served as waste water treatment mechanisms for over a century while deliberately constructed wetlands have been used in the United States since the early 1970s (Kadlec and Knight, 1996). CTW systems have been successfully used to treat waste water containing various contaminants including explosive residue, highway runoff, acid mine drainage, volatile organic compounds from fuel, landfill leachate, nitrogen-containing industrial discharges, agricultural runoff, and ADF contaminated storm water (Higgins and Maclean, 2002; Lorion, 2001; Kadlec and Knight, 1996).

There are two basic types of CTW, surface flow and subsurface flow. The major difference between the two is the location of the water level in relation to the soil surface. Each design has been used successfully to treat various types of containments including ADF-laden runoff; and each has advantages and disadvantages depending upon the situation in which it is to be used (Naval Facilities Engineering Command, 2004; Revitt *et al*., 2001).

The first and most common type in the United States is the surface flow CTW (SFCTW). In this wetland, there is open water on top of the soil substrate through which wetland plants grow. The main advantage in choosing this design is that it is cheaper and easier to construct and maintain than a subsurface flow CTW. This type of wetland has been popular not only as a treatment system but also for the creation of wildlife habitat. A SFCTW may require more land to reach the same treatment capacity as a subsurface type, and is more susceptible to the effects of air temperature (Naval Facilities Engineering Command; 2004, Lorion, 2001; Chong *et al*. 1999).

The second type, currently more common in Europe, is the subsurface flow CTW (SSFCTW). Here the water to be treated flows below the surface of an open-graded substrate in which wetland plants grow. There should be no standing water on the surface of a properly designed SSFCTW. Keeping the flow below the surface limits human exposure and does not create a habitat for waterfowl and other wildlife or breeding areas for mosquitoes. This characteristic of SSFCTWs makes them more suitable for use near airports due to the reduction in bird air strike hazard (BASH). SSFCTWs have also exhibited higher contaminant removal efficiencies, possibly due to greater surface area for microbial growth. They are also more resistant to cold temperatures as the surrounding soil insulates the region in which degradation is taking place. SSFCTWs are more difficult to design hydraulically and more expensive to construct so they may not be the best choice if the previously stated public safety concerns are not an issue (Naval Facilities Engineering Command, 2004; Higgins and MacLean 2001).

Modeling of Constructed Wetland Treatment Systems

The proper design of constructed treatment wetland depends on the ability to make some assumptions regarding their performance in their intended application. Rousseau *et al*. (2004) provide on overview of the various methods used to predict SSFCTW performance. The techniques currently in common use ranged from simple rules of thumb for maximum loading through regression analysis to first-order contaminant degradation models. Variable-order Monod-type kinetic models were discussed as a method that is essentially similar to the previously mentioned first-order models, but includes provisions that can account for process saturation as maximum loading rates are reached. Finally, the review mentions the attempt of Wynn and Liehr (2001) to create what the literature refers to as a mechanistic, compartmental model for

SSFCTW performance. This method of representation is also known as system dynamics (SD) modeling. Artificial neural networking has also been explored as a means of simulating treatment wetland performance (Tomenko *et al*., 2007).

First order modeling is currently considered the “state of art” in constructed wetland simulation and design (Rousseau *et al*., 2004). The predominant form of this model is the first order decay with residual presented by Kadlec and Knight (1996). This model assumes a first-order rate of decay based on the concentration of the contaminant of interest above a non-degradable background concentration. The other major factor that effects the magnitude of contaminant removal is the residence time of contaminated water in the wetland which is itself based on wetland volume, influent flow, and media void ratio. In practice, the values of the first order decay rate (k) and the background BOD (C^*) are determined in one of two ways, depending upon the situation. If the model is to be used for design, the values are determined by comparing those calculated for similar wetlands that are already in operation. The model may also be used to predict output under different operating conditions in a system where the values of k and C^* have already been determined from observed data. Significant variation in these values has been observed between different wetlands of the same general type (Kadlec and Knight, 1996).

There are several criticisms and advantages to the first-order decay models. The major criticisms of the approach are that it aggregates many complex biological processes into a single rate, it assumes steady state conditions, and it does not take into account a maximum level of contaminant loading at which decay ceases to follow first-order kinetics. The advantages, however, are that it is simple but still has a foundation in some of the inherent characteristics of the wetland, unlike a simple input-output regression model.

Wynn and Liehr (2001) addressed the first and second criticisms of the first-order approach stated above in the creation of a mechanistic, compartmental or SD model of SSFCTW performance. Their model consisted of linked sub-models that simulated the important, inherent biological processes of the wetland including the carbon and nitrogen cycles, water and oxygen balances, and microbial growth and metabolism. The model builders made the assumption that steady state conditions would hold for short time periods. The model simulates wetland function over a short time step (in the case of this study 90 minutes) then resets initial values before simulating the next step. These short, sequential, steady-state time steps are intended to approximate the dynamic behavior of the system as conditions change due to operation.

Glycol Attenuation in Constructed Treatment Wetlands

Subsurface flow constructed treatment wetlands have been used at several commercial airports around the world as a portion of the treatment system for ADF-contaminated storm water. Such systems are currently in operational use at London Heathrow International Airport in the United Kingdom, Edmonton International Airport in Canada, and the ABX Air Park in Wilmington OH (Naval Facilities Engineering Service Center, 2004; Higgins and Maclean, 2002; Revitt *et al.*, 2001). The Naval Facilities Engineering Command (NAVFAC) conducted a technology demonstration project the purpose of which was to test the feasibility of using SSFCTWs for ADF-laden storm water treatment at DoD airfields. (Naval Facilities Engineering Service Center, 2004) A pilot scale wetland was constructed at Westover ARB in Chicopee MA and remains in operation despite the end of the study. The NAVFAC researchers cited that a lack of awareness and understanding of this technology is a major obstacle to its more widespread adoption, especially within the DoD.

One of the most often cited applications is the inclusion of a SSFCTW for storm water treatment at London Heathrow International Airport. Chong *et al*. (1999) presented the results of a pilot study conducted at Heathrow to assess the suitability of an SSFCTW as part of a treatment system for the facility. This article concentrated on the varieties of microorganisms that perform glycol degradation in the wetland, but also drew many general conclusions about the feasibility of the technology. These conclusions included that microbial action remained significant through the winter months, shock loadings of glycol had no adverse effects on the populations of microorganisms, and that the subsurface flow type of wetlands offered the best potential for year round performance. Building, in part, on the previously mentioned study, Revitt *et al*. (2001) described the final inclusion of the wetland into Heathrow's operational treatment system. The authors of this study suggest that SSFCTWs could best be employed as a "front end" treatment used to eliminate a portion of the pollutants before the waste is delivered for other action; or as a "final polish" step immediately prior to release into the environment. Accordingly, the wetland at Heathrow is used as in conjunction with other methods to reduce effluent BOD concentrations to acceptable levels before it is delivered to a conventional wastewater treatment plant. Revitt and his colleagues (2001) report that they believe a SSFCTW would need to be "unacceptably large" to be used as the sole treatment option at a large commercial airport.

Despite the pronouncements of Revitt *et al*. (2001), those responsible for runoff treatment as Edmonton International Airport (EIA) have decided to use a SSFCTW system as their sole ADF-contaminated storm water treatment system. This effort is described in Higgins and MacLean (2002) who aptly specify the article pertains to, "The Use of a Very Large Sub-Surface Flow Constructed Wetland…," in the paper's title. This effort has been reported as largely successful both by the latter authors, and as touted on the EIA Corporate website, where it is stated that the system works so well that effluent is directly discharged to the adjoining creek with no further treatment (Edmonton Airports, Inc., 2009).

Identifying and Modeling BOD Degrading Processes in Wetlands

The consensus in the literature is that microbial utilization is the major underlying processes responsible for contaminant removal in wetland systems (Chong *et al*., 1999; Kadlec and Knight, 1996). This mechanism is also identified as the major activity in other wastewater treatment methods as well (Tchobanoglous and Burton, 1991). Rates of growth, substrate concentration, and substrate utilization can all be linked by established relationships, providing a basis for modeling conditions within the wetland system (Wynn and Liehr, 2001; Crites and Tchobanoglous, 1998).

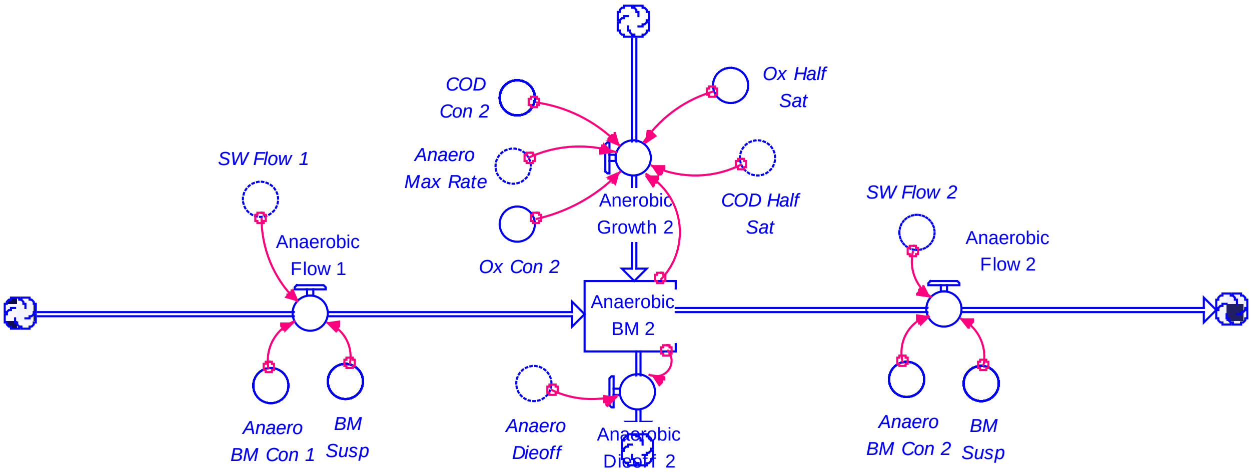
The type of biomass found in a wetland system at any given time depends upon the conditions at that time. The convention is that these can be generally categorized as either aerobic or anaerobic microbes depending upon their oxygen use characteristics; and the dominant type will shift as oxygen level within the system change (Wynn and Liehr, 2001). Many anaerobic microbes, included some know to utilize PG, produce methane as a result of their metabolism (Zitomer *et al*., 2003). The presence of methane is likely to lead to a population of methanotrophic microbes in the wetland water. As methanotrophs utilize oxygen in their respiration it has been suggested that some competition for the gas takes place between methanotrophs and other aerobic microbes (Thompson, 2008; van Bodegom *et al*., 2001).

Wetland plants are also known to introduce both oxygen and BOD-inducing substances to the wetland through their roots (Kadlec and Knight, 1996). The introductions of these substances are important in the maintenance of microbial populations in the wetland (Butler *et al*. 2003). Research has suggested that plants control the release of these substances for the purpose of maintaining an environment suitable to health and growth (Thompson, 2008; Sorrell, 1999). There is agreement that macrophyte action is a non-trivial factor in wetland dynamics.

III. Methodology

Modeling Approach

A system dynamics approach was used to generate the findings in this study. The effort focused on devising a relevant but generic causal structure for a SSFCTW intended to reduce COD in storm water that can be customized to model the behavior of a particular wetland. STELLA version 9 software (Isee Systems, 2007, formally distributed by High Performance Systems) was used to create a visually attractive product that captures the structures needed to effectively model the system. The software converts the icon-based model into a corresponding system of differential equations which the software is able to numerically integrate across a period of time. This approach allows the model to take into account the numerous interactions that are taking place between various model factors simultaneously. The model boundary includes storm water and contaminant input to the CTW, travel of the storm water through the CTW with corresponding contaminant transport, biological activity within the wetland, changes to contaminant levels as the storm water travels through the wetland, and storm water exit from the wetland including contaminant levels in the effluent. The model requires user inputs defining wetland geometry, wetland construction, local conditions, contaminant introduction, and volume of input. Figure 1 below is an example of model structure and is followed by the differential equation that governs stock.



$$\frac{dAnerobicBM2}{dt} = \left[AnaeroMaxRate \bullet \left(\frac{CODCon2}{CODCon2 + CODHalfSat} \right) \bullet \left(\frac{OxHalfSat}{OxCon2 + OxHalfSat} \right) \bullet AnaerobicBM2 \right]$$
$$+ \left(SWFlow1 \bullet AnaeroBMCon1 \bullet BMSusp \right) - \left(AnaeroDieoff \bullet AnaerobicBM2 \right) - \left(SWFlow2 \bullet AnaeroBMCon2 \bullet BMSusp \right)$$

Fig 1: Anaerobic Biomass Stock with Structures and Defining Equasion

Several of the parameters in this equation are defined by other differential equasions in other portions of the model, and change with respect to time. This interdependence is at the heart of the dynamic nature of the model.

The model uses a compartmental approach to represent the transport and degradation of ADF-induced COD through the wetland. Instead of using a single compartment to represent a certain state for the entire wetland, as previously presented by Wynn and Liehr (2001), this model follows their suggestion and represents the wetland as multiple, smaller cells constructed in series. Each cell is treated as an individual system with its own levels of contaminant, nutrients, and other factors that effect the degradation of COD in that cell. The model also simulates the flow of storm water from one cell to the next which drives the transport of the other substances and characteristics of interest to a corresponding stock for the receiving cell. This structure results in several parallel transport chains interacting with one another within the cells.

One of the characteristics of the system dynamic approach is that structural elements may be added or modified as a result of outcomes observed during analysis. The final structure of each subsystem will be described in this chapter. Those elements that have been significantly influenced during analysis will be identified here; however, the nature of the analysis from which the changes resulted will be more fully discussed in the following chapter.

Modeling of Storm Water Flow

The amount of storm water available for entry in the wetland depends upon the amount of precipitation that has fallen and the size of the tributary area that drains to the system. Tributary area is simply input in square meters (m^2) to represent the amount of pavement upon which storm water occurs. To provide a realistic amount and frequency for the precipitation data set, meteorological observation data from Westover ARB were obtained covering the time period of November 1997 to April 2003 (Air Force Combat Climatology Center, 2008). This set of data covers the same time period as the ADF use data presented in the Naval Facilities Engineering Service Center (2004) technical report previously cited. A 30-day period was chosen to cover the duration of the simulation. Daily rainfall totals were divided by 24 hours to calculate a constant rainfall rate that is represented in a discontinuous graph in the model. The rate, in meters per hour (m/hr), for any given time is multiplied by the tributary area to yield a rate of storm water becoming available to enter the wetland in cubic meters per hour (m^3/hr).

Water may also enter through rainfall directly on the top of the wetland. A rainfall inflow is assigned to each wetland cell. These inflows draw upon the same precipitation data used to determine the surface runoff; however, the rain rate is multiplied by the area of each wetland cell to determine the volume of water entering directly.

The model is meant to represent a wetland treatment system that requires very low levels of human intervention to operate. A low-maintenance system of this type is attractive to organizations that operate in budget and manpower constrained environment. For this reason, inflow and outflow of storm water to and from the wetland has been modeled in such a way as to be free from imposed control and dependent on the amounts of water queued for entry or exit. Initially, a pipe flow formula that derived flow from the head differential between the inlet box and a buried inflow pipe in the first wetland cell was envisioned as this is the common configuration in SSFCTWs. Due to the circular logic inherent in this approach (flow rate being partially dependent on frictional head loss that is itself dependent on flow) it is not possible to model this relationship without requiring the user to input a “system curve” for the envisioned inflow pipe. Instead, a weir flow formula was chosen as the basis of the inflow and outflow models. The reason for this choice is that weir flows are known relationships that relate water depth to flow rate. The formulae require a few simple parameter inputs, and allow the model to simulate flow through the wetland free of potentially costly imposed control devices.

Kadlec and Knight (1996) aptly stated, “A design model must first do an adequate job of predicting wetland hydraulics.” The model used to generate the findings of this study breaks the wetland into a number of discrete sections that represent a block of porous wetland media. Wynn and Liehr (2001) reported that, “Darcy’s Law is the only simple model for flow through porous materials.” The model structure governing wetland flow is therefore formulated using the aforementioned law. Hydraulic residence time is a major factor studied in wetland treatment systems; so any model must satisfactorily predict water flow to be valid for other factors.

Simply stated, Darcy's Law posits that, flow through a porous media is proportional to the head differential and inversely proportional to the length over which that differential exists (Todd, 1980). Simplifications are made in this model with respect to the calculation of head differential. First, it is assumed that velocity induced head can be safely ignored because of the low velocity nature of this type of system (Todd, 1980). Second, as this is a model of a gravity-flow system and atmospheric pressure is assumed to be constant across the entire wetland, pressure induced head is in turn assumed to be equal across the wetland. With those simplifications made, elevation is the only factor considered in the in the head differential. Assuming a flat-bottom in the CTW, elevation for a specific wetland cell can be represented by the depth of water in that cell. Depth is calculated by dividing the current volume in the wetland cell by the surface area of the cell and then by the void ratio of the material specified as the wetland media. This calculation is meant to represent the average depth across the entire cell. The head differential is then calculated as the difference in depth between any two adjacent wetland cells. The length of flow needed in the flow formula is defined as the wetland cell length and is meant to represent the center to center distance between any two adjacent cells.

Two other factors are needed to implement the Darcy's Law formula to model flow through porous media. The first of these quantities is the cross-sectional area through which the water is flowing. In a system such as a pipe filter which is always filled, this value is simply the cross-section of the pipe. In this model, however, the proportion of the media actually experiencing flow varied with the depth of storm water in each cell. To capture the dynamic nature of this value in an open system like this, the area is calculated as the mean of the depths between adjacent cells multiplied by the width of the CTW. Using this formulation requires the assumption that flow is taking place across the entire width of the CTW, which is reasonable considering that water is usually fed across the entire bed width (Naval Facilities Engineering Service Center, 2004). The final value that must be considered when using Darcy's Law is the hydraulic conductivity of the media. This value is an intrinsic property of the particular media being used and will be entered as a parameter in this model. Values of hydraulic conductivity can vary by orders of magnitude for a given class of material. Research has been conducted that attempts to directly measure the value of this parameter for a particular wetland (Sanford *et al*., 1995). There are also general guideline values for particular classes of material in hydrology guides and texts (Todd, 1980). A range of representative values will be explored in the analysis of this model.

In most wetlands of this type, outflow is controlled using a buried, perforated pipe at the far end of the wetland set a certain distance above the bottom of the bed to promote the retention of some water during dry conditions. The perforated pipe joins an outlet that exits the wetland. As in the case of the outlet, this type of structure would require the input of a system curve to avoid circular logic in the model. For this reason, a similar weir equation is used to determine outflow rate. The envisioned structure is that of a rectangular weir beyond the end of the last cell, set at such an elevation that it allows the retention of some water in the wetland when all flow has ceased.

Introduction of Substances to the Wetland

Along with storm water, other substances must enter the wetland from the outside. These items include PG from ADF use (denoted as COD in the model), the normal COD content of storm water, COD exuded by plant roots in the wetland, COD introduced by decaying biomass atop the wetland, and oxygen. ADF-induced contamination enters from the pavement along with storm water. Daily ADF use is converted to a constant introduction rate for each day ADF was used. The volume of ADF contributes directly to the volume of storm water and to a mass of PG queued to enter the wetland based upon the assumption of a 75% PG mixture with the remainder of the applied ADF being made up of water (Naval Facilities Engineering Service Center, 2004). Once queued, COD enters the wetland at a rate determined by inflow and concentration identical to the process of substances passing between wetland cells explained below. Oxygen is introduced to the wetland by three mechanisms, with storm water influent, with rain, and through plant roots. Since storm water is assumed to be in a shallow sheet flow across the pavement before it enters the wetland, the concentration is assumed to be a maximum representative oxygen concentration for temperatures just above freezing. A similar assumption is made for rain that is falling through the atmosphere before entering the wetland. Plant root introduction of oxygen is based upon a simplified representation of gas diffusion that will be further detailed in the section pertaining to the oxygen stock.

Substance Transport Across Wetland

In order to adequately model the interaction of the individually designed cells as a coherent wetland, the flow of substances, dissolved and suspended, in the storm water contained in a particular cell to an adjacent cell must be represented. This characterization is achieved by first calculating a concentration for each type of item to be transported. In the case of dissolved substances and suspended biomass the concentration is reported in kilograms per cubic meter (kg/ m^3) of storm water in the corresponding cell. For substances, the current concentration is multiplied by the flow of storm water between the cells (measured in cubic meters per hour [m^3/hr]) resulting in a flow of mass between stocks calculated in kilograms per hour (kg/hr). There is an additional consideration in the case of biomass as only a small portion is suspended and therefore available for transport. That proportion is an additional multiplier in the biomass flow calculation. All other biomass is assumed to be attached to wetland media in the form of a biofilm and remains stationary.

Wetland Cell Structure

Each defined wetland cell is represented by a set of components that determine the state of cell and transformations that take place as the constituents move along the transport chains. Each cell can be thought of as an individual wetland linked to the other by the passage of storm water as described previously. A cell is assumed to be a completely mixed system with uniform properties and concentrations throughout its entire wetted volume; representing a similar assumption to the one made by Wynn and Liehr (2001) that the wetland could be characterized as similar a continuously stirred tank reactor (CSTR). Each component and its function and interactions with other components within the same cell will be discussed in the sections that follow.

