Fate and Transport of Algae in a Constructed Stormwater Wetland

By

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Acronyms

- Ammonia nitrogen (NH_3-N)
- Chlorophyll a (Chl a)
- Constructed Stormwater Wetland (CSW)
- Constructed Wetland (CW)
- Department of Environmental Protection (PADEP)
- Dissolved Oxygen (DO)
- New Jersey Department of Environmental Protection (NJDEP)
- National Research Council (NRC)
- Nitrate (NO_3)
- Nitrite (NO_2)
- Organic Matter (OM)
- Orthophosphate (PO_4^{3-})
- Storm Water Management Model (SWMM)
- Stormwater Control Measures (SCM)
- Total Dissolved Solids (TDS)
- Total Kjeldahl Nitrogen (TKN)
- Total Kjeldahl Phosphorus (TKP-P)
- Total Nitrogen (TN)
- Total Phosphorus (TP)
- Total Suspended Solids (TSS)
- Villanova University Constructed Stormwater Wetland (VU CSW)

Abstract

It is important to understand the biological, chemical and physical processes of any water body in order to determine the mass balance of pollutants into and out of the system. An understanding of the mass balance allows for the analysis of the fate and transport of the constituents in the water body. For this research, the fate and transport of one such constituent (algae) in the Villanova University Constructed Stormwater Wetland (VU CSW) was analyzed.

The site is monitored continuously for parameters such as flow rate and temperature. The water quality is monitored periodically (~two sampling events/month) during baseflow and storm conditions. Storm events are defined as > 0.25 inches of precipitation in a 24-hour period and baseflow conditions are defined as starting after 72 hours without rain or when the flow at the outlet is lower than 0.1 cfs. The main purpose of the wetland is to remove pollutants and reduce the flow rate.

The mass balance in the VU CSW follows the general concept of any mass balance (Accumulation = Inflow - Outflow). A mass balance of algae was performed in the CSW in order to determine the exportation of algae from the CSW. Volume of the wetland, flow, chlorophyll a concentration and organic matter were the parameters used to calculate the mass balance. According to the mass balance, the main mass of Chl a was in the inlet forebay of the CSW. The range of Chl a accumulated in the inlet forebay was below detection up to 48 gr. The range of mass of Chl a leaving the inlet forebay was 0.004 – 12 gr, while the range of Chl a leaving the CSW was 0.001- 0.12 gr. Therefore, exportation of algae from the CSW was minimal in comparison with the amount of algae accumulated in the inlet forebay. Also, the mean consumption of PO_4^{3-}-P in the CSW during baseflow was 0.06 mg/L and 0.01 mg/L during storm

events in the CSW. Nevertheless, the uptake of PO_4^{3-} by algae was lower than the actual removal of phosphate. The uptake of PO_4^{3-} by algae was < 0.02 mg/L-P.

Chapter 1

1.1 Background

Human activities can bring negative effects in the environment. Any substance that can cause a negative effect in the environment is considered a pollutant which has to be controlled in order to reduce adverse impacts. Pollutants can come from different sources, although human activities (i.e. agriculture, change of land use, and others) are one source of production of pollutants which can affect the environment (Scholz, 2011).

Changing land cover and land use influence the physical, chemical, and biological conditions of downstream waterways (NRC, 2008). More impervious areas mean that the water cannot infiltrate into the soil. Therefore, there is more runoff bringing an excessive amount of pollutant load to water bodies. Most of the impervious cover in an urban watershed or sub-watershed can be organized into three main categories: rooftops, transport system and recreational facilities (EPA, 2005).

One of the major problems of runoff is the amount of pollutants that are transported into water bodies (i.e sediment, metals, nutrients and others) due to the development of cities and the increase of impervious area, which has an effect on the water cycle. Urbanization of the landscape profoundly affects how water moves both above and below ground during and following storm events (NRC, 2008). Furthermore, the storage of water into the ground, the groundwater discharge, and the evaporation decrease as well due to the increase of impervious area.

Urban stormwater runoff is recognized as a potential pollutant source for downstream waterways and aquatic ecosystems. The amount and types of pollutants carried in stormwater runoff will vary according to land use, the intensity and duration of rainfall events, and the time between rainfall events (Greenway, 2010). Stormwater is the water originated from precipitation, ice melt and snow, and the stormwater runoff is the generated by those. Stormwater runoff carries nutrients, sediments, metals, and other pollutants. Nutrients are important to maintain a balance in the ecosystem, but high amounts of nutrient can be detrimental for the environment because they are one of the factors that stimulate the growth of algae (Greenway, 2010; Kadlec and Knight, 1995).

Stormwater Control Measures (SCM) are defined by the National Research Council (2008) as "*a technique, measure, or structural control that is used for a given set of conditions to manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner"*. Stormwater Control Measures reduce or mitigate the generation of stormwater runoff and associated pollutants. These practices include both structural or engineered devices as well as nonstructural measures such as land-use planning, site design, land conservation, education, and stewardship practices (NRC, 2008). Stormwater Control Measures facilities such as constructed stormwater wetlands, rain gardens, pervious pavements, infiltration trenches, vegetated swales, and others have the purpose of controlling the volume of runoff, reducing peak flow and improving water quality.

Constructed stormwater wetlands (CSWs) are shallow marsh systems planted with emergent vegetation that are designed to treat stormwater runoff (PADEP, 2006). Standard constructed stormwater wetlands are engineered wetland systems used to remove a wide range of pollutants from land development sites by directing stormwater runoff through an open, marsh system where pollutants are removed through settling and both uptake and filtration by the vegetation (NJDEP, 2004). The site of research of this study is a constructed stormwater wetland (CSW).

Constructed stormwater wetlands design and hydrodynamic conditions contribute to the pollutant reductions and the ability to achieve design standards, although the physical design may be the key in pollutant removal (Wadzuk et al., 2010). Furthermore, constructed stormwater wetlands improve runoff quality through settling, filtration, uptake, chemical and biological decomposition, volatilization, and adsorption (PADEP, 2006).

Constructed stormwater wetlands are designed for the purpose of removing bacteria, enteric viruses, suspended solids, BOD, nitrogen (predominantly as ammonia and nitrate), metals, and phosphorus (Scholz, 2011). Pollutant removal varies depending on flow condition (Wadzuk et al., 2010), and its effectiveness varies by season and may be affected by the age of the wetland (PADEP, 2006). The major difference between CSW's performance during storm events and baseflow is the residence time (Wadzuk et al., 2010). Peak flow rate is primarily controlled in CSWs throughout the transient storage above the normal water surface. Constructed stormwater wetlands can achieve some volume reduction through evapotranspiration, especially during small storms (PADEP, 2006).

Constructed stormwater wetlands are usually planted with emergent vegetation (EPA, Vol. 1, 1995). The goal of planting CSWs is to generate dense, diverse vegetation that mimics nearby natural wetlands (EPA, Vol. 5, 1995). Both vascular (the higher plants) and non-vascular plants (algae) are important in CSWs (EPA, Vol. 1, 1995). Algae provide some of the first indications of changes in wetlands because they respond directly to many environmental changes, they have high dispersal rates, and they have rapid growth rates (EPA, 2002). Some of the mechanisms that influence the growth of algae are solar radiation, runoff, water temperature and nutrient (nitrogen, phosphorus) input (EPA, 2008; Thomann and Mueller, 1987).

1.1.1 Villanova University Constructed Stormwater Wetland

The Villanova University Constructed Stormwater Wetland (VU CSW) is located at the northeast end of campus. The Constructed Stormwater Wetland receives runoff from the main and west campus of the university and the outflow discharges into the Mill Creek. Before 1999, the site was a stormwater detention basin that was about one acre in size and constructed with an underdrain which allowed the site remain dry during baseflow events but fill during storm events. The Constructed Stormwater Wetland was constructed in 1999 and redesigned in 2010 with the purpose of improving pollutant removal and flow rate reduction performance. Past research performed at Villanova University showed that if the flow path of the meanders were lengthened, better water quality as well as reduced flow rates would prevail. The area of the wetland is approximately 0.78 acres. The performance of the VU CSW is monitored through the wetland by collecting samples from the inlet, outlet, and meander 1 (M1), meander 2 (M2) and meander 3 (M3) (Figure 1.1).

The Constructed Stormwater Wetland is equipped to monitor the dissolved oxygen and temperature at the inlet, meander 1, meander 3 and outlet and the flow from the main and west campus as well as the flow discharging to Mill Creek. In addition, there is a rain gauge next to the VU CSW that monitors precipitation, evaporation, air temperature, solar radiation, relative humidity and wind speed. The Constructed Stormwater Wetland, due to its large area and high plant density, removes suspended solids and nutrients during storm events and baseflow conditions throughout the year (Wadzuk et al., 2010).

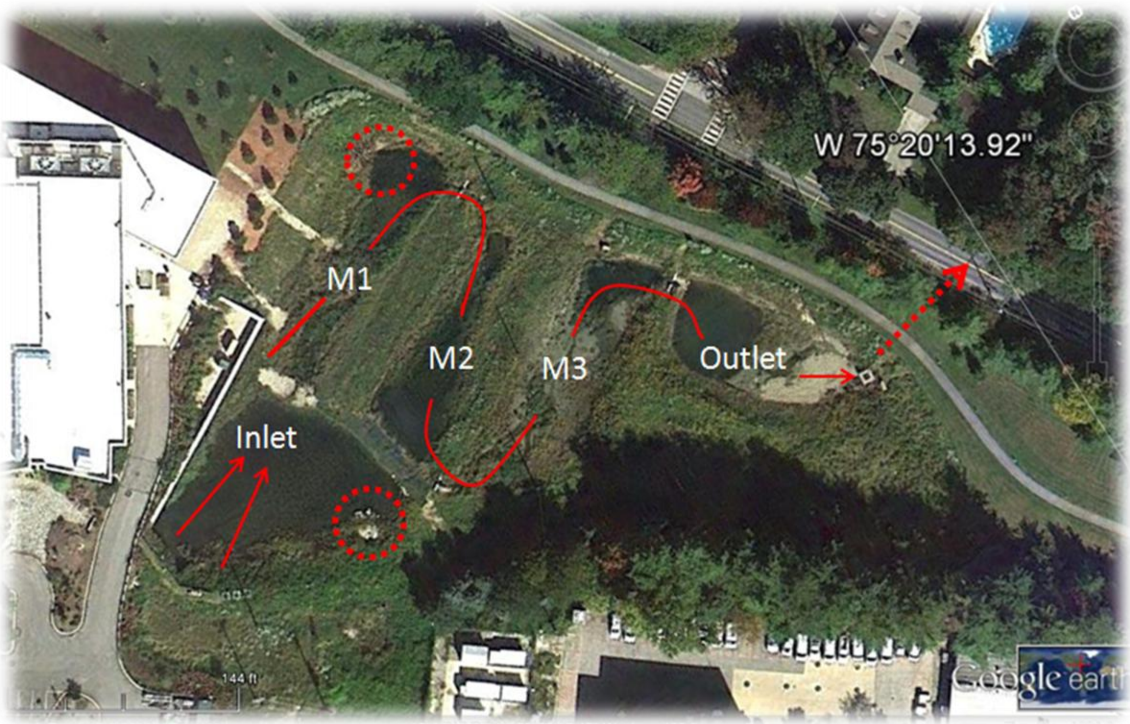

Figure 1.1 Villanova University Constructed Stormwater Wetland (VU CSW)

Source: Stormwater Wetland Smartbook

1.2 Objectives of Study

The main objective of this research was to analyze the fate and transport of algae in a constructed stormwater wetland (CSW).

The specific objectives of this study were to:

1. Calculate the mass of algae in the CSW
2. Determine correlations between chlorophyll a (i.e. algae) and factors that stimulate algal growth.
3. Verify the seasonal variation of algae and nutrients in the CSW.
4. Estimate the contribution of algae on the reduction of phosphate in the CSW.

Chapter 2 Literature Review

2.1 Constructed Stormwater Wetlands

Constructed stormwater wetlands (CSWs) are one type of stormwater control measure (SCM) that control volume of runoff, reduce peak flow and improve water quality. The principal water quality objective of a CSW is the retention of fine sediment and nutrients (Birch et al., 2004). Water quality improvement in a surface flow CSW may involve a variety of processes such as flocculation, sedimentation, gas transfer, adsorption, biological degradation, photosynthesis and plant uptake (Tao, 2010). However, the pollutant concentration and flow rate are variable in CSWs and the performance of CSWs treating pollutants depend on the amount of runoff into the stormwater wetland (Yu et al., 2012). Important water quality parameters in CSWs are turbidity, temperature, color, radioactivity, organic compounds, nutrients, biochemical oxygen demand, acidity, alkalinity, dissolved oxygen, minerals, oil, sludge, herbicides, and pesticides (EPA, 1977).

Research has shown the efficiency and performance of CSWs removing pollutants such as Total Suspended Solids (TSS), Total Phosphorus (TP), Total Nitrogen (TN), Total Kjeldahl Nitrogen (TKN), Orthophosphate (PO_4), Ammonia (NH_3-N), Nitrate (NO_3), Nitrite (NO_2) and Total Dissolved Solids (TDS) (Carleton et al., 2000; Wadzuk et al., 2010; Yu et al., 2012). Table 2.1 shows percent removals of pollutants in CSWs. The variation in the performance of CSWs removing pollutants could vary due to variations in the hydraulic residence time of the CSW, the design of the CSW, the type of pollutant to be removed, the conditions of the CSW (baseflow or storm events conditions).

Table 2.1 Pollutant percent removal from CSWs

Location	TSS	TP	OP	TKN	TN	NH_3-N	TDS	NO_2	NO_3
Manassas, Virginia[a]	57.9	45.9	35.8	25.5	21.7	54.7	-	-	-
Jeongeup, Korea[b]	-87.1	-	58.2	28.7	15.9	79.9 (NH_4-H)	-	-	-
Riverwood, Sydney[c] (during dry weather)	-98 - 46	12	-	9	-	-	-	-	-
Spain (Lagoon)[d]	42	45	-	-	30	-	-	-	-
Spain (Lagoon)[d]	28	49	-	-	28	-	-	-	-
VU-CSW (baseflow conditions)[e]	45	63	65	62	71	-	40	73	84
VU CSW (storm events)[e]	48	40	30	29	37	-	44	26	53

[a] Carleton et al., (2000) [c] Birch et al., (2004) [e] Wadzuk et al., (2010)
[b] Yu et al., (2012) [d] Rodrigo et al., (2013)

Wadzuk et al. (2010) documented that the greatest removal of each pollutant during storm events and baseflow conditions varied by season and year. Rinker (2013) explained that the reasons for the increased performance during baseflow conditions were the increased hydraulic retention time, the hydrodynamics that dictate the flow paths within the various functional design components of the system (e.g. inlet sediment forebay, shallow runs, deep zones, etc.) and the microhabitat dynamics and nutrient interactions with the biota. Water quality improvement in wetlands and ponds is promoted by a complex array of chemical, biological and physical actions (Wong et al., 1999). The performance of CSWs removing pollutants is highly variable and depends on the amount of runoff into the stormwater wetland (Yu et al., 2012).

Nutrients (i.e nitrogen, phosphorus) are essential to aquatic organisms, but excessive amounts could lead to negative effects on the environment. For example, nutrients are essential for plants growth but, in excess, they can cause algal blooms, increasing the growth of unicellular algae and cyanobacteria (Greenway, 2010). The main nutrients that can lead to an algal bloom are nitrogen and phosphorus. Phosphorus is a nutrient required for plant growth and is frequently a limiting factor for vegetative productivity in freshwater systems (Kadlec and Knight, 1995). Whereas nitrogen is considered one of the limiting factors in coastal water (Mitsch and

Gosselink, 2015). Organisms within the wetland require phosphorus for growth and incorporate it in their tissues. The most rapid uptake is by microbiota (bacteria, fungi, algae, microinvertebrates, etc) because these organisms grow and multiply at high rates (Kadlec and Knight, 1995). The nutrient uptake by plants is expected to vary according to the season, especially in temperate climates, with chemical retention greatest in the growing seasons (spring and summer) due to higher rates of microbial activity and macrophyte productivity (Scholz, 2011).

The presence of algae can increase the suspended solids concentration and organic matter content of water bodies. According to the PADEP (2006), the performance of a wetland to reduce total suspended solids (TSS) and total phosphorus (TP) is 85%, but this depend on many variables such as the temperature, flow, vegetation inside the wetland, retention time and season of the year.

2.2 Eutrophication

Eutrophication is the excessive growth of aquatic plants, both attached and planktonic, to levels that are considered to be an interference with desirable water uses (Thomann and Muller, 1987). Eutrophication can seriously affect the quality of any water body because of decreases in dissolved oxygen. A rise in water temperature might easily be the factor which stimulates an excessive growth of algae (EPA, 1977), generating, therefore, a eutrophication problem.

Eutrophication of water bodies results in phytoplankton blooms and reduced water clarity because of light absorption by phytoplankton and increased concentrations of dissolved organic compounds produced by phytoplankton (Vymazal, 1995). Some of the factors which influence eutrophic conditions in water bodies are runoff with a high content of nutrients, such as nitrogen and phosphorus, solar radiation and temperature. These factors can lead to algae blooms which could have negative effects in the quality of water bodies. A eutrophic SCM is not wanted as it leads to poor aesthetic conditions, reduced ecological quality as well as decreased treatment (Wium-Andersen et al., 2013).

2.3 Algae

According with Flugel (2010), algae *are aquatic photosynthetic benthic and planktonic plants, ranging from micron-size unicellular forms to giant kelps several meters long*. One of the principal reasons for the importance of algae is their ability to give rise to very large quantities of organic matter in the water (EPA, 1977). The main focus of this research was on plankton, which are floating plants in the water. Unattached microorganisms that are dispersed individually or in colonies in water are designated collectively as planktonic. Normally, most of the growth of algae in the stream is caused by planktonic organisms which are usually dominated by rotifers and diatoms (EPA, 1977).

Algae provide some of the first indications of changes in wetlands because they respond directly to many environmental changes, they have high dispersal rates, and they have rapid growth rates (EPA, 2002). Some of the mechanisms that influence the growth of algae are solar radiation, runoff, water temperature and nutrients input (nitrogen, phosphorus) (EPA, 2008; Thomann and Mueller, 1987). Algal growth depends on the environment and the area where they are growing. Algal blooms typically occur during the summer or in environments with high temperature, nutrients and runoff inputs. While during the winter, with low temperatures, low light intensities, and short days, phytoplankton biomass and productivity are generally low in spite of elevated nutrient concentrations (Vymazal, 1995). Furthermore, algal growth can vary from one water body to another, and within a water body. Water flow depth, travel time and geometry of the water body are factors which influence the concentration or amount of algae in different parts of a water body.

The type of algae defines the characteristic of the algae species. Different types of algae can be found inside a water body. Research conducted by Quinn (2014) in the VU CSW found that the inlet of the VU CSW was dominated by light green surface algae throughout the summer. The algae became more copious during the summer under baseflow conditions, transforming the surface of the inlet pond in an ostensibly green solid mass. On the other hand, the outlet contained another algal species which was typically submerged (Quinn, 2014).

2.3.1 Chlorophyll a

Chlorophyll a measures the level of algae in a water body although it does not provide information about the type of algae species (Thomann and Mueller, 1987). Chlorophylls are the basic pigments involved in light absorption and photochemistry in higher plants, algae and photosynthetic bacteria (Vymazal, 1995). They are common indicators of biomass for algal studies because the problem of sorting algae from non-algal material is avoided (Westlake et al., 1998).

Algal primary productivity is mainly influenced by nutrients, light, temperature, grazing and successional cycles (Vymazal, 1995). Chlorophyll a is an indicator of the amount of algae in water bodies, varying according to the season of the year, travel time, water flow, and other parameters. In a constructed wetland which receives urban and agricultural runoff in Ontario, Canada, Goulet and Pick (2001) found that in the fall, chlorophyll a and pH decreased, suggesting declines in growth rates or die-off. In the same way, Rios et al., (1998) found that the plankton population in September, although multispecies, was dominated by diatoms while detritus was dominant in December. The optimum temperature for a diatom to grow is 18 – 30 °C (EPA, 1977). The main season for algae growth is during the summer because growth conditions are ideal to stimulate the growth of algae in water bodies.

Chlorophyll a and parameters such as water temperature and nutrients have been reported in different studies (Table 2.2). Research conducted by Wu and Mitsch (1998) in two newly constructed riparian freshwater wetland in Columbia, Ohio showed that the average chlorophyll a concentrations decreased from the inflow to middle to outflow consistently in the freshwater wetlands.

Table 2.2 Reported parameters in CSWs

Name /Wetland type	Chl a (mg/L)	Water temperature (°C)	DO (mg/L)	pH	Ammonia -N (mg/L)	Nitrate-N (mg/L)	Orthophosphate-P (mg/L)
Jericho / SW* [a]	0.519 ± 0.159	26.8 ± 5.2	>20	8.2 ±1.1	0.21±0.3	0.29±0.27	0.06±0.01
Fishtrap Creek /SW* [a]	0.0054 ± 0.0028	22.6±5.8	11.9±2.4	7.6 ±0.5	0.04±0.01	0.04±0.01	0.01±0.01
Wood leachate treatment wetland [a]	0.0009 ± 0.001	13.8±3.4	0.4±0.1	5.1 ±0.4	0.16±0.1	0.07±0.05	0.66±0.32
Alma gol / NW** [b]	0.004-0.156	-	-	-	0.10-11.9	0.01-2.75 0.01-0.39*- (nitrite*-)	0.02-3.7 (Phosphate)
Odense pond / SW* [c]	0.288 ± 0.136	-	-	-	-	-	-
Constructes freshwater wetland [d]	0-0.288	-	-	-	-	-	-
Golden pond* (sediment basin)[e]	0.004 ±0.001	-	-	-	-	-	-
Golden pond* (wetland 1)[e]	0.005 ±0.003	-	-	-	-	-	-
Golden pond* (wetland 2)[e]	0.003 ±0.001	-	-	-	-	-	-

*Stormwater wetland (SW)
**Natural wetland (NW)
[a] Tao (2010)
[b] Bblali et al., (2013)
[c] Wium-Andersen et al., (2013)
[d] Wu and Mitsch (1998)
[e] Greenway (2010)

2.4 Organic Matter (OM)

Organic matter supports many different kinds of organisms which feed on it, forming the base of a developed trophic pyramid (Westlake et al., 1998). The organic matter in natural waters can be from both autochthonous and allochthonous natural origin and anthropogenic activities (Leloup et al., 2013). Several groups of primary producers can be distinguished in any type of wetland, which tend to have different fates: macrophytes, filamentous algae, microphytic algae and autotrophic microorganisms (Westlake et al., 1998). The production by living organisms (mainly phytoplankton and bacteria) are autochthonous sources of natural organic matter whereas allochthonous sources of natural organic matter include soils and catchment inputs brought by runoff (Leloup et al., 2013).

OM concentrations from phytoplankton algae are higher during the growing season. Therefore, the production of organic matter during the summer is higher and then starts to decrease during the fall. Lower concentrations of OM are typical during winter and beginning of spring, and then start to increase again at the end of spring. Algae productions vary according to the type of algae. They are common constituents of shallow marsh ponds and other areas, regularly, but not necessarily inundated. This type of algae seems to develop and decline quickly and to decompose rapidly (Westlake et al., 1998).

Management of particulate organic matter in stormwater treatment measures is important. If systems become overloaded by organic matter, the depletion of oxygen may prevent aerobic respiration (required by macro aquatic organisms) as well as nitrification (Taylor et al., 2005), which is an obligate aerobic process and is the biological conversion of ammonia (NH_4^+) to nitrate (NO_3^-) (Maltby and Barker, 2009).

2.5 Nutrients

Stormwater runoff contains excess nutrients, which are one of the major factors that stimulate algae growth and lead to eutrophication. The two most significant nutrients considered in the growth of algae are nitrogenous compounds and phosphates. These, together with carbon dioxide, are generally the materials whose availability determines the quantity and quality of algal growth (EPA, 1977). Excessive nutrients are the key factor of eutrophication with phosphorus being one of the crucial nutrients (Huang, 2016). The eutrophication process can be expressed as the following equation (Harrison, 1999; Beaugrand, 2015; Huang, 2016).

$$106\ CO_2 + 16\ NO_3^- + HPO_4^{2-} + 122\ H_2O + 18\ H^+ \rightarrow C_{106}\ H_{263}\ O_{110}\ N_{16}\ P + 138\ O_2$$

The availability of nutrients is essential for algae growth but it is common that one nutrient is more abundant than other. Therefore, one nutrient will be the limited factor for algae growth. When the ratio between nitrogen and phosphorus is greater than 10 for lakes dominated by non-point sources, phosphorus is typically the limited factor for algae growth (Thomann and Mueller, 1987).

