9-1-2012

Floating Wetland Systems for Nutrient Removal in Stormwater Ponds

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Recommended Citation

Chang, Ni-Bin; Wanielista, Martin; and Chopra, Manoj, "Floating Wetland Systems for Nutrient Removal in Stormwater Ponds" (2012). *BMP Trains Research and Publications*. 1.
https://stars.library.ucf.edu/bmptrains-research/1

Summary of Final Report, BDK78 985-01
September 2012

Floating Wetland Systems for Nutrient Removal in Stormwater Ponds

BACKGROUND

Wet detention ponds are frequently used in stormwater management systems as part of a treatment train for attenuation of flow and removal of pollutants. Wet detention ponds designed and operated according to commonly used standards and specifications remove nutrients but the removal of nitrogen has remained low, about 30-40% concentration reduction on a yearly basis. A Floating Treatment Wetland (FTW) composed of selected plants suspended in a wet detention pond was proposed in this research to improve the removal of nutrients before discharge from a pond.

OBJECTIVES

The primary objective was to document improvement in water quality when a FTW was used in a wet detention pond. Design and maintenance issues for the deployment of a FTW were defined and documented for additional nutrient removal when used in wet detention ponds. Explicit tasks were implemented to aid in the specification of plants, media to hold plants, pond area coverage, location of a FWT within a pond, removal rates, and maintenance activities to sustain removal while not producing detrimental effects within the pond water or plant environments.

FINDINGS AND CONCLUSIONS

By all observations, a FTW offered an innovative and naturally harmonious solution for pollutant reduction. The FTWs of this research blended into a pond environment and removed nutrients. In this research, a FTW removed pollutants by directly assimilating them into their macrophytes as well as a FTW provided a suitable environment for microorganisms to decompose or transform pollutants to the gas phase, which reduced their concentrations in pond water.

All media used to support the plants were acceptable, but expanded clay and tire crumb media was most cost effective, plants were sustained, and plant growth was superior to the use of other media. The plants that should be used to sustain removal were recommended. A diversity of plants was recommended. The plants should also be replaced at least once a year. For Florida conditions, the replacement was recommended in the fall when runoff into the wet ponds is reduced significantly relative to the summer rainy season. The removal of plants was also supported by the finding that toxins were produced when the FTW was not removed late in the year and when runoff was relatively low. This is due to the fact the FTW was more efficient in removing nutrients than the algal masses. Thus some of the algal masses died and their toxins were released. The FTW pond area coverage recommended was 5% but when additional nutrient loads were added to the wet detention pond (as an example, from a fountain) a 10% area coverage was recommended.

The additional credit for concentration reduction from the deployment of a FTW in a wet detention pond was recommended as 12%. The credit assumes plant selection, area coverage, pond location, and maintenance recommendations are followed. Considerable amounts of data from laboratory containers, outdoor mesocosms and full scale deployment were used to support the findings.

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BENEFITS

The primary benefit was to offer transportation stormwater system designers and other stormwater professionals an additional option for the removal of nutrients. This was timely in regards to numeric nutrient criteria that were considered for various locations not only in the State of Florida but across the Nation. Furthermore a credit was recommended for nutrient reduction when a FTW was designed and maintained according to the recommendations of the report. This credit can be used in cost effective nutrient removal evaluation of discharges to water bodies and especially those subjected to total maximum daily loads (TMDL) limitations or defined as nutrient impaired waters.

This research project was conducted by Ni-Bin Chang, Marty Wanielista, Manoj Chopra, and students of the Stormwater Management Academy at the University of Central Florida. For more information, contact Rick Renna, Project Manager, at (850) 414-4351, or Rick.Renna@dot.state.fl.us.

Final Report FDOT Project BDK78 985-01

Floating Wetland Systems for Nutrient Removal in Stormwater Ponds

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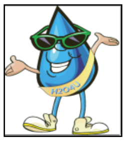

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Editorial Review by Erica Kresh
September 2012

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation. Furthermore, the authors are not responsible for the actual effectiveness of these floating wetlands or for drainage problems that might occur due to their improper use. This does not promote the specific use of any of these particular systems.

METRIC CONVERSIONS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
In	inches	25.4	millimeters	mm
Ft	feet	0.305	Meters	m
Yd	yards	0.914	Meters	m
Mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
Ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	ml
Gal	gallons	3.785	Liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
Oz	ounces	28.35	Grams	g
Lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL

TEMPERATURE (exact degrees)				
°F	fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
Fc	foot-candles	10.76	Lux	lx
Fl	Foot-lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
Lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
Mm	millimeters	0.039	Inches	in
M	meters	3.28	Feet	ft
M	meters	1.09	Yards	yd
Km	kilometers	0.621	Miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3

m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
G	grams	0.035	Ounces	oz
Kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^oC	celsius	1.8C+32	fahrenheit	^oF

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

TECHNICAL REPORT DOCUMENTATION

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Floating Wetland Systems for Nutrient Removal in Stormwater Ponds	5. Report Date September 1, 2012 6. Performing Organization Code Stormwater Management Academy
7. Author(s) Dr. Martin P. Wanielista, Dr. Ni-Bin Chang, Dr. Manoj Chopra, Zhemin Xuan, Kamrul Islam, Zachary Marimon	8. Performing Organization Report No. SMA 1660 7026
9. Performing Organization Name and Address Stormwater Management Academy University of Central Florida Orlando, FL 32816	10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDK78 985-01
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399	13. Type of Report and Period Covered Final Report Mar. 3, 2010 – Sep. 1, 2012 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A Floating Treatment Wetland (FTW) was recommended for installation in a wet detention pond. An additional 12% removal of nitrogen and phosphorus was recommended provided the wet ponds and the FTW satisfy design, installation and maintenance standards. Specific recommendations were made relative to FTW pond area coverage, plant selection, and plant locations. Maintenance recommendations included the removal of FTW plants in the fall of each year and re-planting in the late winter of the following year. Data were provided in this report from laboratory containers, mesocosm ponds (primarily 16 feet or 5 meter diameter ponds), and two operational stormwater ponds to support all recommendations. The location of FTWs within a pond was recommended in relatively tranquil pond waters or not near the faster moving influent and effluent waters.