Chemical Oxygen Demand

The chemical oxygen demand stock (COD X) represents an aggregate mass (kg) of PG that is introduced through ADF application, typical storm water contaminants, remnants of decayed biomass, and any compounds that wetland plants exude into the storm water that is available for utilization by microbes in the wetland cell with the exception of methane. COD enters the cell through inflows when dissolved in storm water, through decay of microbial biomass within the cell, and through an aggregate flow representing exudation by plant roots and leaching of biomass decaying atop the wetland. The COD introduced by decaying microbes is defined by multiplying the die-off outflow from each of the microbe stocks by a general biomass COD ratio of 1.42 units COD per unit biomass as reported in Tchobanoglous and Burton (1991). Plant root and decaying plant matter introduction of COD is regulated by a maximum aerial rate and goal-seeking structure similar to that described earlier for plant oxygen introduction. The selection of this structure was based on the assumption that plants will control their rate of introduction based on their own needs in a manner similar to the control of oxygen release. The goal parameter was set based on the average background BOD observed in several wetlands and reported in Kadlec and Knight (1996). This substance exits the cell with storm water flow or it is utilized by aerobic and anaerobic microbes as an energy source. These stocks represent the main pollutant of interest in for ADF contaminated waters.

Oxygen

The oxygen stock (Oxygen X) represents the mass (kg) of dissolved molecular oxygen available for utilization by microbes in the wetland cell. Oxygen enters the cell along with storm water flow and through direct rainfall and plant roots. The first two entry methods simply rely on a volume of water entering and oxygen concentration of that water. Plant root introduction of oxygen is represented by a simplified diffusion-based structure. The basic parameter used in this representation is a maximum rate of oxygen transfer per unit area of mature wetland. This parameter was set based on the range of experimentally determined rates reported by Kadlec and Knight (1996). Thompson (2008) reported that oxygen transfer to the surrounding wetland water was limited by the area available for the transfer to take place. To account for this limitation, the maximum rate is multiplied by the proportion of the total cell depth that is filled with water; meant to represent the proportion of total root area in contact with storm water. Sorrell (1999) also reported that the rate at which plants release oxygen from their roots is dependent on the concentration and demand for oxygen in the surrounding soil and water. This dependence is addressed with a simple goal-seeking structure where the rate of oxygen release approaches zero as the oxygen concentration in that cell approaches saturation. The goal seeking structure was added as a result of infeasible levels of oxygen concentration being observed during analysis. Oxygen exits the cell through one of two mechanisms. First, it may travel along with the storm water in which it is dissolved, or it may be utilized by aerobic microbes in the wetland including those degrading COD and methanotrophic microbes that utilize dissolved methane.

Methane

The methane stock (CH4 X) represents the mass (kg) of dissolved methane available for utilization by microbes in the wetland cell. Methane is introduced with inflow of storm water from a previous cell or as a product of anaerobic respiration within the cell. There is no inflow of dissolved methane into the first wetland cell as it is assumed to be produced by the anaerobic microbes within the wetland. The rate of methane production is based on the anaerobic utilization rate of COD and the stoichiometric equations for anaerobic utilization of PG presented by Zitomer and Tonuk (2003). The gas leaves the cell with storm water flow, through utilization as an energy source by methanotrophs, or through desorption if concentrations become higher than can be supported by current wetland conditions. The desorption outflow was added as a result of infeasible methane concentrations observed during analysis. Dissolved methane in effluent is also a contributor to the total COD output of the wetland.

Aerobic Biomass

The aerobic biomass stock (Aerobic BM X) represents the mass (kg) of microbes within the wetland cell that utilize non-methane COD inducing substances for energy and oxygen in respiration. Biomass may build within the wetland through the travel of suspended microbes with storm water from a previous cell, or through microbial growth within the wetland. There is no suspended inflow to the first wetland cell, as an initial population of these microbes is assumed to be present in each wetland cell but not in significant numbers in runoff. This growth is one of the drivers of both the COC and oxygen utilization outflows mentioned previously. The first order growth rate is governed by a Monod kinetic model borrowed from the work of Wynn and Liehr (2001). The expression used for aerobic microbes is shown in Eq. 1 below.

$$\mu = \mu_{\max} \bullet \left(\frac{COD}{COD + K_{COD}} \right) \bullet \left(\frac{Ox}{Ox + K_{Ox}} \right)$$

The maximum aerobic growth rate is **Error! Bookmark not defined.** $\mu_{\max}\left(hr^{-1}\right)$, COD is the chemical oxygen demand concentration of the cell (kg/m^3), K_{COD} is the chemical oxygen demand half saturation rate (kg/m^3), *Ox* is the oxygen concentration in the wetland cell (kg/ m^3), and K_{Ox} is the oxygen half saturation rate (kg/ m^3). Using this formula assumes that growth will be proportional to the availability of both an energy source and oxygen. Microbial die-off is modeled as a simple first-order outflow and is one method of biomass exiting the cell along with the transport of suspended microbes in storm water.

Methanotrophic Biomass

The methanotrophic biomass stock (MT Biomass X) represents the mass of microbes in the wetland cell that utilize dissolved methane for energy and oxygen in respiration. While these microorganisms are by definition aerobic, they are being separately modeled due to their use of a substrate other than the primary contaminant of interest. The assertion has been made that competition for oxygen may take place between methanotrophs and other aerobic microbes in a wetland environment (Thompson, 2008). Since methane is a primary product of anaerobic breakdown of PG , there should be a non-trivial amount present in the wetland (Zitomer and Tonuk, 2003). Methanotroph population growth is represented using the same type of Monod model used to model aerobic growth with the notable modification of replacing COC with CH4, the methane concentration yielding the formula shown in below:

$$\mu = \mu_{\max} \bullet \left(\frac{CH4}{CH4 + K_{CH4}} \right) \bullet \left(\frac{Ox}{Ox + K_{Ox}} \right)$$

This model requires the same assumption as to the availability of both oxygen and an energy source. As with the aerobic biomass model, methanotroph die-off is governed as a first order drain on the stock, and microbes may also leave the cell through travel of suspended biomass in storm water.

Anaerobic Biomass

The anaerobic biomass stock (Anaerobic BM X) represents the mass of microbes in the cell that use COD as an energy source but do not require oxygen. These microbes are also assumed to produce methane as a result of their utilization of more complex energy sources. Considering the high COD observed in most ADF-contaminated runoff, low oxygen conditions are likely to be very common in most SSFCTWs used to attenuate the effect of these substances. Anaerobic biomass growth is also represented using a Monod kinetic model similar to the previous two presented. The formula involves the same factors as the aerobic biomass growth model; however, the dissolved oxygen concentration (Ox) is replace with the oxygen half saturation constant (K_{ox}) in the numerator of the oxygen portion of the formula, yielding the equation shown in Eq. 3:

$$\mu = \mu_{\max} \bullet \left(\frac{COD}{COD + K_{COD}} \right) \bullet \left(\frac{K_{Ox}}{Ox + K_{Ox}} \right)$$

This shift creates an inversely proportional relationship between dissolved oxygen concentration and anaerobic microbial growth. It works in concert with the other two growth expressions to allow a shift to the well suited microbes as the oxygen levels shift

(Wynn and Liehr, 2001). No wetland is ever strictly aerobic or anaerobic, so both types of growth can occur simultaneously to some degree (Thompson, 2008; Wynn and Liehr, 2001). Anaerobic microbial death is modeled as a first order drain and microbes may leave the cell if suspended in flowing storm water.

Major Feedback Mechanisms

One characteristic of natural systems that a system dynamic modeling approach attempts to capture is the tendency of such system to have inherent feedback mechanisms that allow the system to return to a state of relative stability when perturbed. The relationships between the state variables in the model are composed of structural elements that reproduce the feedback mechanisms inherent to the system. There are two types of feedback loops that are represented in the causal structure of the system. The first are compensating loops. These are loops in which the influence of two or more entities upon one another tends to keep each of the in check. The other type are reinforcing loops. These loops allow entities to compound upon one another sending each into exponential growth or decay. The major feedback loops of a wetland cell's microbial system are shown in Fig. 1 below.

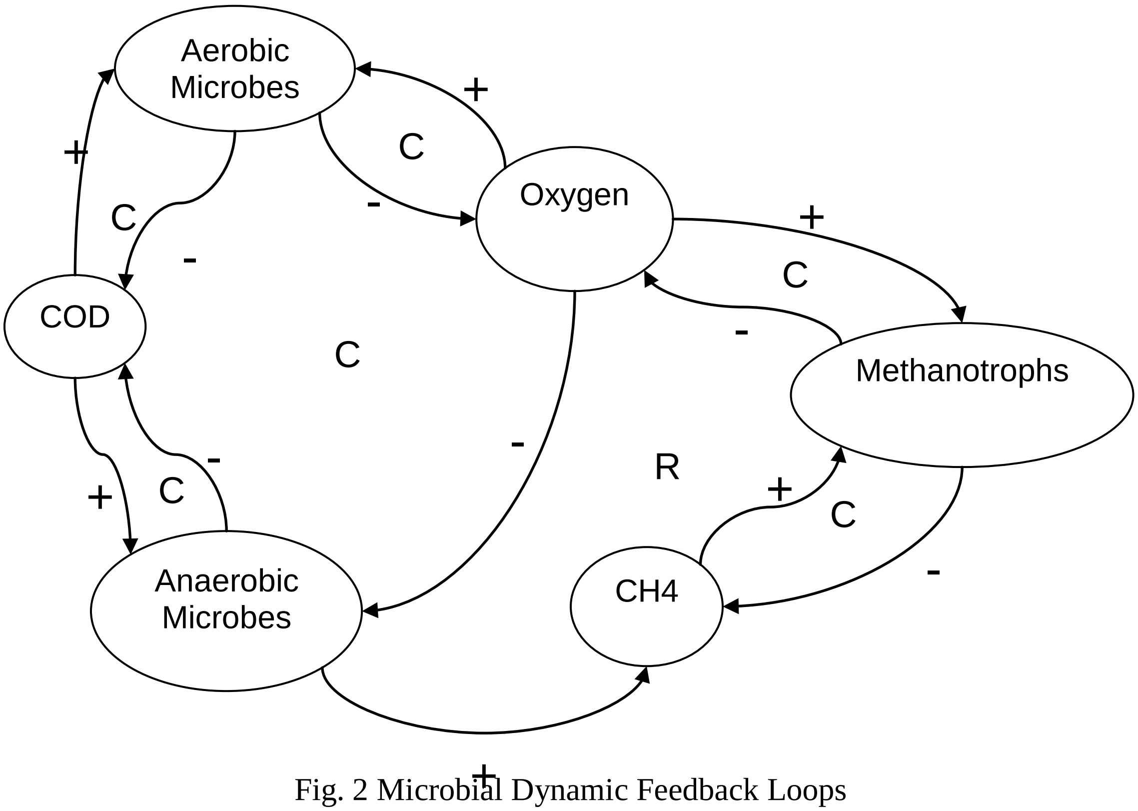


Fig. 2 Microbial Dynamic Feedback Loops

In this diagram, the entities represent the same stocks noted in section 3.5 as well as the ancillary structure associated with the stock. These components, such as growth and decay flows and rate parameters, have been generalized for the sake of clarity. As the diagram indicates, there are five simple compensating loops formed between the pairs microbes and the resources they need to maintain growth. There is also one larger compensating structure between the aerobic and anaerobic microbes. Here, a glut of aerobic microbes will cause a drop in the level of oxygen. That drop will, in turn, promote the growth of anaerobic microbes. As the anaerobic microbes grow they will utilize COC energy sources, reducing their concentration. The reduction of energy source availability will retard the growth of aerobic microbes. Finally, the reduction of aerobic microbes will increase the availability of oxygen, completing the loop. There is also one reinforcing loop in the causal structure that involves the concept of oxygen competition by methanotrophs. As anaerobic microbes degrade COD, they produce methane (CH4). This increase in available CH4 would tend to promote the growth of methanotrophs. Methanotrophs utilize oxygen in growth, reducing the stock of oxygen in the system. A drop in the concentration of oxygen promotes more anaerobic growth. The resource compensation loops should keep the reinforcing structure in check; however, this structure does suggest that a symbiotic relationship exists between anaerobic and methanotrophic microbes that may develop at the expense of COD-utilizing aerobic microbes due to methaotroph monopolization of oxygen.

Dimensional Consistency

As this model is represents as system of differential equations as an interdependent set of flows, stocks, parameters and calculated quantities, special care must be taken to ensure that units assigned to all entities in the model agree with one another. All entities in the model must represent the same type of quantity using the same unit. Many factors and parameters taken from the literature were originally reported using different units. In most cases, these values were converted outside the model and the correctly unitized value was incorporated. In a few cases, however, the complexity of the expression to be represented led to the determination that an explicit conversion factor should be included in the model. Examples of this inclusion are time converters (seconds to hours) for CTW inflow and outflow and standard metric volume conversions for rain rate and ADF inflow volumes.

The units used to represent each quantity in this model are displayed in Table 1 below:

Table 1: Basic Units Used in Model

Quantity	**Unit**
Length	Meter (m)
Mass	Kilogram (kg)
Time	Hour (h)
Volume	Cubic Meter (M^3)

Other units assigned to entities in the model are derived from these basic units or are units from other systems that have been retained to ease data entry and are subject to the explicit conversions mentioned previously.

IV. Analysis and Results

Analysis of System Dynamics Models

As stated in the previous chapter, the construction and analysis of system dynamic models are not wholly separate activities. The process of analysis can reveal behavior that suggests adjustments to structure ranging from the addition of whole new elements to the aggregation or disaggregation of existing ones. Structural elements are added and analyzed in an iterative manner until the model is sufficiently robust to meet its intended purpose. In this chapter those instances of analysis that led to a specific change in model structure will be identified as such.

The analysis of this model employs several of the "Tests for Building Confidence in System Dynamics Models" suggested by Forrester and Senge (1980). The use of each test is not explicitly called out during discussion of the analysis, but the material presented in the paper was used a guideline to examine the behavior of the model. Though historical data related to a particular wetland project is used to provide realistic inputs to the system, behavior reproduction and other tests that relate the model to a real-world system were not performed. The model created in this effort is intended to represent a customizable core wetland structure model that can be applied to a particular constructed wetland management and/or design problem.

Steady State Conditions

The first step in building confidence and understanding in the dynamic nature of the model is to manipulate the environmental inputs in such a way as to induce a predictable expected behavior. In the case of this model, the inherent feedback mechanisms suggest that the state variables should approach a steady state if environmental input variables are held constant. The environmental variables in question are precipitation, ADF inputs to the wetland, and oxygen content of incoming storm water. The state variables to be monitored for each wetland cell were the storm water volumes (SW X), mass of chemical oxygen demand (COD X), oxygen mass (Oxygen X), aerobic biomass (Aerobic BM X), methanotrophic biomass (MT Biomass X), dissolved methane mass (CH4 X), and anaerobic biomass (Anaerobic BM X).

For the initial testing phase, storm water inflow and ADF input were set to values that approximated the mean rates for the 30 days of highest ADF use indicated in the Westover deicing log data (Naval Facilities Engineering Service Center, 2004; Air Force Combat Climatology Center, 2008). These values are 4 m^3/h and 7 kg/h, respectively. Oxygen content of both incoming storm water and direct rainfall was set to 12.4 g/m^3 (converted to kg within the model).

The initial intent of the model was to provide a 720 hour (30 day) simulation of wetland behavior and output prediction. Initial state variable values were reset to their corresponding values at the end of a model run in an iterative manner in an attempt to induce steady state behavior. After several iterations, it was determined that the 720 hour timeframe was not adequate for all steady-state trends to fully develop. The simulation timeframe was increased by an order to magnitude (to 7,500 hours) to ensure that all state variables were behaving in a predictable and bounded manner. There is also a relatively short time period at the beginning of the simulation where the values shift erratically before smoothing toward their steady-state. This behavior is caused by discrepancies between the entered initial values and the true steady state. The implications of this self correction period will be addressed during dynamic input testing.

Figures 2, 3, and 4 below show the values for the three biomass quantities as well as oxygen and COD mass for CTW cells 1, 2, and 3 respectively of the initial, three-cell model. Figure 5 displays the mass of methane in each wetland cell. It is important not to focus on the positions of the traces relative to one another as each one is plotted on its own scale. Instead the graph is interpreted and conclusions can be drawn by looking at the trends of the state variables relative to one another. The graph of methane mass shows the effects of methane desorption from the storm water. Once the concentration reaches the maximum that can be dissolved in the water, it will start to be released from the wetland into the atmosphere at a rate proportional to the excess dissolved gas and the area from which it may be desorbed.