2.5.1 Nitrogen

Nitrogen is considered a macronutrient and is present in the Earth in different forms such as nitrogen gas, nitrite, nitrate, organic nitrogen, ammonia and ammonium. Being a macronutrient, it is one of the main nutrients present in water bodies and that stimulates the growth of organisms in water. Nitrogen could be a limiting factor for algae to grow in water bodies. Quinn (2014) suggested that nitrogen was the limiting factor in the VU CSW.

As nitrogen species are transported in aqueous conditions, they are subject to a range of transformation processes (Taylor et al., 2005) such as settlement, denitrification and microbial and plant uptake. Nitrogen removal in CSWs is accomplished primarily by physical settlement, nitrification, denitrification and plant and microbial uptake. Plant uptake does not represent permanent removal unless plants are routinely harvested (Healy and Cawley, 2002).

The cycle of nitrogen (Figure 2.1) in wetlands has both organic and inorganic forms of nitrogen entering to the wetland which can break down into different forms of nitrogen. Nitrogen reactions in wetlands can effectively process inorganic N through nitrification and denitrification, ammonia volatilization, and plant uptake. A significant portion of dissolved organic N that is assimilated by plants is returned to the water column during breakdown of detrital tissue or soil organic matter, and the majority of this dissolved organic N is resistant to decomposition. Under these conditions, water leaving wetlands may contain elevated levels of N in organic form (EPA, 2008).

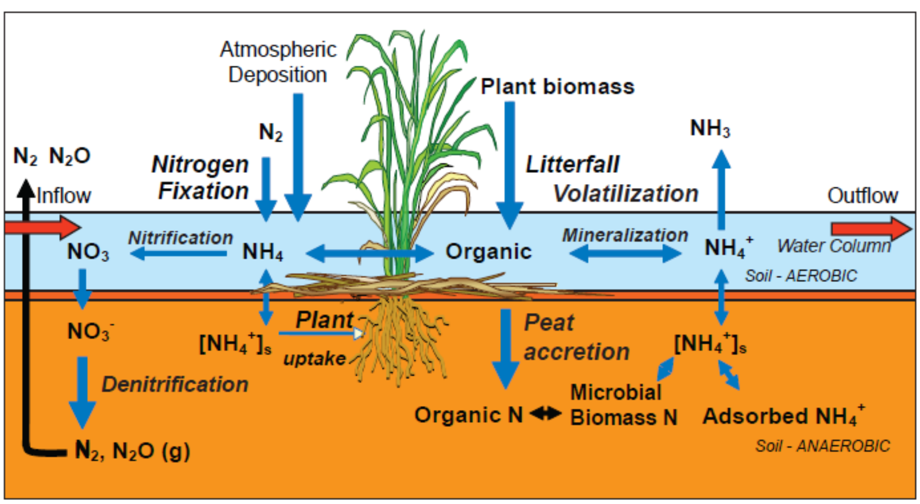

Figure 2.1 Nitrogen cycle in wetlands (EPA, 2008)

The nitrogen chemical transformation from inorganic to organic compounds and back from organic to inorganic require energy to proceed, and others transformation processes release energy, which is used by organisms for growth and survival (Kadlec and Knight, 1995). The speed of the nitrogen cycle depends on the environmental conditions, organisms present in the water body ecosystem and the interaction between soil and water.

Ammonium has been observed to be undetectable during a phytoplankton bloom in May and June (Mei et al., 2005). In the summer, a significant portion of the uptake of ammonium is utilized in the formation of macrophyte tissues taken up by the microflora such as algae (Kadlec and Knight, 1995). Thus, the incoming nitrogen species can be processed in a large internal cycle of nitrogen: ammonium uptake by plants, organic N release from decay, nitrification, denitrification, and mineralization of organic N to ammonium.

2.5.2 Phosphorus

Phosphorus is a macronutrient essential for the growth of algae and it tends to be the limited nutrient for algae growth in freshwater systems. Organisms within the wetland require phosphorus for growth and incorporate it in their tissues. The most rapid uptake is by microbiota (bacteria, fungi, algae, microinvertebrates, etc) because these organisms grow and multiply at high rates (Kadlec and Knight, 1995).Therefore, because phosphorus is a nutrient, the addition of this element to the wetland can stimulate growth and causes increases in biomass (Kadlec and Knight, 1995).

The different reactions of phosphorus in wetland include sedimentation, precipitation, flocculation and uptake and release of phosphorus by plants. The different forms of phosphorus in wetlands are dissolved organic and inorganic phosphorus, and particulate organic and inorganic phosphorus. The removal of phosphorus in wetlands is a complex process (Figure 2.2). Dissolved inorganic P (DIP) is generally bioavailable, whereas dissolved organic (DOP) and particulate organic P (POP) forms generally must be transformed into particulate inorganic P (PIP) forms before becoming bioavailable. Both biotic and abiotic mechanisms regulate relative pool sizes and transformations of P compounds within the water column and soil (EPA, 2008).

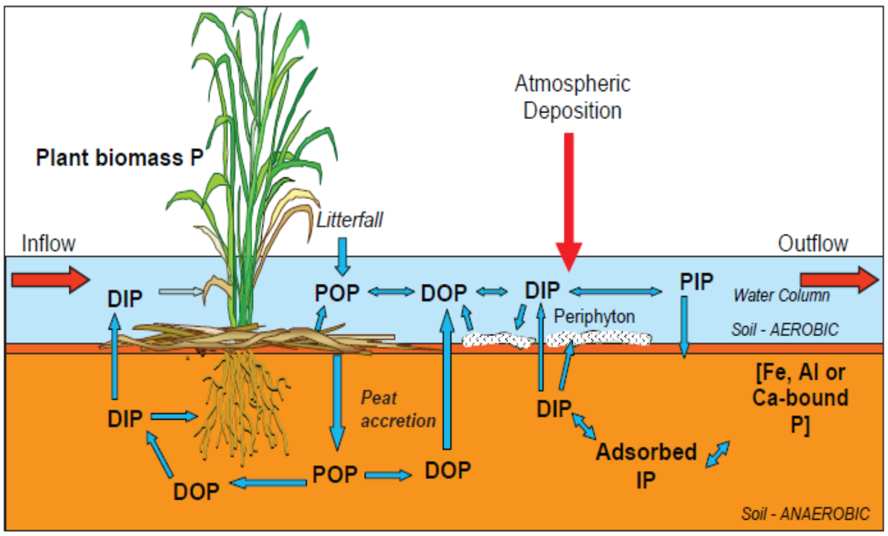

Figure 2.2 Phosphorus cycle in wetlands (EPA, 2008)

Chapter 3 Methodology

The objective of this research was to determine and evaluate the fate and transport of algae in a CSW. To meet this objective, it was essential to analyze the different factors that stimulate algae growth. Some of these factors were flow rate, temperature and nutrients. Therefore, this chapter explains the procedures used to determine and analyze the different factors. This research was conducted from May until October 2015.

3.1 Villanova University Constructed Stormwater Wetland (VU CSW) monitoring

The VU CSW was monitored continuously for parameters such as flow rate, dissolved oxygen, temperature, and weather data. The instrumentations to measure the temperature, and the influent and effluent flow of the wetland were installed at multiple locations throughout the CSW (Table 3.1, Figure 3.1). The data from these were recorded in 5 minutes intervals and transmitted through a wireless server to a computer. The data from each device was verified and downloaded once per month to see if there was any problem or device disconnection, and to analyze the data.

Table 3.1 Wetland instrumentation

Device	Location (see Figure 3.1)
Greyline flow sensor (model: AVFN-II-A1A1A1C1A)	Inlet west pipe (1)
Greyline flow sensor (model: AVFM 5.0)	Inlet main pipe (2)
Greyline flow sensor (model: AVFM 5.0)	Outlet (5)
American Sigma 2149 tipping bucket rain gauge	Close the inlet forebay of the wetland (1)
Dissolved oxygen probe (model RDO PRO Probe)	Inltet (1), M1 (3), Outlet (5)
Campbell Scientific 107 temperature probes	Inlet (1), M1 (3), M3 (4), Outlet (5)
HACH American Sigma (Automated sampler) (model 900MAX Portable Sampler)	Inlet (1), M1 (3), Outlet (5)

Figure 3.1 CSW monitoring site locations data

For this research, the water flow rate, temperature and rainfall data were analyzed to see how these parameters influenced the concentration of Chlorophyll a (Chl a) within the CSW. The temperature data presented is the mean temperature in the inlet forebay, meander 1 (M1) and outlet. Data from 2011 to 2015 were analyzed in order to find a pattern in the physical and chemical behavior of the wetland.

3.2 Flow Rate

The flow rate data presented was recorded by the flow sensors installed in the inlet main and west pipe, and in the outlet of the CSW (Figure 3.1). When the flow sensor was not working, the flow rate was generated by modeling the area of CSW using the Storm Water Management Model (SWMM) created by the US Environmental Protection Agency (US EPA). From May until the end of August (August 26th, 2015), the flow sensor installed in the inlet west pipe was not working. Therefore, the flow rate for this pipe was generated using SWMM. In the same way, on July 10th, 2015 the flow sensor of the inlet main pipe stopped working. Thus, the flow rate for July, August, September and October was generate using SWMM. The data from the flow sensor and the flow generated using SWMM is presented in the Appendix (Table A.2).

The flow rate reported in this research is the mean flow rate during the entire day. To perform the mass balance of algae and organic matter in the CSW, the mean daily inflow rate was the sum of the daily main flow rate of the inlet main pipe + the daily main flow rate of the inlet west pipe, while the daily outflow rate was the daily mean flow rate at the outlet.

3.3 Water Quality

The water quality was monitored periodically (~two sampling events/month) during baseflow and storm conditions, where storm events were defined as > 0.25 inches of precipitation in a 24 hour period. Meanwhile, baseflow conditions were defined as starting after 72 hours without rain or when the flow at the outlet was lower than 0.1 cfs. To analyze the water quality, samples were collected from the wetlands during baseflow and storm events.

3.3.1 Samples Collection

During baseflow conditions and storm events, samples were collected from the inlet, meander 1, meander 2, meander 3 and outlet (Figure 3.2) in order to see how the concentration of Chl a decreased or increased through the wetland. The samples in the inlet were collected in three locations called In1, In2 and In3 (Figure 3.2). The samples were brought to the Water Resources Laboratory of Villanova University to analyze for Chlorophyll a, total suspended solids (TSS), organic matter (OM), orthophosphate (PO_4^{3-}), Total Kjeldahl Phosphorus (TKP-P) and nitrogen (different forms on nitrogen) immediately. Samples were usually collected on two or three consecutive days.

Figure 3.2 Sampling locations

Samples were collected in HACH 575ml polyethylene bottles from which 250 ml were used to test TSS, 30 - 100 ml to test Chl a and 10 ml to test phosphate. When sample collection was performed with the VUSP graduates assistants group, two sample bottles usually were collected. The second bottle was used to analyze Chl a. The samples tested for nutrients were transferred to 25 ml and 50 ml bottles and put it in the fridge for a maximum 28 days. To preserve the sample, 0.1 ml of nitric acid was added to the 50 ml bottle. The nutrients analyzed from the preserved bottles were TKN and TKP-P. The other nutrients such as phosphate and nitrite were analyzed from the 25 ml bottle.

Sample collection was performed from May 26th to October 29th, 2015. In total, thirty one samples were collected during this period, 20 during baseflow conditions and 11 during storm events.

Table 3.2 Information about date of sample collection and events

Date	Event
5/26/2015	Baseflow
6/13/2015	Baseflow
6/14/2015	Baseflow
6/15/2015	Baseflow
6/16/2015	Storm event
6/22/2015	Storm event
6/24/2015	Storm event
6/26/2015	Storm event
6/27/2015	Storm event
6/28/2015	Storm event
7/7/2015	Baseflow
7/9/2015	Baseflow
7/16/2015	Storm event *
7/17/2015	Storm event
7/21/2015	Baseflow

Date	Event
7/23/2015	Baseflow *
8/27/2015	Baseflow *
8/31/2015	Baseflow
9/1/2015	Baseflow
9/3/2015	Baseflow *
9/8/2015	Baseflow
9/9/2015	Baseflow
9/11/2015	Storm event *
9/15/2015	Baseflow
9/17/2015	Baseflow *
9/23/2015	Baseflow
10/5/2015	Storm event *
10/7/2015	Baseflow
10/8/2015	Baseflow
10/20/2015	Baseflow
10/29/2015	Storm event *

* Collected with VUSP graduate assistants

3.3.1 Chlorophyll a (Chl a)

Chlorophyll a was the main test of this research. The Chl a procedure was performed according to Standard Methods (2005). The sample collection was typically performed in the afternoon between 2-4 p.m. The day before sample collection, Whatman filters (1.5 µm pores) were put in the oven for 2 hours. After collecting samples for the Chl a test, 30 - 100 ml of the sample was filtered and then the filter was macerated by adding 3 ml of an aqueous acetone solution (90% acetone, 10% $MgCO_3$). After each sample was macerated, it was transferred to a 15 ml centrifuge tube that was covered with aluminum foil, and then placed in fridge at 4 °C for 13 - 15 hours.

After taking out the samples from the fridge, the samples were centrifuged (Figure 3.3) at 500 g for 30 minutes, then 10 ml of the sample was transferred to a cuvette and the optical density from the 400U Spectrophotometer (Figure 3.4) was read at 750, 664, 647 nm and 630 nm. Then the samples were acidified with 0.33 ml of 0.1 *N* HCL and the optical density was read again after 90 seconds of the acidification at 750 and 665 nm.

Figure 3.3 Centrifuge

Figure 3.4 400U Spectrophotometer

The Chl a concentration was calculated according to the Jeffrey and Humphrey Trichromatic equation and the Lorenzen's Peheopigment – Corrected Chl a and Pheo a equation.

Jeffrey and Humphrey Trichromatic equation

$$Ca\left(\frac{mg}{L}\right) = 11.85(\mathrm{OD664}) - 1.54(\mathrm{OD647}) - 0.08(\mathrm{OD630})$$

$$Chl\left(\frac{mg}{m^3}\right) = \frac{Ca * extract\ volume, L}{Volume\ of\ sample, m^3}$$

Lorenzen's Peheopigment – Corrected Chl a and Pheo a equation

$$Chl\ a\ \left(\frac{mg}{m^3}\right)\frac{26.7\ (664b - 665a)\ Volume\ of\ extract, L}{Volume\ od\ sampl, L * Light\ path\ length\ of\ width\ of\ curvette}$$

The units for Chl a in mg/m^3 were converted to mg/L.

In order to verify the Chl a results, monthly calibration curves (Figure 3.5) were develop from a chlorophyll a stock solution standard (Sigma-Aldrich Cas# 479-61-8) used to prepare Chl a dilutions. The stock solution was diluted at different concentration from 0.025 to 10 mg/L Chl a in order to obtain concentrations in the range measured in the samples. The procedure to develop the calibration curve was the same used to measure Chl a in CSW samples. The chlorophyll stock solution (as is pure chlorophyll) is sensitive to light. Chl a test procedures always were performed under dark conditions in the laboratory.

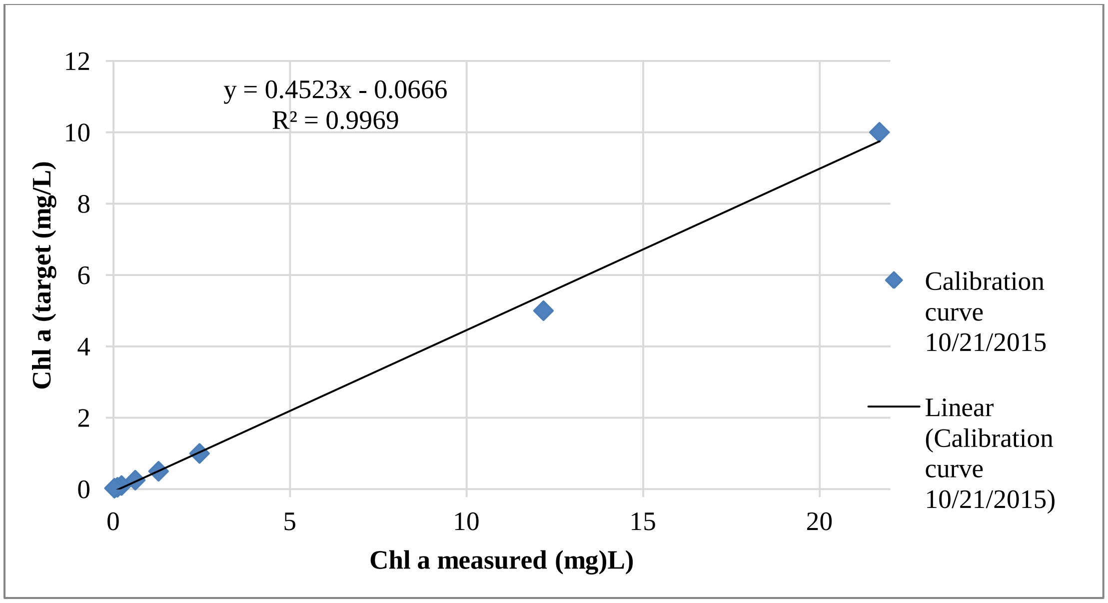

Figure 3.5 Chl a calibration curve

3.3.2 Total Suspended Solids (TSS)

To perform TSS tests, approximately 250 ml of sample was filtered through a Whatman 1.5 µm filter. It is important to allow the sample to filter for several minutes to ensure that all dissolved materials have completely passed through the membrane. The pre-weighed filters were then placed in the oven at a temperature of 105°C for 3-6 hours. Then they are placed in a dessicator to cool before being weighted.

3.3.3 Organic Matter (OM)

The organic matter test was performed after finishing the TSS procedure. Filters from the TSS analysis were places in an oven at a temperature of 550°C for 30 minutes, and then they were placed in a dessicator to cool prior to being weighted (Figure 3.6).

Figure 3.6 Filters after weighted

3.3.4 Nutrients

Nutrients were determined in the Water Resources Laboratory. The different forms of nitrogen and phosphorus determined in the lab were analyzed in order to evaluate the performance of the CSW removing nutrients and the influence of nutrients on algae growth.

3.3.4.1 Nitrogen

The different forms of nitrogen determined in the Water Resources Laboratory were Total Keldahl Nitrogen (TKN), nitrate and nitrite. The USEPA Method 351.2 is the procedure used to determine TKN, USEPA 353.2 to determine nitrite, and discrete analysis (Systea Easy 1-Reagent, CASRN 14797-55-8) to determine the combination of nitrate plus nitrate (the nitrite concentration must then be subtracted from this combined (nitrate + nitrite) concentration to determine the nitrate concentration). To perform TKN, 25 ml of preserved sample was transferred to a tube, then 5 ml of copper sulfate digestion was added to the glass tube, then the glass sample is placed in the digester for approximately 3:30 hours. After the digestion process, the sample was diluted and then transferred to EasyChem cups and placed in the fridge until analyzed using the Chinchilla Scientific discrete nutrient analyzer (EasyChem). Nitrate and nitrite tests were performed 48 hours maximum after the sample collection. These procedures were performed in the EasyChem as well.

3.3.4.2 Phosphorus

The different forms of phosphorus determined in the Water Resources Laboratory and used for this research were total phosphorus and orthophosphate. The USEPA method 365.4 was the procedure used to quantify Total Kjeldahl Phosphorus (TKP-P) and USEPA method 365.1 was used to quantify orthophosphate. To perform TKP-P, 5 ml of every preserved sample was transferred to a glass vial; then 0.04 g of ammonium persulfate crystal and 0.1 ml of 11 N sulfuric acid were added to the glass vial, and then placed in an autoclave for 30 minutes. After taking out the glass vials from the autoclave, they were transferred to EasyChem cups and placed in the fridge until analyzed using the EasyChem. Orthophosphate test were performed 48 hours maximum after the sample collection. This procedure was performed in the EasyChem as well.

The procedure followed to quantify orthophosphate, when samples were taking without the VUSP graduates assistants group, was the DR/400 HACH procedure (Method 8048). For this procedure, 10 ml of the sample was placed in a cuvette and the content of one PhosVer 3 phosphate Powder Pillow was added to the cuvette. The sample was mixed for two minutes and then, after two minutes, the phosphate concentration was determined using a Spectrophotometer.

3.4 Tracer Test

Three tracer tests during baseflow were performed in the inlet forebay in order to analyze algal dynamics in that area of the CSW. A Keystone Rhodamine WT liquid was used as a tracer. The concentration of the tracer dye was 200,000 mg/L. From this stock solution, 100 mL of the stock solution was released in the wetland for the tracer test. Two Precision Measurement Engineering Inc. Cyclops-7 Loggers were utilized to read the data. Two Cyclops-7 were calibrated at 0 µg/l and 100 µg/l. The calibration was performed the day before the tracer tests. Cyclops-7 uses a visible light emitting diode to detect the tracer dye (Rhodamine WT liquid).

The tracer dye was released at the beginning of the inlet forebay (point 1 in Figure 3.7). Cyclops-7 Loggers were placed at In 2 and In 3 inside the inlet forebay (points 2 and 3, respectively, in Figure 3.7). Cyclops-7 loggers were left 5 days in the CSW and then taken out to analyze the recorded data. The equation 3.1 was used to calculate the mean retention time.

$$t = \frac{\int_0^{œ} t\, C(t)dt}{\int_0^{œ} C(t)dt} \qquad \text{(eq 3.1)}$$

Where,

C (t) is the concentration of the Rhodamine dye with time

t is the time

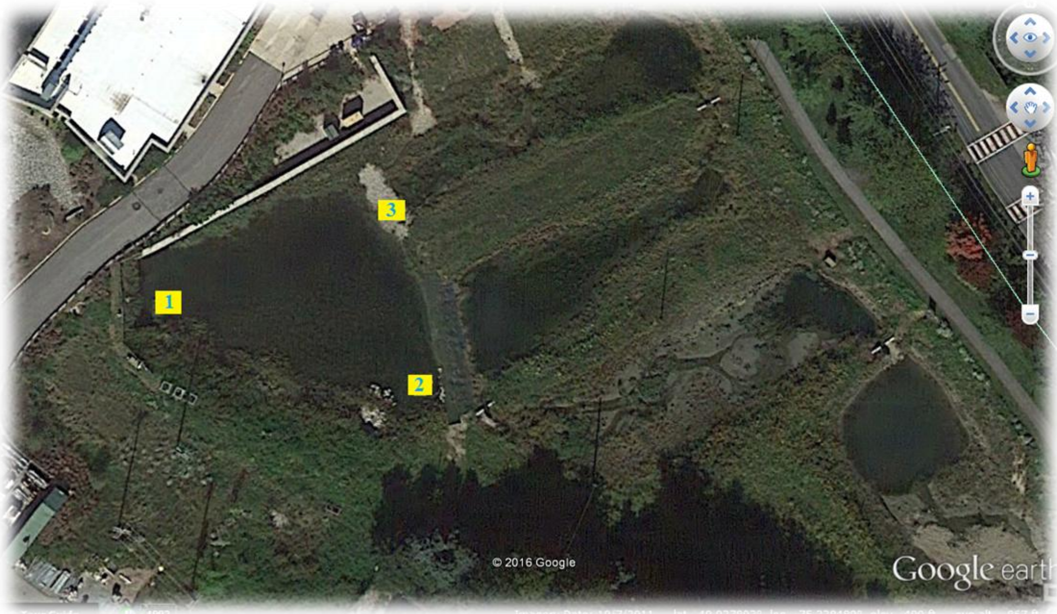

Figure 3.7 Location of Cyclops-7

3.5 Mass Balance

This research analyzed the fate and transport of algae in the VU CSW. The general equation to calculate a mass balance was:

$$Accumulation = Inflow - Outflow \qquad \text{(eq. 3.2)}$$

The equation of mass balance for any chemical in any control volume during any time interval is (Hemond and Fechner-Levy, 2000):

Change in accumulation of mass = mass transported in – mass transported out + growth – mass eliminated by sinks (eq 3.3)

Chapter 4 Results

4.1 Villanova University Constructed Stormwater Wetland (VU CSW)

Tracer tests were performed in the VU CSW in order to understand the dynamic of the CSW during the growing season of algae. Also, the volume of the wetland was determined in the inlet forebay to perform a mass balance of algae and organic matter in the CSW.

4.1.1. CSW Inlet Forebay Volume Estimation

During the summer of 2015, a survey was performed in the inlet forebay of the CSW to determine its volume. The elevation and water depth were measured at different locations inside of the inlet forebay (Figure 4.1 and Table 4.1). The deepest area of the inlet forebay was located at the beginning of the inlet (point 18 with a depth of 3.08 ft). Other deep areas were located in the middle of the inlet and toward the end of the inlet (points 13, 14 and 15) (Figure 4.2). The collection of samples for this research was performed at location DO, point 4 and at the end of the inlet (point 1).

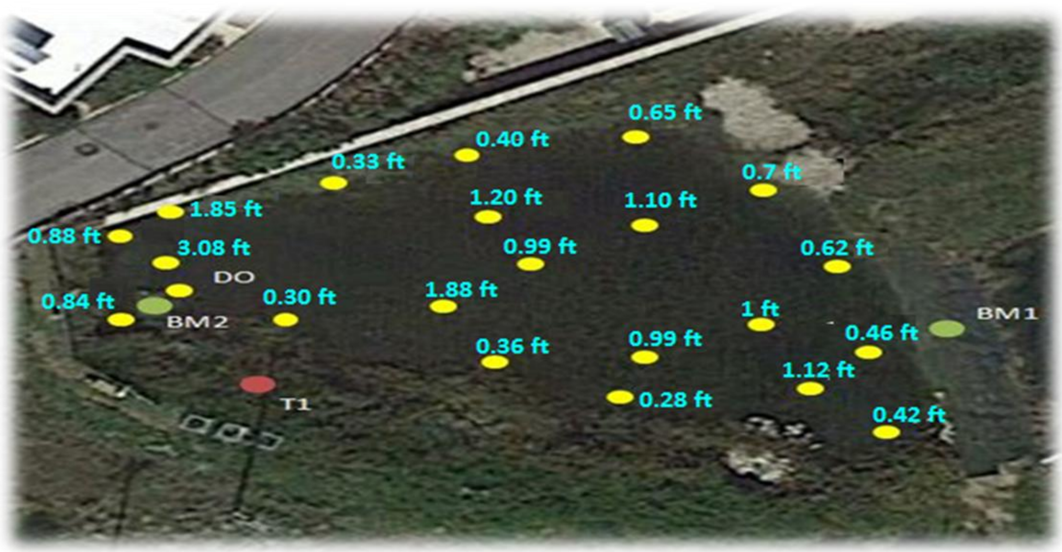

Figure 4.1 Wetland survey point

Table 4.1 Water depth at different points inside of the CSW

ID	Elevation (ft)	Water depth (ft)
1	395.01	0.7
2	395.13	0.62
3	395.32	0.46
4	395.32	0.42
5	395.45	0.28
6	395.16	0.36
7	395.64	0.30
8	394.88	0.84
9	394.87	0.88
9.25	393.88	1.85
9.5	395.41	0.33
10	395.31	0.40
11	395.08	0.65
13	394.61	1.10
14	394.68	1.00
15	394.62	1.12
16	394.83	0.99
17	393.84	1.88
18	392.59	3.08
19	394.47	1.20
20	394.71	0.99

Figure 4.2 Wetland surveys points identification

In order to calculate the volume of water in the inlet forebay, it was divided in six cross-sections (Figure 4.2). The volume of the CSW inlet during baseflow conditions calculated during the summer 2015 was 219 m³ (Table 4.2). For this research, this was the inlet forebay volume used for any mass balance calculation.

Table 4.2 Volume calculated of the CSW inlet

Volume of CSW				
Cross-section	**Area (ft^2)**	**Volume (ft^3)**	**Volume (L)**	**Volume (m^3)**
CS4 (7-18)	672	1,273	36,039	36
CS5 (6-9.5)	549	1,122	31,776	32
CS6 (5-10)	581	961	27,220	27
CS7 (4-11)	1,092	2,959	83,785	84
CS8 (4-11, In 3)	890	1,036	29,329	29
CS9 (8-9)	432	380	10,748	11
Total Volume	**4,216**	**7,730**	**218,898**	**219**

4.1.2. Tracer Tests

Three tracer tests were performed for In 3 and two for In 2 in the CSW during baseflow to determine the hydraulic residence time of water in the inlet forebay. Cyclops-7 rhodamine dye sensors were placed at In 2 and In 3 of the inlet forebay, while the rodhamine dye was introduced at In 1 (Figure 4.3).

Figure 4.3 Samples collection locations in the CSW

From the concentration vs time curve of the tracer test results (Figure 4.4 - 4.6), it is not accurate to argue that the inlet forebay is a completely mixed water body at least during the algae growing season. The area under the curve for In 3 for the trace test performed on August 27th, 2015 was approximately 14 times the area under the curve for In 2 (Figure 4.4). While, for the tracer test performed on October 22nd, the area under curve for In 3 was approximately 1.2 times the area for In 2 (Figure 4.6). This means that a significant amount of the tracer never made it to In 2 on August 27th but most of the tracer made it to In 2 on October 22nd. The tracer test performed on October 22nd showed a hydraulic residence time longer than the two previous tracer tests (Table 4.3). A lower flow rate and different wind direction during the tracer tests from October 22nd to

October 27th could have been the reason for a higher hydraulic residence time (Table 4.4). Another explanation for the variations in detention time between the two tracer studies could be due to the presence of algae. Algae were observed floating in the inlet forebay on August 27th (Figure 4.7) and September 17th, 2015 when tracer tests were performed. While on October 22nd, algae were not observed (Figure 4.8). The lack of algae means the tracer could disperse throughout the inlet forebay more. Therefore, the inlet forebay residence time could have been longer on October 22nd due to the lack of excessive algae.

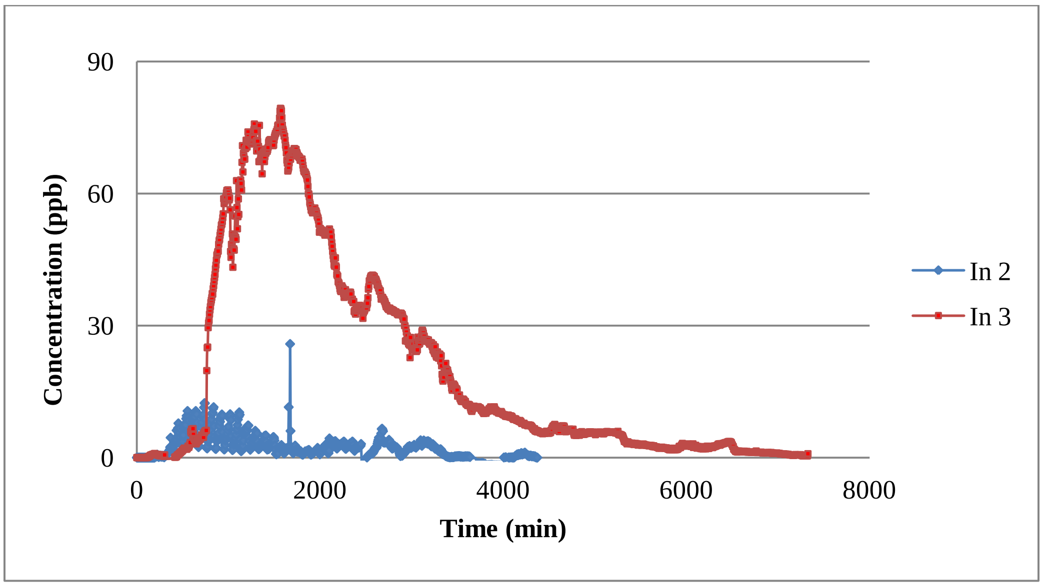

Figure 4.4 Residence time distribution curve from In1-In2 and In1-In3, 08/27/2015

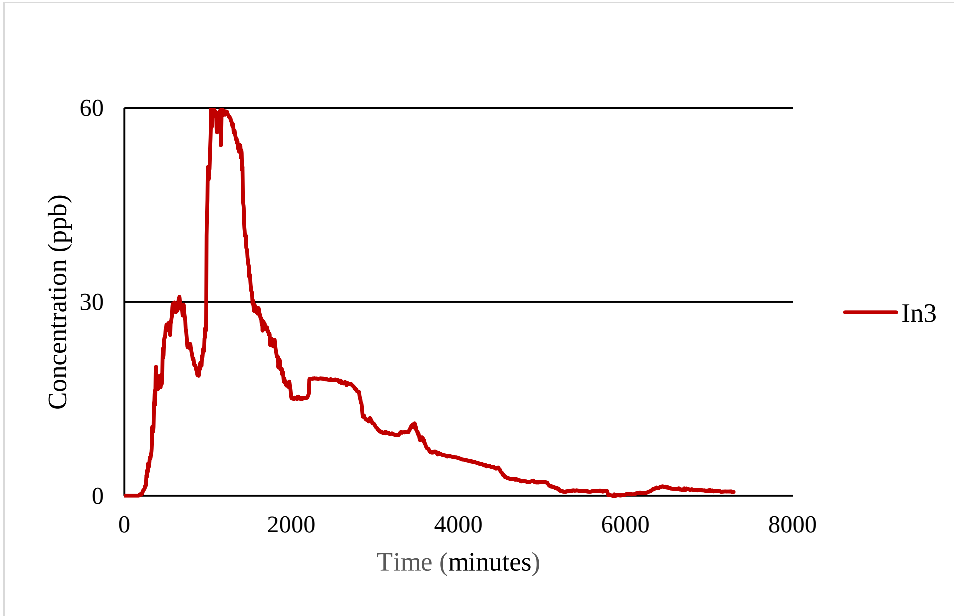

Figure 4.5 Residence time distribution curve from In1-In2 and In1-In3, 09/17/2015

The dynamics of the inlet forebay in In2 are different from In3 (Figures 4.4 and 4.6). Therefore, it is important that further research be performed in the inlet forebay in order to understand the dynamics of the inlet forebay during the growing and non-growing season of algae.

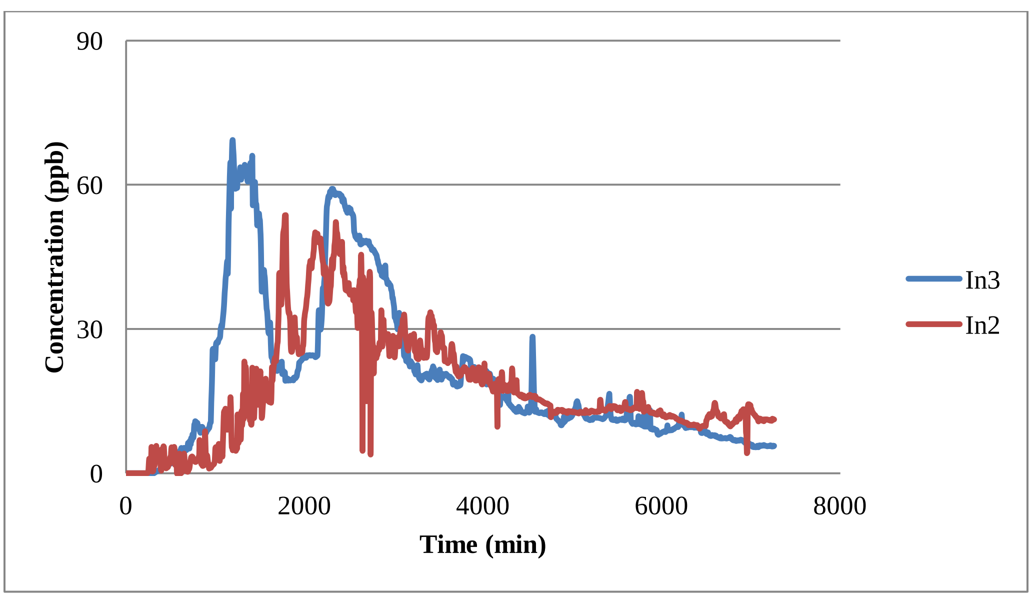

Figure 4.6 Residence time distribution curve from In1-In2 and In1-In3, 10/22/2015

The high standard deviation for In2 mean residence time is further proof of how different the dynamics are in that area of the inlet forebay (Table 4.3). But as there were just two data points about this, further research is important to be performed in that area.

Table 4.3 Tracer tests results

Dates	Mean time (hr)		Peak time (hr)		Area under the curve (ppb/min)	
	In2	In3	In2	In3	In2	In3
8/27/2015	25	37	28	26	10,341	145,519
9/17/2015	-	31	-	17	-	85,254
10/22/2015	59	50	30	20	126,227	145,517
Mean	42	40	29	21		
STDE	24	10	1	5		
n	2	3	2	3		

Table 4.4 Weather information during tracer tests

Dates	Mean Flow (cfs)	Wind Speed (mph)	Wind Direction
8/27/2015	0.21	1	NW
8/28/2015	0.22	1	NW
8/29/2015	0.16	2	SW
8/30/2015	0.77	2	SW
8/31/2015	0.26	3	W-SW
9/17/2015	0.19	-	S-W
9/18/2015	0.22	1	S
9/19/2015	0.29	2	S
9/20/2015	0.26	3	N
9/21/2015	0.22	2	E-NE
9/22/2015	1.05	2	NE
10/22/2015	0.18	1	SW
10/23/2015	0.12	2	N-NW
10/24/2015	0.14	1	S-E
10/25/2015	0.18	2	W-NW
10/26/2015	0.14	-	W-NW
10/27/2015	0.14	2	E

Figure 4.7 Condition of the inlet forebay on August 27th, 2015 at the start of the rhodamine dye tracer test

Figure 4.8 Condition of the inlet forebay on October 22nd, 2015 at the start of the rhodamine dye tracer test

4.2 Algae in the VU CSW

4.2.1. Chlorophyll a (Chl a) Concentration Profile

Chlorophyll a (Chl a) tests were performed as an indicator of algal biomass in the Villanova University Constructed Stormwater Wetland (VU CSW). Thirty one samples were collected at different locations inside the CSW during baseflow and storm events from May 26th until October 29th, 2015. Twenty samples were collected during baseflow and 11 during storm events. Samples were collected in the three meanders of the CSW, in the outlet and in the inlet (Figure 4.3). In the inlet, the samples were collected in three different locations inside of the inlet because every summer this is the area of the CSW where algae are visually detected. Results from the inlet are presented as the mean of the sample results in the inlet when the Chl a concentration was measured at the three locations. The three points selected in the inlet are located at the entrance of the CSW (In1) from where the water comes in, in an extreme eastern corner of the inlet (In2) and at the end of the inlet (In3). These three points were used to evaluate the exportation of algae during baseflow and storm event conditions from the inlet forebay of the CSW.

According to the chlorophyll a results (Table 4.5), at the beginning of the summer the concentration of Chl a was low. But then, as the summer progressed, Chl a concentration started to increase in the CSW and then decreased when summer ended (Figure 4.9). The higher concentrations of Chl a were measured in the inlet forebay, specifically at In2. Low concentrations of Chl a were measured in the meanders. Before, after, and during storm events, the main concentration of Chl a was mostly at In 2 and In3 (Figure 4.10 and 4.11). Lower concentrations of Chl a were measured in the meanders.

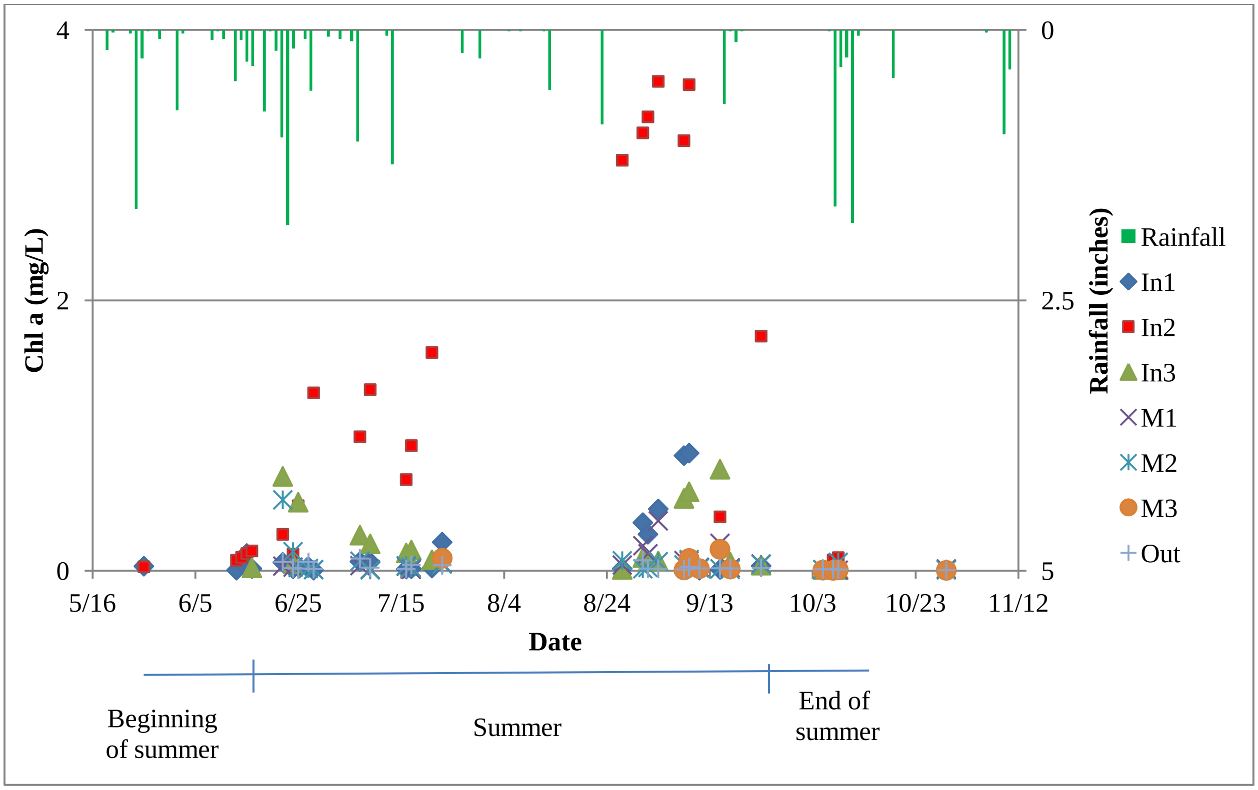

Figure 4.9 Chl a concentration vs time in the CSW

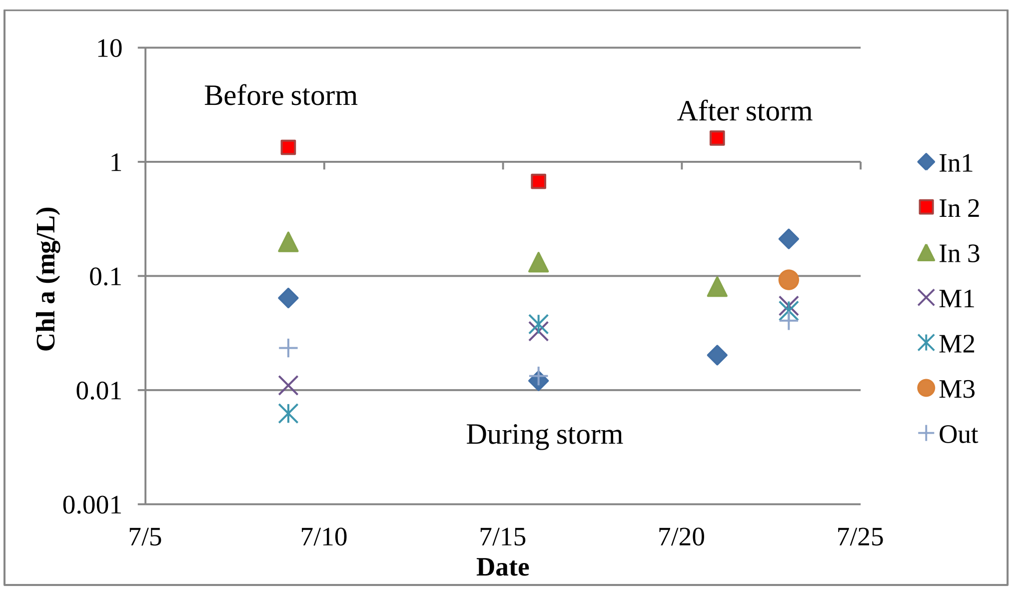

Figure 4.10 Chl a concentration before, during and after a storm event (July 09th – 21st, 2015)

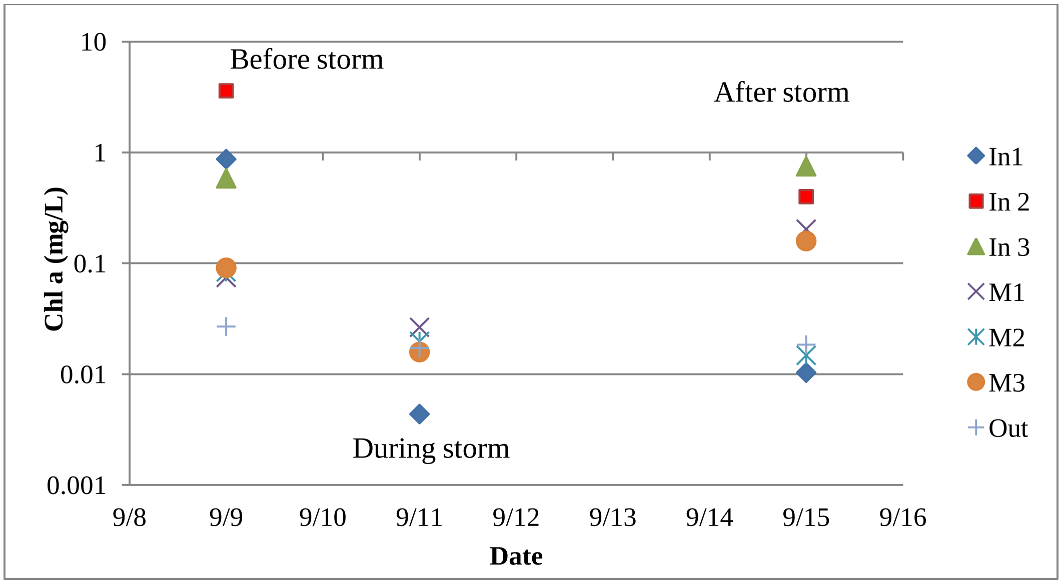

Figure 4.11 Chl a concentration before, during and after a storm events (September 09th – 15th, 2015)

Table 4.5 Results chlorophyll a concentration in the CSW

Date	Chl a (mg/L)									Comment	Rainfall (inches)	Mean water temperature (°C)			Mean flow (cfs)	
	No.	In1	In2	In3	Mean inlet	M1	M2	M3	Out	Event		Inlet	Outlet	M1	*** Inlet	Outlet
5/26/2015	1	0.03	0.03	-	-	-	-	-	-	Baseflow	0	22	24	23	0.2	0.1
6/13/2015	2	0.005	0.08	-	-	-	-	-	-	Baseflow	0	20	27	25	0.18	0.0
6/14/2015	3	0.06	0.10	-	-	-	-	-	-	Baseflow	0.09*	19	28	24	0.2	0.12
6/15/2015	4	0.13	0.13	-	-	-	-	-	-	Baseflow	0.01	18	26	24	0.2	0.1
6/16/2015	5	0.02	0.15	0.02	0.06	-	-	-	-	Storm event	0.08	20	26	24	0.25	0.1
6/22/2015	6	0.06	0.27	0.70	0.34	0.03	0.52	-	0.07	Storm event	0	21	26	24	0.2	0.0
6/24/2015	7	0.01	0.12	0.05	0.06	0.03	0.14	-	0.02	Storm event	0.19	21	25	23	0.2	0.1
6/25/2015	8	0.03	0.48	0.51	0.34	0.03	0.02	-	0.02	Storm event	0	21	24	22	0.37	0.2
6/27/2015	9	0.03	-	-	-	-	0.02	-	0.06	Storm event	1	19	20	20	2.8	1.1
6/28/2015	10	0.004	1.32	-	-	0.01	0.01	-	0.01	Storm event	1.79	20	20	21	0.6	0.6
7/7/2015	11	0.07	0.99	0.26	0.44	0.04	0.07	-	0.09	Baseflow	0	21	26	24	0.2	0.1
7/9/2015	12	0.06	1.34	0.20	0.53	0.01	0.01	-	0.02	Baseflow	1.03*	21	24	23	0.9	0.6
7/16/2015	13	0.01	0.67	0.13	0.27	0.03	0.04	-	0.01	Storm event	0	20	23	21	0.2	0.2
7/17/2015	14	0.01	0.93	0.15	0.36	0.01	0.02	-	0.04	Storm event	0	20	24	23	0.2	0.1
7/21/2015	15	0.02	1.61	0.08	0.57	-	-	-	-	Baseflow	0	20	27	25	0.2	0.1
7/23/2015	16	0.21	-	-	-	0.05	0.05	0.09	0.04	Baseflow	0	20	24	22	0.2	0.1
8/27/2015	17	0.02	3.04	0.01	1.02	0.04	0.07	-	-	Baseflow	0	19	21	20	0.2	0.08
8/31/2015	18	0.36	3.24	0.10	1.23	0.19	0.01	-	0.08	Baseflow	0	20	23	24	0.2	0.06
9/1/2015	19	0.27	3.36	0.07	1.23	0.13	0.02	-	0.02	Baseflow	0	20	24	23	0.2	0.1