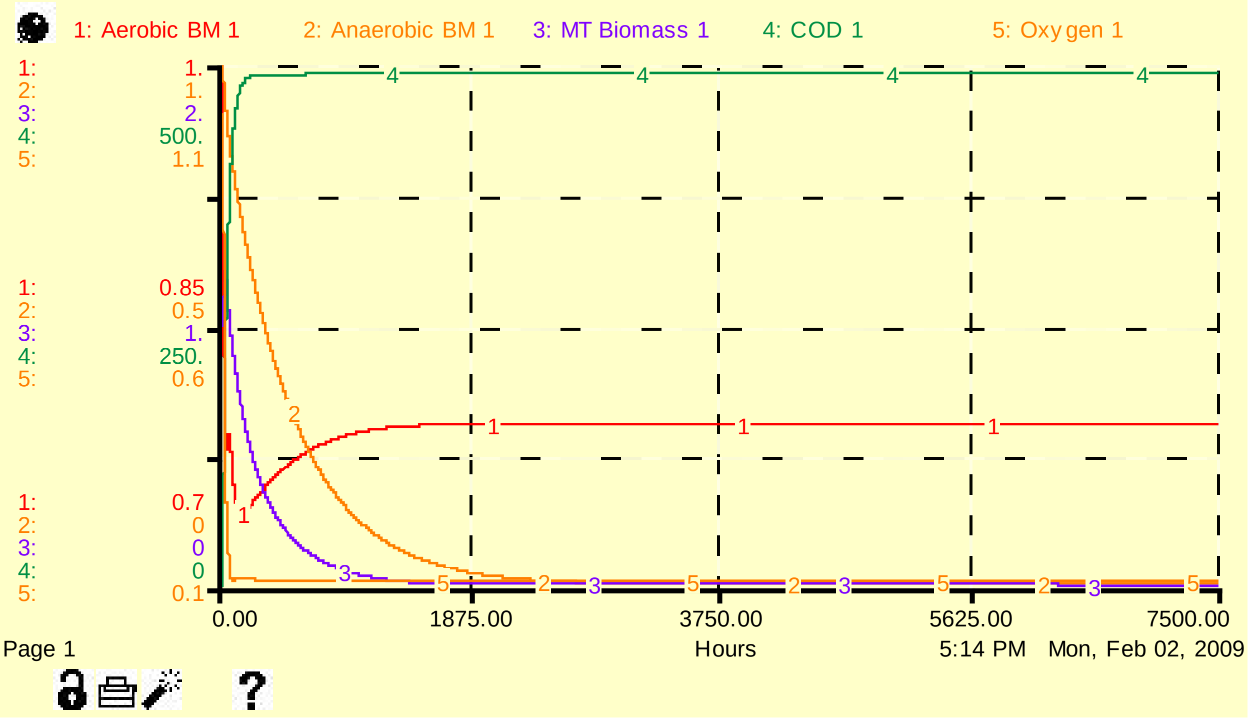


Fig. 3. CTW 1 State Variable Steady States

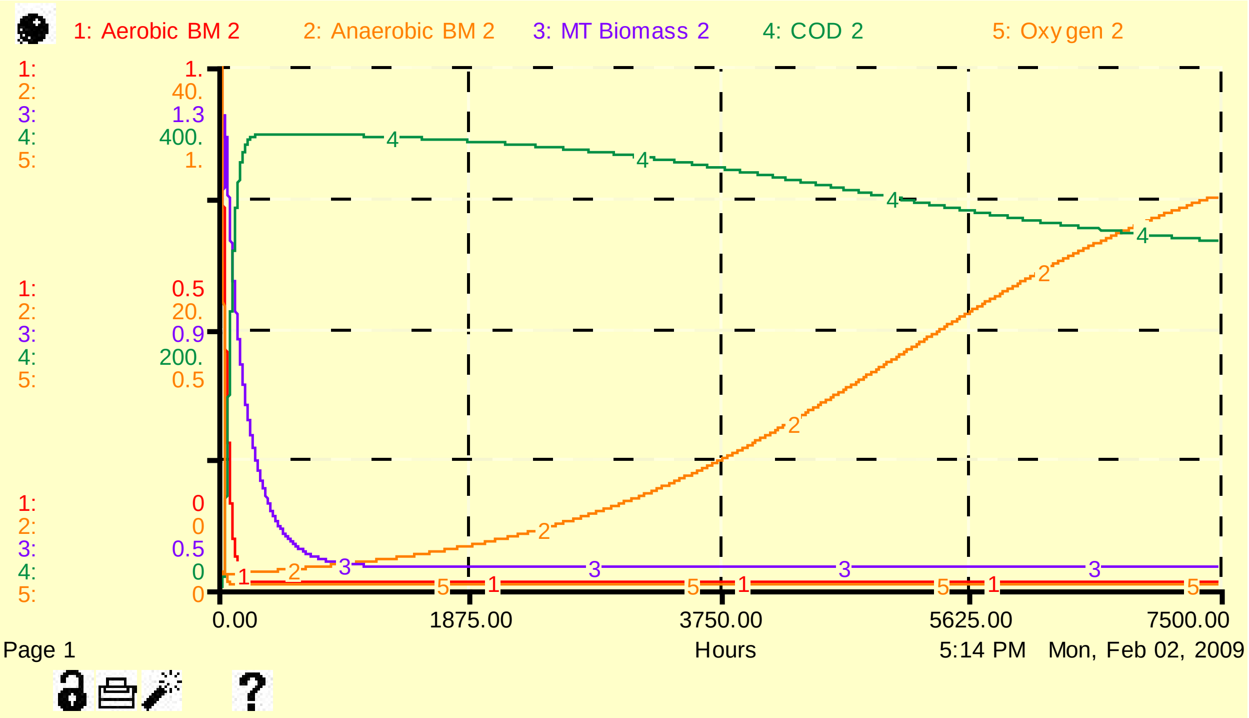


Fig. 4. CTW 2 State Variable Steady States

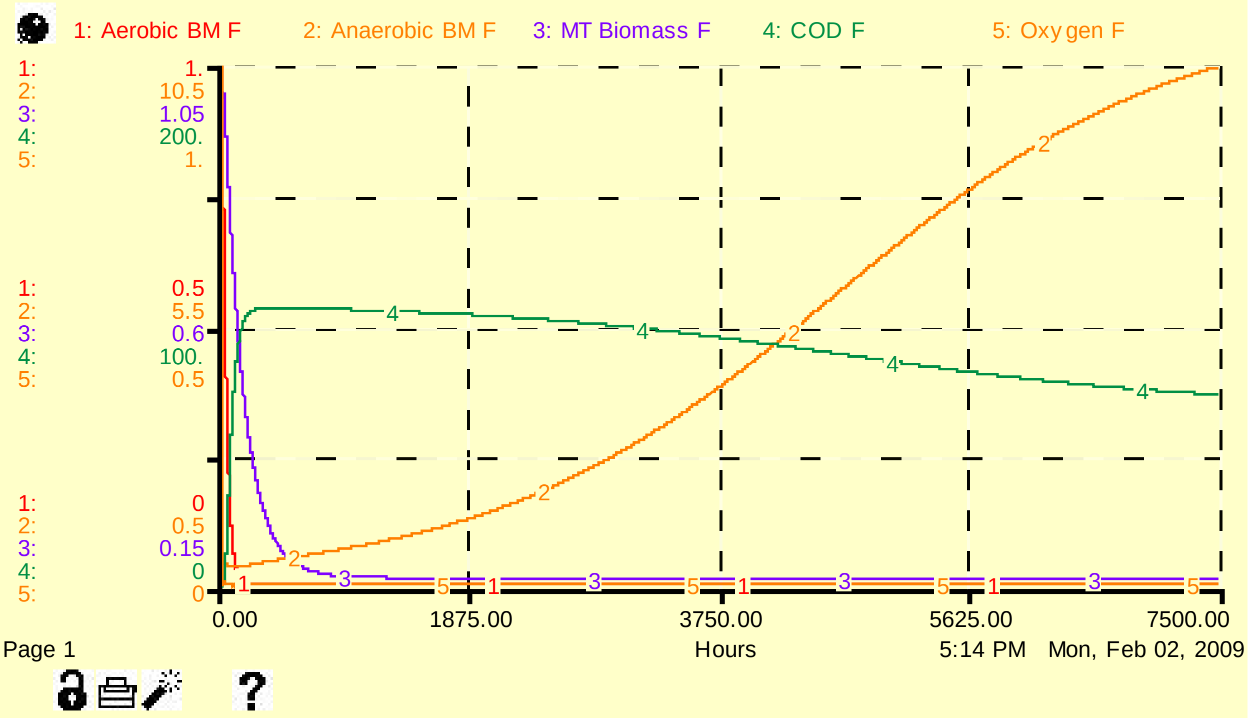


Fig. 5. CTW 3 State Variable Steady States

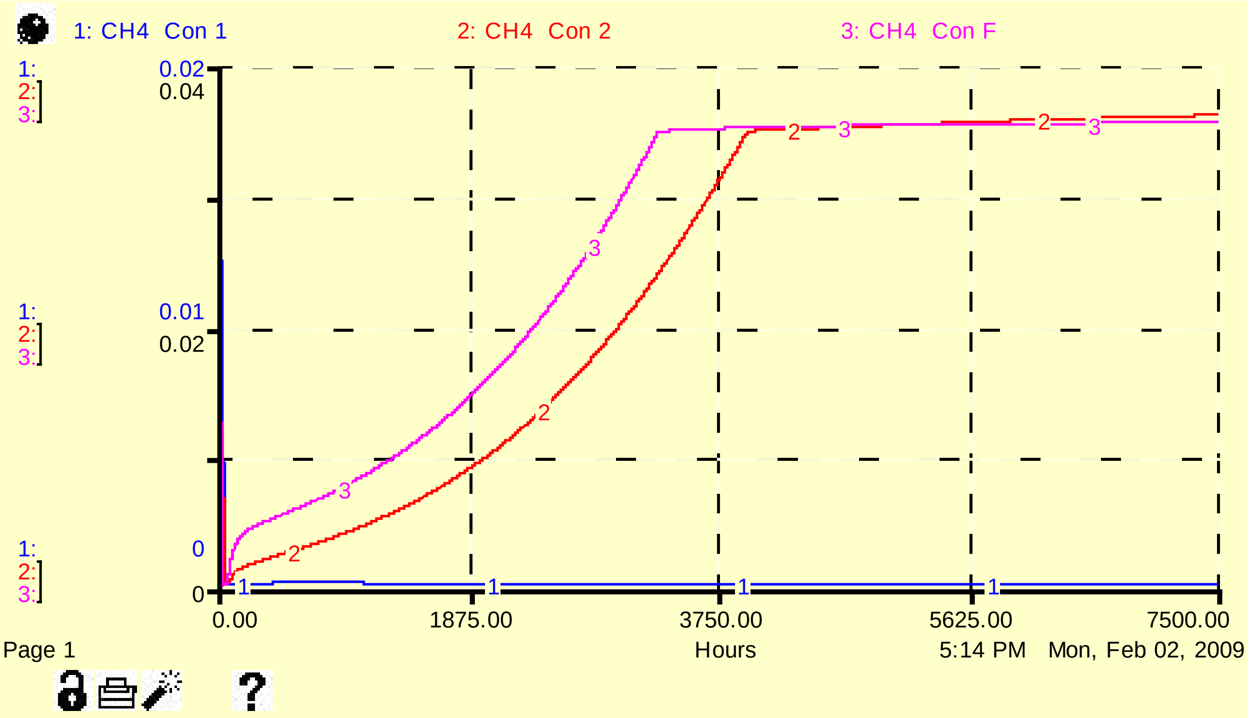


Fig. 6. CTW Methane Steady States

The steady state behaviors shown in the graphs indicate a marked difference in the proportion and behavior of aerobic and anaerobic microbes in each of the wetland cells. This difference can be attributed to the difference in usable oxygen reaching the cells.

The first cell receives well-aerated runoff soon after it leaves the pavement surface as well as oxygen-rich direct rainfall and macrophyte root oxygen inputs. The continuous input of oxygen keeps the concentration in the cell high enough to support a significant aerobic microbe population. The inhibitory effect of oxygen on anaerobic microbes induces that biomass trace to exhibit a first-order decay trend in line with the die-off mechanism. Next, without the methanogenic anaerobes to supply a substrate (see Fig. 4), the methanotroph population also decays.

The second and third wetland cells display similar behavior to one another. In both cells, the only oxygen sources are direct rain, macrophyte roots, and any carried over from the previous cell. The aerobic population in the first cell greatly depletes the available oxygen, so its concentration in the storm water flowing to the second cell is relatively low. The low concentration of oxygen provides an opportunity for anaerobic biomass to develop. The growth of anaerobes in turn leads to methane production, providing a substrate for methanotroph growth. The ability of methnotrophs to grow at lower oxygen concentrations allows them to out-compete the COD-utilizing aerobes despite the slower maximum growth potential of the former; a condition that agrees with findings reported by Lokshina et. al (2001). Methanotroph growth consumes oxygen, keeping concentrations at a level conducive to continued anaerobe presence. This condition is an example of the reinforcing loop shown in Fig. 1 in Chapter 3. Importance of this relationship is illustrated in Figs. 6 and 7 below. These graphs represent the conditions in the second and third wetland cells. The initial mass of methanotrophs is set to zero to prevent them from having any influence on the behavior of the other wetland microbes. Without the methanotrophs to consume available oxygen, levels remain too high to promote anaerobic microbe growth.

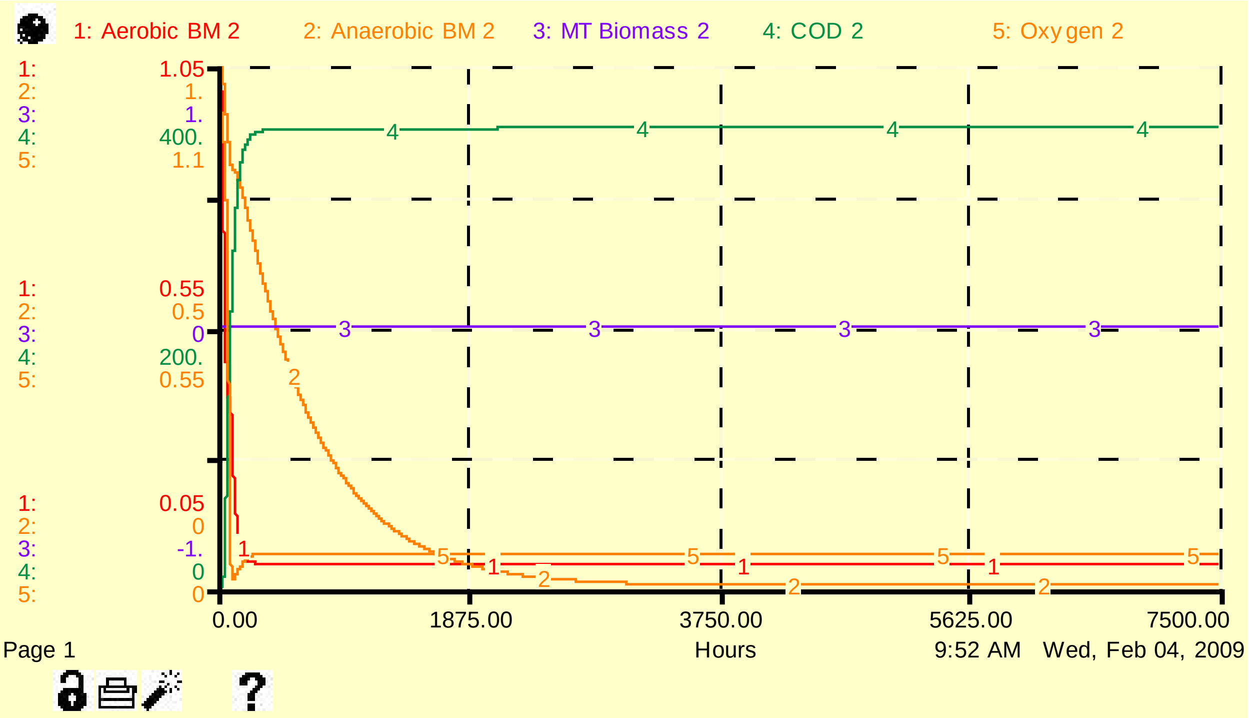


Fig. 7. Conditions in CTW Cell 2 with no methanotroph biomass

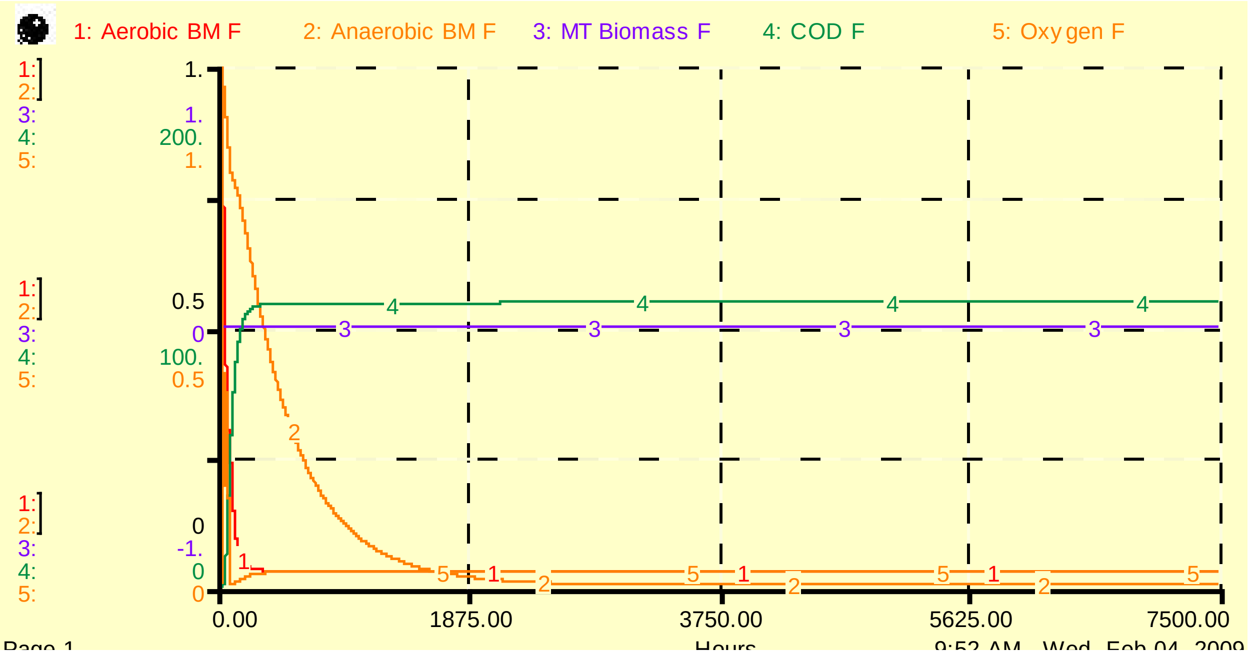


Fig 8. Conditions in CTW Cell 3 with no methanotroph biomass

The lack of methanotrophs also has implications with the treatment efficiency of the wetland. While there is a nontrivial increase in the aerobic biomass in the second CTW cell, this additional biomass is not enough to make up for the loss of COD consumption by the anaerobes. As a result treatment efficiency (as measured by the percent of total COD entering the wetland that did not exit) drops from approximately 15 percent to two percent. There are two reasons why anaerobic biomass provides greater treatment potential than aerobic. First, anaerobic microbes are significantly less efficient in utilizing energy sources. This inefficiency is manifested in a much lower biomass yield per mass of substrate utilized. The inverse of this yield rate is used to formulate a comsumption rate of COD in this model which is and order of magnitude higher for anaerobic versus aerobic microbes. The second factor is that, coupled with the high consumption rate, the mass of anaerobic microbes is only limited by the amount of COD available. Provided oxygen levels remain low (a condition that can be achieved with a healthy methanotroph population) anaerobic biomass will grow at a rate determined solely by COD concentrations.

Model Resolution Analysis

For ease of structural development, the model was initially constructed with the minimum number of cells considered necessary to include all structural possibilities. The unique cell types represented are a first cell that included input mechanisms, a transitional central cell, and a final cell with output structures. This three cell model represents storm water and substances entering, transiting, and exiting the wetland as biomass acts upon it. There is likely to be a marked shift in the conditions of an actual wetland from beginning to end; however, this shift will happen in a gradual manner unlike the clear distinctions represented in the model. A greater number of cells representing a smaller portion of the wetland would more closely approximate the continuous nature of the wetland. Therefore the effects of greater resolution were explored.

The resolution analysis was conducted under the under the steady state inputs, long timeline conditions described earlier in the chapter. The size of the objective wetland used for analysis was set to 20 meters wide by 60 meters long, resulting in a 20 meter by 20 meter cell area for the initial three-cell model. For ease of iteration, the initial mass of the dissolved gas and biomass stocks were set to one kilogram per cell for the three cell model and defined as a fraction with the denominator being the number of cells. The length of each wetland cell was similarly defined. Iteration could now be conducted by replicating the structure of the center transitional cell and inserting it into the model just ahead of the final cell. The influence lines for next-cell storm water depth on previous cell outflow as well as the transport flows for storm water, substances, and biomasses were reconnected. After the reconnection and resetting of initial masses and section length, the model is ready to be run in the higher resolution configuration.

A metric was set for iteration of the model based upon the removal efficiency exhibited by each configuration. New cells would be added to the model until the magnitude of the change in removal efficiency of the latest iteration compared to the previous iteration was less than or equal to ten percent. This standard is based on two assumptions about model behavior. First, that a higher resolution model would better approximate the continuous nature of an actual wetland providing a more accurate simulation of the behavior of the system. Second, that a smaller relative difference of each iteration (in terms of reduced cell size) would result in a diminishing magnitude of removal efficiency change.

The assumption of diminishing magnitude differences held true through all iterations up to the eight-cell model. This version also met the analysis goal with a change of -5.9 percent over the seven-cell model. As this version of the model met the goals it was chosen for most of the dynamic input testing discussed later. Iteration of the model beyond eight cells did yield some interesting results.

There is evidence that the assumption of greater accuracy with greater resolution may not necessarily be infinitely applicable without major changes to model structure. Despite meeting the previously set goals, the model was iterated beyond eight cells to further explore the trend of diminishing magnitude of removal efficiency changes with greater resolution. This result was not observed in the construction of models comprised of nine, ten, and eleven cells. Removal efficiency for models comprised of three to eight cells varied within a range of 16 to 22 percent with the eight-cell model producing an efficiency reading of 20.24 percent. This measure dropped precipitously to 11.05 percent for the ten and 2.18 percent for the eleven-cell model. The drop in efficiency can be attributed to a dramatic shift in the penetration of oxygen into the wetland. In models of eight or fewer cells, the cells representing the first 25 to 40 percent of the wetland’s length were observed to be primarily aerobic (defined as a cell that displays a stable aerobic population and steady decay of the anaerobic and methanotrophic biomasses by the end of a steady-state model run). The proportion of primarily aerobic wetland also did not steadily increase between those values but varied within them with each new partitioning of the model. Beyond eight cells, however, the aerobic portion of wetland rose to 44.4, 60, and 100 percent for the nine, ten, and eleven-cell models, respectively. Due to the significantly higher substrate consumption rate and higher maximum biomass potential of the anaerobic microbes the elimination of a viable population of these microorganisms in the wetland lead to the significant drop in efficiency.

The transition to a primarily aerobic wetland in the higher resolution versions of the model appear to be the result of a chain reaction induced by the inability of the small aerobic biomass to react quickly enough to the oxygen and COD saturated environment of the first few wetland cells. While the rate of growth is very high, the actual consumption of oxygen is relatively low. In subsequent cells, anaerobic growth will begin along with methanotrophic suppression of oxygen concentration. The inflow of additional oxygen is initially absorbed by the methanotrophs, but not quickly enough to prevent the retardation of anaerobe growth. Without significant methanogenesis, methanotroph quickly overshoot the supply of methane, and their population collapses, sharply reducing oxygen consumption in the cell and causing a spike in oxygen concentration with subsequent flow to the next cell. At levels of initial biomass two and ten times those used during iteration this trend does not develop with one and zero cells respectively developing a primarily aerobic character.

Because a subsurface flow wetland is largely insulated from direct transfer of oxygen from the atmosphere and the substrate being treated is mainly harmful due to its propensity to induce anoxic conditions in receiving waters, a largely aerobic wetland does not seem likely to develop. The observed behavior is likely due to the interaction of several factors related to the modeling process. First, there is a constant supply of oxygen-saturated water to the wetland under steady-state input that is not present under dynamic conditions. Next, the assumption of a completely-mixed wetland cell may no longer be valid as the ratio of length to width becomes so great. In the case of the eleven-cell model, the cell width remains at 20 meters while the length has shrunk to under 5.5 meters.

Biomass Reaction

Lack of noticeable biomass reaction to COD inputs is a condition that plagued earlier versions of the model. The lack especially of aerobic biomass growth in the presence of elevated levels of COD and oxygen ran counter to the common understanding of the introduction of a COD-exerting substance to a body of water. The expected behavior in this case would be a bloom of aerobic microbes quickly depleting oxygen. That bloom would be followed by growth of anaerobic biomass, further depleting COD. Anaerobic growth would support a population of methanotrophs, keeping oxygen levels suppressed. Aerobic biomass will return once there is an oxygen input beyond the capacity of the methanotrophs to absorb. The reestablishment of aerobic conditions can take place as a result of an influx of highly oxygenated water or that COD concentrations are depleted enough that anaerobic methane production and resultant oxygen utilization by methanotrophs wanes.

For treatment to be effective, biomass must be able to utilize a significant portion of the substrate before it is carried away with storm water flow. As the magnitude of biomass growth is determined by a first-order relationship, the level present when an input of substrate occurs will have an effect on the magnitude of the short term biomass reaction. Early versions of the model did not retain a level of biomass during low ADF input periods that was able to have a timely effect on COD levels. The levels approaching zero were also not characteristic of typical wetlands. To remedy this situation, two structural elements were added. First, the contribution of microbial productivity was incorporated by adding an inflow of COD driven by the die-off outflow of each type of biomass. Second, was the aggregated contribution of plant productivity and decaying biomass atop the wetland.

The second element governing biomass responsiveness that was modified was the kinetic parameter for half saturation concentration of COD that have a part in governing the growth of both aerobic and anaerobic microbes. Attempts were made to mathematically convert parameters presented in the literature, particularly Wynn and Liehr (2001) and van Bodegom (2001), resulting in a value of 3 kg/m^3. This value is extremely high when compared to those presented specifically for COD concentrations in other treatment processes and was an extremely influential factor in the sluggish response. Using a value of 0.04 kg/m^3 as reported for activated sludge processes resulted in a graph that much more closely resembled the bloom and collapse behavior expected of this type of system.