Date	Chl a (mg/L)									Comment	Rainfall (inches)	Mean water temperature (°C)			Mean flow (cfs)	
	No.	In1	In2	In3	Mean inlet	M1	M2	M3	Out	Event		Inlet	Outlet	M1	*** Inlet	Outlet
9/3/2015	20	0.46	3.62	0.07	1.38	0.37	0.07	-	0.01	Baseflow	0	21	24	23	0.2	0.1
9/8/2015	21	0.85	3.18	0.54	1.52	0.08	0.04	0.01	0.01	Baseflow	0	21	23	23	0.2	0.1
9/9/2015	22	0.87	3.60	0.58	1.68	0.07	0.08	0.09	0.03	Baseflow	0	21	24	24	0.2	0.1
9/11/2015	23	0.004	-	-	-	0.03	0.02	0.02	0.02	Storm event	0.68	22	22	22	1.0	0.3
9/15/2015	24	0.01	0.40	0.75	0.39	0.20	0.01	0.16	0.02	Baseflow	0	20	19	19	0.3	0.04
9/17/2015	25	0.01		0.06	0.04	0.02	0.01	0.01	0.02	Baseflow	0	21	19	20	0.2	0.04
9/23/2015	26	0.04	1.74	0.04	0.60	0.05	0.05	-	0.02	Baseflow	0	19	18	18	0.1	0.04
10/5/2015	27	0.01	-	0.01	-	0.01	0.01	0.005	0.01	Storm event	0	17	14	14	0.2	0.1
10/7/2015	28	0.01	0.08	0.01	0.03	0.01	0.005	0.003	0.01	Baseflow	0	18	15	17	0.1	0.04
10/8/2015	29	0.01	0.10	0.01	0.04	0.005	0.06	0.01	0.01	Baseflow	0	18	16	17	0.1	0.04
10/20/2015	30	0.02	0.25	0.02	0.10	0.1	0.01	0.002	0.01	Baseflow	0	14	9	11	0.2	0.04
10/29/2015	31	0.01	-	-	-	0.01	0.01	0.003	0.01	Storm event	0.36	17	17	17	2.1	0.5

* Samples were collected before it rained
*** Sum of the mean flow from inlet main and inlet west (see appendix A.2 for more information)

Tables 4.6 and 4.7 show results of chlorophyll a concentration in the CSW during baseflow and storm events, respectively. These results are summarized in Figure 4.12. The results show higher concentrations of Chl a in the entire inlet forebay (Figure 4.12). It seems that the forebay is the most suitable area of the CSW for algae to grow, especially during baseflow conditions. This could be because of the geometry of the inlet forebay and also the depth of the inlet forebay. The area of the inlet forebay with the higher concentration of the Chl a was In2, which is located in the eastern corner or the wetland. The low flow rate during baseflow conditions is a factor playing an important role in the amount of algae at In 2 in the inlet forebay. After the tracer tests data shown in section 4.2, it implies that the wind speed and direction also could be another factor playing a role in amount of algae in In2. Although, the concentration of Chl a in the meanders was low (< 0.1 mg/L), the standard deviation was comparable to the averages (Figure 4.12, Table 4.6 and 4.7). Therefore, the concentration of Chl a in meanders vary significantly.

Table 4.6 Results chlorophyll a concentration in the CSW during baseflow conditions

Date	Chl a (mg/L) Baseflow									Rainfall (inches)	Mean water temperature (°C)			Mean Flow (cfs)	
	No.	In1	In2	In3	Mean inlet	M1	M2	M3	Out		Inlet	Outlet	M1	*** Inlet	Outlet
5/26/2015	1	0.03	0.03	-	-	-	-	-	-	-	22	24	23	0.2	0.1
6/13/2015	2	0.005	0.08	-	-	-	-	-	-	-	20	27	25	0.18	0.0
6/14/2015	3	0.062	0.10	-	-	-	-	-	-	0.09*	19	28	24	0.2	0.12
6/15/2015	4	0.128	0.13	-	-	-	-	-	-	0.01	18	26	24	0.2	0.1
7/7/2015	5	0.07	0.99	0.26	0.44	0.04	0.07		0.09	-	21	26	24	0.2	0.1
7/9/2015	6	0.06	1.34	0.20	0.53	0.01	0.01		0.02	1.03*	21	24	23	0.9	0.6
7/21/2015	7	0.02	1.61	0.08	0.57	-	-	-	-	-	20	27	25	0.2	0.1
7/23/2015	8	0.21	-	-	-	0.05	0.05	0.09	0.04	-	20	24	22	0.2	0.1
8/27/2015	9	0.02	3.04	0.01	1.02	0.04	0.07	-	-	-	19	21	20	0.2	0.08
8/31/2015	10	0.36	3.24	0.10	1.23	0.19	0.01	-	0.08	-	20	23	24	0.2	0.06
9/1/2015	11	0.27	3.36	0.07	1.23	0.13	0.02	-	0.02	-	20	24	23	0.2	0.1
9/3/2015	12	0.46	3.62	0.07	1.38	0.37	0.07	-	0.01	-	21	24	23	0.2	0.1
9/8/2015	13	0.85	3.18	0.54	1.52	0.08	0.04	0.01	0.01	-	21	23	23	0.2	0.1
9/9/2015	14	0.87	3.60	0.58	1.68	0.07	0.08	0.09	0.03	-	21	24	24	0.2	0.1
9/15/2015	24	0.01	0.40	0.75	0.39	0.20	0.01	0.16	0.02	-	20	19	19	0.3	0.04
9/17/2015	15	0.01	-	0.06	-	0.02	0.01	0.01	0.02	-	21	19	20	0.2	0.04
9/23/2015	16	0.04	1.74	0.04	0.60	0.05	0.05	-	0.02	-	19	18	18	0.1	0.04
10/7/2015	17	0.01	0.08	0.01	0.03	0.01	0.00	0.00	0.01	-	18	15	17	0.1	0.0
10/8/2015	18	0.01	0.10	0.01	0.04	0.00	0.06	0.01	0.01	-	18	16	17	0.1	0.04
10/20/2015	19	0.02	0.25	0.02	0.10	0.11	0.01	0.00	0.01	-	14	9	11	0.2	0.0
Mean		0.2	1.5	0.2	0.8	0.09	0.04	0.05	0.03						
Median		0.05	1.2	0.07	0.6	0.05	0.04	0.01	0.02						
STD		0.3	1.45	0.24	0.6	0.10	0.03	0.06	0.03						

*Samples were collected before it rained.

*** Sum of the mean flow from inlet main and inlet west

Table 4.7 Results chlorophyll a concentration in the CSW during storm events

Date	Chl a (mg/L) Storm event									Rainfall (inches)	Mean water temperature (°C)			Mean Flow (cfs)	
	No.	In1	In2	In3	Mean inlet	M1	M2	M3	Out		Inlet	Outlet	M1	*** Inlet	Outlet
6/16/2015	1	0.02	0.15	0.02	0.06		-	-	-	0.08	20	26	24	0.2	0.1
6/22/2015	2	0.06	0.27	0.70	0.34	0.03	0.52	-	0.07	-*	21	26	24	0.2	0.0
6/24/2015	3	0.01	0.12	0.05	0.06	0.03	0.14	-	0.02	0.19	21	25	23	0.2	0.1
6/25/2015	4	0.03	0.48	0.51	0.34	0.03	0.02	-	0.02	-*	21	24	22	0.37	0.2
6/27/2015	5	0.03	-	-	-	-	0.02	-	0.06	1.00	19	20	20	2.8	1.1
6/28/2015	6	0.00	1.32	-	-	0.01	0.01	-	0.01	1.79	20	20	21	0.6	0.6
7/16/2015	7	0.01	0.67	0.13	0.27	0.03	0.04	-	0.01	-*	20	23	21	0.2	0.2
7/17/2015	8	0.01	0.93	0.15	0.36	0.01	0.02	-	0.04	-*	20	24	23	0.2	0.1
9/11/2015	9	0.00	-	-	-	0.03	0.02	0.02	0.02	0.68	22	22	22	1.0	0.3
10/5/2015	10	0.01	-	0.01	-	0.01	0.01	0.00	0.01	-*	17	14	14	0.2	0.1
10/29/2015	11	0.01	-	-	-	0.01	0.01	0.00	0.01	0.36	17	17	17	2.1	0.5
AVG		0.02	0.56	0.23	0.241	0.02	0.08	0.01	0.03						
Median		0.01	0.48	0.13	0.31	0.03	0.02	0.005	0.02						
STDE		0.02	0.44	0.27	0.14	0.01	0.16	0.01	0.02						

-* It was raining days before.
*** Sum of the mean flow from inlet main and inlet west

The Chl a concentrations measured in this research are in the range of values obtained in research performed in stormwater wetlands and ponds by Tao (2010), Wium-Andersen et al., (2013), Wu and Mitsch (1998) and others (Figure 4.12, Table 2.2). The only value out of this range is the Chl a concentration measured in In2.

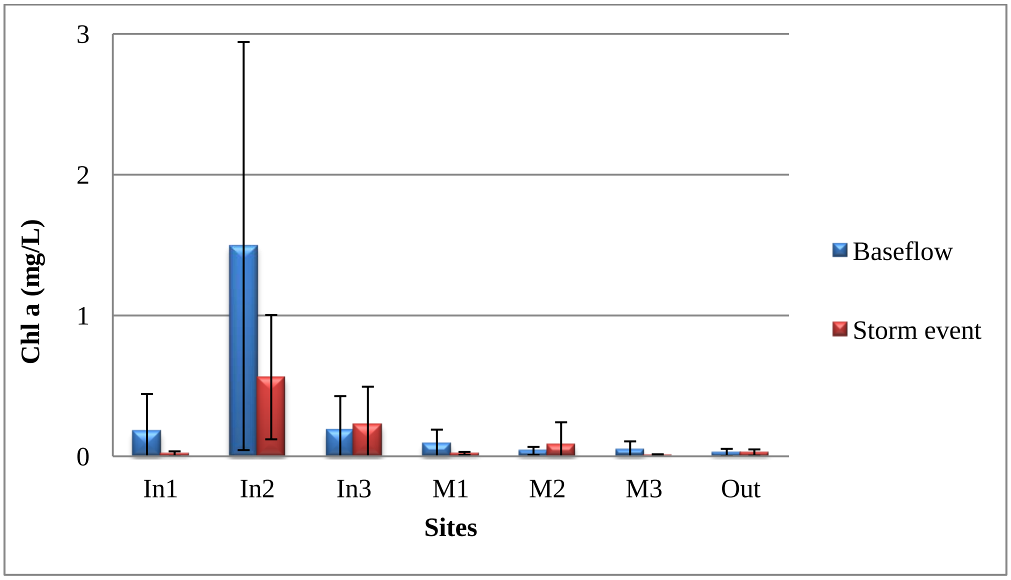

Figure 4.12 Average chlorophyll a concentration in the CSW

As the main population of algae was visually observed and measured in the inlet forebay (Table 4.5 and Figure 4.12), on two occasions samples were collected at different spots of the inlet forebay during baseflow in order to estimate the percent distribution of algae in the forebay (Figure 4.13). According to the Chl a results and observation, In 2, 4, and 7 were the areas with higher concentrations of Chl a in the inlet forebay, while lower concentrations of Chl a were at the beginning and the end of the inlet (Table 4.8). It seems that in In 2, algae stay stagnant (or float slowly) and start to increase. This forms a layer of algae growing and covering the inlet until In 7 or farther. Algae usually were not visually covering In 5, but on September 3rd, almost the entire inlet was cover of algae (Figure 4.14).

Table 4.8 Samples collected different spot of the inlet forebay

Date	Chlorophyll (mg/l)								
	In1	In2	In3	In4	In5	In6	In7	IW	IM
7/21/2015	0.02	1.61	0.08	0.46	0.05	0.58	0.22	0.04	0.01
9/3/2015	0.46	3.62	0.07	0.43	2.38	0.17	1.04	0.01	0.01

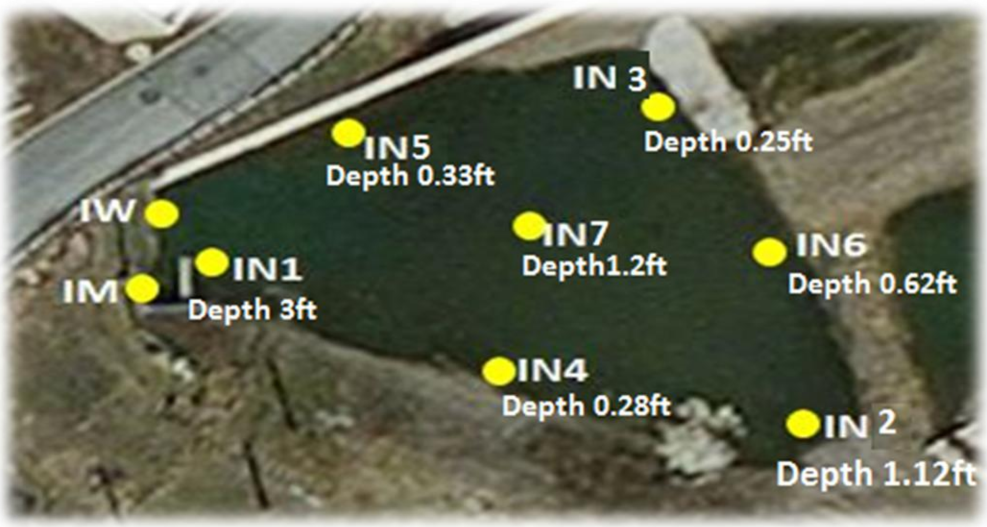

Figure 4.13 Samples collected at different spots in the inlet forebay

Figure 4.14 Inlet forebay condition on September 3rd, 2015

4.3 Organic Matter (OM)

The concentrations of organic matter measured in the CSW during multiple storm and baseflow events can be found in appendix A.1. A linear correlation between chlorophyll a and organic matter was observed in the CSW (Figure 4.15). This correlation could be used in the future to predict the concentration of Chl a or OM in the CSW.

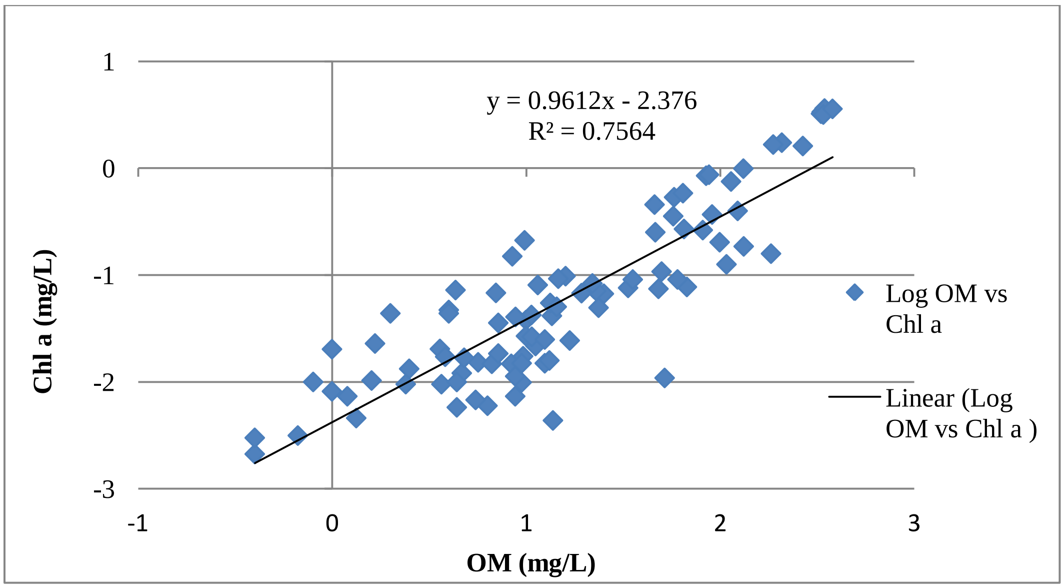

Figure 4.15 Correlation between organic matter and chlorophyll a

4.3.1. Seasonal variation of organic matter

One hypothesis at the beginning of this research was related to the seasonal variation of organic matter in the CSW. As phytoplankton are a form of organic matter (Jorgensen et al., 2005), it was expected that OM would be higher during the summer because of increased temperatures and solar radiation (and thus increase algal growth) and lower during the winter because of decreased algal growth. Organic matter was analyzed in the CSW from November 2014 until October 2015. This data is presented in order to analyze the seasonal organic matter in the CSW during baseflow (Table 4.9) and storm events (Table 4.10). From the data collected and analyzed, it was noticed that the concentration of organic matter increased in the summer under baseflow conditions and then started to decrease during the fall. These fluctuations correlated with decreasing Chl a concentrations at the beginning of the fall (Table 4.6). Concentrations of organic matter observed during winter and spring were low as well. Furthermore, it was observed that the organic matter concentrations were higher in the inlet forebay during the summer under baseflow conditions. The inlet forebay is the area where algae mainly grow. In the same way, in the fall under baseflow, the concentrations of organic matter are higher than during the winter and spring in the inlet forebay. In general, this description of the behavior of OM indicates a seasonal dynamic of OM in the CSW, where it implies that the main concentration of OM in the CSW is in the summer during baseflow conditions because this is the growing season of algae.

Table 4.9 Seasonal organic matter concentrations during baseflow

OM (mg/L) Baseflow					
Season	**In**	**M1**	**M2**	**M3**	**Out**
Spring	5.3±3 (n=2)	5.4±2.9 (n=2)	4.8±2.7 (n=2)	4.3±1.9 (n=2)	6.3±2.8 (n=2)
Summer	78.0±66.1 (n=10)	47.1±49.2 (n=9)	18.5±13.3 (n=9)	10.1±5.4 (n=4)	18.6±20.8 (n=9)
Fall	44.8±65 (n=7)	28.7±32.5 (n=7)	6.8±7.9 (n=5)	37.7±67.6 (n=6)	14.2±15.3 (n=7)
Winter	7.6±2.5 (n=5)	4.6±2.2 (n=5)	3.2 (n=1)	4.7±1.9 (n=4)	3.5±1.4 (n=5)

Table 4.10 Seasonal organic matter concentration during storm events

OM (mg/L) Storm event					
Season	**In**	**M1**	**M2**	**M3**	**Out**
Spring	4.3 (n=1)	3 (n=1)	-	-	3.2 (n=1)
Summer	23.9±30 (n=4)	12.7±10.2 (n=4)	12.5 (n=1)	-	6.0±3.9 (n=4)
Fall	11.7±9 (n=5)	6.6±5.9 (n=2)	1 (n=1)	0.4 (n=1)	6.3±3.1 (n=5)
Winter	9.2±3.6 (n=3)	4.2±1.3 (n=2)	-	-	5.0±3.6 (n=3)

Figure 4.16 shows the seasonal variation of OM in the CSW over time. During the fall, the concentration of OM is low, decreasing more during the winter and spring. Organic Matter concentration increased during the summer.

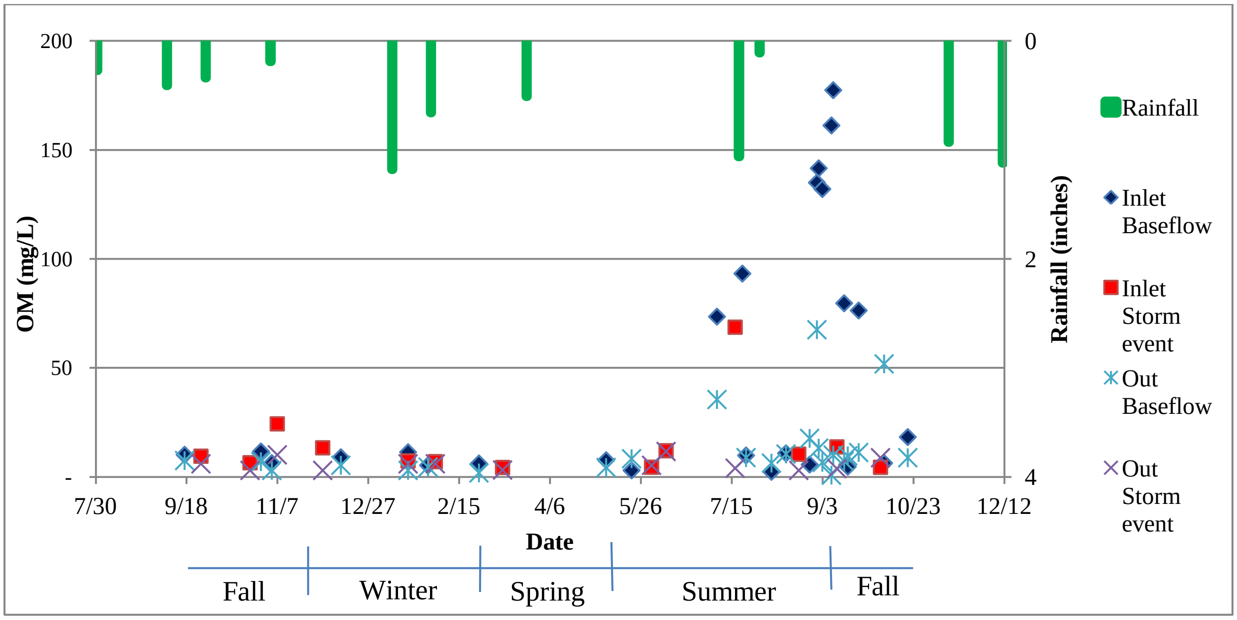

Figure 4.16 Organic Matter vs time at the inlet (average of In1, In2 and In3) and outlet of the CSW from 9/2014 to 10/2015

4.4 Orthophosphate

Orthophosphate (PO_4^{3-}) was one of the nutrients analyzed in the CSW in order to understand the performance of the CSW removing PO_4^{3-}. Results show that PO_4^{3-} was removed from the CSW during baseflow conditions (Figure 4.17 and 4.18). On the other hand, during storm events, the performance of the CSW with respect to PO_4^{3-} removal seems to be low (Figure 4.19 and 4.20). The 50% exceedance concentration of phosphate during storm event at the outlet and the inlet is 0.05 mg/L. The decrease in phosphate concentration during baseflow conditions and not during storm events could be due to the difference in flow rate between baseflow and storm conditions. Flow rates are higher during storm events (Appendix A.2) resulting in phosphate having less time to be removed by physical sedimentation. Also, there may be resuspension of phosphate during storm events due to high flow rates.

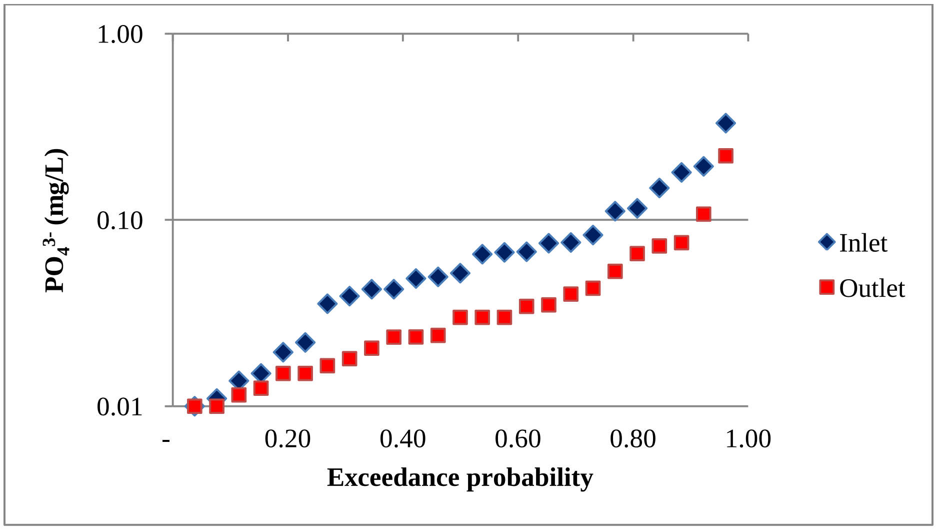

Figure 4.17 PO_4^{3-} exceedance probability during baseflow

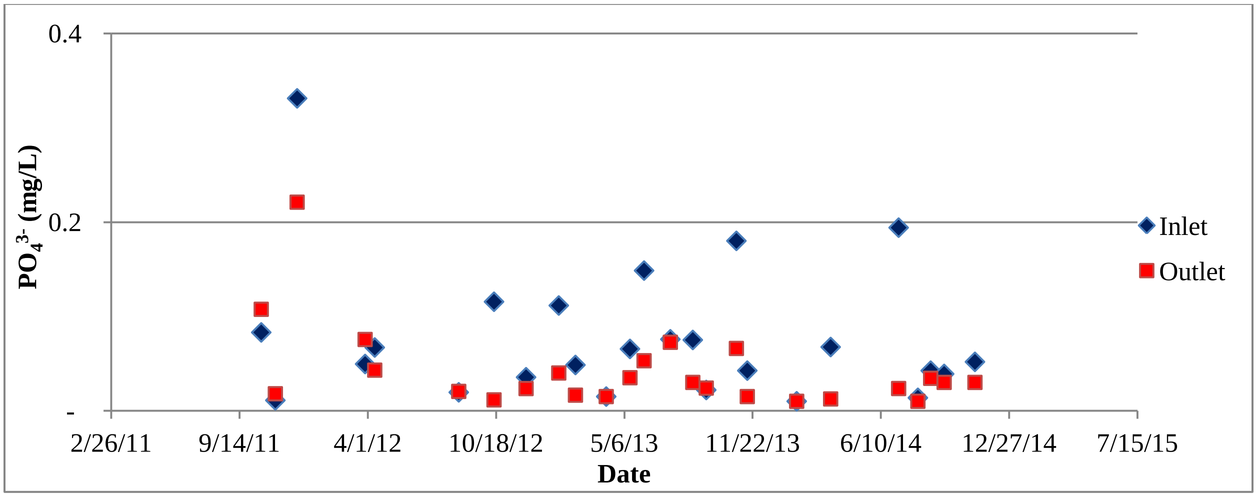

Figure 4.18 PO_4^{3-} in the CSW over the time during baseflow

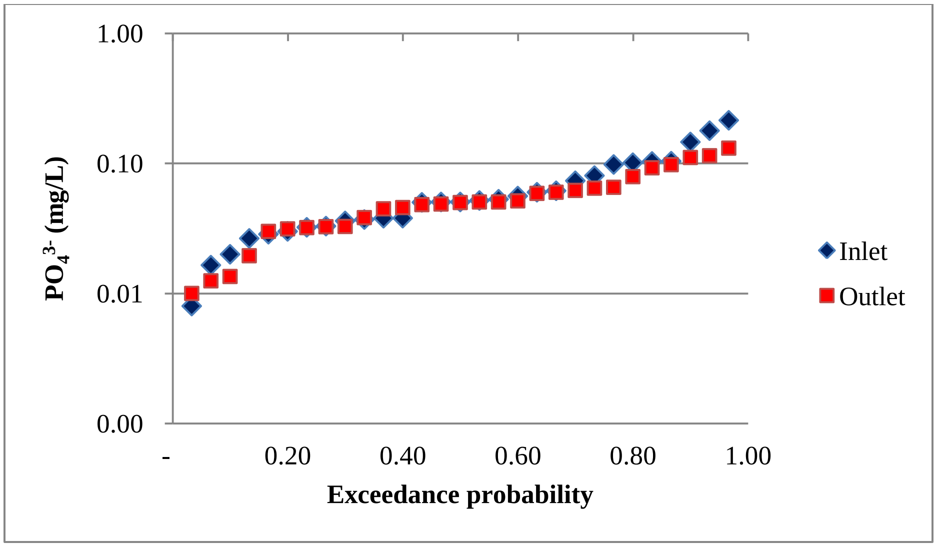

Figure 4.19 PO_4^{3-} exceedance probability during storm events

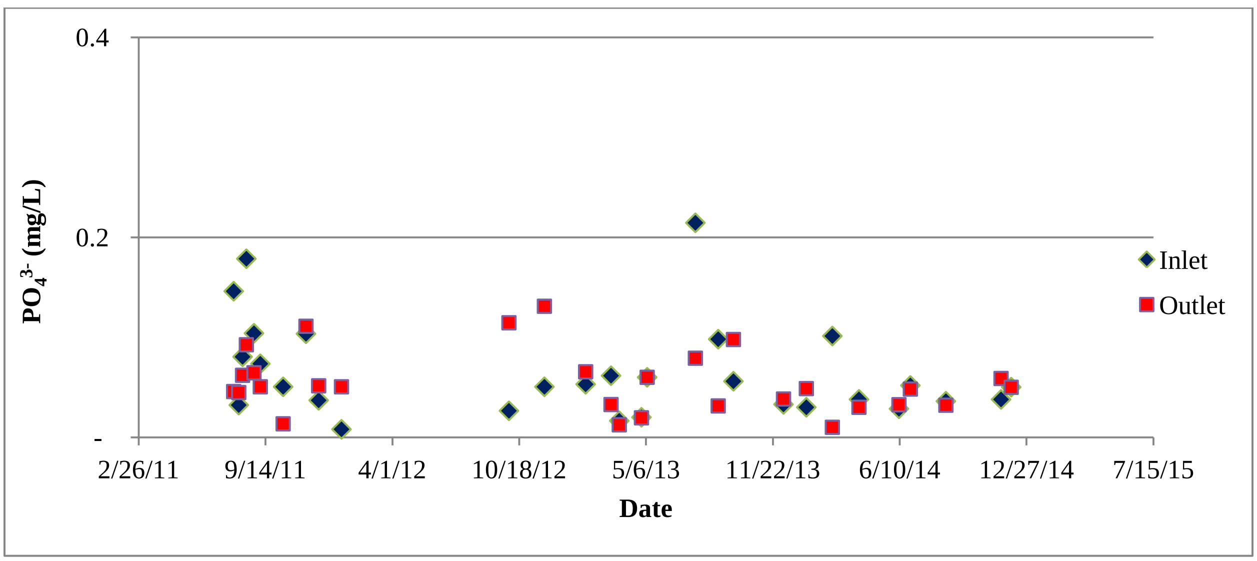

Figure 4.20 PO_4^{3-} in the CSW over the time during storm events

4.5 Total Kjeldahl Phosphorus (TKP-P)

There was removal of total phosphorus (as measured by TKP analysis) in the CSW under baseflow conditions (Figure 4.21). While during storm events, it seems that the removal of TKP-P in the CSW was not as pronounced as during baseflow (Figure 4.22). The median TKP-P concentration in the inlet was 0.17 mg/L, while in the outlet was 0.06 mg/L under baseflow conditions. But during storm events the median TKP-P concentration was 0.14 mg/L in the inlet and 0.13 mg/L in the outlet (indicating only a small reduction of TKP-P in the CSW during storm events).

Phosphorus is an extremely active element biologically and chemically (Matby and Barker, 2009). Therefore, maybe the high removal performance of the CSW during baseflow conditions was due to plant/algae uptake. Nevertheless, the high flow rate coming into the CSW during storm events could be affecting the performance of the CSW removing TKP-P by not allowing the time for the plant/algae uptake to take place.

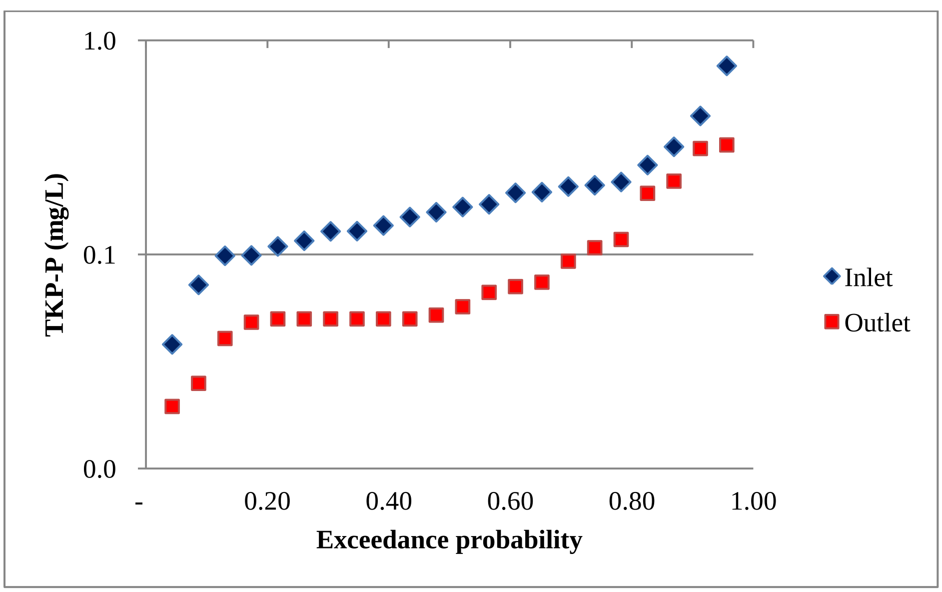

Figure 4.21 TKP-P exceedance probability during baseflow

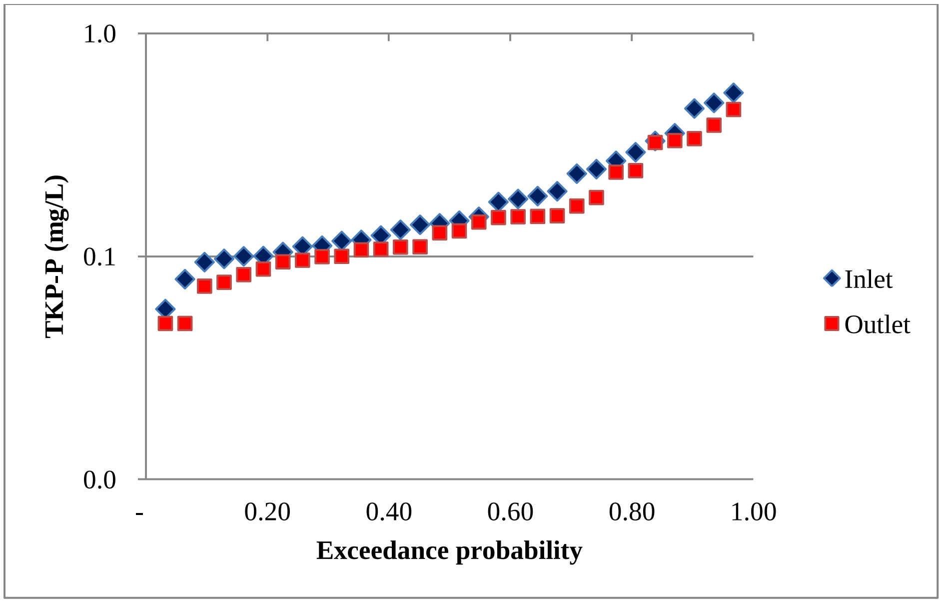

Figure 4.22 TKP-P exceedance probability during storm events

4.6 Total Nitrogen (TN)

Total nitrogen is represented by the inorganic and organic form of nitrogen. Therefore, to evaluate the performance of the CSW removing TN, the different forms of nitrogen such as Total Kjeldahl Nitrogen (TKN), nitrate (NO_3^-) and nitrite (NO_2^-) were analyzed in the CSW. Total Nitrogen (TN) is the sum of TKN, which is the total concentration of organic nitrogen and ammonia, and NOx, which is the sum of NO_3^- and NO_2^-. TKN and NOx concentrations for each storm event can be found in Appendix A.3 – A.8. From the exceedance probability analysis there was an observed removal of TN in the CSW during baseflow and storm event (Figure 4.23 and 4.24) with more removal occurring during baseflow. The median TN concentration in the inlet was 2.93 mg/L, while in the outlet was 0.74 mg/L under baseflow conditions. Whereas during storm events, the median TN concentration was 1.96 mg/L in the inlet and 1.36 mg/L in the outlet. Factors affecting the performance of the CSW to remove nitrogen could be the microbial activities in the wetland and uptake by plants (Neptune, 2015; Scholz, 2011).

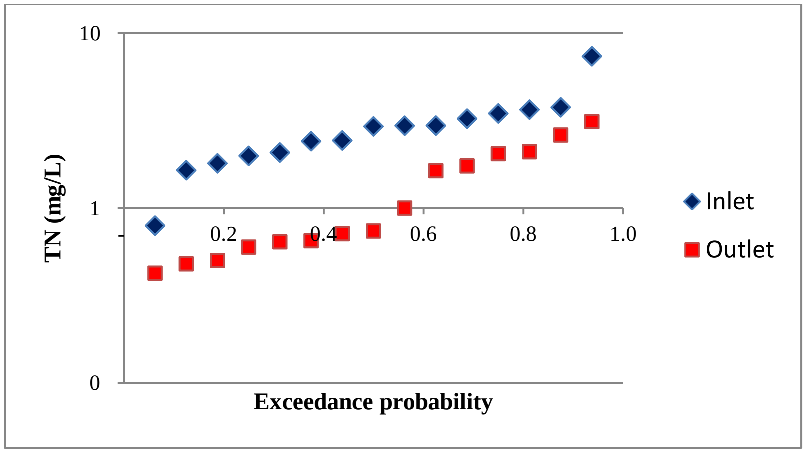

Figure 4.23 Total nitrogen exceedance probability in the CSW during baseflow

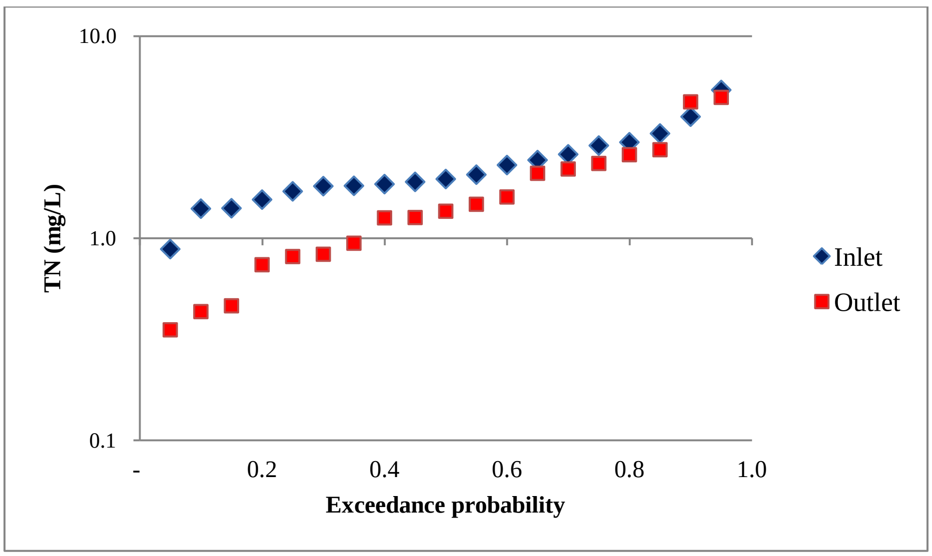

Figure 4.24 Total nitrogen exceedance probability in the CSW during storm events

4.7 Seasonal Variations in Nutrient Removal

One of the factors that influence the growth of algae are nutrients. Seasonal variations in inlet and outlet concentrations of different forms of nitrogen and phosphorus are presented in Tables 4.11 and 4.12. The performance of the CSW removing nutrients per season was also analyzed (Tables 4.13, 4.14). These nutrients were measured from 2011 until 2014 and analyzed in order to understand the dynamic of the CSW removing nutrients.

NO_3^- is one of the main forms of nitrogen available in the CSW (Tables 4.11 and 4.12). The removal of NO_3^- is higher during baseflow conditions than during storm events (Table 4.13). The percent removal of NO_3^- under baseflow conditions is 54% during the spring, 96% during the summer, 73% during the fall and 64% during the winter, while under storm conditions is 42% during the spring, 61% during the summer, 52% during the fall and 14% during the winter. This higher removal during baseflow could be because of the increased microbiological activities in the CSW or increased plant/algal uptake.

Table 4.11 Seasonal nutrients concentration during baseflow

Baseflow								
Paramater	**Spring**		**Summer**		**Fall**		**Winter**	
	In	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
TN	3.8±2 (n=5)	2.0±0.8 (n=5)	2.6±1 (n=3)	1.3±1.2 (n=3)	2.6±0.8 (n=6)	0.7±0.4 (n=6)	0.8± (n=1)	0.6± (n=1)
TKN	1.9±2.2 (n=6)	1.2±0.8 (n=6)	1.1±0.6 (n=5)	1.4±1.2 (n=5)	0.8±0.3 (n=6)	0.3±0.1 (n=6)	1.5±0.2 (n=3)	0.9±0.3 (n=3)
NO_2	0.1±0.02 (n=7)	0.04±0.03 (n=7)	0.1±0.05 (n=10)	0.01±0.01 (n=10)	0.1±0.02 (n=9)	0.02±0.02 (n=9)	0.1±0.1 (n=5)	0.1±0.1 (n=5)
NO_3	1.6±0.5 (n=5)	0.7±0.6 (n=5)	1.3±0.6 (n=7)	0.1±0.1 (n=7)	1.8±0.7 (n=9)	0.5±0.4 (n=9)	2.1±2 (n=4)	0.8±0.6 (n=4)
NO_x	1.8±0.6 (n=6)	0.7±0.5 (n=6)	1.4±0.7 (n=7)	0.1±0.04 (n=6)	1.9±0.6 (n=9)	0.5±0.4 (n=9)	2.4±2 (n=4)	1.4±1.1 (n=4)
TKP-P	0.2±0.1 (n=6)	0.1±0.1 (n=6)	0.3±0.2 (n=7)	0.1±0.1 (n=7)	0.2±0.04 (n=5)	0.1±0.1 (n=5)	0.2±0.05 (n=4)	0.1±0.03 (n=4)
PO_4^{3-}	0.1±0.02 (n=5)	0.04±0.03 (n=5)	0.1±0.1 (n=7)	0.03±0.02 (n=7)	0.1±0.1 (n=8)	0.04±0.03 (n=8)	0.1±0.1 (n=5)	0.1±0.1 (n=5)

Table 4.12 Seasonal nutrients concentration during storm events

Storm event								
Paramaters	**Spring**		**Summer**		**Fall**		**Winter**	
	In	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)	Conc. (mg/L)
TN	2.6±0.9 (n=5)	2.6±1.5 (n=5)	2.6±1.3 (n=8)	1.6±1.5 (n=8)	1.6±0.3 (n=2)	1.0±0.3 (n=2)	1.8±0.9 (n=3)	1.5±0.8 (n=3)
TKN	1.0±0.6 (n=9)	1.3±1.1 (n=9)	1.3±0.9 (n=9)	1.1±1.2 (n=9)	0.7±0.3 (n=3)	0.5±0.2 (n=3)	1.1±0.8 (n=6)	0.7±0.4 (n=6)
NO_2	0.04±0.01 (n=8)	0.04±0.02 (n=8)	0.04±0.02 (n=12)	0.03±0.02 (n=12)	0.1±0.04 (n=8)	0.03±0.02 (n=8)	0.1±0.02 (n=8)	0.1±0.04 (n=8)
NO_3	1.3±0.6 (n=5)	0.7±0.2 (n=5)	0.9±0.9 (n=10)	0.4±0.2 (n=10)	1.1±0.7 (n=7)	0.6±0.4 (n=7)	1.5± (n=1)	1.3± (n=1)
NO_x	1.1±0.7 (n=6)	0.7±0.3 (n=6)	1.0±0.8 (n=11)	0.5±0.4 (n=11)	1.1±0.7 (n=8)	0.6±0.4 (n=8)	1.4±0.1 (n=2)	1.1±0.4 (n=2)
TKP-P	0.1±0.05 (n=9)	0.1±0.1 (n=9)	0.3±0.1 (n=7)	0.3±0.1 (n=7)	0.2±0.1 (n=6)	0.1±0.1 (n=6)	0.2±0.2 (n=8)	0.1±0.1 (n=8)
PO_4^{3-}	0.04±0.02 (n=5)	0.03±0.02 (n=5)	0.1±0.1 (n=10)	0.1±0.02 (n=10)	0.1±0.03 (n=7)	0.1±0.04 (n=7)	0.04±0.03 (n=7)	0.04±0.02 (n=7)

Table 4.13 shows nutrient percent removal in the CSW during baseflow and storm events. A positive percent removal during baseflow conditions was observed for all nutrients, except for TKN during the summer. From a general perspective the performance of the CSW removing nutrients is positive.

Also, it was observed that during the summer, the performance of the wetland removing these nutrients was higher than other seasons, except for total nitrogen, whose percent removal was higher during the fall (72% to be more specific). The performance of the CSW at removing nutrients during the summer under baseflow conditions might be because summer is the growing season of plants, which could be using these nutrients to grow. Meanwhile, positive and negative removal of pollutants was observed during storm events. This could be because of differences in the hydraulic residence time. Neptune (2015) found that the hydraulic residence time in the CSW during baseflow was 96 ± 13 hours and during storm events was 48 ± 19 hours. Therefore, potentially because of the long hydraulic residence time (HRT) in the CSW during baseflow, the performance of the CSW removing pollutant is positive. Meanwhile shorter HRT during storm event and higher flow rate could affect the performance of the wetland at removing pollutants during storm events.

Table 4.13 Nutrients percent removal

Percent removal								
Baseflow					**Storm**			
Parameter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
TN	48	50	72	18	0.3	37	35	13
TKN	40	-26	62	42	-26	21	24	32
NO_2	37	79	68	14	-14	27	52	-4
NO_3	54	93	73	64	42	61	52	14
NO_x	60	94	74	42	41	51	49	21
TKP-P	30	62	53	60	-17	8	16	47
PO_4^{3-}	32	57	45	42	21	45	-45	-1

The overall ratio between total nitrogen and total phosphorus was calculated in the CSW (Table 4.14, 4.15 and Figure 4.25). The ratio between total nitrogen and total phosphorus is a way to know which nutrient is the limited factor in the growth of plants. When the ratio of N/P is less than 10, nitrogen is the limited nutrient in the water body. But if the N/P is greater than 10, phosphorus is the limited factor (Thomann and Mueller, 1987). The results suggest that phosphorus is the limited nutrient in the CSW. But, as the results are close to 10 and due to high standard deviations, it may not be correct to make a statement about the limiting nutrient. For that reason, the nutrient limited factor in the CSW could be nitrogen or phosphorus.