The addition of both of the previously mentioned elements solved another serious inconsistency with the behavior of the model when compared to actual treatment wetlands. One of the major variables in the design and modeling of treatment wetlands as a whole is the loading rate, defined as the contaminant loading per unit wetland area (Kadlec and Knight 1996). Increasing the total wetland area, and therefore lowering the loading rate, is a simple method of increasing the treatment capacity of the wetland. Before the addition of the macrophyte COD introduction and adjustment of the half saturation parameter, increasing the wetland size decreased the treatment efficiency and increased the total COD output until the wetland became large enough to simply store the input COD. Once those changes were made, treatment efficiency rose and total output fell until the wetland became large enough for its inherent COD production to overshadow the storm water inputs.

Use as a Design/Management Tool

One of the stated purposes of this modeling effort was to create a tool that would be useful in the design and management of constructed wetlands intended to attenuate ADF-laden storm water. There are two main areas of concern that will be explored in this analysis. First is the efficacy of the wetland system in reducing effluent COD levels. The other characteristic of concern is the capacity of the wetland to accept the flow of storm water required without experiencing prolonged surface flow. These factors will be explored using actual ADF use and precipitation data to construct realistically intermittent and varied inputs to which the mechanisms of the model must react.

Dynamic Lead Time

Natural systems tend to have feedback mechanisms that bring the system back to a neutral state when perturbed. This tendency can be taken advantage of when using the model to provide output predictions. In the 8-cell model there are 56 separate state variables that must have initial values set before the simulation can commence. It would be very difficult to ascertain and accurately set the value of any of these variables at any given time. The natural feedback mechanisms represented in the model can be used to dynamically “set” the initial conditions at the beginning of the window of interest. The following discussion details the procedure used to find the adequate amount of historical data that would need to be input for the variables to be close to a stable value at the start of a 30-day window of interest.

The general method for identifying an adequate amount of lead time to consistently dynamically set the initial conditions for a simulation run involves iteratively moving the start date of the simulation back while holding the end date constant. The results of simulations were compared to one another to assess the effect of the entered initial conditions on the result of the model. The goal of the analysis was to extend the timeline to and adequate length so that the magnitude of the difference in results would be no more that ten percent of the value of a given run for a given entered initial condition and that the difference between the standard initial mass (1 kg/400 m^2 of wetland area) and two and ten time that mass would also be no more than ten percent. The initial baseline runs were performed using the 30 day period of highest ADF output at Outfall 001 in the data presented for Westover ARB (13 February 2003 to 14 March 2003) (Naval Facilities Engineering Service Center 2004). The model run was then extended in ten-day intervals by moving back the start date up to a total simulation length of 120 days. Beyond that the model was expanded in 30-day increments until the goal was reached at a total length of 210 days.

The analysis goal was originally to be applied to each of the 56 state variables in the 8-cell model to assure the virtual start of a simulation run at the beginning of the window of interest would be consistent regardless of initial conditions entered. Under this paradigm, the final value of each variable at the end of the entire model run was recorded and compared to the results of other runs allowing the entire length of the simulation run to be considered historical “lead time.” After several iterations, it was determined that assessing convergence of 56 variables was an impractical proposition. The focus of the analysis was shifted to a single measure of effectiveness for the entire wetland, namely the total COD output over the final 30 days of the model run. This measure is consistent with the total maximum daily load (TMDL) limits used for permitting limits by the environmental enforcement bodies (Naval Facilities Engineering Service Center 2004, Kentucky Department for Environmental Protection Division of Water 1997) Under this regimen, the final 30 days of the simulation are considered the "window of interest" and any duration prior to that represents the "lead time."

The analysis resulted in a recommendation of including 180 days of historical information prior to the window of interest. The comparative percentage differences between the 180 and 210 total day simulations and between the standard and multiple initial mass levels are shown in Table 2. below:

Table 2: Final Dynamic Lead Time Analysis Results.

	Initial Mass (IM)	Initial Mass X2	Initial Mass X10
Previous Run Length	1.4%	1.7%	5.5%
Difference from IM	N/A	-.08%	-3.0%

Simulation runs conducted prior to the readjustment of the COD half saturation concentration down from 3 kg/m^3 resulted in convergence on a much shorter timeline with respect to runs started at different initial biomasses. The ability of anaerobic biomass to persist longer when characterized by the lower half saturation constant appeared to be the major factor in the convergence taking longer under these conditions. The between run length differences converged in both cases with at a total model run length of only 50 days. If the results generated by including ten times the standard initial mass are omitted, the results converge in respect to both between run length and between entered initial masses at 50 days. These results suggest that if there is a high degree of confidence in known, reasonable values for initial mass, the amount of historical data needed to dynamically set initial values could be greatly reduced.

While this analysis used a consistent set of actual weather and ADF use data as a 30-day window of interest, the inputs in this portion of the model run could be represented by anticipated meteorological and ADF use condition to assess the impact of planned operations. Also, a composite or selected set of anticipated maximum loading conditions could be entered as a design case to ensure that adequate capacity will be provided by a proposed wetland. The effects of other proposed management actions, such as detention and controlled introduction of storm water to the wetland, batch operation, deicing activity centralization, or ADF use reduction could all be examined using the same core model.

Storm Water Flow Capacity

One of the characteristics of a subsurface flow wetland that make it attractive for use at airfields is that there is no surface water to attract wildlife. If, however, the inflow of storm water exceeds the flow capacity of the wetland, the system can experience surface flow. This condition is undesirable for wildlife attraction reasons, and also because it allows storm water to bypass the attached microbial growth surfaces of the wetland media. Short circuiting of the wetland can have a severely detrimental effect on the systems ability to degrade contaminants. This analysis will compare several options for preventing surface flow in the wetland. These actions will include adjustment to wetland size, capacity of input and output structures, and the volume of storm water to be processed. These actions can also have implications related to the microbial dynamics and treatment effectiveness of wetland, so these effects will also be discussed.

The results of the analysis are reported as changes from a baseline structure. The baseline wetland dimensions for this analysis are set as roughly those of the CTW used in the Westover ARB technology demonstrator (Naval Facilities Engineering Service Center, 2004). Those dimensions are a width of 70 meters, a length of 40 meters (resulting in a five meter section length for the eight-cell model) and a bed depth of 0.6 meters. The input and output control structures are modeled as sharp crested, rectangular weirs one meter in width. The elevation of the input weir is set above wetland elevation and is not adjusted in the analysis. The output weir is set at a baseline elevation of 0.2 meters above the bottom of the wetland. The baseline tributary pavement area for the analysis is 25,000 m^2. The input data set used is the same as the 210-day total length simulation previously presented in the dynamic lead time analysis. Initial conditions are set at the standard initial mass levels previously presented (1kg/400m^2). Wetland COD outputs and changes are based on the total output for the final 30-day period of the simulation as in the dynamic lead time analysis. The structure of the model ensures that the first wetland cell will always have the greatest depth, so attainment of the analysis goal for a given configuration will be assessed by examining a plot of the depth in the first cell.

A few of the assumptions made in the construction of the model must be taken into account in this analysis. First, is that the structure of the storm water flow model does not recognize when depths exceed the depth of the wetland media. In an actual wetland, water flowing on the surface will flow much more quickly than the water in

Darcian flow through the porous media. The model treats all storm water as if it is flowing below the media surface, regardless of depth. This condition will slow the readjustment time and overestimate the duration of a surface flow condition. Therefore, while limited surface flow during high volume weather events may be an acceptable condition, the goal during analysis is to find situations that totally eliminate surface flow. Also, unlike the Westover CTW, the model does not include any sort of overflow in the inlet structure that bypasses the wetland; all precipitation over the tributary area will be processed through the wetland.

The first examinations were undertaken to explore the effect of wetland dimensions on storm water levels. Changes in wetland width were found to effect the ability of water to pass through the wetland. This change is likely due to an increase in the cross-sectional area available for flow when the CTW is widened. Changing none of the baseline parameters with the exception of wetland width, the wetland was expanded to 500m wide before depth remained below 0.6m throughout the run. The ease of transport did not translate into a significant improvement in effectiveness, however. Despite an increase of wetland area by a factor of more than seven, the total COD output for the 30-day window of interest fell by only 3.7 percent. Increasing wetland length was found to provide no discernable improvement to the water level of the wetland. This observation can be attributed to an increase in the distance of flow identified in the Darcy's Law model which corresponds to the physical reality that water introduced at one end of the wetland must travel its entire length to exit. Any improvement that could be had from a simple increase in available storage volume appear to be offset by the increase direct rain water volume that is a result of additional wetland area. Length did, however, have a profound impact on the effectiveness of the wetland in reducing COD output. A doubling of the wetland length resulted in a 19.8 percent reduction in the in total COD for the 30-day window. Much of this enhancement can be attributed to increased residence time of storm water in the wetland, which affords a greater opportunity for wetland microbes to utilize COD inducing substances.

Control Structures

The next portion of the analysis examined the influence of the control structures on the dynamics of storm water flow. The structures were manipulated by adjusting the width of both the input and output weirs and the crest height of the output weir. All of these adjustments were found to be negligible. As the flow is intermittent, the system seemed to compensate for narrower or wider weirs with proportionate adjustments to the flow height during the short periods of flow. Also, the increase of the width of the output weir to match the width of the wetland with insignificant impact is evidence that the hydraulic conductivity of the wetland media and not the output structure is the limiting factor for storm water flow. Again, the reduction of the weir crest height had an effect on the amount of storm water retained during low precipitation conditions, but not on the crest depth levels seen during high flows.

The final portion of the flow analysis examined the effect of the area drained to the wetland on storm water depth. A reduction in this area would result in a reduction of the amount of storm water available to enter the wetland. This adjustment also results in higher concentrations of COD entering the wetland. With the other aspects of the system in their baseline configuration, the area was reduced to 3,500m^2 to bring crest depths below the analysis goal. The smaller area did result in a marked improvement in COD removal as output fell to 61.8 percent of the baseline. As with length increases, decreasing the amount of influent processed increases the residence time storm water experiences within the wetland.

Design Mini-Case

The model can be used as a design tool in an iterative process. Given an unconstrained site on which to construct the wetland, the main factors important to treatment effectiveness and storm water flow that are available for manipulation by the designer are the length and width of the wetland bed. Even with a constrained site a simulation like this one could be used to examine the orientation that takes greatest advantage of the aspect ration of the plot. The factors around which the design must contend are likely to be the area to be drained and a maximum COD output. Representative ADF use and meteorological data would also be required. The case that follows demonstrates an envisioned design sequence.

In this case the wetland must treat the effluent from a 6000 m^2 centralized deicing pad. The discharge permit allows no more than 3000 kg COD in storm water effluent over any 30-day period. The 210-day simulation run used previously are the representative ADF use and weather data for this exercise. The designer must attempt to meet the storm water flow and treatment requirements using a little land as possible. A "best guess" baseline model run should be conducted as a point of departure. Taking into account the influences of width and length on differing aspects of wetland performance, the designer should choose one to optimize first. As surface water flow must be avoided to mitigate wildlife attraction, adequate width must first be provided. The wetland would be made incrementally wider until surface flow is eliminated. Once that aspect has been addressed, the length of the wetland can be adjusted to provide more or less treatment capability depending upon the current state relative to the goal. In the presented scenario, the wetland was assigned a width and 130 m and a length of 44 m. These dimensions eliminated surface flow and provided a COD output of 2,757 kg over the 30-day window of interest.

Temperature Dynamics Model

During this effort there was an attempt to include wetland temperature dynamics into the structure of the model. A lack of significant temperature effect on the treatment effectiveness of SSFCTW systems is reported numerous times in the relevant literature, most notable by Kadlec and Knight (1996). This condition would seem counter to conventional knowledge of the microbial growth dynamics upon which treatment depends. The literature review revealed some potential knowledge gaps that served as impetus for this modeling attempt. First, that the temperature in question was usually air or input water temperature, not water temperature within the wetland. Next, that the models currently in common use treat temperature effects as a simple multiplier on the total treatment capability of the wetland, and do not delve into the actual causal structure for any effects. Finally, there is little mention of the potential that relatively stable below ground temperatures may be moderating atmospheric temperature shifts within the wetland. These perceived gaps led to the formulation of two hypotheses concerning the reason for a lack of temperature effect. First, the close proximity to locations of relatively stable underground temperature may cause wetland temperatures to remain relatively stable as well. Second, while wetland temperatures do vary significantly, the shifts effect aspects of wetland dynamics that offset one another resulting in no real net effect with regard to measures of treatment capability.

The temperature portion of the model attempted to retain the character of the other transport chains in the model by treating temperature essentially as a concentration of energy in the storm water. The stock of energy in each cell was structured to interact with two heat sinks, the ground below the wetland which remained at a constant temperature and the atmosphere above it that would change in temperature according the meteorological data obtained for Westover ARB. (Air Force Combat Climatology Center 2008) The transfer of energy between the sinks and the wetland water in the model is governed by Fourier's Law of Thermal Conduction (Karlekar and Desmond, 1977). Using the aforementioned law, energy is transferred across a gradient from higher temperature to lower temperature areas. That gradient exists across a distance, and the rate of energy flow is proportional to the magnitude of the gradient and governed by the thermal conductivity of the intervening volume. That intervening volume was represented by the air and wetland media above the water surface within the wetland cell and by the distance from the bottom of the wetland to the depth where ground temperature remains constant.

There were difficulties building confidence in the temperature model that led to its omission from the final model. The major challenges were an inability to find a reputable source for observations or calculation methods of constant temperature depth, problems with calculating a proper composite thermal conductivity for the air and wetland media mix between the water and atmospheric heat sink, and trouble determining a method of properly sequestering energy between the water in a cell and the media. The sequestration problem was particularly vexing because it introduced non-uniform properties within a cell. Unlike transported substances, energy exists within the media as well as the storm water. Only that energy residing in the water is available for transport to the next cell while that in the media remains stationary. The flow of water of a different temperature into the cell would result in a within-cell gradient that would take time to equalize. Given the additional complexity of that structure and the numerous reports of little or no temperature effect in the literature the decision was made to simply accept the assumption of no effect rather than attempt to represent it in the model structure.

V. Conclusion

This chapter will focus on the conclusions drawn from the modeling process both in light of the focus areas stated in the introduction and other insights gained during this endeavor. Among those insights are areas where further study would help increase the usefulness of the model and advance pertinent knowledge of the subject.

Assessment of Research Objectives

1. Explore the use of a system dynamics approach to modeling subsurface flow constructed treatment wetland system.

The modeling effort identified several strengths in the use of a system dynamics modeling method for this type of system. First among these strengths is that the model is constructed of a series of sub-models that simulate the underlying processes responsible for wetland treatment function. Also, the feedback mechanisms both within and between the sub-models are described and accounted for by observed natural occurrences. These factors provide an advantage in the level of understanding that can be gained over models such as the first order with background type currently in common use that attempt to categorize all wetland processes with a few external parameters. While they may be convenient, they lack the range of policy actions that can be explored with a system dynamics approach. The model created in this effort also accounts for spatial variations in the character of the wetland by being constructed as a set of cells in series. This again can allow for an understanding of effects on the wetland beyond simple changes in input and output. The transport chain structure could also allow the addition of influences involving other nutrients and substances with relative ease. Finally, the ability to allow the feedback mechanisms represented to adjust the model for a non-precise starting point is a major advantage to this type of method.

The method does present a few weaknesses when used in this type of application. One of these is that there are a large number of parameters, especially those dealing with microbial growth, that have not been adequately quantified in this specific situation. A range of sources and calculations were undertaken to find a truly plausible range for these parameters. While there is confidence that the structural elements are fundamentally sound, it is still difficult to definitively state that the storm water flows and biomass reactions are in scale with one another. The other weakness is that there would be a variety of structure types represented in a "fully developed" model. This effort focused mostly on the core processes that take place within the wetland itself. Representations of other portions of the model such as plant oxygen and COD introduction or storm water collection and input that more robustly simulate actual structures may have an effect on the behavior of the core model and, at the very least, would provide even more policy manipulations that could be explored. Construction of the full model would require a fully interdisciplinary approach to ensure all sub-models are well constructed.

2. Identify factors important to the performance of subsurface flow constructed treatment wetland systems, especially those being used to attenuate deicer-induced water quality issues.

To assess the success in meeting this research objective there needs to be some discussion as to what constitutes a "factor important to performance." As can be seen in the analysis, each structural element and parameter has some sort of effect on the performance of the model. This discussion will identify those that revealed themselves as influential. The factors will be divided into two categories. First will be an assessment of those factors that influence the processes within the wetland and its sub-models. After that, there will be mention of those more macroscopic aspects that are generally more able to be influenced.

The small scale dynamics of the wetland model are ultimately the foundation upon which it is built. Some of the factors are important to the reliability of the model. Assuring the kinetic coefficients and yield rates are within plausible ranges is an important step in building confidence in the model's output. There are other facets that may allow for fine tuning of policy and can be used in management and design activities. The penetration of oxygen and levels of COD concentration in the wetland can have a profound effect on which type of microbe is dominant. Also, the hydraulic conductivity of the wetland media is a very influential factor in flow and residence time for the wetland system.

Larger scale factors include those that are most able to be manipulated in design and management. The size, ratio of length to width, and desired hydraulic input are all factors that can be addressed in a design effort. It has been stated that residence time is the most influential factor in the effectiveness of a treatment wetland system (Mudgett 1995). That factor cannot be directly manipulated without operating a batch-loaded treatment system. In a natural flow system like the one modeled in this effort, residence time is a product of the factors mentioned previously. Identifying a minimum desirable residence time given a limit on available space will point to a maximum input volume and may ultimately drive toward a more centralized deicing operation. That the geometric design of the wetland of importance is no great revelation, but further support for its importance is a reminder that it should not be taken lightly.

Finally, the actual input of ADF to the wetland is a very important factor in design and management, but must be considered separately due to some unique considerations that stretch beyond the modeling effort. This quantity can only be considered a "semi-controlled" input as enough must be used to ensure safe, effective operations. This necessity, however, should not be taken as license to ignore other actions that may improve the environmental situation. Even those organizations that have incorporated a well designed SSFCTW into their ADF management systems should continue to explore pollution prevention options that will reduce the demands placed on the wetland and, ultimately, the environment.

3. Build a useful tool for design and management of constructed treatment wetland systems.

Some aspects of the usefulness of the model as a management and design tool were demonstrated in the previous chapter; here will be discussed improvements that could be made to increase that usefulness. First, there needs to be more work on adding better simulations for input and output structures for storm water in and out of the wetland. Also, while using the current model as a tool may be a simple task for a person well versed in the modeling software package, there may need to be work on creating a more intuitive interface so the model can be used by environmental manager. The STELLA® software package does include an interface layer for each model, but developing this aspect of the tool is beyond the scope of this research effort.

Suggestions for Further Research

As with any research effort many additional questions are generated in addition to the answers discovered. The following sections will outline some suggestions for further investigation and how they relate to improvement of the model. The core structures of this model may be utilized for applications other than modeling treatment of ADF-contaminated waste; and these applications may require some other research. The discussion presented here will focus on the current application of the model.

One of the difficulties encountered in building the model was locating appropriate Monod kinetic parameters to govern microbial growth within the model. Parameters were taken from a number of other areas that were considered to be adequately representative, such as those calculated for methanotrophs in rice patties (van Bodegom *et al*. 2001). Non-reliance on precise parameter values is a hallmark and strength of the system dynamics method; however, variations of an order of magnitude or more can and will have effects on behavior. Research to ascertain a plausible range of values for these coefficients for the organisms that reduce mainly ADF-induced BOD in a wetland system would help build further confidence in the model.

The storm water collection and inflow portions of the model were conceived as a simple set of structures that would reasonably simulate a drainage system that delivers intermittent, precipitation-dependent inputs to the wetland. The actual process of storm water collection, transport, and input to the wetland has many more steps that are not explicitly represented. Further research and development of that portion of the model would add realism to the input timeline for the wetland. A factor that was not included that may have a noticeable effect is the collection of snow, storage of ADF in snow banks, and later release during melt. As formulated, the model more closely represents the "worst case" reported by Corsi, Booth and Hall (2001) of a freezing rain event requiring heavy deicing and resulting in almost immediate transport of large volumes of ADF the drainage system. As a "worst case", this type of event is a good candidate for a design case, however the current model does not take into account that there may be ADF stored in snow banks that is released during a freezing rain storm that adds to the already elevated levels of glycol entering the system.

The temperature model that was mentioned at the end of the previous chapter may have some benefit to the model if developed further. This development may also drive the need for research into the ways wetland storm water temperature effect the underlying processes represented in the various sub-models. Many of the parameters presented in the literature were calculated at temperatures that are likely significantly higher than those found in a wetland operating during winter. It is not implausible, considering the purpose of glycol in ADF is to depress freezing point, that portions of the wetland may be operating with liquid storm water at temperatures below zero degrees Celsius. In microbiological terms, these temperatures near the freezing point of water could be considered "extreme" and result in different behaviors.