Table 4.14 Nutrients concentration in the CSW during baseflow

Nutrients Baseflow																
	TN		TKN		NO_2		NO_3		NO_x		TKP-P		PO_4^{3-}		TN/TKP-P ratio	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Ave. Conc. (mg/L)	2.9	1.3	1.3	0.9	0.1	0.1	1.7	0.5	1.8	0.6	0.2	0.1	0.1	0.04	20	15.7
Median Conc. (mg/L)	2.9	0.7	1.1	0.6	0.1	0.0	1.4	0.2	1.7	0.3	0.2	0.1	0.1	0.03	16.5	10.7
STD	1.5	0.9	1.3	0.8	0.2	0.4	1.0	0.5	0.9	0.7	0.1	0.1	0.1	0.04	16.4	13.4
n	15	15	20	20	32	32	25	25	26	26	23	23	25	25	11	11

Table 4.15 Nutrients concentration in the CSW during storm events

Storm																
	TN		TKN		NO_2		NO_3		NO_x		TKP-P		PO_4^{3-}		TN/TKP-P ratio	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Ave Conc. (mg/L)	2.3	1.8	1.1	1.0	0.05	0.04	1.08	0.53	1.48	0.68	0.20	0.16	0.06	0.05	14.3	11.5
Median Conc. (mg/L)	1.9	1.4	0.2	0.7	0.04	0.04	0.90	0.44	0.94	0.56	0.14	0.13	0.05	0.05	17.4	10.6
STD	1.0	1.3	0.8	0.98	0.03	0.03	0.73	0.36	2.11	0.50	0.13	0.10	0.05	0.03	7.1	8.3
n	18	18	27	27	36	36	23	23	29	28	30	30	29	29	11	11

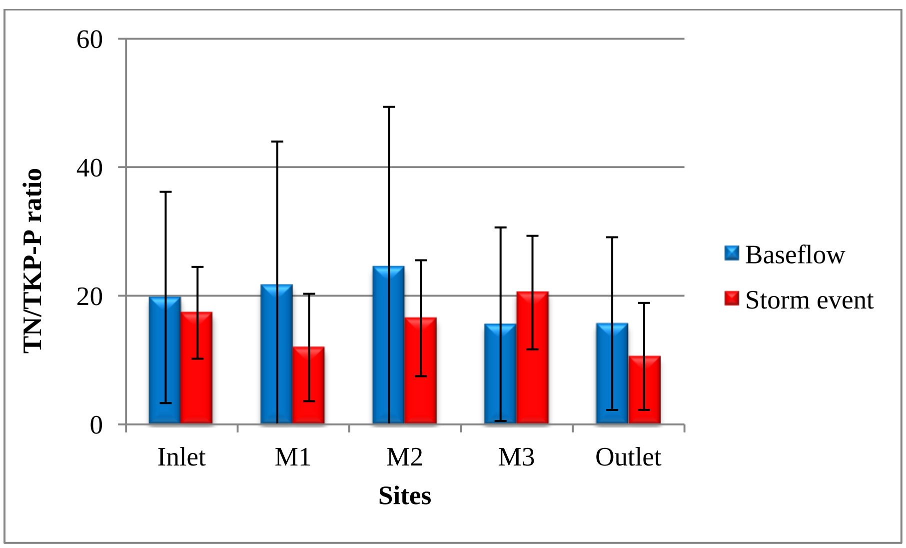

Figure 4.25 TN/TKP-P ratio in the CSW

4.8 Trophic Status

The trophic classification used in this research is the trophic classification used for lakes. If the concentration of total phosphorus is higher than 0.02 mg/L and the chlorophyll a concentration is higher than 0.01 mg/L (Thomann and Mueller, 1987), the trophic status indicates that the water body is eutrophic. From the data presented in this research, concentration of total phosphorus and chlorophyll a are higher than these values (Tables 4.5, 4.14 and 4.15). The mean concentration of Chl a in the CSW was 0.57 mg/L at the inlet and 0.03 mg/ L at the outlet during baseflow, while during storm events, the mean concentration of Chl a was 0.20 mg/L at the inlet and 0.03 mg/ L at the outlet. The mean concentration of TKP-P in the CSW was 0.20 mg/L at the inlet and 0.10 mg/ L at the outlet during baseflow, while during storm events, the mean concentration of TKP-P was 0.20 mg/L at the inlet and 0.16 mg/ L at the outlet. Thus, the data indicates that the CSW is under eutrophic conditions.

4.9 Flow

The flow data in the CSW was analyzed in order to evaluate how the flow coming in to the wetland affects the growth of algae in the CSW. The greatest monthly mean flow coming in to the CSW was reported in October (Table 4.16, Figure 4.26). While the most rainfall was received in June, 8.1 inches. Higher flow coming in to the CSW was measured in September and October.

Table 4.16 Monthly mean flow from June 2015 to October 2015

Month	Flow (cfs)		Rain (Inches)	Number of storms
	Inlet	Outlet		
June	0.5	0.3	8.1	12
July	0.3	0.2	3.6	7
August	0.2	0.1	1.4	2
Sept	0.8	0.1	2.8	3
October	1.1	0.2	3.9	4

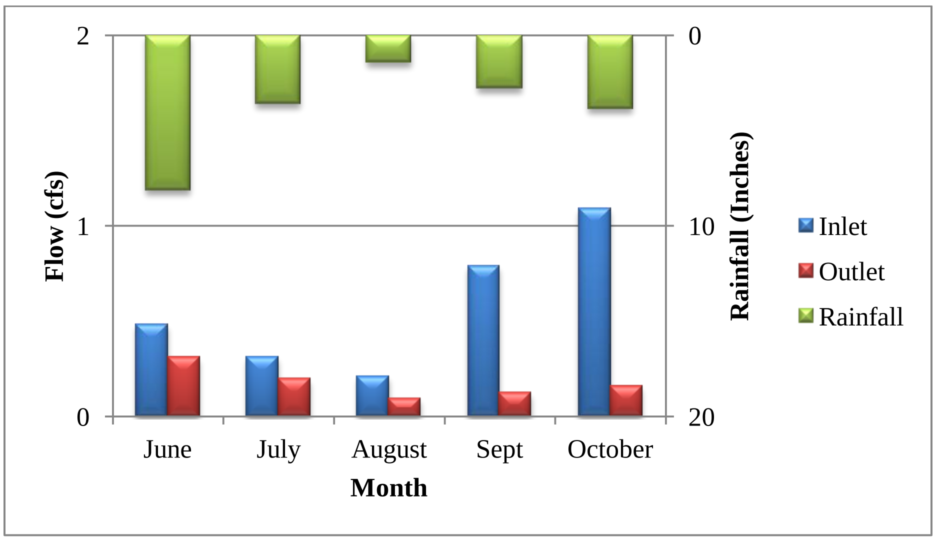

Figure 4.26 Monthly mean flow and total rainfall during the summer 2015

4.10 Temperature

Temperature is another factor which stimulates the growth of algae. This could have caused the high concentration of chlorophyll a in the inlet of the CSW. High temperatures were reported from June to September (Table 4.17 and Figure 4.27) and significant Chl a concentration were measured during these months. But in October, when water temperature decreased, the Chl a concentration in the inlet decreased as well. Nevertheless, in the outlet the story was different. The mean concentration of Chl a at the outlet was 0.03 mg/L during baseflow and storm event, while the mean concentration of Chl a in the entire inlet forebay was 0.8 mg/L during baseflow and 0.2 mg/L during storm events. This significantly lower Chl a concentration in the outlet in comparison with the Chl a concentration in the inlet could be because algae are settling down in the system or getting stuck within vegetation instead of leaving the CSW (Figure 4.28). The geometry of meanders and the outlet could also be a factor that does not permit a significant growth of algae in these areas of the CSW. Furthermore, there could be less Chl a concentration at the outlet because there was significantly less N and P at the outlet during baseflow conditions.

Table 4.17 Monthly mean water temperature from June 2015 to October 2015

Month	**Temperature °C**	
	Inlet	**Outlet**
June	20	23
July	20	25
August	20	23
Sept	20	21
October	16	13

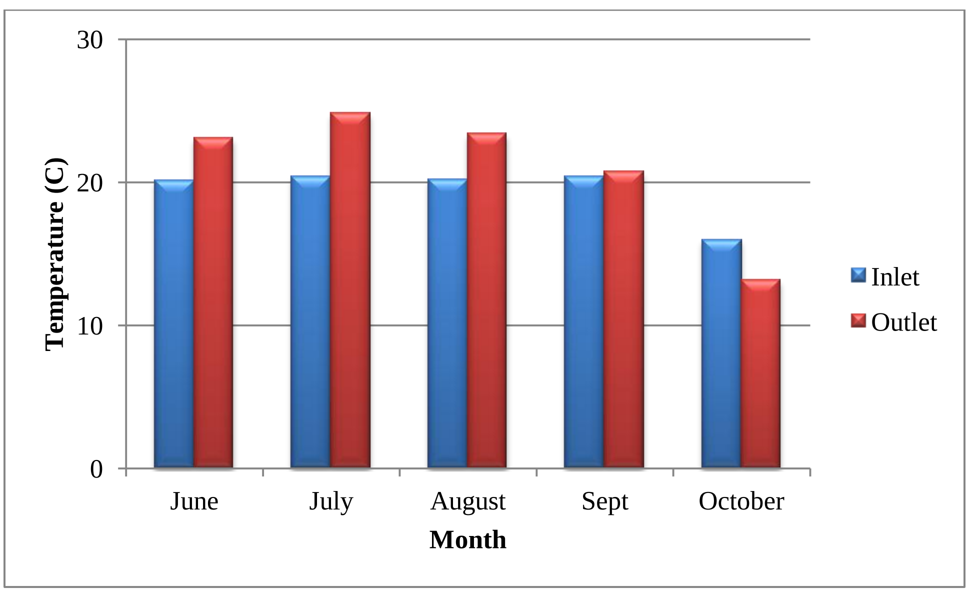

Figure 4.27 Monthly mean water temperature during the summer 2015

Figure 4.28 Algae stuck within vegetation above the water level in M1 after leaving the inlet forebay on July 17th, 2015 (Two days before it rained 1.24 inches)

Chapter 5 Mass Balance in the Constructed Stormwater Wetland

5.1 Mass Balance of Chlorophyll a (Chl a)

A mass balance of Chl a was performed in the CSW with an emphasis on the inlet forebay. For the performance of this mass balance, accumulation is the mass of Chl a accumulated in the inlet forebay in a time period, and the mass out of the inlet is the mass of Chl a leaving the inlet forebay. Some assumptions were made in order to perform the mass balance. One assumption was that initial mass in (mass transport in) of Chl a was zero. While the mass of Chl a leaving the inlet forebay was estimated by multiplying the volume coming into the wetland over the time period under evaluation with the mean inlet forebay Chl a concentration over the period of the mass balance calculation. Another assumption was the volume of the wetland was constant. The mass balance was focused on the inlet forebay because this was the area with the greatest amount of Chl a measured. In a survey performed in the inlet forebay in the summer, the volume of the wetland was calculated to be 218,900 L (Section 4.1). This was the volume used to calculate the accumulation of Chl a in the CSW. The initial mass was calculated by multiplying the mean inlet forebay Chl a concentration at the beginning of the mass balance period by the volume of the inlet forebay. Whereas, the mass final was calculated by multiplying the inlet forebay mean Chl a concentration at the end of the mass balance period by the volume of the inlet forebay.

The general equation of mass balance was applied to calculate the transport of Chl a in the CSW (Eq 5.1 – 5.6).

- $Accumulation = Mass\ transport\ in - Mass\ out - growth$ (Eq 5.1)
- $Vol\ out\ inlet = flow \times days$ (Eq 5.2) ($mean\ inlet\ flow * \ time\ day\ of\ event$)
- $Mass\ out\ of\ inlet = Vol\ out\ inlet\ \times Chl\ a\ mean\ In$ 3 (Eq 5.3)

- $mass\ in\ inlet = Volume\ of\ forebay \times Mean\ Chl\ a\ inlet$ (Eq 5.4)
- $Change\ accumulation\ (Storage) = mass\ final - mass\ initial$ (Eq 5.5)
- $Mass\ produced\ (growth) = Change\ of\ storage + mass\ out\ of\ inlet$ (Eq 5.6)

An example calculations is as shown below – 08/27 – 08/31

$$vol\ out\ inlet = \left(0.18\ \frac{ft^3}{sec}\right)\left(\frac{1L}{28.3ft^3}\right)\left(\frac{86400\ sec}{1\ day}\right) * (4\ days) = 2{,}197\ L$$

$$mass\ out\ of\ inlet = (2{,}197\ L) \times (0.054\ \frac{mg}{L})\ (\frac{1\ g}{1000\ mg}) = 0.12\ \text{g}$$

$$mass\ initial = (218{,}900\ L) \times (1.02\ \frac{mg}{L})(\frac{1\ g}{1000\ mg}) = 223\ \text{gr}$$

$$mass\ final = (218{,}900L) \times (1.23\left(\frac{mg}{L}\right))\ (\frac{1\ g}{1000\ mg}) = 269\ \text{gr}$$

$$change\ in\ storage = (269 - 223)gr = 46\ \text{gr}$$

$$Mass\ produced\ (growth) = (46 + 0.12)gr = 46gr$$

Different dates were selected to calculate the mass of Chl a growing in the inlet forebay (Table 5.1). Calculations were performed during baseflow, storm events and a combination of both in order to understand Chl a dynamics in the inlet forebay.

Table 5.1 Chlorophyll a concentration in days over the mass balance calculation

Date	Chl a (mg/L)					Comment
	In1	In2	In3	Mean Inlet	Outlet	Event
6/22/2015	0.06	0.3	0.69	0.34	0.07	Storm event
6/24/2015	0.02	0.1	0.05	0.06	0.02	Storm event
6/25/2015	0.03	0.5	0.51	0.34	0.02	Storm event
7/7/2015	0.07	0.99	0.26	0.44	0.09	Baseflow
7/9/2015	0.06	1.3	0.19	0.53	0.02	Baseflow
7/9/2015	0.06	1.3	0.19	0.53	0.02	Baseflow*
7/16/2015	0.01	0.7	0.13	0.27	0.01	Storm event
7/16/2015	0.01	0.7	0.13	0.27	0.01	Storm event
7/17/2015	0.02	0.9	0.15	0.37	0.04	Storm event
8/27/2015	0.02	3.0	0.01	1.02	-	Baseflow
8/31/2015	0.4	3.2	0.09	1.23	0.08	Baseflow
8/31/2015	0.4	3.2	0.09	1.23	0.08	Baseflow
9/1/2015	0.3	3.4	0.07	1.23	0.02	Baseflow
9/3/2015	0.5	3.6	0.07	1.38	0.02	Baseflow
9/3/2015	0.5	3.6	0.07	1.38	0.02	Baseflow
9/8/2015	0.9	3.2	0.54	1.52	0.01	Baseflow
9/9/2015	0.9	3.6	0.5	1.68	0.03	Baseflow
9/11/2015	0.004	-	-	-	0.02	Storm event
9/15/2015	0.01	0.39	0.75	0.39	0.02	Baseflow
9/15/2015	0.01	0.39	0.75	0.39	0.02	Baseflow
9/17/2015	0.01	-	0.06	-	0.02	Baseflow
9/23/2015	0.04	1.74	0.04	0.60	0.02	Baseflow
10/7/2015	0.01	0.08	0.01	0.03	0.01	Baseflow
10/8/2015	0.01	0.09	0.01	0.04	0.01	Baseflow
10/8/2015	0.01	0.09	0.01	0.04	0.01	Baseflow
10/20/2015	0.02	0.25	0.02	0.09	0.01	Baseflow

*Samples were collected before it rained

As Chl a is an indicator of the amount of algae in a water body, the mass of Chl a growing in the inlet forebay was calculated (Table 5.2). In the period of time between August 27th and August 31st, 2015, the mass Chl a accumulated in the inlet forebay was 46 gr, while the mass of Chl a leaving the inlet forebay was 0.12 gr. The same trend happened between September 03rd and 08th, 2015, the mass of Chl a accumulated in the inlet forebay was 30 gr, while the mass of Chl a leaving the inlet forebay was 0.9 gr. In general, the mass balance of Chl a showed that the amount of Chl a leaving the inlet forebay was minimal compared to the amount of Chl a growing in the inlet forebay.

Just before a storm event on June 22nd, 2015, the accumulation of Chl a in the inlet forebay was 75 gr, then the inlet forebay cleared up after it rained 0.75 inches on June 23rd, 2015 (Figure 5.1 and 5.2). Two days later on June 25th, 2015, algae accumulation was observed (Figure 5.3). The mass balance analysis indicated that 74 grams of Chl a was accumulated. This is comparable to the amount of Chl a concentration accumulated before the storm event. As Chl a is an indicator of the amount of algae, the rapid increase of the mass of Chl a in the inlet after rained on June 23rd, 2015 could have been stimulated by flow coming into the CSW, sunlight, temperature or nutrients. Also, it is important to mention that the mass of Chl a leaving the inlet was not significant compared with the amount of algae accumulated before it rained.

Algae accumulation was observed between July 7th and 9th, 2015. The mass balance analysis indicated that 20 gr of Chl a was accumulated in the inlet forebay (Table 5.2). The mass of algae leaving the inlet forebay was 0.3 gr which is minimal compared with amount of Chl accumulated in the inlet forebay. The collection of samples on July 9th was performed before it rained 1.03 inches the same day.

On September 09th, 2015 under baseflow condition, the amount of Chl a accumulated in the inlet forebay was 368 gr. Then, on September 10th, 2015 it rained 0.68 inches. Five days later, the mass of Chl a measured in the inlet was 85 gr which was significantly lower than the mass of Chl a accumulated on September 09th. The mass of Chl a leaving the inlet forebay was 12 gr. Maybe after this storm event, Chl a started to move through other areas of the CSW such as M1, M2 and outlet pond or stay stagnant within vegetation. It is important to mention that the collection of samples was at the beginning of each meander and not in the pond of the meander or outlet forebay.

Growth and accumulation of Chl a started to decrease at the beginning of the fall. This indicates that temperature was a factor controlling the growth of algae during the fall in the inlet forebay. The accumulation of algae in the inlet forebay during baseflow might be because factors such as water temperature, flow coming into the CSW and sunlight were playing their role stimulating the growth of algae. Flow coming into the wetland carrying nutrients could have stimulated the growth of algae in the CSW. The concentration of nutrients in the inlet and outlet were presented in chapter 4 (Table 4.14 and 4.15).

Table 5.2 Mass balance of Chl a in the inlet forebay of the CSW

Date	Chl a (mg/L)				Comment		Mass out of the inlet forebay				Accumulation		Growth (g)	Growth per day (g/day)
	In1	In2	In3	Chl a mean Inlet	Event	Rainfall (Inches)	** Mean Flow (cfs)	Day (d)	Vol (L)	Mass out (g)	Accumulation (g)	Change Accumulation (g)		
6/22/2015	0.06	0.27	0.69	0.34	Storm event	0	0.40	3	3,661	1.5	75	-0.8	0.8	0.3
6/24/2015	0.02	0.12	0.05	0.06		0.19								
6/25/2015	0.03	0.48	0.51	0.34		0					74			
7/7/2015	0.07	0.99	0.26	0.44	Baseflow	0	0.21	2	1,282	0.3	97	20	21	10
7/9/2015	0.06	1.34	0.19	0.53		1.03*					117			
7/9/2015	0.06	1.34	0.19	0.53	Baseflow	1.03*	0.47	7	10,038	2	117	-57	-56	-8
7/16/2015	0.01	0.67	0.13	0.27	Storm event	0					60			
7/16/2015	0.01	0.67	0.13	0.27	Storm event	0	0.21	1	641	0.1	59	20	20	20
7/17/2015	0.02	0.93	0.15	0.37		0					80			
8/27/2015	0.02	3.04	0.01	1.02	Baseflow	0	0.18	4	2,197	0.1	223	46	46	12
8/31/2015	0.36	3.24	0.09	1.23		0					269			
8/31/2015	0.36	3.24	0.09	1.23	Baseflow	0	0.21	3	1,922	0.2	269	33	33	11
9/1/2015	0.27	3.36	0.07	1.23		0								
9/3/2015	0.46	3.62	0.07	1.38		0					303			
9/3/2015	0.46	3.62	0.07	1.38	Baseflow	0	0.19	5	2,899	0.9	303	30	31	6
9/8/2015	0.85	3.18	0.54	1.52		0					333			
9/9/2015	0.87	3.59	0.58	1.68	Baseflow	0	0.98	6	17,941	12	368	-284	-272	-45
9/11/2015	0.004	-	-	-	Storm event	0.01								
9/15/2015	0.01	0.39	0.75	0.39	Baseflow	0					85			
9/15/2015	0.01	0.39	0.75	0.39	Storm event	0	0.22	8	5,370	2	85	48	49	6
9/17/2015	0.01	-	0.06	0.04	Baseflow	0								
9/23/2015	0.04	1.74	0.04	0.60		0					132			

Date	Chl a (mg/L)				Comment		Mass out of the inlet forebay				Accumulation		Growth (g)	Growth per day (g/day)
	In1	In2	In3	Chl a mean Inlet	Event	Rainfall (Inches)	** Mean Flow (cfs)	Day (d)	Vol (L)	Mass out (g)	Accumulation (g)	Change Accumulation (g)		
10/7/2015	0.006	0.08	0.01	0.03	Baseflow	0	0.14	1	427	0.004	7	2	2	2
10/8/2015	0.01	0.09	0.01	0.04		0					9			
10/8/2015	0.01	0.09	0.01	0.04	Baseflow	0	0.27	12	9,886	0.2	9	12	12	1
10/20/2015	0.02	0.25	0.02	0.09		0					21			

* Samples were collected before it rained
** Sum of mean flow rate from inlet West and inlet Main

Figure 5.1 Inlet forebay on June 22nd, 2015 (day before it rained)

Figure 5.2 Inlet forebay on June 24th, 2015 (1 day after 0.75 inches)

Figure 5.3 Inlet forebay on June 25th, 2015 (2 day after rained 0.75 inches)

The main focus on the mass balance of Chl a in the CSW was in the inlet forebay because data about volume and flow was available. The volume in meanders was not available. It was observed that the concentration of Chl a was lower in meanders than in the inlet forebay (Table 4.5). The mass of Chl a in the outlet was calculated according to the same procedure that the mass of Chl a out from the inlet forebay (Equation 5.1 - 5.6, but applied for the outlet). It was observed that the mass of Chl a leaving the CSW at the outlet was negligible in comparison with the mass of Chl a leaving the inlet forebay (Table 5.3). The range of mass of Chl a leaving the inlet forebay was 0.004 – 12 gr, while the range of mass of Chl a leaving the CSW was 0.001-0.12 gr. Moreover, the exportation of Chl a from the wetland during baseflow and storm events (Table 5.4) was minimal compared with the amount of Chl a accumulated in the inlet forebay (Table 5.2).

Table 5.3 Mass of Chl a in the outlet of the CSW

Date	Chl a (mg/L) Outlet	Comment	Rainfall	Outlet of CSW					Mass out per day leaving the inlet (g/day)
		Event		*** Flow outlet (cfs)	Days (d)	Vol (L)	Mass out (g)	Mass out per day (g/day)	
6/22/2015	0.065	Storm event	0	0.2	3	1,739	0.06	0.02	0.51
6/24/2015	0.019		0.75						
6/25/2015	0.017		0						
7/7/2015	0.091	Baseflow	0	0.2	2	915	0.05	0.03	0.15
7/9/2015	0.023		1.03*						
7/9/2015	0.023	Baseflow	0	0.3	7	6,621	0.12	0.02	0.24
7/16/2015	0.013	Storm event	0						
7/16/2015	0.013	Storm event	0	0.2	1	488	0.01	0.01	0.09
7/17/2015	0.044		0						
8/31/2015	0.016	Baseflow	0	0.1	3	824	0.03	0.01	0.05
9/1/2015	0.015		0						
9/3/2015	0.010		0						
9/3/2015	0.010	Baseflow	0	0.1	5	1,068	0.01	0.003	0.18
9/8/2015	0.027		0						
9/9/2015	0.017	Baseflow	0	0.2	6	3,661	0.08	0.01	2
9/11/2015	0.018	Storm event	0.01						
9/15/2015	0.017		0						
9/17/2015	0.022	Baseflow	0	0.1	8	1,220	0.02	0.003	0.2
9/23/2015	0.011		0						
10/7/2015	0.009	Baseflow	0	0.04	1	122	0.001	0.001	0.004
10/8/2015	0.007		0						
10/8/2015	0.007	Baseflow	0	0.1	12	2,563	0.02	0.002	0.01
10/20/2015	0.006		0						

* Samples collected before it rained
*** Mean flow rate from the outlet

5.2 Chlorophyll a (Chl a) Uptake of Nutrients

The nutrient uptake by the mass of Chl a produced in the inlet forebay in the CSW was measured to determine how much orthophosphate was being removed by algae using the following stoichiometry equation (Harrison, 1999; Beaugrand, 2015; Huang, 2016):

$$106\ CO_2 + 16\ NO_3 + HPO_4 + 122\ H_2O + 18\ H \rightarrow \underbrace{C_{106}\ H_{263}\ O_{110}\ N_{16}\ P}_{\text{Algae 3560 gr/mol}} + 138\ O_2$$

Calculations were performed as shown:

PO_4^{3-}-P expected to be consumed to produce the X mass of Chl a

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$$(Mass\ of\ Chl\ a\ accumulated)\left(\frac{1mmole\ algae}{3560\ mg\ algae}\right)\left(\frac{1\ mmole\ P}{1\ mmole\ algae}\right)\left(\frac{31\ mg\ P}{1\ mmole\ P}\right)$$

$$(46{,}038\ mg)\left(\frac{1mmole\ algae}{3560\ mg\ algae}\right)\left(\frac{1\ mmole\ P}{1\ mmole\ algae}\right)\left(\frac{31\ mg\ P}{1\ mmole\ P}\right) = 401 \text{ mg mg-P}$$

PO_4^{3-}-P should have been consumed to produce the X mass of Chl a

$$\left(\frac{\text{PO4−P expect to be consumed}}{flow\ (cfs)}\right)\left(\frac{1\ d}{86{,}400\ sec}\right)\left(\frac{1}{\#\ days}\right)\left(\frac{1\ ft^3}{28.3\ L}\right)$$

$$\left(\frac{401mg-P}{0.18\ cfs}\right)\left(\frac{1\ d}{86{,}400\ sec}\right)\left(\frac{1}{4\ days}\right)\left(\frac{1\ ft^3}{28.3}\right) = 0.0002 \text{ mg/L - P}$$

A summary of the predicted phosphate consumed based on accumulation of Chl a is provided in Table 5.4. The predicted PO_4^{3-}-P consumed by mass of Chl a was lower than 0.0003 mg/L - P. As chlorophylls are the basic pigments involved in light absorption and photochemistry in higher plants, algae and photosynthetic bacteria (Vymazal, 1995), it is the common indicator of biomass for algal studies because the problem of sorting algae from non-algal material is avoided (Westlake et al., 1998). Although Chl a can provide information about the level of algae in the CSW in general, it cannot be used to predict the consumption of PO_4^{3-}-P because Chl a represents the concentration of the pigment in the algae and not the total mass of the algae.

Table 5.4 PO_4^{3-}-P consumed by Chl a in the inlet forebay

Date	**Mean Flow (cfs)	Day (d)	Accumulation (mg-Chl a)	PO_4^{3-}-P expected to be consumed (mg-P)	Predicted PO_4^{3-}-P consumed by algae (mg/L-P)	****Mean PO_4^{3-}-P mg/L expected to be consumed
6/22/2015 6/24/2015 6/25/2015	0.40	3	-767	-7	-0.000002	0.01
7/7/2015 7/9/2015	0.21	2	20,425	178	0.0002	0.06
7/9/2015 7/16/2015	0.47	7	-57,231	-498	-0.00006	0.06
7/16/2015 7/17/2015	0.21	1	20,092	175	0.0003	0.01
8/27/2015 8/31/2015	0.18	4	46,038	401	0.0002	0.06
8/31/2015 9/1/2015 9/3/2015	0.21	3	33,299	290	0.00002	0.06
9/3/2015 9/8/2015	0.19	5	30,591	266	0.00001	0.06
9/9/2015 9/11/2015 9/15/2015	0.98	6	-283,858	-2,472	-0.0002	0.01
9/15/2015 9/17/2015 9/23/2015	0.22	8	47,603	415	0.00001	0.01
10/7/2015 10/8/2015	0.14	1	1,752	15	0.00004	0.06
10/8/2015 10/20/2015	0.27	12	12,293	107	0.00001	0.06

** Sum of mean flow rate from inlet West and inlet Main during the period of time

**** Removal of PO_4^{3-}-P expected in the CSW (different between mass in and mass out in the entire wetland) (Table 4.14 and 4.15).

5.3 Mass Balance of Organic Matter (OM)

A mass balance of OM was performed in the CSW as well (Table 5.5), especially in the inlet forebay, in order to see how much OM were being released from the CSW. The equations used to calculate the mass balance of Chl a were applied for the mass balance of OM. Also, the same assumptions were taken into account (Section 5.1). The only difference was that OM concentration was used instead of Chl a concentration. The same assumptions made in section 5.1 about volume of water in the inlet forebay were made for these calculations. Eight different dates were selected to calculate the mass of OM in the inlet forebay. Calculations were performed during baseflow, storm events and a combination of both in order to understand OM dynamic in the inlet forebay. The concentration of OM measured in the inlet forebay was used to perform the mass balance of OM (Appendix A.1). The mass balance shows that exportation of OM from the inlet forebay was less than the mass of OM accumulated. Therefore, some particles may be settling down to the bottom of the wetland instead of leaving the inlet forebay.

Table 5.5 Mass balance OM in the inlet forebay

OM (mg/L)					Event	Mass out of Inlet forebay					Accumulation			Growth (g)	Growth per day (g/day)
Date	**In1**	**In2**	**In3**	**Mean Inlet**		**** Mean Flow (cfs)**	**Days (d)**	**Vol (L)**	**Mass out (g)**	**Mass per day (g/d)**	**Volume (L)**	**Accumulation (g)**	**Change *Accu. (g)**		
7/7/2015	7	132	82	74	Baseflow	0.21	2	1,282	86	43	218,900	16,088	587	673	336
07/9/2015	16	160	53	76								16,676			
7/7/2015	7	132	82	74	Baseflow	0.40	10	12,205	549	55	218,900	16,088	-1,058	-509	-51
7/17/2015	10	188	9	69	Storm event							15,030			
8/31/2015	57	332	16	135	Baseflow	0.21	3	1,922	40	13	218,900	29,543	2,636	2,677	892
9/1/2015	65	334	25	142											
9/3/2015	74	346	22	147								32,181			
9/3/2015	74	346	22	147	Baseflow	0.19	5	2,899	115	23	218,900	32,181	3,105	3,220	644
9/8/2015	85	341	58	161								35,286			
9/9/2015	88	380	64	177	Baseflow	0.98	6	17,941	1,600	267	218,900	38,830	-21,397	-19,796	-3,299
9/11/2015	14	-	-	-	Storm event										
9/15/2015	2	123	114	80	Baseflow							17,432			
9/15/2015	2	123	114	80	Baseflow	0.22	8	5,370	416	52	218,900	17,432	1,260	1,675	209
9/17/2015	5	-	-	-											
9/23/2015	8	208	41	85								18,693			
10/7/2015	1	1	3	8	Baseflow	0.4	1	427	1	1	218,900	1,847	278	279	279
10/8/2015	3	24	3	10								2,125			
10/8/2015	3	24	3	10	Baseflow	0.27	12	9,886	30	3	218,900	2,125	1,874	1,904	159
10/20/2015	5	70	5	18								3,999			

* Accu. = Accumulation

** Sum of mean flow rate from inlet West and inlet Main

The mass of OM leaving the CSW was generally lower in comparison with the mass of OM leaving the inlet forebay (Table 5.6). The range of the mass of OM leaving the inlet forebay was 1 – 1,600 gr, while the range of mass of OM leaving the CSW was 4 – 157 gr. This could be because the main mass of algae is in the inlet forebay. Also, maybe settling mechanisms are occurring in the CSW and, for that reason, OM settling to the bottom of the CSW instead of being exported out of it.

Table 5.6 Mass of OM in the Outlet of the CSW

Date	**OM Out (mg/L)**	**Event**	**Mass Outlet of CSW**					**Mass leaving the inlet (g/day)**
			***** Mean Flow outlet (cfs)**	**Days (d)**	**Vol (L)**	**Mass out (g)**	**Mass out per day (g/day)**	
7/7/2015	36	Baseflow	0.15	2	915	19	9	43
7/9/2015	6							
7/7/2015	36	Baseflow	0.3	10	7,933	157	16	55
7/17/2015	4	Storm event						
8/31/2015	68	Baseflow	0.1	3	824	24	8	13
9/1/2015	13							
9/3/2015	7							
9/3/2015	7	Baseflow	0.1	5	1,068	4	1	23
9/8/2015	1							
9/9/2015	10	Baseflow	0.2	6	3,661	26	5	267
9/11/2015	4	Storm event						
9/15/2015	7	Baseflow						
9/15/2015	7	Baseflow	0.1	8	1,220	11	1	52
9/17/2015	10							
9/23/2015	11							
10/7/2015	52	Baseflow	0.04	1	122	4	4	1
10/8/2015	8							
10/8/2015	8	Baseflow	0.1	12	2,563	21	2	3
10/20/2015	9							

*** Mean flow rate from outlet

5.4 Correlation of Organic Matter Mass Balance to Nutrient Uptake

The nutrient uptake by algae in the inlet forebay (using OM as an indicator of algal mass) was measured to determine how much orthophosphate was being removed by algae using the following stoichiometry equation (Harrison, 1999; Beaugrand, 2015; Huang, 2016) (Table 5.8):

$$106\ CO_2 + 16\ NO_3 + HPO_4 + 122\ H_2O + 18\ H \rightarrow \underbrace{C_{106}\ H_{263}\ O_{110}\ N_{16}\ P}_{\substack{\text{Algae} \\ \text{3560 gr/mol}}} + 138\ O_2$$

Calculations were performed in the same way shown in section 5.2 for uptake of nutrients by Chl a. From the PO_4^{3-}-P concentration data in the CSW shown in Chapter 4 (Tables 4.14 and 4.15), the mean consumption of PO_4^{3-}-P in the CSW during baseflow was 0.06 mg/L and 0.01 mg/L during storm events in the CSW. It was, therefore, expected that the predicted PO_4^{3-}-P consumed by algae in the inlet forebay be similar to this number. Nevertheless, it seems that the predicted consumption of PO_4^{3-}-P by algae was lower than the actual removal of phosphate (Table 5.7). The PO_4^{3-}-P predicted to be consumed by algae was < 0.02 mg/L-P. It is implied that there are other phosphate removal mechanisms in the CSW such as storage in soil or uptake by plants (macrophytes or other type of plants in the CSW) or consumption of phosphate by algae in other parts of the CSW.

Table 5.7 PO_4^{3-}-P consumed by algae in the inlet forebay

Date	**Mean Flow (cfs)	Day (d)	Storage (mg-algae)	PO_4^{3-}-P expected to be consumed (mg-P)	Predicted PO_4^{3-}-P consumed by algae (mg/L-P)	****Mean PO_4^{3-}-P mg/L expected to be consumed
7/7/2015 7/17/2015	0.40	10	-1,058,007	-9,213	-0.001	0.01
8/31/2015 9/1/2015 9/3/2015	0.21	3	2,636,289	22,956	0.02	0.06
9/3/2015 9/8/2015	0.19	5	3,105,029	27,038	0.01	0.06
9/9/2015 9/11/2015 9/15/2015	0.98	6	-21,396,683	-186,319	-0.013	0.01
9/17/2015 9/23/2015	0.22	8	1,259,658	10,969	0.003	0.06
10/7/2015 10/8/2015	0.14	1	278,000	2,421	0.007	0.06
10/8/2015 10/20/2015	0.27	12	1,873,767	16,317	0.002	0.06

**** Removal of PO_4^{3-}-P expected in the CSW (different between mass in and mass out in the entire wetland) (Table 4.14 and 4.15).

Chapter 6 Conclusions

The Constructed Stormwater Wetland can be considered eutrophic resulting in increased algal concentrations during the summer and fall. During the summer 2015, the algal population was seen in the CSW growing and covering the inlet forebay. The amount of algae in the CSW was quantified by measuring chlorophyll a and organic matter from June to October 2015. Chl a results show that there was algae in the CSW. The growth of algae in the CSW was implied to be affected by factors such as flow, water temperature and sunlight. Temperature appears to be the main factor that controls the growth of algae in the CSW in the middle of the summer and into the fall.

The major mass of Chl a accumulated in the inlet forebay of the CSW because of the high hydraulic residence time during baseflow and the dynamics of the CSW in the inlet forebay, especially in Inlet 2, where the highest concentrations of Chl a were measured. It is implied that algae inhibit the flow in Inlet 2, and, in some cases, the wind speed and direction as well. Accumulation of algae in the CSW after a storm event with high intensity could take two or three days to reach the mass of algae accumulation before the storm event. The low Chl a concentration in the outlet in comparison with the Chl a concentration in the inlet could be because algae are settling down in the system or getting stuck within vegetation instead of leaving the CSW. Exportation of organic matter from the CSW was minimal in comparison with the mass of organic matter accumulated in the CSW. There was a direct correlation between chlorophyll a and organic matter because algae are made up of organic matter. Also, OM concentrations were higher during the summer than other seasons (which was similar to chlorophyll a). During the fall, with the decrease of temperature, the mass of algae decreased as well.

The removal of nutrients was higher during baseflow than during storm event, which might be because of the high residence time and low flow coming into the CSW. On the other hand, high flow rates during storm events can interfere with the performance of the CSW removing pollutants. There are nutrients available in the CSW but algae are not the main consumer of them during the summer. It seems that there are other mechanisms for the removal of nutrients from the CSW. Calculations from algal production stoichiometry show that the phosphate uptake by algae is not the main loss mechanism of phosphate in the CSW.

Results show that the VU CSW is performing well at removing nutrients. But, nevertheless, the CSW has a eutrophication problem due to high concentrations of Chl a. In the future, the capacity of the CSW to remove pollutants could be affected due to the high accumulation of nutrients and organic matter in the CSW.

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Appendix

Table A.1 Organic Matter data

OM (mg/L)										Event
Date	No.	In1	In2	In3	Mean Inlet	M1	M2	M3	Out	
9/17/2014	1	10.17	-	-	-	27.33	-	9.33	7.50	Baseflow
9/26/2014	2	9.50	-	-	-		-	-	6.00	Storm event
10/23/2014	3	6.50	-	-	-		-	-	3.00	Storm event
10/29/2014	4	11.67	-	-	-	8.33	-	7.33	7.00	Baseflow
11/4/2014	5	6.33	-	-	-	6.00	-	5.50	3.00	Baseflow
11/7/2014	6	24.33	-	-	-		-	-	10.11	Storm event
12/2/2014	7	13.33	-	-	-		-	-	3.00	Storm event
12/12/2014	8	9.00	-	-	-	7.83	-	7.00	5.33	Baseflow
1/18/2015	9	11.33	-	-	-	3.00	-	-	3.00	Baseflow
1/18/2015	10	7.33	-	-	-	3.33	-	-	6.00	Storm event
1/29/2015	11	5.33	-	-	-	3.33	-	3.00	4.50	Baseflow
2/2/2015	12	7.00	-	-	-	5.17	-	-	6.00	Storm event
2/26/2015	13	6.17	-	-	-	3.00	3.17	3.33	1.83	Baseflow
3/11/2015	14	4.33	-	-	-	3.00	-	-	3.17	Storm event
5/7/2015	15	7.67	-	-	-	3.33	2.83	3.00	4.33	Baseflow
5/21/2015	16	3.00	-	-	-	7.50	6.67	5.67	8.33	Baseflow
6/1/2015	17	4.44	-	-	-	27.50	-	-	5.33	Storm event
6/9/2015	18	12.00	-	-	-	9.67	-	-	11.67	Storm event
7/7/2015	19	7.00	132.00	81.50	-	10.00	23.00	-	35.50	Baseflow
7/9/2015	20	15.88	160	52.66	76.18	2.46	2.46	-	5.88	Baseflow
7/17/2015	21	9.50	188.00	8.50	-	9.50	12.50	-	4.00	Storm event
7/21/2015	22	1.00	267.25	11.50	-	-	-	-	-	Baseflow
7/23/2015	23	9.83	-	-	-	13.33	23.67	14.67	8.83	Baseflow
8/6/2015	24	2.33	-	-	-	11.00	5.67	2.33	6.33	Baseflow
8/14/2015	25	10.83	-	-	-	13.67	15.33	11.83	10.50	Baseflow
8/21/2015	26	10.42	-	-	-	4.25	-	-	3.00	Storm event
8/27/2015	27	5.67	-	-	-	10.67	48.17	11.75	17.67	Baseflow
8/31/2015	28	57.40	331.52	16.00	134.97	132.50	12.50	-	67.50	Baseflow
9/1/2015	29	65.20	334.27	25.20	141.56	108.00	16.80	-	13.20	Baseflow
9/3/2015	30	73.60	345.78	21.67	147.02	91.00	19.33	-	6.67	Baseflow
9/8/2015	31	84.80	340.80	58.00	161.20	33.60	2.00	-	0.80	Baseflow
9/9/2015	32	87.76	380.00	64.40	177.39	22.40	22.00	60.40	10.00	Baseflow
9/11/2015	33	13.77	-	-	-	10.71	-	-	3.83	Storm event
9/15/2015	34	1.60	123.32	114.00	-	99.60	8.40	183.20	7.20	Baseflow
9/17/2015	35	4.67	-	-	-	1.67	3.67	2.50	9.67	Baseflow

OM (mg/L)										Event
Date	**No.**	**In1**	**In2**	**In3**	**Mean Inlet**	**M1**	**M2**	**M3**	**Out**	
9/23/2015	36	7.20	208.18	40.80	-	14.40	4.00	-	11.20	Baseflow
10/5/2015	37	4.40	-	4.40	-	2.40	1.00	0.40	8.80	Storm event
10/7/2015	38	1.44	21.41	2.46	8.44	5.50	1.33	0.67	51.83	Baseflow
10/8/2015	39	2.46	24.20	2.46	9.71	6.7	2.6	3.25	7.6	Baseflow
10/20/2015	40	4.80	46.40	3.60	18.27	50.00	1.20	0.40	8.80	Baseflow

Table A.2 Flow data - Temperature data

Start Time	Temp . Inlet (°C)	Temp. Outlet (°C)	Temp. M1 (°C)	Temp. M3 (°C)	Q inlet main (cfs)	Q inlet west (cfs)	SWMM Model inlet main (cfs)	SWMM Model inlet west (cfs)	Total Q inlet (cfs)	Total Q Outlet (cfs)	Rain
5/25/15	20.95	21.69	21.27	20.80	0.02			0.13	0.15	0.07	-
5/26/15	22.04	23.67	22.65	22.48	0.02			0.13	0.15	0.07	-
5/27/15	20.32	24.23	23.37	23.43	0.10			0.23	0.33	0.33	0.18
5/28/15	20.93	24.08	23.31	23.41	0.09			0.14	0.23	0.32	0.02
5/29/15	22.71	24.07	23.09	22.91	0.05			0.13	0.18	0.29	-
5/30/15	21.88	24.62	23.78	23.73	0.03			0.13	0.16	0.29	-
5/31/15	22.26	25.02	24.12	24.08	0.02			0.13	0.16	0.27	0.03
6/1/15	20.15	21.45	20.77	20.96	0.46			1.34	1.81	1.25	1.65
6/2/15	17.19	16.91	16.76	16.37	0.21			0.39	0.60	0.66	0.26
6/3/15	18.92	17.32	17.82	17.09	0.04			0.16	0.20	0.35	0.01
6/4/15	19.12	18.10	18.26	17.54	0.03			0.13	0.16	0.30	-
6/5/15	19.54	18.74	19.19	18.31	0.07			0.20	0.28	0.36	0.08
6/6/15	20.93	21.03	21.39	20.77	0.03			0.13	0.16	0.29	-
6/7/15	21.14	21.18	20.63	19.94	0.02			0.13	0.15	0.27	-
6/8/15	21.56	21.94	21.38	21.21	0.20			0.66	0.85	0.49	0.74
6/9/15	21.58	23.14	22.24	22.29	0.09			0.27	0.37	0.37	0.03
6/10/15	21.89	24.50	21.71	21.63	0.03			0.13	0.16	0.04	-
6/11/15	21.32	25.72	23.66	23.39	0.03			0.13	0.16	0.04	-
6/12/15	20.28	27.03	25.14	25.16	0.05			0.13	0.18	0.05	-
6/13/15	20.20	27.46	24.82	25.12	0.05			0.13	0.18	0.04	-
6/14/15	19.32	27.52	24.42	24.79	0.05			0.18	0.24	0.12	0.09
6/15/15	18.23	26.12	24.07	24.69	0.05			0.14	0.19	0.10	0.01
6/16/15	19.61	26.47	24.19	24.82	0.05			0.20	0.25	0.14	0.08
6/17/15	20.02	25.79	22.58	23.04	0.02			0.13	0.16	0.04	-
6/18/15	19.13	21.50	20.72	20.72	0.22			0.58	0.80	0.51	0.47
6/19/15	19.63	23.10	22.13	22.40	0.08			0.22	0.30	0.17	0.09
6/20/15	18.64	24.16	22.56	22.80	0.09			0.26	0.35	0.06	0.29
6/21/15	22.16	24.93	24.12	24.21	0.19			0.59	0.78	0.54	0.33
6/22/15	21.02	26.47	24.16	24.40	0.03			0.13	0.16	0.04	-
6/23/15	19.65	25.72	23.94	24.04	0.12			0.78	0.90	0.37	0.75

Start Time	Temp . Inlet (°C)	Temp. Outlet (°C)	Temp. M1 (°C)	Temp. M3 (°C)	Q inlet main (cfs)	Q inlet west (cfs)	SWMM Model inlet main (cfs)	SWMM Model inlet west (cfs)	Total Q inlet (cfs)	Total Q Outlet (cfs)	Rain
6/24/15	21.49	24.81	22.80	22.42	0.03			0.16	0.18	0.10	0.01
6/25/15	21.20	23.84	21.58	21.38	0.09			0.28	0.37	0.25	0.19
6/26/15	21.01	22.98	22.05	21.79	0.16			0.63	0.79	0.24	0.99
6/27/15	18.78	20.07	19.72	19.62	0.74			2.07	2.82	1.10	1.80
6/28/15	20.24	20.40	20.75	20.23	0.22			0.33	0.55	0.62	0.17
6/29/15	19.27	21.86	20.23	20.24	0.04			0.13	0.17	0.15	-
6/30/15	20.70	22.83	21.70	21.42	0.07			0.18	0.25	0.21	0.08
7/1/15	21.74	23.37	23.07	22.61	0.17			0.45	0.62	0.51	0.56
7/2/15	19.90	22.61	21.24	20.90	0.09			0.13	0.22	0.12	-
7/3/15	22.52	23.11	21.84	21.47	0.09			0.13	0.22	0.12	-
7/4/15	19.76	22.50	21.60	21.37	0.10			0.16	0.27	0.21	0.06
7/5/15	20.78	23.11	21.93	21.65	0.06			0.13	0.19	0.11	-
7/6/15	20.11	24.09	22.95	23.00	0.07			0.18	0.25	0.21	0.08
7/7/15	20.68	25.72	24.34	24.48	0.03			0.14	0.16	0.11	-
7/8/15	19.50	25.64	23.89	24.27	0.06			0.19	0.26	0.20	0.10
7/9/15	21.17	24.14	23.38	23.44	0.10			0.82	0.92	0.62	1.03
7/10/15	22.18	25.09	23.63	23.56	-		0.09	0.14	0.23	0.23	-
7/11/15	23.46	25.84	23.44	23.26	-		0.08	0.13	0.21	0.10	-
7/12/15	22.57	25.49	23.58	22.96	-		0.08	0.13	0.21	0.10	-
7/13/15	20.09	25.64	23.60	23.41	-		0.08	0.13	0.21	0.11	-
7/14/15	19.16	25.49	23.94	23.83	-		0.09	0.16	0.25	0.15	0.05
7/15/15	21.16	23.04	22.90	22.59	-		0.44	1.09	1.53	0.96	1.24
7/16/15	20.39	23.20	21.24	21.25	-		0.08	0.13	0.21	0.19	-
7/17/15	19.87	23.96	22.65	21.85	-		0.08	0.13	0.21	0.13	-
7/18/15	19.04	24.48	23.79	23.39	-		0.08	0.13	0.21	0.18	-
7/19/15	19.88	26.65	25.49	25.44	-		0.08	0.13	0.21	0.16	-
7/20/15	20.39	27.76	26.42	26.29	-		0.08	0.13	0.21	0.18	-
7/21/15	19.62	27.00	24.86	24.93	-		0.08	0.13	0.21	0.11	-
7/22/15	20.07	25.39	22.68	22.87	-		0.08	0.13	0.21	0.08	-
7/23/15	19.73	24.33	21.99	21.48	-		0.08	0.13	0.21	0.08	-
7/24/15	19.31	23.95	21.62	21.22	-		0.08	0.13	0.21	0.03	-
7/25/15	19.39	24.31	22.11	21.58	-		0.08	0.13	0.21	0.02	-
7/26/15	19.73	25.31	23.60	23.08	-		0.08	0.13	0.21	0.04	-
7/27/15	20.54	24.75	24.03	23.80	-		0.14	0.32	0.46	0.34	0.21
7/28/15	19.49	25.72	24.45	24.26	-		0.08	0.13	0.21	0.13	-
7/29/15	19.39	26.48	25.07	25.01	-		0.08	0.13	0.21	0.11	-
7/30/15	20.12	25.67	24.60	24.77	-		0.16	0.38	0.54	0.38	0.26
7/31/15	21.09	25.22	23.37	23.50	-		0.08	0.14	0.22	0.11	-
8/1/15	20.80	24.81	22.94	22.73	-		0.08	0.12	0.20	0.05	-