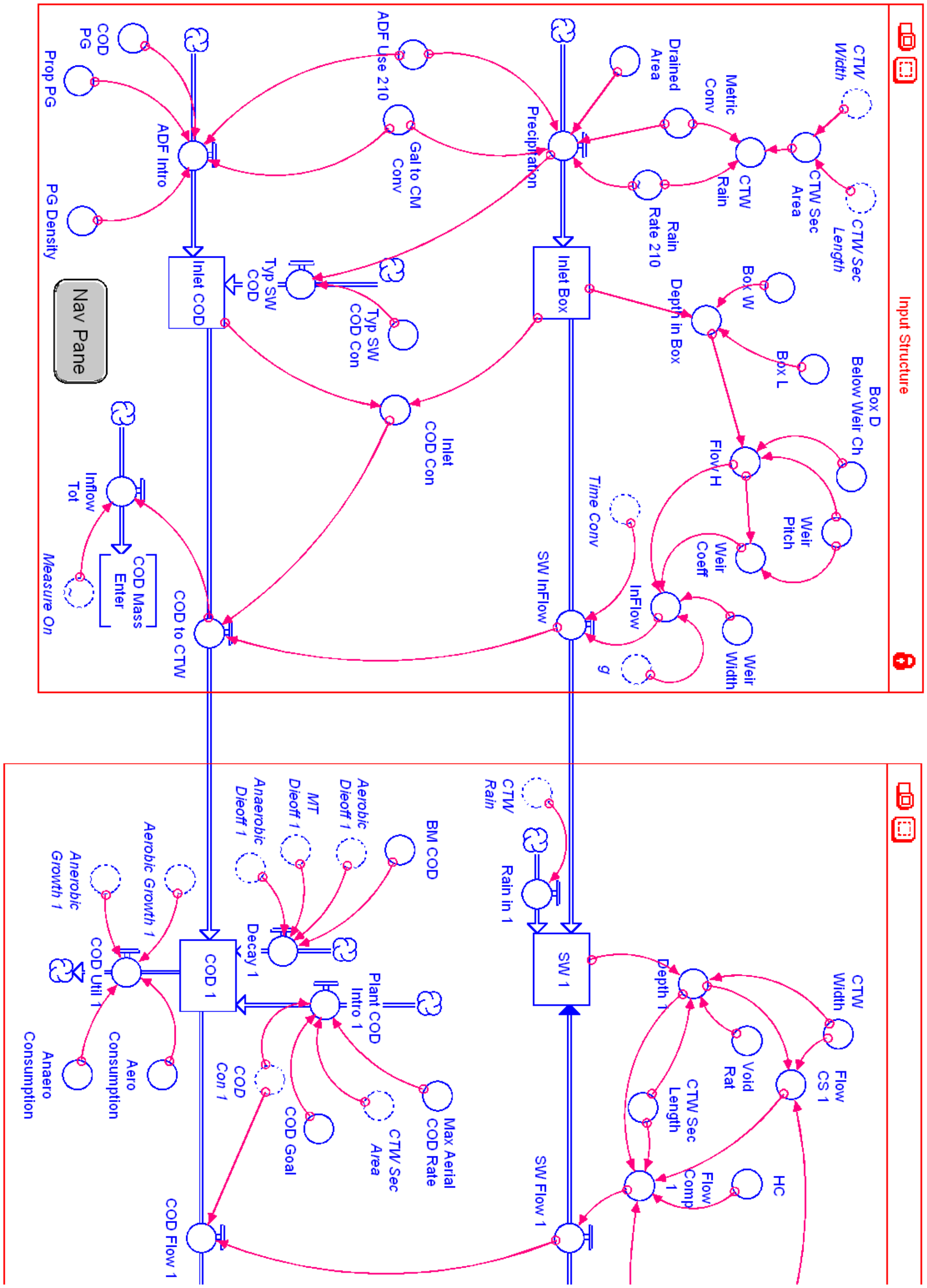
The introductions of both oxygen and COD to the wetland by plants are represented by highly aggregated and simplified goal seeking structures that assume that plants possess mechanisms with which they attempt to control the environment in which they reside. The existence and operation of these mechanisms have been studied and modeled previously (Thompson, 2008; Sorrell, 1999). The exact mechanisms, rates, and other nuances of the plant roots as a system are not explicitly represented. A more robust model of these influences may be a significant addition to the model, especially if it takes into account seasonal differences.

One reason given for the observation of greater contaminant removal rates in subsurface flow wetlands as opposed to surface flow is that there is a greater area in the subsurface flow type for attached microbial growth (Naval Facilities Engineer Service Center, 2004). The area available changes with the depth of storm water in any given section of the wetland. The effects of the actual area available for attached growth and possibly the degree to which it is utilized may account for another important aspect of wetland dynamics.

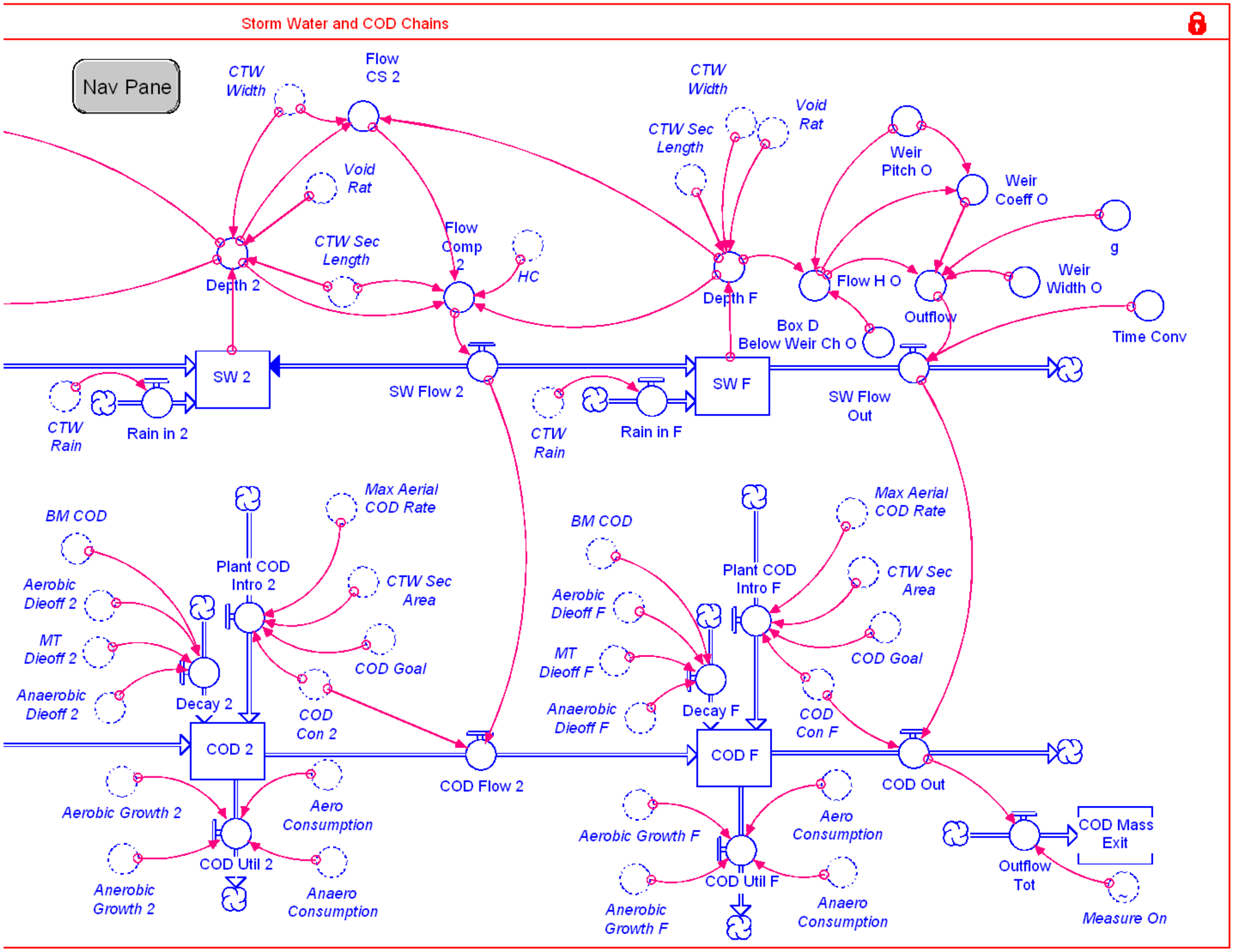
The final area where further research would be beneficial focuses more on land use than actual wetland dynamics. As mentioned previously, large SSFCTWs have been used to successfully for this exact application at airfields around the world (Higgins and MacLean, 2002). The location of open land areas of adequate size and suitable for construction of treatment wetlands is a major challenge to the widespread adoption of this technology. Most major civilian and military airfields have vast areas of level land dedicated to clear zones, runoff areas, and infields. Much effort is spent making these areas unattractive to wildlife and keeping them free of obstructions to enhance safety in the event an aircraft leaves the primary airfield surfaces. It may be worth investigating weather a mature, well constructed, and well maintained SSFCTW is any more attractive to wildlife than airfield land maintained in the current fashion. As for the event of an aircraft entering the wetland bed if it leaves the primary surface, there is the possibility the bed of granular media could bring the vehicle to a quicker, safer stop much like a gravel runoff area slows a careering racecar that slides off a turn on a road racing course.

Research into these areas could lead to the discovery of a highly beneficial use for these land areas that will not reduce and may even increase airfield safety.

Appendix A: STELLA Flow Diagram



- 1 -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CTW Width
Flow CS 2
Void Rat
CTW Sec Length
Flow Comp 2
HC
Depth 2
SW 2
SW Flow 2
CTW Rain
Rain in 2
CTW Width
CTW Sec Length
Void Rat
Weir Pitch O
Weir Coeff O
g
Depth F
Flow H O
Outflow
Weir Width O
Box D Below Weir Ch O
Time Conv
SW F
SW Flow Out
CTW Rain
Rain in F
BM COD
Aerobic Dieoff 2
MT Dieoff 2
Anaerobic Dieoff 2
Decay 2
Plant COD Intro 2
Max Aerial COD Rate
CTW Sec Area
COD Goal
COD Con 2
COD 2
COD Flow 2
Aerobic Growth 2
Aero Consumption
COD Util 2
Anerobic Growth 2
Anaero Consumption
BM COD
Aerobic Dieoff F
MT Dieoff F
Anaerobic Dieoff F
Decay F
Plant COD Intro F
Max Aerial COD Rate
CTW Sec Area
COD Goal
COD Con F
COD F
COD Out
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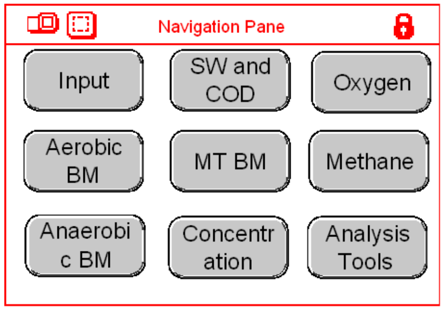
Anaero Consumption
Outflow Tot
COD Mass Exit
Measure On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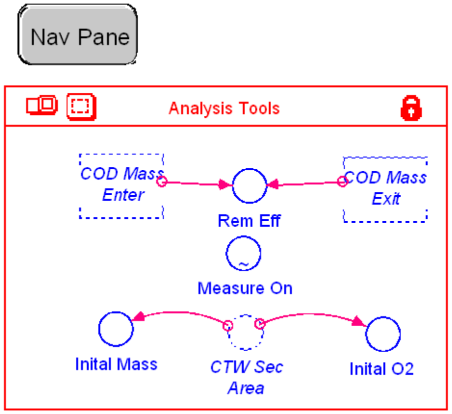
Input
SW and COD
Oxygen
Aerobic BM
MT BM
Methane
Anaerobic BM
Concentration
Analysis Tools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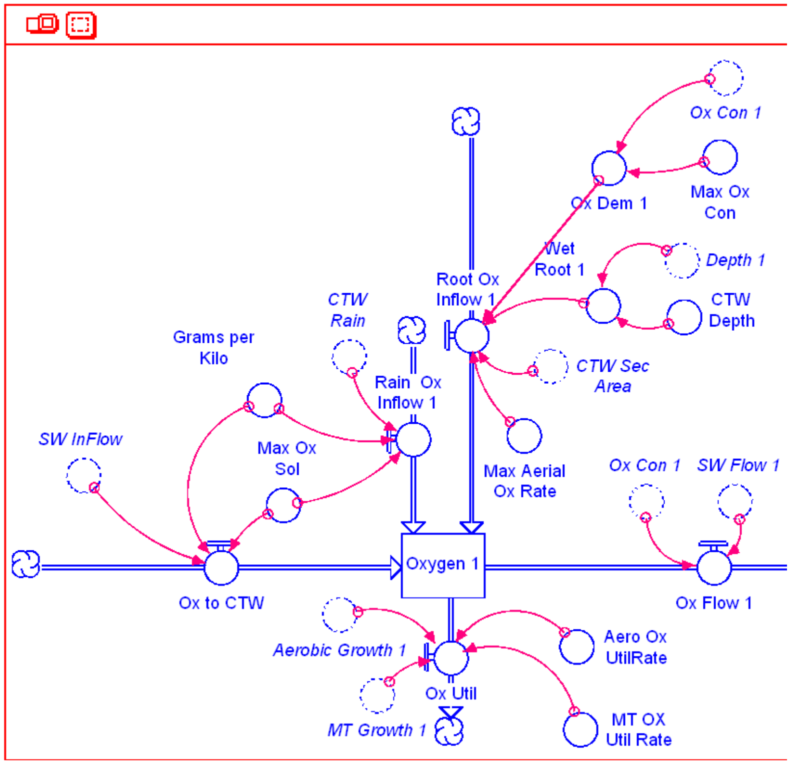
Analysis Tools
COD Mass Enter
Rem Eff
COD Mass Exit
Measure On
Inital Mass
CTW Sec Area
Inital O2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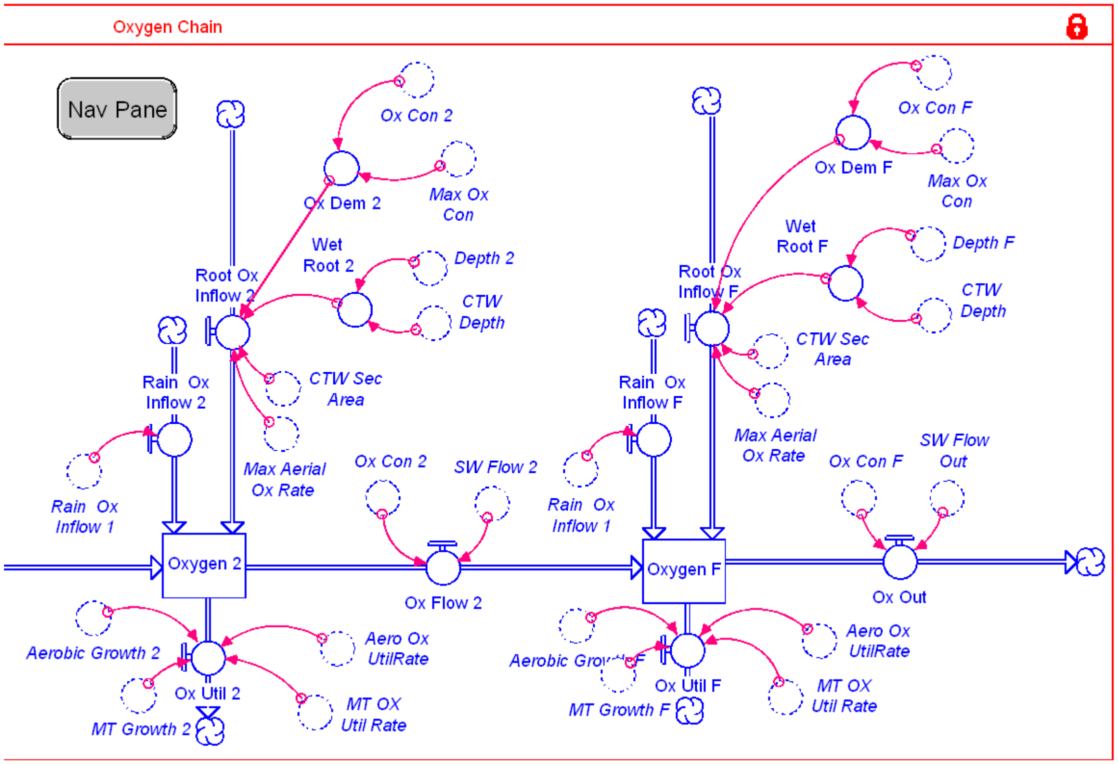
Max Ox Con
Ox Dem 1
Wet Root 1
Depth 1
CTW Depth
Root Ox Inflow 1
CTW Rain
Grams per Kilo
Rain Ox Inflow 1
CTW Sec Area
Max Aerial Ox Rate
SW InFlow
Max Ox Sol
Ox Con 1
SW Flow 1
Oxygen 1
Ox to CTW
Ox Flow 1
Aerobic Growth 1
Aero Ox UtilRate
Ox Util
MT Growth 1
MT OX Util Rate


Oxygen Chain
Nav Pane
Ox Con 2
Ox Dem 2
Max Ox Con
Wet Root 2
Depth 2
CTW Depth
Root Ox Inflow 2
CTW Sec Area
Max Aerial Ox Rate
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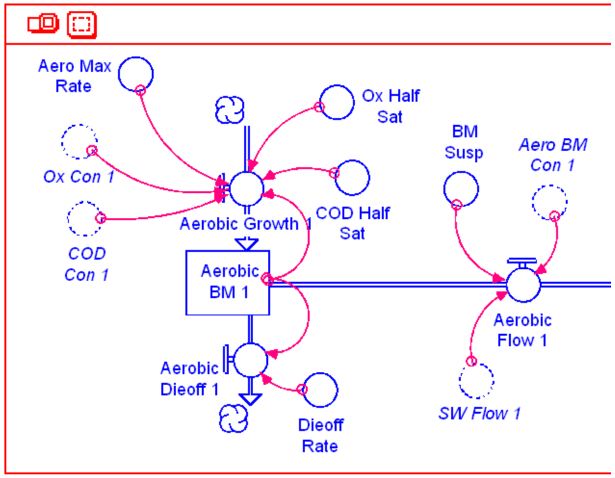
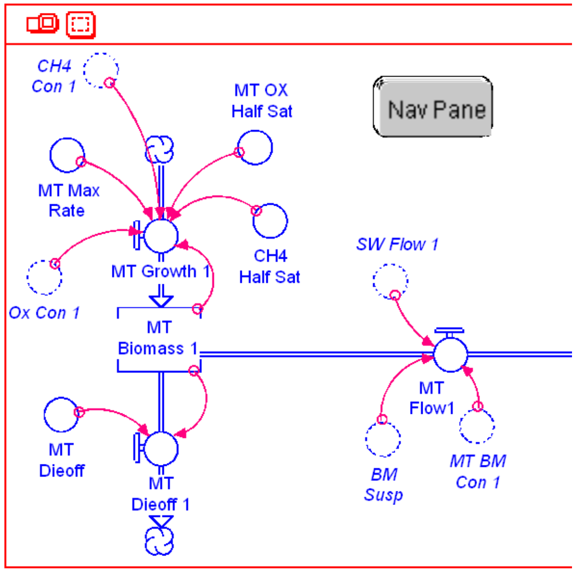
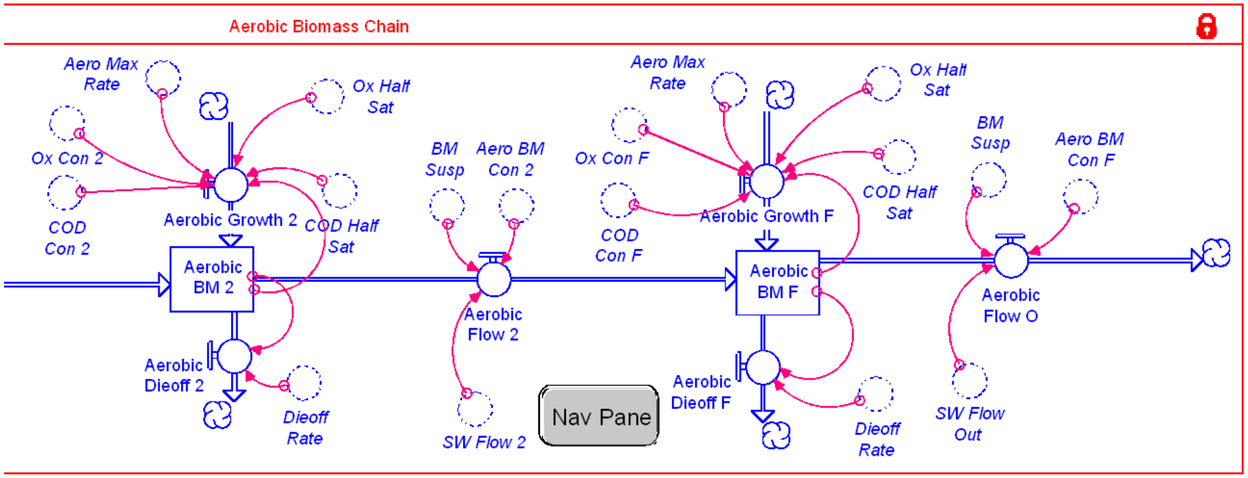
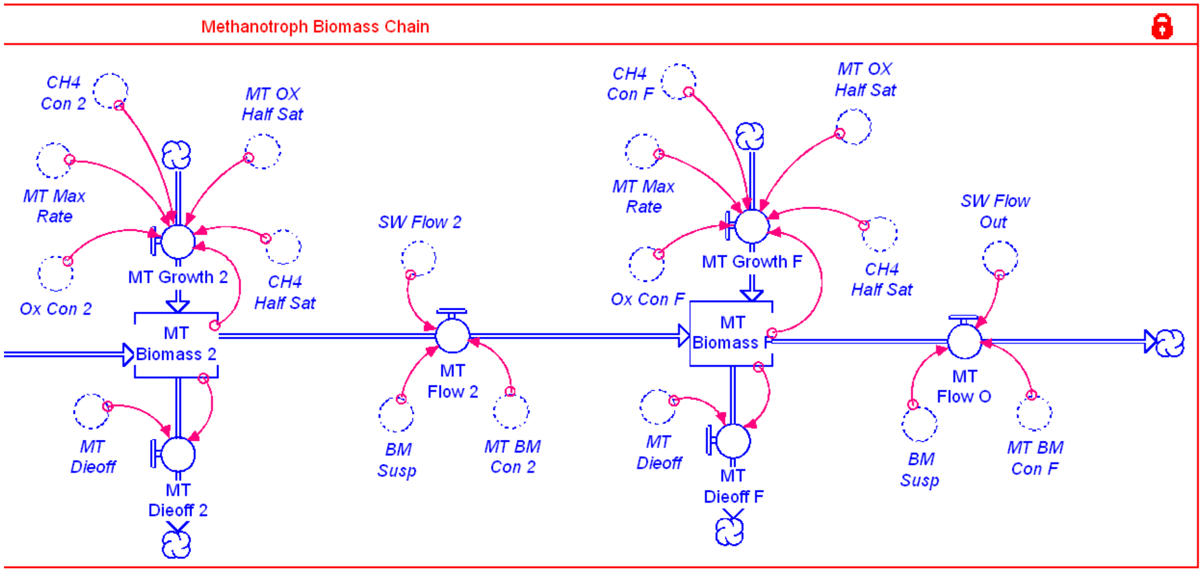
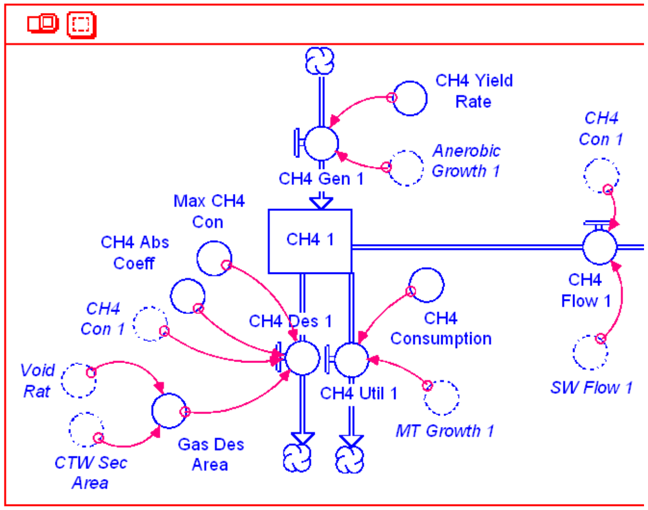
Rain Ox Inflow 1
Oxygen 2
Ox Con 2
SW Flow 2
Ox Flow 2
Aerobic Growth 2
Ox Util 2
Aero Ox UtilRate
MT Growth 2
MT OX Util Rate
Ox Con F
Ox Dem F
Max Ox Con
Wet Root F
Depth F
CTW Depth
Root Ox Inflow F
CTW Sec Area
Max Aerial Ox Rate
Rain Ox Inflow F
Rain Ox Inflow 1
Oxygen F
Ox Con F
SW Flow Out
Ox Out
Aerobic Gro F
Ox Util F
Aero Ox UtilRate
MT Growth F
MT OX Util Rate