Start Time	Temp . Inlet (°C)	Temp. Outlet (°C)	Temp. M1 (°C)	Temp. M3 (°C)	Q inlet main (cfs)	Q inlet west (cfs)	SWMM Model inlet main (cfs)	SWMM Model inlet west (cfs)	Total Q inlet (cfs)	Total Q Outlet (cfs)	Rain
8/2/15	20.17	24.40	22.31	21.97	-		0.08	0.12	0.20	0.05	-
8/3/15	20.27	24.56	23.11	22.59	-		0.08	0.12	0.20	0.05	-
8/4/15	20.24	25.00	23.53	23.35	-		0.08	0.12	0.20	0.06	0.01
8/5/15	20.08	24.66	22.47	22.24	-		0.08	0.12	0.20	0.07	-
8/6/15	19.64	23.73	21.77	21.37	-		0.08	0.12	0.20	0.06	0.01
8/7/15	19.51	23.81	22.37	22.04	-		0.08	0.12	0.20	0.09	-
8/8/15	19.02	23.22	21.55	21.07	-		0.08	0.12	0.20	0.08	-
8/9/15	18.87	22.69	21.76	21.29	-		0.08	0.12	0.20	0.09	-
8/10/15	18.59	21.60	20.99	20.76	-		0.08	0.12	0.20	0.13	0.01
8/11/15	21.15	21.86	22.26	21.88	-		0.21	0.12	0.33	0.59	0.55
8/12/15	20.77	23.10	21.93	21.79	-		0.08	0.12	0.20	0.08	-
8/13/15	20.60	22.77	21.73	20.89	-		0.08	0.12	0.20	0.07	-
8/14/15	20.15	22.58	21.47	20.36	-		0.08	0.12	0.20	0.03	-
8/15/15	20.23	23.40	22.95	21.88	-		0.08	0.12	0.20	0.03	-
8/16/15	20.25	24.08	23.60	22.76	-		0.08	0.12	0.20	0.03	-
8/17/15	20.38	24.79	24.27	23.56	-		0.08	0.12	0.20	0.03	-
8/18/15	20.37	25.27	24.50	23.95	-		0.08	0.12	0.20	0.05	-
8/19/15	20.35	25.41	24.77	24.53	-		0.08	0.12	0.20	0.11	-
8/20/15	21.50	24.78	24.14	24.36	-		0.28	0.12	0.40	0.38	0.87
8/21/15	23.30	24.79	24.09	23.58	-		0.14	0.12	0.26	0.37	-
8/22/15	22.40	23.82	21.76	21.13	-		0.08	0.12	0.20	0.05	-
8/23/15	21.20	22.61	21.14	20.05	-		0.08	0.12	0.20	0.04	-
8/24/15	20.67	22.60	22.12	20.83	-		0.08	0.12	0.20	0.04	-
8/25/15	21.03	23.56	23.29	22.29	-		0.08	0.12	0.20	0.05	-
8/26/15	19.30	22.31	21.14	20.13	-	0.21	0.08		0.29	0.04	-
8/27/15	18.91	21.07	20.46	19.19	-	0.10	0.08		0.18	0.08	-
8/28/15	18.87	20.75	19.90	18.96	-	0.11	0.08		0.19	0.04	-
8/29/15	18.93	21.16	20.69	19.40	-	0.08	0.08		0.16	0.04	-
8/30/15	19.44	22.28	22.46	21.27	-	0.09	0.08		0.17	0.05	-
8/31/15	19.69	23.49	23.55	22.79	-	0.11	0.08		0.19	0.06	-
9/1/15	20.42	23.73	23.22	22.82	-	0.14	0.08		0.22	0.10	-
9/2/15	20.59	23.53	23.10	22.49	-	0.14	0.08		0.22	0.10	-
9/3/15	20.64	23.99	23.32	22.74	-	0.12	0.08		0.20	0.07	-
9/4/15	20.80	24.20	23.84	23.23	-	0.11	0.08		0.19	0.09	-
9/5/15	20.67	23.64	22.99	22.46	-	0.12	0.08		0.20	0.09	-
9/6/15	20.41	22.22	21.01	20.12	-	0.11	0.08		0.19	0.06	-
9/7/15	20.73	22.31	22.29	21.00	-	0.10	0.08		0.18	0.07	-
9/8/15	20.85	23.24	23.43	22.48	-	0.12	0.08		0.20	0.07	-
9/9/15	20.96	24.34	24.44	23.67	-	0.09	0.08		0.17	0.07	-

Start Time	Temp . Inlet (°C)	Temp. Outlet (°C)	Temp. M1 (°C)	Temp. M3 (°C)	Q inlet main (cfs)	Q inlet west (cfs)	SWMM Model inlet main (cfs)	SWMM Model inlet west (cfs)	Total Q inlet (cfs)	Total Q Outlet (cfs)	Rain
9/10/15	22.53	23.20	23.43	23.17	-	3.02	0.22		3.24	0.67	0.68
9/11/15	21.56	22.47	22.20	21.52	-	0.91	0.10		1.01	0.30	0.01
9/12/15	20.88	21.06	21.02	20.20	-	1.50	0.10		1.61	0.16	0.11
9/13/15	20.30	19.91	19.33	19.01	-	0.25	0.09		0.33	0.11	0.01
9/14/15	19.55	18.54	17.61	16.72	-	0.19	0.08		0.27	0.05	-
9/15/15	20.43	18.51	18.70	16.91	-	0.18	0.08		0.26	0.04	-
9/16/15	21.00	19.00	19.78	17.75	-	0.15	0.08		0.23	0.04	-
9/17/15	21.18	19.39	20.40	18.30	-	0.11	0.08		0.19	0.04	-
9/18/15	21.23	19.67	20.65	18.60	-	0.14	0.08		0.22	0.05	-
9/19/15	21.16	20.30	21.65	19.83	-	0.21	0.08		0.29	0.07	-
9/20/15	21.07	20.52	21.25	19.88	-	0.18	0.08		0.26	0.05	-
9/21/15	19.65	18.66	18.44	17.29	-	0.14	0.08		0.22	0.05	-
9/22/15	19.40	18.02	18.23	17.16	-	0.13	0.08		0.21	0.05	-
9/23/15	19.13	18.47	18.05	16.77	-	0.07	0.08		0.15	0.04	-
9/24/15	19.02	18.26	17.84	16.07	-	0.14	0.08		0.22	0.04	-
9/25/15	19.26	18.16	18.43	16.70	-	0.11	0.08		0.19	0.04	-
9/26/15	18.64	17.63	17.80	16.37	-	0.11	0.08		0.19	0.05	-
9/27/15	18.34	17.25	17.42	16.20	-	0.08	0.08		0.16	0.05	-
9/28/15	19.42	18.74	19.82	18.55	-	0.27	0.08		0.36	0.05	0.01
9/29/15	20.69	20.79	21.77	20.92	-	3.18	0.41		3.59	0.40	1.63
9/30/15	21.25	22.36	22.28	21.87	-	8.48	0.34		8.81	0.69	0.34
10/1/15	18.39	18.63	17.58	17.36	-	1.32	0.12		1.44	0.32	0.25
10/2/15	15.42	14.12	14.00	13.78	-	17.1	0.57		17.68	1.10	1.78
10/3/15	16.44	11.98	12.99	12.24	-	1.34	0.13		1.48	0.59	0.05
10/4/15	16.63	12.80	13.75	12.96	-	0.16	0.08		0.24	0.15	-
10/5/15	16.98	13.63	14.24	13.01	-	0.11	0.08		0.19	0.06	-
10/6/15	17.44	14.27	15.45	13.54	-	0.15	0.08		0.23	0.05	-
10/7/15	17.71	15.27	16.82	15.17	-	0.06	0.08		0.14	0.04	-
10/8/15	17.73	15.55	16.56	14.86	-	0.06	0.08		0.14	0.04	-
10/9/15	18.27	16.91	17.93	16.74	-	1.45	0.20		1.65	0.34	0.44
10/10/15	17.41	17.12	15.69	14.92	-	0.07	0.08		0.15	0.09	-
10/11/15	16.72	14.59	14.19	12.42	-	0.06	0.08		0.14	0.05	-
10/12/15	17.30	14.15	15.26	13.12	-	0.12	0.08		0.20	0.04	-
10/13/15	17.65	14.79	16.53	14.65	-	0.06	0.08		0.14	0.05	-
10/14/15	17.35	14.61	15.57	14.34	-	0.10	0.08		0.18	0.04	-
10/15/15	16.30	13.92	14.16	12.97	-	0.07	0.08		0.15	0.06	-
10/16/15	15.81	13.05	13.05	11.76	-	0.04	0.08		0.12	0.05	-
10/17/15	14.73	11.55	11.18	10.02	-	0.14	0.08		0.22	0.05	-

Start Time	Temp. Inlet (°C)	Temp. Outlet (°C)	Temp. M1 (°C)	Temp. M3 (°C)	Q inlet main (cfs)	Q inlet west (cfs)	SWMM Model inlet main (cfs)	SWMM Model inlet west (cfs)	Total Q inlet (cfs)	Total Q Outlet (cfs)	Rain
10/18/15	13.36	9.75	8.98	8.02	-	0.07	0.08		0.15	0.05	-
10/19/15	12.47	8.39	8.12	6.63	-	0.04	0.08		0.12	0.05	-
10/20/15	13.91	9.22	10.90	8.92	-	0.07	0.08		0.15	0.04	-
10/21/15	15.51	10.89	13.15	10.98	-	0.04	0.08		0.12	0.04	-
10/22/15	16.07	12.08	14.22	11.98	-	0.10	0.08		0.18	0.04	-
10/23/15	15.94	12.16	13.72	11.94	-	0.04	0.08		0.12	0.04	-
10/24/15	14.30	11.20	11.34	9.76	-	0.06	0.08		0.14	0.04	-
10/25/15	15.85	12.47	13.91	12.51	-	0.09	0.08		0.18	0.04	0.02
10/26/15	14.35	11.34	11.40	10.03	-	0.06	0.08		0.14	0.04	-
10/27/15	13.61	10.12	10.08	8.77	-	0.06	0.08		0.14	0.04	-
10/28/15	16.34	13.21	14.70	13.64	-	5.03	0.34		5.38	0.82	0.96
10/29/15	17.06	16.86	16.58	16.09	-	1.90	0.20		2.10	0.54	0.36
10/30/15	15.15	13.22	11.70	11.21	-	0.08	0.08		0.16	0.04	-
10/31/15	13.75	10.62	9.55	8.59	-	0.21	0.08		0.29	0.04	-

Table A.3 TKN concentration during baseflow

TKN (mg/L) Baseflow							
Date	No.	Rain	Inlet	Outlet	M1	M2	M3
11/9/2011	1	0	0.62	0.44	0.36	0.42	0.32
3/28/2012	2	0	1.06	0.82	0.95	0.77	0.62
4/12/2012	3	0	1.06	1.01	0.92	0.99	0.96
5/21/2012	4	0	6.37	2.82	3.80	6.08	4.81
9/11/2012	5	0	1.08	0.37	0.77	0.85	0.64
12/4/2012	6	0	1.75	1.04	1.58	1.56	0.94
1/24/2013	7	0	1.35	0.56	0.58	0.52	0.73
2/19/2013	8	0	1.45	1.06	0.72	0.83	0.91
4/8/2013	9	0	1.48	0.82	1.58	0.71	0.59
5/15/2013	10	0	0.91	0.93	1.54	1.06	0.85
6/6/2013	11	0	1.23	2.99	1.60	0.99	0.72
7/17/2013	12	0	1.78	0.59	0.52	0.59	1.12
8/21/2013	13	0	0.24	0.48	0.37	0.44	0.28
9/11/2013	14	0	0.56	0.26	0.93	0.36	1.26
10/28/2013	15	0	0.68	0.27	0.33	0.43	0.39
11/14/2013	16	0	1.29	0.26	0.36	1.32	0.44
3/24/2014	17	0	0.68	0.57	0.99	0.66	0.54
7/8/2014	18	0	0.83	0.43	0.42		0.77
8/7/2014	19	0	1.50	2.51	0.62		0.55
11/4/2014	20	0	0.51	0.20	2.28		1.42
AVG			1.32	0.92	1.06	1.09	0.94
Median			1.07	0.58	0.84	0.77	0.73
STD			1.26	0.85	0.84	1.33	0.96

Table A.4 TKN concentration during storm event

TKN (mg/L) Storm event							
Date	No.	Rain	Inlet	Outlet	M1	M2	M3
7/26/2011	1	0.44	0.60	0.29	0.31	0.10	0.28
8/3/2011	2	0.81	1.37	1.16	1.04	0.84	0.92
8/9/2011	3	2.03	3.01	4.12	5.12	1.29	0.99
8/15/2011	4	0.54	2.85	1.02	1.32	1.32	1.31
8/27/2011	5	7.96	1.08	1.26	1.14	1.16	1.42
9/6/2011	6	5.44	0.46	0.51	0.58	0.92	0.68
1/12/2012	7	1.71	1.45	0.41	0.89	0.42	0.45
4/23/2012	8	2.50	1.00	2.15	2.56	4.45	1.86
5/10/2012	9	0.72	2.63	4.02	2.24	2.78	3.02
10/2/2012	10	0.50	1.04	0.78	0.80	0.68	0.99
1/31/2013	11	1.85	0.88	0.81	0.66	1.93	0.86
2/11/2013	12	0.53	2.60	1.47	1.56	0.90	1.02
3/12/2013	13	1.15	0.55	0.53	0.42	0.58	0.38
3/25/2013	14	0.64	0.97	0.75	0.58	0.79	0.69
4/29/2013	15	0.50	1.08	0.93	1.66	0.82	0.70
5/8/2013	16	0.97	0.71	0.54	0.54	0.76	0.58
6/10/2013	17	2.70	0.41	0.60	1.82	0.74	0.72
7/23/2013	18	1.36	0.76	0.24	0.46	0.59	1.16
8/28/2013	19	1.32	1.07	0.21	0.60	0.44	0.66
12/9/2013	20	0.44	0.64	0.47	0.76	0.45	0.77
1/14/2014	21	0.26	0.35	0.94	0.88	1.10	1.31
3/12/2014	22	0.50	0.50	0.67	0.77	0.50	0.50
4/7/2014	23	0.43	0.67	0.88	0.84	0.83	1.20
4/30/2014	24		1.12	1.20			
6/27/2014	25		0.92	0.62			
11/17/2014	26		0.63	0.33			
12/3/2014	27		0.62	0.38			
AVG			1.11	1.01	1.20	1.06	0.98
Median			0.92	0.75	0.84	0.82	0.86
STD			0.76	0.98	1.04	0.93	0.58

Table A.5 NO_x concentration during baseflow

NO_x (mg/L) Baseflow							
Date	No.	Rain	Inlet	Outlet	M1	M2	M3
10/18/2011	1	0	1.29	1.00	1.48	1.55	1.11
11/9/2011	2	0	2.34	1.19	1.80	1.50	1.32
12/13/2011	3	0	2.59	2.76	2.82	2.80	2.81
2/23/2012	4	0	1.84	1.28	1.84	1.53	1.40
3/28/2012	5	0	1.35	0.92	1.46	0.97	0.91
4/12/2012	6	0	2.41	1.04	1.55	1.11	1.04
5/21/2012	7	0	1.00	0.30	0.80	0.67	0.60
6/20/2012	8	0	1.13	0.01	0.08	0.11	0.07
7/11/2012	9	0	2.40		1.09	0.95	0.87
9/11/2012	10	0	2.68	0.34	0.73	0.74	0.30
10/15/2012	11	0	2.97	0.68	1.44	1.14	0.77
1/24/2013	12	0	0.12	0.09	0.13	0.12	0.12
4/8/2013	13	0	1.47	0.18	0.44	0.33	0.20
5/15/2013	14	0	2.09	0.29	0.48	0.32	0.30
7/17/2013	15	0	0.65	0.15	1.95	0.78	0.30
9/11/2013	16	0	1.43	0.22	2.13	4.53	0.16
10/28/2013	17	0	1.39	0.32	1.00	0.66	0.54
11/14/2013	18	0	1.95	0.38	1.86	1.30	1.43
1/30/2014	19	0	4.99	1.42	2.25	0.91	0.67
3/24/2014	20	0	2.24	1.53	1.19	0.72	0.46
5/14/2014	21	0			0.63	0.30	0.16
7/8/2014	22	0	0.81	0.07	0.10		0.06
7/22/2014	23	0	1.18	0.07	0.14		0.13
8/7/2014	24	0	2.15	0.10			
8/27/2014	25	0	1.41	0.08	0.30		0.16
9/17/2014	26	0	1.84	0.12	0.11		0.10
11/4/2014	27	0	1.29	0.22	0.69		0.10
AVG			1.81	0.59	1.10	1.10	0.62
Median			1.66	0.30	1.05	0.91	0.38
STD			0.94	0.66	0.78	1.00	0.63

Table A.6 NO_x concentration during storm event

NOx (mg/L) Storm event							
Date	No.	Rain	Inlet	Outlet	M1	M2	M3
7/26/2011	1	0.44	1.69	0.14	1.14	0.58	0.28
8/3/2011	2	0.81	0.03	0.93	0.75	0.82	0.69
8/9/2011	3	2.03	0.29	0.60	0.91	0.61	0.51
8/15/2011	4	0.54	0.02	0.33	1.41	4.80	0.54
8/27/2011	5	7.96	2.54	1.33	2.67	2.48	1.80
9/6/2011	6	5.44	0.94	0.32	0.92	0.90	0.69
10/12/2011	7	0.33	0.90	0.86	0.95	0.91	0.84
11/17/2011	8	0.79	1.61	0.96	1.26	1.20	0.60
12/7/2011	9	2.71	1.53	1.34	1.47	1.53	1.38
4/23/2012	10	2.50	0.96	0.59	0.84	0.76	0.62
5/10/2012	11	0.72	1.35	0.95	1.24	1.01	1.29
6/12/2012	12	0.80	1.28		0.42		
10/2/2012	13	0.50	0.76	0.49	0.44	0.36	0.30
11/27/2012	14	0.56	0.92	1.24	1.11	1.08	1.01
3/25/2013	15	0.64	1.09	0.85	2.46	0.94	0.84
5/8/2013	16	0.97	0.39	0.25	0.32	0.41	0.29
6/10/2013	17	2.70	1.71	0.54	0.93	0.67	0.56
7/23/2013	18	1.36	0.94	0.12	0.58	0.24	0.13
8/28/2013	19	1.32	0.82	0.26	0.65		0.48
9/21/2013	20	1.42	2.61	0.07	0.43	0.21	0.14
12/9/2013	21	0.44	11.89	2.20	3.55	2.87	2.02
1/14/2014	22	0.26	1.51	1.35		1.57	1.76
4/7/2014	23	0.43	2.31	0.38	1.05	0.58	0.29
4/30/2014	24		0.70	1.00			
6/27/2014	25		0.63	0.32			
8/22/2014	26		0.88	0.29			
10/22/2014	27		0.65	0.16			
11/17/2014	28		0.64	0.48			
12/3/2014	29		1.27	0.70			
AVG			1.48	0.68	1.16	1.17	0.77
Median			0.94	0.56	0.94	0.90	0.61
STD			2.11	0.50	0.79	1.07	0.55

Table A.7 TN concentration during baseflow

TN (mg/L) Baseflow							
Date	No.	Rain	Inlet	Outlet	M1	M2	M3
11/9/2011	1	0	2.96	1.63	2.16	1.93	1.85
3/28/2012	2	0	2.41	1.74	2.41	1.73	1.53
4/12/2012	3	0	3.47	2.04	2.46	2.10	2.00
5/21/2012	4	0	7.37	3.12	4.60	6.75	5.41
9/11/2012	5	0	3.76	0.71	1.50	1.60	0.94
1/24/2013	6	0	0.79	0.65	0.71	0.64	0.85
4/8/2013	7	0	2.95	1.00	2.02	1.04	0.78
7/17/2013	8	0	2.43	0.74	2.47	1.37	1.42
9/11/2013	9	0	1.99	0.48	3.06	4.89	1.42
10/28/2013	10	0	2.08	0.60	1.33	1.09	0.94
11/14/2013	11	0	3.24	0.64	2.22	2.62	1.87
3/24/2014	12	0	2.93	2.10	2.17	1.46	1.00
5/14/2014	13	0			0.63	0.30	0.16
7/8/2014	14	0	1.64	0.50	0.52		0.83
8/7/2014	15	0	3.65	2.61			
11/4/2014	16	0	1.80	0.42	2.97		1.53
AVG			2.90	1.27	2.08	2.12	1.50
Median			2.93	0.74	2.17	1.60	1.42
STD			1.49	0.87	1.07	1.79	1.19

Table A.8 TN concentration during storm event

TN (mg/L) Storm event						
Date	No.	Inlet	Outlet	M1	M2	M3
7/26/2011	1	2.30	0.43	1.45	0.68	0.56
8/3/2011	2	1.40	2.09	1.79	1.66	1.61
8/9/2011	3	3.29	4.72	6.02	1.90	3.08
8/15/2011	4	2.87	1.36	2.73	6.12	1.84
8/27/2011	5	5.41	2.59	3.81	3.64	3.22
9/6/2011	6	1.41	0.83	1.49	5.69	1.37
4/23/2012	7	1.96	2.74	3.40	5.22	2.49
5/10/2012	8	3.99	4.97	3.48	3.79	4.28
10/2/2012	9	1.81	1.26	1.24	1.04	1.29
1/31/2013	10	0.88	0.81	0.66	1.93	0.86
2/11/2013	11	2.60	1.47	1.56	0.90	1.02
3/25/2013	12	2.06	1.60	1.77	1.73	1.52
7/23/2013	13	1.70	0.35	1.05	0.82	1.29
8/28/2013	14	1.90	0.46	1.25	0.44	1.13
1/14/2014	15	1.85	2.34		2.66	3.07
4/7/2014	16	2.98	1.26	1.92	1.41	1.49
4/30/2014	17	1.81	2.20			
6/27/2014	18	1.55	0.94			
AVG		2.32	1.80	2.24	2.48	1.88
Median		1.93	1.41	1.77	1.82	1.51
STD		1.08	1.33	1.41	1.86	1.04

Calibration curve

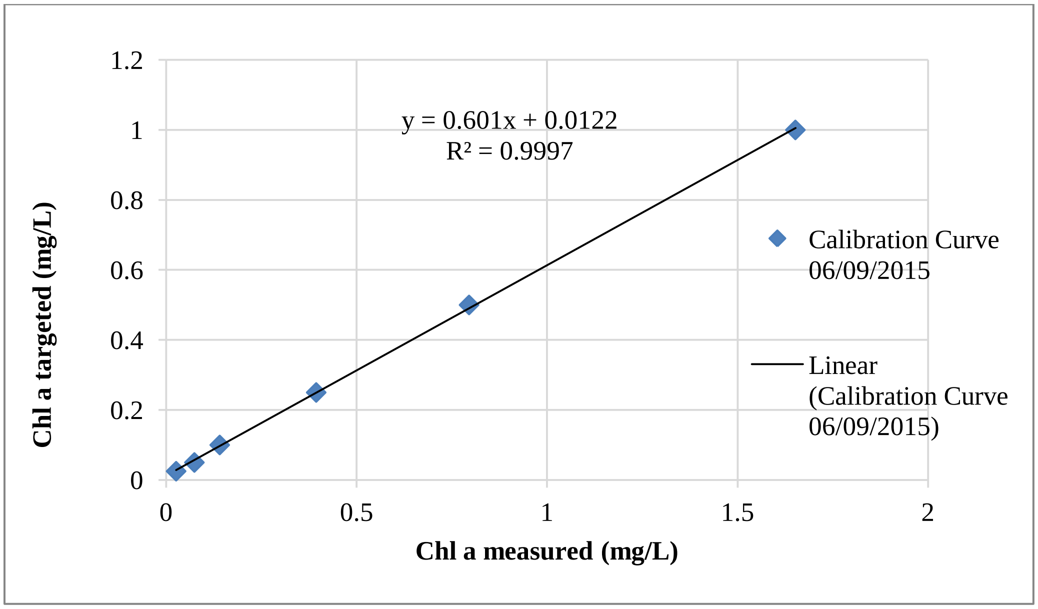

Figure A.1 Chl a calibration curve June 06, 2015