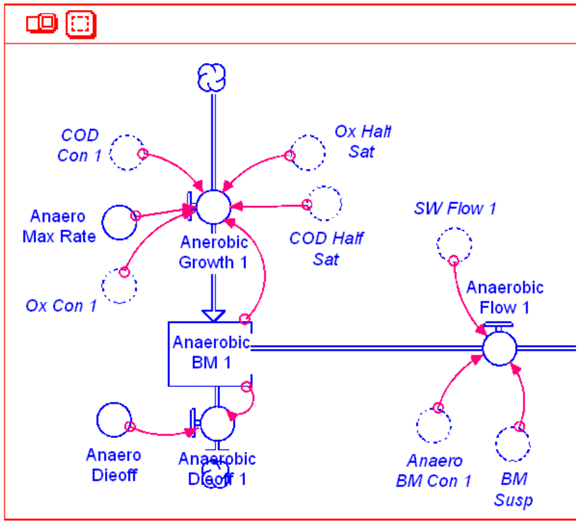

Aero Max Rate
Ox Half Sat
Ox Con 1
BM Susp
Aero BM Con 1
COD Half Sat
Aerobic Growth 1
COD Con 1
Aerobic BM 1
Aerobic Flow 1
Aerobic Dieoff 1
SW Flow 1
Dieoff Rate


CH4 Con 1
MT OX Half Sat
Nav Pane
MT Max Rate
CH4 Half Sat
MT Growth 1
SW Flow 1
Ox Con 1
MT Biomass 1
MT Flow1
MT Dieoff
MT Dieoff 1
BM Susp
MT BM Con 1

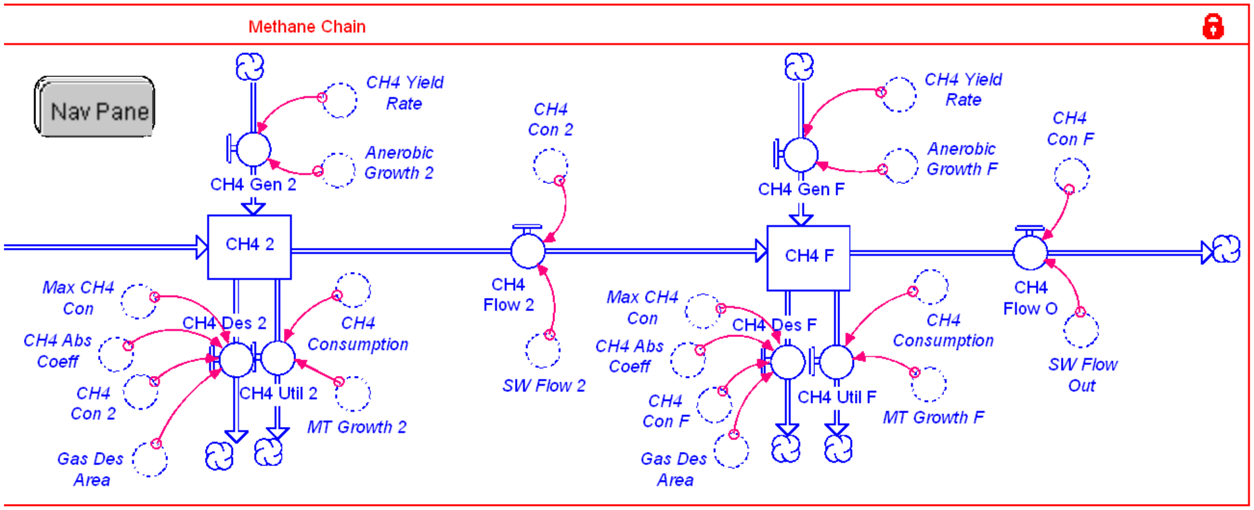

Aerobic Biomass Chain

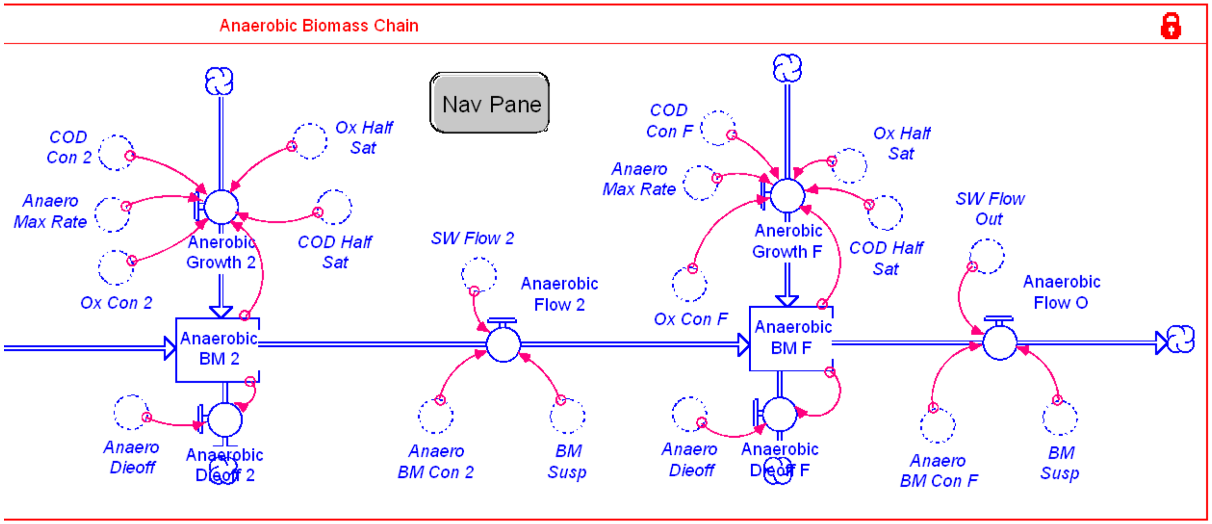

Methanotroph Biomass Chain

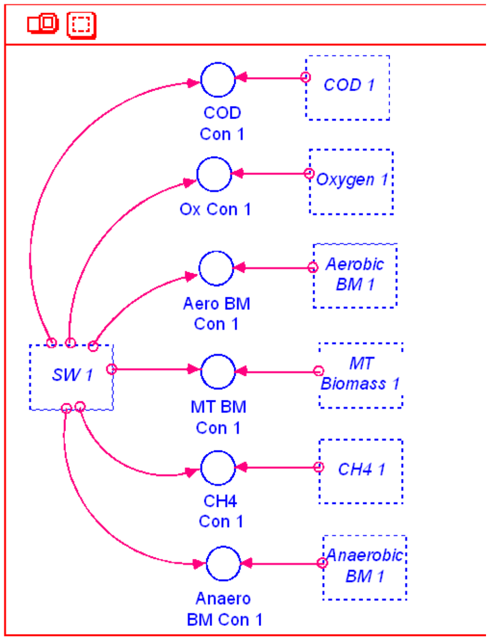

CH4 Yield
Rate
CH4
Con 1
Anerobic
Growth 1
CH4 Gen 1
Max CH4
Con
CH4 1
CH4 Abs
Coeff
CH4 Des 1
CH4
Consumption
CH4
Flow 1
CH4
Con 1
Void
Rat
CH4 Util 1
SW Flow 1
MT Growth 1
Gas Des
Area
CTW Sec
Area

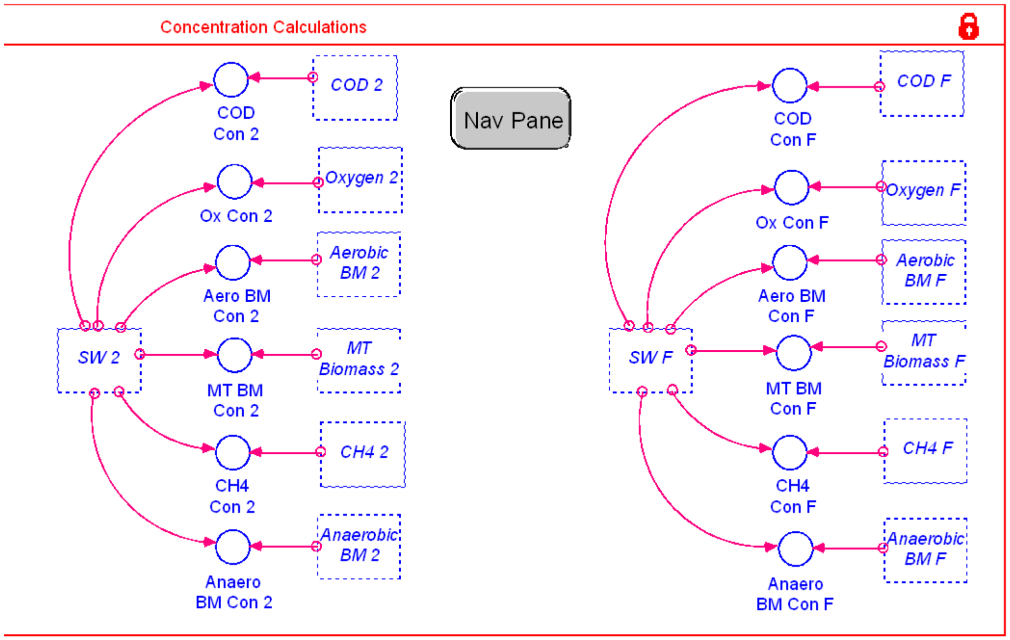

COD
Con 1
Ox Half
Sat
Anaero
Max Rate
SW Flow 1
Anerobic
Growth 1
COD Half
Sat
Ox Con 1
Anaerobic
Flow 1
Anaerobic
BM 1
Anaero
Dieoff
Anaerobic
Dieoff 1
Anaero
BM Con 1
BM
Susp

- 7 -


Methane Chain
Nav Pane
CH4 Yield Rate
Anerobic Growth 2
CH4 Gen 2
CH4 2
Max CH4 Con
CH4 Abs Coeff
CH4 Con 2
Gas Des Area
CH4 Des 2
CH4 Util 2
CH4 Consumption
MT Growth 2
CH4 Con 2
CH4 Flow 2
SW Flow 2
CH4 Yield Rate
Anerobic Growth F
CH4 Gen F
CH4 F
Max CH4 Con
CH4 Abs Coeff
CH4 Con F
Gas Des Area
CH4 Des F
CH4 Util F
CH4 Consumption
MT Growth F
CH4 Con F
CH4 Flow O
SW Flow Out


Anaerobic Biomass Chain
Nav Pane
COD Con 2
Anaero Max Rate
Ox Con 2
Ox Half Sat
COD Half Sat
Anerobic Growth 2
Anaerobic BM 2
Anaero Dieoff
Anaerobic Dieoff 2
SW Flow 2
Anaerobic Flow 2
Anaero BM Con 2
BM Susp
COD Con F
Anaero Max Rate
Ox Con F
Ox Half Sat
COD Half Sat
Anerobic Growth F
Anaerobic BM F
Anaero Dieoff
Anaerobic Dieoff F
SW Flow Out
Anaerobic Flow O
Anaero BM Con F
BM Susp


COD 1
COD Con 1
Oxygen 1
Ox Con 1
Aerobic BM 1
Aero BM Con 1
SW 1
MT Biomass 1
MT BM Con 1
CH4 1
CH4 Con 1
Anaerobic BM 1
Anaero BM Con 1


Concentration Calculations
Nav Pane
COD Con 2
COD 2
Ox Con 2
Oxygen 2
Aero BM Con 2
Aerobic BM 2
SW 2
MT BM Con 2
MT Biomass 2
CH4 Con 2
CH4 2
Anaero BM Con 2
Anaerobic BM 2
COD Con F
COD F
Ox Con F
Oxygen F
Aero BM Con F
Aerobic BM F
SW F
MT BM Con F
MT Biomass F
CH4 Con F
CH4 F
Anaero BM Con F
Anaerobic BM F

Appendix B: Model Entity Table

Name	Units	Description	Determination	Source
ADF Intro	Kg/h	Rate of deposition of ADF-induced COD into storm water	Calculated from the rate of ADF use, proportion of ADF that is PG and the density of PG	Naval Facilities Engineering Service Center, 2004
ADF Use X	M^3	Volume of aircraft deicing fluid introduced to storm water	User Determined	Naval Facilities Engineering Service Center, 2004
Aero BM Con X	kg/M3	Concentration of aerobic biomass in wetland cell	Calculated from SW volume and biomass	
Aero Consumption	none	Inverse biomass yield ratio of aerobic biomass, mass substrate consumed per unit new biomass created	Entered Constant	van Bodegom *et al*, 2001
Aero Max Rate	kg/kg/hr	Maximum biomass growth rate for aerobic microbes	Entered Constant	van Bodegom *et al*, 2001
Aero Ox Util Rate	none	Oxygen used per unit biomass growth	Determined based on stoichiometry of primary substrate	Wynn and Liehr, 2001
Aerobic BM X	Kg	COD utilizing aerobic biomass in a wetland Cell	Sum of biomass growth minus dieoff and suspended biomass transported with SW	
Aerobic Dieoff X	Kg/h	Rate of dieoff of aerobic biomass in wetland cell	First order drain on biomass stock	
Aerobic Flow X	Kg/h	Rate of flow of aerobic biomass with SW from a wetland cell	Calculated from biomass concentration, SW flow, and proportion of suspended biomass	
Aerobic Growth X	Kg/h	Growth rate of aerobic biomass in a wetland cell	Calculated using Monod kinetic expression with substrate concentrations	Wynn and Liehr, 2001
Anaero BM Con X	kg/M3	Concentration of anaerobic biomass in wetland cell	Calculated from SW volume and biomass	
Anaero Consumption	none	Inverse biomass yield ratio of anaerobic biomass, mass substrate consumed per unit new biomass created	Entered Constant	Tchobanoglous and Burton, 1991
Anaero Dieoff	kg/kg/hr	First order rate of biomass dieoff	Assumed to be 1/3 of max growth rate	
Anaero Max Rate	kg/kg/hr	Maximum biomass growth rate for anaerobic microbes	Entered Constant	Wynn and Liehr, 2001

Anaerobic BM X	Kg	Mass of anaerobic microbes in wetland cell	Sum of biomass growth minus dieoff and suspended biomass transported with SW	
Anaerobic Dieoff X	Kg/h	Rate of dieoff of anaerobic biomass in wetland cell	First order drain on biomass stock	
Anaerobic Flow X	Kg/h	Rate of flow of anaerobic biomass with SW from a wetland cell	Calculated from biomass concentration, SW flow, and proportion of suspended biomass	
Anaerobic Growth X	Kg/h	Growth rate of anaerobic biomass in a wetland cell	Calculated using Monod kinetic expression with substrate concentrations	Wynn and Liehr, 2001
BM COD	none	Mass chemical oxygen demand per unit of decayed biomass	Determined from typical biomass composition reported in literature	Tchobanoglous and Burton, 1991
BM Susp	none	Proportion of biomass suspended and available for transport with SW	Entered Constant	
Box D Below Weir Ch	M	Depth of box below the entry to the inflow and overflow weirs (part of weir equation)	User Determined	
Box D Below Weir Ch O	M	Depth of box below the entry to the outflow weir (part of weir equation)	User Determined	
Box L	M	Length of Inlet Box	User Determined	
Box W	M	Width of Inlet Box	User Determined	
CH4 Abs Coeff	M/hr	Coefficient regulating sorption of methane to and from water	Reasonable value determined through trial	
CH4 Con X	kg/m3	Concentration of dissolved methane in wetland cell	Calculated from methane mass and SW volume	
CH4 Consumption	none	Inverse biomass yield used to determine methane utilizations as a function of biomass growth	Determined from values reported in literature	van Bodegom *et al*, 2001
CH4 Des X	Kg/h	Rate of methane desorption from SW when saturation concentration is exceeded	Calculated using sorption expression	Crites and Tchobanoglous, 1998
CH4 Flow X	M^3/h	Rate of methane movement with storm water from a wetland cell	Calculated from gas concentration and SW flow	

CH4 Gen X	Kg/h	Introduction of methane through COD utilization by methanogenic anaerobes	Determined by anaerobic growth and CH4 yield rate	
CH4 Half Sat	kg/m3	Monod half saturation methane concentration for methanotrophic growth expression	Entered Constant	van Bodegom *et al*, 2001
CH4 Util X	kg/h	Rate of methane utilization by methanotrophs	Calculated from MT growth and consumption rate	
CH4 X	Kg	Mass of dissolved methane in wetland cell	Calculated as sum of methane generated by methanogen and that carried in with SW minus the mass utilized by methanotrophs, desorbed from the storm water, and carries away with storm water	
CH4 Yield Rate	none	Rate of methane production based on growth of methanogenic anaerobes	Determined based on stoichiometry reported in literature	Zitomer and Tonuk, 2003
COD Con X	Kg/M^3	Concentration of COD in wetland cell	Calculated from SW volume and COD mass	
COD Flow X	Kg/h	Rate of COD moving with storm water between wetland cells	Calculated from SW flow and COD concentration	
COD Half Sat	kg/M3	Monod half saturation COD concentration for aerobic and anaerobic growth expressions	Entered Constant	van Bodegom *et al*, 2001
COD Mass Enter	Kg	Cumulative total of all COD entering wetland for efficiency calculation	Sum of inflow total	
COD Mass Exit	Kg	Cumulative total of all COD exiting wetland for efficiency calculation	Sum of outflow total	
COD Out	Kg/h	Rate of COD leaving CTW	Calculated from SW flow and COD concentration	
COD PG	none	Mass of chemical oxygen demand exerted by a unit mass of propylene glycol	Entered Constant	Safferman *et al*., 1991
COD to CTW	Kg/h	Rate of COD entering wetland with SW	Calculated from SW inflow and inlet COD concentration	

COD Util X	Kg/h	Rate of utilization of COD-inducing substances as a growth substrate for biomass	Calculated from inverse yield rates and biomass growth	
COD X	Kg	The mass of COD present in a wetland cell	Sum of initial level, inflow from storm water chain, that introduced by decaying biomass, and outflow along storm water chain	
CTW Depth	M	Depth of wetland media	User Determined	
CTW Rain	M^3/Hr	Volume of rain water directly entering each wetland cell	Calculated from rain rate and cell area	
CTW Sec Area	M^2	Area of each wetland cell	Calculated from section length and width	
CTW Sec Length	M	Length of each wetland section (cell)	User Determined	
CTW Width	M	Width of wetland	User Determined	
Decay X	Kg/h	Rate of COD added to wetland cell by biomass decay	Calculated from unit biomass COD and biomass dieoff rates	
Depth in Box	M	Depth of SW in Inlet Box	Calculated from volume stock and box size	
Depth X	M	Depth of storm water in a CTW cell	Calculated from wetland cell area, storm water volume, and media void ratio	
Dieoff Rate	kg/kg/hr	First order rate of aerobic biomass dieoff	Assumed to be 1/3 of max growth rate	
Drained Area	M^2	Tributary area from which storm water is collected	User Determined	
Flow Comp X	M^3/h	Computation of Darician flow between CTW Cell and next cell	Calculated from the depth differential, section length and width, and hydraulic conductivity of media	
Flow CS X	M^2	The cross sectional area through which traveling storm water flows between two wetland cells	Calculated as the mean depth between adjacent cells times CTW width	
Flow H	M	Depth of water over rim of weir	Calculated from depth in inlet and weir characteristics	
Flow H O	M	Depth over outflow weir	Calculated using CTW cell depth and weir geometry	

g	M/s^2	Acceleration Due to Gravity	Entered Constant	Chen and Liew, 2003
Gal to CM Conv	Gal/M3	Conversion to allow ADF use to be entered in gallons	Entered Constant	Chen and Liew, 2003
Gas Des Area	M2	Area available for desorption of excess methane	Calculated from section area and media void ratio	
Grams per Kilo	g/kg	Unit conversion to allow oxygen solubility to be entered in grams per liter	Entered Constant	Chen and Liew, 2003
HC	M/h	(Hydraulic Conductivity) Property governing flow through porous medium	Entered Constant	Todd, 1980
In Flow	M^3/s	Final calculation of weir flow rate in Vol/s	Calculated from weir specifications and depth in inlet	
Inflow Tot	Kg/h	Duplication of COD inflow for efficiency calculation	Determined by inflow	
Initial Mass	Kg	Analytical tool to easily set initial levels of biomass, COD, and CH4 mass in cells	User Determined	
Initial O2	Kg	Analytical tool to easily set initial level of oxygen mass in cells	User Determined	
Inlet Box	M^3	The volume of storm water that is queued to enter the wetland	Sum of precipitation flow and CTW inflow	
Inlet COD	Kg	The mass of Chemical Oxygen Demand (COD) queued to enter the CTW	Sum of ADF COD, typical SW COD, and COD carried in CTW inflow	
Inlet COD Con	Kg/M^3	COD concentration in inlet box	Calculated from volume in inlet box and mass of COD	
Max Aerial Ox Rate	Kg/m^2/hr	Maximum rate of oxygen introduction by plant roots per unit wetland area	Entered Constant	Kadlec and Knight, 1996
Max CH4 Con	kg/m3	Saturation concentration of methane based on storm water temperature	Entered Constant	
Max Ox Sol	g/l	Saturation concentration of oxygen in storm water	Entered Constant	Tchobanoglous and Burton, 1991
Measure On	none	Analytical that defines the window of interest	User Determined	
Metric Conv	M/in	Allows rain rate entry in inches/hour	Entered Constant	Chen and Liew, 2003
MT Biomass X	Kg	Mass of methontrophic biomass in wetland cell	Sum of biomass growth minus dieoff and suspended biomass transported with SW	

MT BM Con X	kg/M3	Concentration of methanotrophic biomass in wetland cell	Calculated from SW volume and biomass	
MT Dieoff	kg/kg/hr	First order rate constant for biomass dieoff	Assumed to be 1/3 of max growth rate	
MT Dieoff X	Kg/h	Rate of dieoff of methanotrophic biomass in wetland cell	First order drain on biomass stock	
MT Flow X	Kg/h	Rate of flow of methanotrophic biomass with SW from a wetland cell	Calculated from biomass concentration, SW flow, and proportion of suspended biomass	
MT Growth X	Kg/h	Growth rate of methanotrophic biomass in a wetland cell	Calculated using Monod kinetic expression with substrate concentrations	Wynn and Liehr, 2001
MT Max Rate	kg/kg/hr	Maximum biomass growth rate for methanotrophic microbes	Entered Constant	van Bodegom *et al*, 2001
MT Ox Half Sat	kg/m3	Monod half saturation oxygen concentration for methanotrophic growth expression	Entered Constant	van Bodegom *et al*, 2001
MT Ox Util Rate	none	Oxygen used per unit biomass growth	Determined based on stoichiometry of primary substrate	Wynn and Liehr, 2001
Outflow Tot	Kg/h	Duplication of COD outflow for efficiency calculation	Determined by outflow	
Ox Con X	Kg/M^3	Concentration of dissolved oxygen in a wetland cell	Calculated from oxygen mass and storm water volume	
Ox Dem X	none	Expression to regulate introduction of oxygen by roots as a function of demand conditions in wetland	Calculated from difference between oxygen concentration and goal concentration	
Ox Flow X	Kg/h	Rate of dissolved oxygen transfer between wetland cells	Calculated from oxygen concentration and SW flow	
Ox Half Sat	Kg/M3	Monod half saturation oxygen concentration for aerobic growth expression and anaerobic inhibition expression	Entered Constant	van Bodegom *et al*, 2001
Ox Out	Kg/h	Rate of oxygen leaving wetland with storm water	Calculated from concentration and outflow rate	

Ox to CTW	Kg/h	Rate of oxygen inflow to wetland with SW	Calculated using storm water inflow and assuming saturation of oxygen	
Ox Util X	Kg/h	Reduction of oxygen mass due to biomass utilization	Calculated from aerobic and MT growth and utilization rates	
Oxygen X	Kg	Mass of dissolved oxygen in wetland cell SW	Sum of inflows with SW, from rain, and from roots and outflows with SW and due to BM utilization	
PG Density	Kg/M3	Density of PG to covert volume to mass	Entered Constant	Naval Facilities Engineering Service Center, 2004
Precipitation	M^3/h	Rate of storm water generation	Calculated from rain rate, tributary area, and the amount of ADF used	
Prop PG	none	Proportion of applied ADF that consists or PG	Entered Constant	Naval Facilities Engineering Service Center, 2004
Rain in X	M^3/h	Storm water added to wetland cell by direct rain on wetland	Calculated from rain rate and wetland area	
Rain Ox Inflow X	Kg/h	Rate of oxygen inflow to wetland cell with direct rain	Calculated using rain inflow and assuming saturation of oxygen equal for all cells	
Rain Rate X	in/hr	Graphical representation of precipitation events	User Determined	Air Force Combat Climatology Center, 2008
Rem Eff	none	Removal efficiency for COD	Calculated as the percentage of COD entering the wetland that is not present in outflow over a set time period.	
Root Ox Inflow X	Kg/h	Rate of oxygen introduction to wetland cell through macrophyte roots	Calculated based on a maximum aerial rate of oxygen introduction and water depth in the cell	Sorrell, 1999

SW Flow Out	M^3/h	Rate of storm water leaving the wetland	Calculated from CTW cell depth and weir equation	
SW Flow Out	M^3/h	Water flow out of wetland from final cell	Calculated from depth in final section and outflow weir equation	
SW Flow X	M^3/h	Water flow between adjacent wetland cells	Calculated from depth differential in two cells (Darcy's Law)	
SW Inflow	M^3/h	Rate of storm water entering wetland from storage inlet box	Calculated from storm water depth in inlet and conditions set by weir equation or user determined for steady state modeling	
SW X	M^3	The volume of storm water in a wetland cell	Sum of initial level, cumulative storm and rain water, and outflow	
Time Conv	s/h	Convert weir equation rate of Vol/s to model scale of Vol/h	Entered Constant	
Typ SW COD Con	Kg/hr	Non-ADF COD in SW	Calculated from Typical concentration and precipitation	
Typ SW COD Con	Kg/M3	Typical COD concentration of urban SW	Entered Constant	
Void Rat	none	Decimal proportion of media volume that is voids that can be filed with storm water	User Determined	Naval Facilities Engineering Service Center, 2004
Weir Coeff X		Expression governing flow over a weir governed by weir properties	Calculated from flow over weir and weir geometry	Lyn, 2003
Weir Pitch	M	Height of weir over its channel floor for input	User Determined	
Weir Pitch O	M	Height of weir over its channel floor for output	User Determined	
Weir Width	M	Width of inflow weir	User Determined	
Weir Width O	M	Width of outflow weir	User Determined	
Wet Root X	none	Proportion of root area that is submerged and available to transport oxygen	Calculated from the depth of the wetland media and depth of water in the wetland cell. Assumes a constant root density with depth.	

Appendix C: STELLA Model Equation Output

Aerobic Biomass Chain

```
Aerobic_BM_1(t) = Aerobic_BM_1(t - dt) + (Aerobic_Growth_1 - Aerobic_Flow_1 -
Aerobic__Dieoff_1) * dtINIT Aerobic_BM_1 = Inital_Mass
INFLOWS:
Aerobic_Growth_1 =
Aerobic_BM_1*(Aero_Max_Rate*(COD_Con_1/(COD_Con_1+COD_Half__Sat))*(Ox
_Con_1/(Ox_Con_1+Ox_Half_Sat)))
OUTFLOWS:
Aerobic_Flow_1 = Aero_BM_Con_1*SW_Flow_1*BM_Susp
Aerobic__Dieoff_1 = Aerobic_BM_1*Dieoff__Rate
Aerobic_BM_2(t) = Aerobic_BM_2(t - dt) + (Aerobic_Growth_2 + Aerobic_Flow_1 -
Aerobic_Flow_2 - Aerobic__Dieoff_2) * dtINIT Aerobic_BM_2 = Inital_Mass
INFLOWS:
Aerobic_Growth_2 =
Aerobic_BM_2*(Aero_Max_Rate*(COD_Con_2/(COD_Con_2+COD_Half__Sat))*(Ox
_Con_2/(Ox_Con_2+Ox_Half_Sat)))
Aerobic_Flow_1 = Aero_BM_Con_1*SW_Flow_1*BM_Susp
OUTFLOWS:
Aerobic_Flow_2 = BM_Susp*Aero_BM_Con_2*SW_Flow_2
Aerobic__Dieoff_2 = Aerobic_BM_2*Dieoff__Rate
Aerobic_BM_F(t) = Aerobic_BM_F(t - dt) + (Aerobic_Growth_F + Aerobic_Flow_2 -
Aerobic_Flow_O - Aerobic__Dieoff_F) * dtINIT Aerobic_BM_F = Inital_Mass
INFLOWS:
Aerobic_Growth_F =
Aerobic_BM_F*(Aero_Max_Rate*(COD__Con_F/(COD__Con_F+COD_Half__Sat))*(
Ox_Con_F/(Ox_Con_F+Ox_Half_Sat)))
Aerobic_Flow_2 = BM_Susp*Aero_BM_Con_2*SW_Flow_2
OUTFLOWS:
Aerobic_Flow_O = BM_Susp*Aero_BM_Con_F*SW_Flow__Out
Aerobic__Dieoff_F = Aerobic_BM_F*Dieoff__Rate
Aero_Max_Rate = .1
BM_Susp = .01
COD_Half__Sat = .04
Dieoff__Rate = .033
Ox_Half_Sat = .0003
```

Anaerobic Biomass Chain

```
Anaerobic_BM_1(t) = Anaerobic_BM_1(t - dt) + (Anerobic__Growth_1 -
Anaerobic_Flow_1 - Anaerobic__Dieoff_1) * dtINIT Anaerobic_BM_1 = Inital_Mass
INFLOWS:
Anerobic__Growth_1 =
Anaerobic_BM_1*(Anaero_Max_Rate*(COD_Con_1/(COD_Con_1+COD_Half__Sat))
*(Ox_Half_Sat/(Ox_Con_1+Ox_Half_Sat)))
```

OUTFLOWS:
Anaerobic_Flow_1 = BM_Susp*Anaero_BM_Con_1*SW_Flow_1
Anaerobic__Dieoff_1 = Anaerobic_BM_1*Anaero_Dieoff
Anaerobic_BM_2(t) = Anaerobic_BM_2(t - dt) + (Anerobic__Growth_2 + Anaerobic_Flow_1 - Anaerobic_Flow_2 - Anaerobic__Dieoff_2) * dtINIT
Anaerobic_BM_2 = Inital_Mass
INFLOWS:
Anerobic__Growth_2 = Anaerobic_BM_2*(Anaero_Max_Rate*(COD_Con_2/(COD_Con_2+COD_Half__Sat))*(Ox_Half_Sat/(Ox_Con_2+Ox_Half_Sat)))
Anaerobic_Flow_1 = BM_Susp*Anaero_BM_Con_1*SW_Flow_1
OUTFLOWS:
Anaerobic_Flow_2 = BM_Susp*Anaero_BM_Con_2*SW_Flow_2
Anaerobic__Dieoff_2 = Anaerobic_BM_2*Anaero_Dieoff
Anaerobic_BM_F(t) = Anaerobic_BM_F(t - dt) + (Anerobic__Growth_F + Anaerobic_Flow_2 - Anaerobic_Flow_O - Anaerobic__Dieoff_F) * dtINIT
Anaerobic_BM_F = Inital_Mass
INFLOWS:
Anerobic__Growth_F = Anaerobic_BM_F*(Anaero_Max_Rate*(COD__Con_F/(COD__Con_F+COD_Half__Sat))*(Ox_Half_Sat/(Ox_Con_F+Ox_Half_Sat)))
Anaerobic_Flow_2 = BM_Susp*Anaero_BM_Con_2*SW_Flow_2
OUTFLOWS:
Anaerobic_Flow_O = BM_Susp*Anaero_BM_Con_F*SW_Flow__Out
Anaerobic__Dieoff_F = Anaerobic_BM_F*Anaero_Dieoff
Anaero_Dieoff = .0033
Anaero_Max_Rate = .01

Analysis Tools
Inital_Mass = CTW_Sec_Area/400
Inital_O2 = CTW_Sec_Area/400
Rem_Eff = IF(COD_Mass_Enter=0) THEN(0) ELSE(((COD_Mass_Enter-COD_Mass_Exit)/COD_Mass_Enter)*100)
Measure_On = GRAPH(TIME)
(0.00, 0.00), (360, 0.00), (720, 0.00), (1080, 0.00), (1440, 0.00), (1800, 0.00), (2160, 0.00), (2520, 0.00), (2880, 0.00), (3240, 0.00), (3600, 0.00), (3960, 0.00), (4320, 1.00), (4680, 1.00), (5040, 1.00)

Concentrations Calculations
Aero_BM_Con_1 = IF(SW_1=0) THEN(0) ELSE(Aerobic_BM_1/SW_1)
Aero_BM_Con_2 = IF(SW_2=0) THEN(0) ELSE(Aerobic_BM_2/SW_2)
Aero_BM_Con_F = IF(SW_F=0) THEN(0) ELSE(Aerobic_BM_F/SW_F)
Anaero_BM_Con_1 = IF(SW_1=0) THEN(0) ELSE(Anaerobic_BM_1/SW_1)
Anaero_BM_Con_2 = IF(SW_2=0) THEN(0) ELSE(Anaerobic_BM_2/SW_2)
Anaero_BM_Con_F = IF(SW_F=0) THEN(0) ELSE(Anaerobic_BM_F/SW_F)
CH4__Con_1 = IF(SW_1=0) THEN(0) ELSE(CH4_1/SW_1)

CH4__Con_2 = IF(SW_2=0) THEN(0) ELSE(CH4_2/SW_2)
CH4__Con_F = IF(SW_F=0) THEN(0) ELSE(CH4_F/SW_F)
COD_Con_1 = IF(SW_1>0)THEN(COD_1/SW_1)ELSE(0)
COD_Con_2 = IF(SW_2>0)THEN(COD_2/SW_2)ELSE(0)
COD__Con_F = IF(SW_F>0)THEN(COD_F/SW_F)ELSE(0)
MT_BM_Con_1 = IF(SW_1=0) THEN(0) ELSE(MT_Biomass_1/SW_1)
MT_BM_Con_2 = IF(SW_2=0) THEN(0) ELSE(MT_Biomass_2/SW_2)
MT_BM_Con_F = IF(SW_F=0) THEN(0) ELSE(MT_Biomass_F/SW_F)
Ox_Con_1 = IF(SW_1=0) THEN(0) ELSE(Oxygen_1/SW_1)
Ox_Con_2 = IF(SW_2=0) THEN(0) ELSE(Oxygen_2/SW_2)
Ox_Con_F = IF(SW_F=0) THEN(0) ELSE(Oxygen_F/SW_F)

Input Structure
COD_Mass_Enter(t) = COD_Mass_Enter(t - dt) + (Inflow_Tot) * dtINIT
COD_Mass_Enter = 0
INFLOWS:
Inflow_Tot = COD_to_CTW*Measure_On
Inlet_Box(t) = Inlet_Box(t - dt) + (Precipitation - SW_InFlow) * dtINIT Inlet_Box = (Weir__Pitch+Box_D_Below_Weir_Ch)*Box_L*Box_W
INFLOWS:
Precipitation = (Drained_Area*Rain_Rate_210*Metric__Conv)+(ADF_Use_210*Gal_to_CM_Conv)
OUTFLOWS:
SW_InFlow = InFlow*Time_Conv
Inlet_COD(t) = Inlet_COD(t - dt) + (ADF_Intro + Typ_SW_COD - COD_to_CTW) * dtINIT Inlet_COD = 0
INFLOWS:
ADF_Intro = ADF_Use_210*Prop_PG*Gal_to_CM_Conv*PG_Density*COD_PG
Typ_SW_COD = Precipitation*Typ_SW_COD_Con
OUTFLOWS:
COD_to_CTW = SW_InFlow*Inlet__COD_Con
Box_D_Below_Weir_Ch = 1
Box_L = 5
Box_W = 10
COD_PG = 1.68
CTW_Rain = Rain_Rate_210*Metric__Conv*CTW_Sec_Area
CTW_Sec_Area = CTW_Sec_Length*CTW__Width
Depth_in_Box = Inlet_Box/(Box_L*Box_W)
Drained_Area = 6000
Flow_H = Depth_in_Box-(Weir__Pitch+Box_D_Below_Weir_Ch)
Gal_to_CM_Conv = .0003786384
InFlow = IF(Flow_H<0) THEN(0) ELSE(Weir_Coeff*((2/3)*(SQRT(2*g)))*Weir_Width*(Flow_H^1.5))
Inlet__COD_Con = IF(Inlet_Box>0)THEN(Inlet_COD/Inlet_Box)ELSE(0)
Metric__Conv = .0254
PG_Density = 1036

Prop_PG = .75
Typ_SW_COD_Con = .06
Weir_Coeff = .602+.075*(Flow_H/Weir__Pitch)
Weir_Width = 1
Weir__Pitch = .6
ADF_Use_210 = GRAPH(TIME)
(0.00, 0.00), (24.0, 0.00), (48.0, 0.00), (72.0, 0.00), (96.0, 0.00), (120, 0.00), (144, 0.00), (168, 0.00), (192, 0.00), (216, 0.00), (240, 0.00), (264, 0.00), (288, 0.00), (312, 0.00), (336, 0.00), (360, 0.00), (384, 0.00), (408, 0.00), (432, 0.00), (456, 0.00), (480, 0.00), (504, 0.00), (528, 0.00), (552, 0.00), (576, 0.00), (600, 0.00), (624, 0.00), (648, 0.00), (672, 0.00), (696, 0.00), (720, 0.00), (744, 0.00), (768, 0.00), (792, 0.00), (816, 0.00), (840, 0.00), (864, 0.00), (888, 0.00), (912, 0.00), (936, 0.00), (960, 0.00), (984, 0.00), (1008, 0.00), (1032, 0.00), (1056, 0.00), (1080, 0.00), (1104, 0.00), (1128, 0.00), (1152, 0.00), (1176, 0.00), (1200, 0.00), (1224, 0.00), (1248, 0.00), (1272, 0.00), (1296, 0.00), (1320, 0.00), (1344, 0.00), (1368, 0.00), (1392, 0.00), (1416, 0.00), (1440, 0.00), (1464, 0.00), (1488, 0.00), (1512, 0.00), (1536, 0.00), (1560, 0.00), (1584, 0.00), (1608, 0.00), (1632, 0.00), (1656, 6.13), (1680, 0.00), (1704, 0.00), (1728, 0.00), (1752, 0.00), (1776, 0.00), (1800, 0.00), (1824, 0.00), (1848, 0.00), (1872, 0.00), (1896, 0.00), (1920, 0.00), (1944, 0.00), (1968, 0.00), (1992, 0.00), (2016, 0.00), (2040, 0.00), (2064, 0.00), (2088, 0.00), (2112, 0.00), (2136, 0.00), (2160, 0.00), (2184, 0.00), (2208, 0.00), (2232, 0.00), (2256, 0.00), (2280, 0.00), (2304, 0.00), (2328, 0.00), (2352, 0.00), (2376, 0.00), (2400, 0.00), (2424, 0.00), (2448, 6.25), (2472, 0.00), (2496, 0.00), (2520, 0.00), (2544, 0.00), (2568, 0.00), (2592, 0.00), (2616, 0.00), (2640, 5.21), (2664, 87.5), (2688, 0.00), (2712, 6.25), (2736, 0.00), (2760, 0.00), (2784, 0.00), (2808, 93.7), (2832, 2.08), (2856, 0.00), (2880, 0.00), (2904, 132), (2928, 45.8), (2952, 7.71), (2976, 0.00), (3000, 0.00), (3024, 0.00), (3048, 0.00), (3072, 0.00), (3096, 0.00), (3120, 0.00), (3144, 0.00), (3168, 0.00), (3192, 0.00), (3216, 0.00), (3240, 0.00), (3264, 0.00), (3288, 0.00), (3312, 0.00), (3336, 0.00), (3360, 0.00), (3384, 0.00), (3408, 10.2), (3432, 0.00), (3456, 0.00), (3480, 0.00), (3504, 0.00), (3528, 0.00), (3552, 0.00), (3576, 0.00), (3600, 0.00), (3624, 0.00), (3648, 0.00), (3672, 0.00), (3696, 0.00), (3720, 0.00), (3744, 0.00), (3768, 0.00), (3792, 0.00), (3816, 0.00), (3840, 0.00), (3864, 0.00), (3888, 0.00), (3912, 0.00), (3936, 39.6), (3960, 12.5), (3984, 0.00), (4008, 6.25), (4032, 33.3), (4056, 5.00), (4080, 0.00), (4104, 0.00), (4128, 0.00), (4152, 0.00), (4176, 254), (4200, 0.00), (4224, 0.00), (4248, 60.4), (4272, 50.0), (4296, 86.3), (4320, 0.00), (4344, 0.00), (4368, 0.00), (4392, 0.00), (4416, 49.8), (4440, 108), (4464, 66.7), (4488, 0.00), (4512, 0.00), (4536, 0.00), (4560, 0.00), (4584, 29.2), (4608, 28.1), (4632, 14.6), (4656, 0.00), (4680, 0.00), (4704, 0.00), (4728, 0.00), (4752, 0.00), (4776, 0.00), (4800, 0.00), (4824, 0.00), (4848, 0.00), (4872, 0.00), (4896, 84.8), (4920, 46.7), (4944, 0.00), (4968, 0.00), (4992, 0.00), (5016, 0.00), (5040, 0.00)
Rain_Rate_210 = GRAPH(TIME)
(0.00, 0.00), (24.0, 0.00), (48.0, 0.00), (72.0, 0.015), (96.0, 0.00), (120, 0.00), (144, 0.0013), (168, 0.0046), (192, 0.0054), (216, 0.00), (240, 0.00), (264, 0.00), (288, 0.0446), (312, 0.0029), (336, 0.00), (360, 0.00), (384, 0.005), (408, 0.00), (432, 0.0063), (456, 0.00), (480, 0.00), (504, 0.00), (528, 0.00), (552, 0.00), (576, 0.00), (600, 0.00), (624, 0.00), (648, 0.00), (672, 0.00), (696, 0.0054), (720, 0.0333), (744, 0.00), (768, 0.00), (792, 0.00), (816, 0.00), (840, 0.00), (864, 0.0017), (888, 0.0054), (912, 0.00), (936, 0.00), (960, 0.0117), (984, 0.035), (1008, 0.0217), (1032, 0.00), (1056, 0.00), (1080,

0.00), (1104, 0.00), (1128, 0.0013), (1152, 0.0042), (1176, 0.005), (1200, 0.00), (1224, 0.00), (1248, 0.00), (1272, 0.00), (1296, 0.00), (1320, 0.0146), (1344, 0.0825), (1368, 0.0063), (1392, 0.0008), (1416, 0.00), (1440, 0.0096), (1464, 0.0058), (1488, 0.0025), (1512, 0.00), (1536, 0.00), (1560, 0.00), (1584, 0.00), (1608, 0.0075), (1632, 0.00), (1656, 0.00), (1680, 0.0313), (1704, 0.00), (1728, 0.00), (1752, 0.00), (1776, 0.00), (1800, 0.00), (1824, 0.00), (1848, 0.00), (1872, 0.0008), (1896, 0.0038), (1920, 0.00), (1944, 0.0258), (1968, 0.004), (1992, 0.00), (2016, 0.00), (2040, 0.00), (2064, 0.0017), (2088, 0.0108), (2112, 0.0263), (2136, 0.00), (2160, 0.00), (2184, 0.0046), (2208, 0.0571), (2232, 0.0179), (2256, 0.0008), (2280, 0.0008), (2304, 0.00), (2328, 0.0208), (2352, 0.0058), (2376, 0.00), (2400, 0.00), (2424, 0.00), (2448, 0.0163), (2472, 0.00), (2496, 0.0046), (2520, 0.00), (2544, 0.00), (2568, 0.00), (2592, 0.0008), (2616, 0.00), (2640, 0.0096), (2664, 0.0042), (2688, 0.00), (2712, 0.00), (2736, 0.00), (2760, 0.00), (2784, 0.00), (2808, 0.0233), (2832, 0.00), (2856, 0.0321), (2880, 0.00), (2904, 0.0067), (2928, 0.00), (2952, 0.00), (2976, 0.00), (3000, 0.0275), (3024, 0.00), (3048, 0.00), (3072, 0.00), (3096, 0.00), (3120, 0.0292), (3144, 0.0179), (3168, 0.00), (3192, 0.00), (3216, 0.00), (3240, 0.00), (3264, 0.0038), (3288, 0.0121), (3312, 0.0529), (3336, 0.0192), (3360, 0.0242), (3384, 0.00), (3408, 0.0071), (3432, 0.00), (3456, 0.0021), (3480, 0.0008), (3504, 0.0004), (3528, 0.00), (3552, 0.00), (3576, 0.00), (3600, 0.00), (3624, 0.00), (3648, 0.00), (3672, 0.0004), (3696, 0.00), (3720, 0.00), (3744, 0.0004), (3768, 0.00), (3792, 0.00), (3816, 0.00), (3840, 0.00), (3864, 0.00), (3888, 0.0017), (3912, 0.0067), (3936, 0.00), (3960, 0.0008), (3984, 0.00), (4008, 0.00), (4032, 0.0021), (4056, 0.0025), (4080, 0.00), (4104, 0.0117), (4128, 0.00), (4152, 0.00), (4176, 0.0175), (4200, 0.00), (4224, 0.00), (4248, 0.0096), (4272, 0.0013), (4296, 0.0021), (4320, 0.00), (4344, 0.00), (4368, 0.00), (4392, 0.00), (4416, 0.0538), (4440, 0.0021), (4464, 0.00), (4488, 0.00), (4512, 0.00), (4536, 0.0363), (4560, 0.0346), (4584, 0.0008), (4608, 0.00), (4632, 0.00), (4656, 0.00), (4680, 0.00), (4704, 0.0021), (4728, 0.015), (4752, 0.00), (4776, 0.00), (4800, 0.00), (4824, 0.00), (4848, 0.00), (4872, 0.00), (4896, 0.013), (4920, 0.00), (4944, 0.00), (4968, 0.00), (4992, 0.00), (5016, 0.00), (5040, 0.00)

Methane Chain

CH4_1(t) = CH4_1(t - dt) + (CH4_Gen_1 - CH4_Flow_1 - CH4_Util_1 - CH4_Des_1) * dtINIT CH4_1 = Inital_Mass
INFLOWS:
CH4_Gen_1 = Anerobic__Growth_1*CH4_Yield_Rate
OUTFLOWS:
CH4_Flow_1 = CH4__Con_1*SW_Flow_1
CH4_Util_1 = MT_Growth_1*CH4__Consumption
CH4_Des_1 = -CH4_Abs_Coeff*Gas_Des_Area*(Max_CH4_Con-CH4__Con_1)
CH4_2(t) = CH4_2(t - dt) + (CH4_Gen_2 + CH4_Flow_1 - CH4_Flow_2 - CH4_Util_2 - CH4_Des_2) * dtINIT CH4_2 = Inital_Mass
INFLOWS:
CH4_Gen_2 = Anerobic__Growth_2*CH4_Yield_Rate
CH4_Flow_1 = CH4__Con_1*SW_Flow_1
OUTFLOWS:
CH4_Flow_2 = CH4__Con_2*SW_Flow_2
CH4_Util_2 = MT_Growth_2*CH4__Consumption

CH4_Des_2 = -CH4_Abs_Coeff*Gas_Des_Area*(Max_CH4_Con-CH4__Con_2)
CH4_F(t) = CH4_F(t - dt) + (CH4_Gen_F + CH4_Flow_2 - CH4_Flow_O - CH4_Util_F - CH4_Des_F) * dtINIT CH4_F = Inital_Mass
INFLOWS:
CH4_Gen_F = Anerobic__Growth_F*CH4_Yield_Rate
CH4_Flow_2 = CH4__Con_2*SW_Flow_2
OUTFLOWS:
CH4_Flow_O = CH4__Con_F*SW_Flow__Out
CH4_Util_F = MT_Growth_F*CH4__Consumption
CH4_Des_F = -CH4_Abs_Coeff*Gas_Des_Area*(Max_CH4_Con-CH4__Con_F)
CH4_Abs_Coeff = 1
CH4_Yield_Rate = 16/4.6
CH4__Consumption = 2.39
Gas_Des_Area = CTW_Sec_Area*Void_Rat
Max_CH4_Con = .035

Methanotroph Biomass Chain
MT_Biomass_1(t) = MT_Biomass_1(t - dt) + (MT_Growth_1 - MT_Dieoff_1 - MT_Flow1) * dtINIT MT_Biomass_1 = Inital_Mass*.1
INFLOWS:
MT_Growth_1 = MT_Biomass_1*(MT_Max_Rate*(CH4__Con_1/(CH4__Con_1+CH4_Half_Sat))*(Ox_Con_1/(Ox_Con_1+MT_OX_Half_Sat)))
OUTFLOWS:
MT_Dieoff_1 = MT_Biomass_1*MT_Dieoff
MT_Flow1 = BM_Susp*MT_BM_Con_1*SW_Flow_1
MT_Biomass_2(t) = MT_Biomass_2(t - dt) + (MT_Growth_2 + MT_Flow1 - MT_Dieoff_2 - MT_Flow_2) * dtINIT MT_Biomass_2 = Inital_Mass*.1
INFLOWS:
MT_Growth_2 = MT_Biomass_2*(MT_Max_Rate*(CH4__Con_2/(CH4__Con_2+CH4_Half_Sat))*(Ox_Con_2/(Ox_Con_2+MT_OX_Half_Sat)))
MT_Flow1 = BM_Susp*MT_BM_Con_1*SW_Flow_1
OUTFLOWS:
MT_Dieoff_2 = MT_Biomass_2*MT_Dieoff
MT_Flow_2 = BM_Susp*MT_BM_Con_2*SW_Flow_2
MT_Biomass_F(t) = MT_Biomass_F(t - dt) + (MT_Growth_F + MT_Flow_2 - MT_Dieoff_F - MT_Flow_O) * dtINIT MT_Biomass_F = Inital_Mass*.1
INFLOWS:
MT_Growth_F = MT_Biomass_F*(MT_Max_Rate*(CH4__Con_F/(CH4__Con_F+CH4_Half_Sat))*(Ox_Con_F/(Ox_Con_F+MT_OX_Half_Sat)))
MT_Flow_2 = BM_Susp*MT_BM_Con_2*SW_Flow_2
OUTFLOWS:
MT_Dieoff_F = MT_Biomass_F*MT_Dieoff
MT_Flow_O = BM_Susp*SW_Flow__Out*MT_BM_Con_F

CH4_Half_Sat = .00045
MT_Dieoff = .006
MT_Max_Rate = .018
MT_OX_Half_Sat = .000061

Oxygen Chain
Oxygen_1(t) = Oxygen_1(t - dt) + (Ox_to_CTW + Root_Ox_Inflow_1 + Rain__Ox__Inflow_1 - Ox_Flow_1 - Ox_Util) * dtINIT Oxygen_1 = Inital_O2
INFLOWS:
Ox_to_CTW = (Max_Ox_Sol*SW_InFlow)/Grams_per_Kilo
Root_Ox_Inflow_1 = Max_Aerial__Ox_Rate*CTW_Sec_Area*Wet_Root_1*Ox_Dem_1
Rain__Ox__Inflow_1 = (CTW_Rain*Max_Ox_Sol)/Grams_per_Kilo
OUTFLOWS:
Ox_Flow_1 = SW_Flow_1*Ox_Con_1
Ox_Util = (Aerobic_Growth_1*Aero_Ox__UtilRate)+(MT_Growth_1*MT_OX__Util_Rate)
Oxygen_2(t) = Oxygen_2(t - dt) + (Root_Ox_Inflow_2 + Rain__Ox__Inflow_2 + Ox_Flow_1 - Ox_Flow_2 - Ox_Util_2) * dtINIT Oxygen_2 = Inital_O2
INFLOWS:
Root_Ox_Inflow_2 = Max_Aerial__Ox_Rate*CTW_Sec_Area*Wet_Root_2*Ox_Dem_2
Rain__Ox__Inflow_2 = Rain__Ox__Inflow_1
Ox_Flow_1 = SW_Flow_1*Ox_Con_1
OUTFLOWS:
Ox_Flow_2 = SW_Flow_2*Ox_Con_2
Ox_Util_2 = (Aerobic_Growth_2*Aero_Ox__UtilRate)+(MT_Growth_2*MT_OX__Util_Rate)
Oxygen_F(t) = Oxygen_F(t - dt) + (Root_Ox_Inflow_F + Rain__Ox__Inflow_F + Ox_Flow_2 - Ox_Out - Ox_Util_F) * dtINIT Oxygen_F = Inital_O2
INFLOWS:
Root_Ox_Inflow_F = Max_Aerial__Ox_Rate*CTW_Sec_Area*Wet_Root_F*Ox_Dem_F
Rain__Ox__Inflow_F = Rain__Ox__Inflow_1
Ox_Flow_2 = SW_Flow_2*Ox_Con_2
OUTFLOWS:
Ox_Out = SW_Flow__Out*Ox_Con_F
Ox_Util_F = (Aerobic_Growth_F*Aero_Ox__UtilRate)+(MT_Growth_F*MT_OX__Util_Rate)
Aero_Ox__UtilRate = 1.23*1.68
CTW__Depth = .6
Grams_per_Kilo = 1000
Max_Aerial__Ox_Rate = .00035/24
Max_Ox_Con = .014
Max_Ox_Sol = 12.4
MT_OX__Util_Rate = 2.38

Ox_Dem_1 = (Max_Ox_Con-Ox_Con_1)/Max_Ox_Con
Ox_Dem_2 = (Max_Ox_Con-Ox_Con_2)/Max_Ox_Con
Ox_Dem_F = (Max_Ox_Con-Ox_Con_F)/Max_Ox_Con
Wet_Root_1 = Depth_1/CTW__Depth
Wet_Root_2 = Depth_2/CTW__Depth
Wet_Root_F = Depth_F/CTW__Depth

Storm Water and COD Chains

COD_1(t) = COD_1(t - dt) + (Decay_1 + COD_to_CTW + Plant_COD_Intro_1 - COD_Flow_1 - COD_Util_1) * dtINIT COD_1 = 0
INFLOWS:
Decay_1 = (Aerobic__Dieoff_1+Anaerobic__Dieoff_1+MT_Dieoff_1)*BM_COD
COD_to_CTW (IN SECTOR: Input Structure)
Plant_COD_Intro_1 = CTW_Sec_Area*Max_Aerial_COD_Rate*((COD_Goal-COD_Con_1)/COD_Goal)
OUTFLOWS:
COD_Flow_1 = SW_Flow_1*COD_Con_1
COD_Util_1 = (Aerobic_Growth_1*Aero__Consumption)+(Anerobic__Growth_1*Anaero_Consumption)
COD_2(t) = COD_2(t - dt) + (COD_Flow_1 + Decay_2 + Plant_COD_Intro_2 - COD_Flow_2 - COD_Util_2) * dtINIT COD_2 = 0
INFLOWS:
COD_Flow_1 = SW_Flow_1*COD_Con_1
Decay_2 = (Aerobic__Dieoff_2+Anaerobic__Dieoff_2+MT_Dieoff_2)*BM_COD
Plant_COD_Intro_2 = CTW_Sec_Area*Max_Aerial_COD_Rate*((COD_Goal-COD_Con_2)/COD_Goal)
OUTFLOWS:
COD_Flow_2 = COD_Con_2*SW_Flow_2
COD_Util_2 = (Aerobic_Growth_2*Aero__Consumption)+(Anerobic__Growth_2*Anaero_Consumption)
COD_F(t) = COD_F(t - dt) + (Decay_F + Plant_COD_Intro_F + COD_Flow_2 - COD_Out - COD_Util_F) * dtINIT COD_F = 0
INFLOWS:
Decay_F = (Aerobic__Dieoff_F+Anaerobic__Dieoff_F+MT_Dieoff_F)*BM_COD
Plant_COD_Intro_F = CTW_Sec_Area*Max_Aerial_COD_Rate*((COD_Goal-COD__Con_F)/COD_Goal)
COD_Flow_2 = COD_Con_2*SW_Flow_2
OUTFLOWS:
COD_Out = SW_Flow__Out*COD__Con_F
COD_Util_F = (Aerobic_Growth_F*Aero__Consumption)+(Anerobic__Growth_F*Anaero_Consumption)
COD_Mass_Exit(t) = COD_Mass_Exit(t - dt) + (Outflow_Tot) * dtINIT COD_Mass_Exit = 0

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INFLOWS:
Outflow_Tot = COD_Out*Measure_On
SW_1(t) = SW_1(t - dt) + (Rain_in_1 + SW_InFlow - SW_Flow_1) * dtINIT SW_1 =
CTW_Sec_Area*Weir__Pitch_O*Void_Rat
INFLOWS:
Rain_in_1 = CTW_Rain
SW_InFlow    (IN SECTOR:  Input Structure)
OUTFLOWS:
SW_Flow_1 = Flow_Comp_1
SW_2(t) = SW_2(t - dt) + (SW_Flow_1 + Rain_in_2 - SW_Flow_2) * dtINIT SW_2 =
CTW_Sec_Area*Weir__Pitch_O*Void_Rat
INFLOWS:
SW_Flow_1 = Flow_Comp_1
Rain_in_2 = CTW_Rain
OUTFLOWS:
SW_Flow_2 = Flow_Comp_2
SW_F(t) = SW_F(t - dt) + (Rain_in_F + SW_Flow_2 - SW_Flow__Out) * dtINIT SW_F
= CTW_Sec_Area*Weir__Pitch_O*Void_Rat
INFLOWS:
Rain_in_F = CTW_Rain
SW_Flow_2 = Flow_Comp_2
OUTFLOWS:
SW_Flow__Out = Outflow*Time_Conv
Aero__Consumption = 2.99
Anaero_Consumption = (1/.0605)*1.64
BM_COD = 1.42
Box_D_Below_Weir_Ch_O = 0
COD_Goal = .02
CTW_Sec_Length = (60/8)*(2/3)*1.1
CTW__Width = 130
Depth_1 = (SW_1/(CTW_Sec_Length*CTW__Width))/Void_Rat
Depth_2 = (SW_2/(CTW_Sec_Length*CTW__Width))/Void_Rat
Depth_F = (SW_F/(CTW_Sec_Length*CTW__Width))/Void_Rat
Flow_Comp_1 = ((Depth_1-Depth_2)/CTW_Sec_Length)*Flow__CS_1*HC
Flow_Comp_2 = ((Depth_2-Depth_F)/CTW_Sec_Length)*Flow__CS_2*HC
Flow_H_O = Depth_F-(Weir__Pitch_O+Box_D_Below_Weir_Ch_O)
Flow__CS_1 = ((Depth_1+Depth_2)/2)*CTW__Width
Flow__CS_2 = ((Depth_2+Depth_F)/2)*CTW__Width
g = 9.806194
HC = 21
Max_Aerial_COD_Rate = 0.01
Outflow =
IF(Flow_H_O<0)THEN(0)ELSE(Weir_Coeff_O*((2/3)*(SQRT(2*g)))*Weir_Width_O*
(Flow_H_O^1.5))
Time_Conv = 3600
Void_Rat = .47
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Weir_Coeff_O = .602+.075*(Flow_H_O/Weir__Pitch_O)
Weir_Width_O = 1
Weir__Pitch_O = .2
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Capt. William J. McLaughlin graduated from Coyle-Cassidy High School, Taunton MA in June 1997. In August of that year he entered Worcester Polytechnic Institute, Worcester MA. He graduated with a Batchelor of Science in Civil and Environmental Engineering in May 2001 and was also commissioned as a second lieutenant in the United Stated Air Force. Captain McLaughlin has served at numerous base-level positions as a member of the 16th Civil Engineer Squadron, Hurlburt Field, FL, 51st Civil Engineer Squadron, Osan AB Republic of Korea, and 431st Civil Engineer Squadron, Einsiedlerhof AS, Germany. He has also held the positions of Executive Officer, Joint Special Operations Air Component, Southwest Asia, in support of Operation ENDURING FREEDOM and Operations Flight Commander, 386 Expeditionary Civil Engineer Squadron, Ali Al Salem AB, Kuwait, in support of Operation IRAQI FREEDOM.

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14. ABSTRACT

Aircraft deicing is vital to safe operation in cold weather environments. Unfortunately, release of glycol-based aircraft deicing fluids (ADF) to waterways adjacent to airfields poses a significant environmental threat. The deicing fluids used at DoD airfields impart a high biochemical oxygen demand (BOD) when they enter waterways. The currently accepted conventional treatment is collection and transport of ADF-laden storm water to a publicly owned treatment works. The volume and BOD concentrations in the storm water often make this type of treatment impractical. Subsurface flow constructed treatment wetlands have been demonstrated to be effective in attenuating ADF-induced BOD. The models currently used to design and model these types of wetlands focus on simple input-output relationships and do not take underlying processes into account. This study explores the use of a system dynamics modeling method as the basis for a useful design and management tool. The model focuses on simulating storm water flow between defined sections of the wetland and microbial kinetics in each section. Microbial utilization of substrates leads to attenuation in well designed wetlands. The model exhibits the potential to be a useful tool for this and possibly other applications

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