The results from the laboratory and mesocosm studies were used to recommend a minimum 5% pond FTW area coverage and included selected plants. The removed species of Nitrogen and Phosphorus were primarily in the dissolved form. It was also noted that under increased dissolved nutrient loadings, a FTW removed additional Nitrogen and Phosphorus, thus making FTWs more reliable in high loading conditions. In this work, high loading conditions were from a fountain stirring up the bottom of the pond, and required an increased FTW pond area coverage of 10%. Maintenance of the plants in the FTW was suggested as once per year to improve removal during runoff times, and to reduce the occurrence of cyanobacteria toxins. The toxins were released when the cyanobacteria died during lower nutrient loading times, or during times of lower runoff.

17. Key Word Wet Detention Ponds, Ecology, Wetlands, Plants, Stormwater, Pollution Control, Nutrients.	18. Distribution Statement No Restrictions

19. Security Classification. (of this report) Unclassified	20. Security Classification. (of this page) Unclassified	21. No. of Pages 179	22. Price

ACKNOWLEDGMENTS

The authors deeply appreciate all of the support from so many dedicated professionals for this project. To complete the research, 19 people were involved.

First and foremost, the authors would like to thank the Florida Department of Transportation for their technical assistance and monetary support. Without their support, research such as this would not be possible. In particular, Rick Renna provided valuable assistance in the development and conduct of the research activities. This work was completed under the guidance of the Stormwater Management Academy located at the University of Central Florida. The staff and students of the Academy provided valuable assistance in the collection and analyses of laboratory and field data.

Additionally, this work would not have been possible without the help of two manufacturers of Floating Treatment Wetlands, namely Beemats and Floating Islands International. We were very thankful for their products and technical assistance.

EXECUTIVE SUMMARY

Excess nutrients generated by continuous and intensive human activities have impacted the health and sustainability of aquatic ecosystems, which may result in eutrophication problems, groundwater contamination, and consequential deterioration of the public health. Stormwater management systems are commonly designed for the removal of excess nutrients. Wet detention ponds are frequently used in stormwater management systems as part of a treatment train for the removal of nutrients both at the local or regional levels. A wet detention pond designed and operated according to commonly used standards and specifications can remove nutrients but the removal of nitrogen has remained low, about 30-40% on a yearly basis. A Floating Treatment Wetland (FTW) was proposed in this research to improve the removal of nutrients in a wet detention pond.

A Floating Treatment Wetland (FTW) offered an innovative naturally harmonious solution. A FTW removed pollutants by directly assimilating them into their macrophytes. A FTW then provided a suitable environment for microorganisms to decompose or transform pollutants to the gas phase, which reduced their concentrations. Two types of materials used in this research to fabricate FTWs were interlocking foam and fibrous matrix. These were applied for the effective removal of nutrients in two stormwater detention ponds (named Pond 4M and Pond 5) with different plants and sorption media under varying nutrient and weather concentrations. The interlocking puzzle cut floating foam mat aided in flexible assemblage in any customized size or shape, while the fibrous matrix mats were designed in a uniform shape.

Water depth, percent area coverage of the FTW, and littoral zone emergent plants were varied in grouped mesocosms in order to determine optimum nutrient removal efficiency and the best combination before being implemented in an actual pond. Pond water was monitored for chemical species on a regular basis to understand the effect that the hydrological cycle and nutrient loading has over time. Consideration was also given to the observations of macrophyte-epiphyte-phytoplankton interactions in order to understand temporal characteristics of plant behavior. Laboratory, mesocosm (primarily 16 feet or 5 meter diameter ponds), and two operating stormwater ponds were used to

collect data. The laboratory and mesocosm data recommended that FTW pond area coverage was not to exceed 5% for normal stormwater inputs. For greater pond loading such as from bottom actuated fountain water, a 10% pond area cover was recommended. These pond area coverage values were based on removal measurements and also supported by other investigations. Also, specific plants were recommended for a FTW.

Results indicated that microcosm plant holding laboratory containers filled with sorption media of 80% expanded clay and 20% tire crumb significantly promoted the biomass growth. Different levels of nutrient concentrations and “cold” conditions affected the plants’ growth. To make the system more viable, irrespective of the seasonal weather conditions, the adoption of mixed vegetation was highly recommended in a FTW.

Both hydrological and water quality parameters were monitored before and after a FTW deployment in two functioning wet detention ponds. In Pond 4M, the overall average of TN concentration reduction reached a high value of 15.04% and a considerable 42.51% for TP. The concentration reduction from inlet to outlet in terms of OP, NO_2+NO_3, and NH_3 were 54.65, 17.51, and 27.66 %, respectively. On the other hand, the highest overall removal of TP, OP, TN, NO_2+NO_3, and NH_3 reached 46.3, 79.5, 16.9, 16.7, and 53.0 %, respectively, in Pond 5. However, it should be noted that Pond 5 had a fountain which increased the mass of dissolved concentrations in the water column. The operating Hydraulic Residence Time (HRT), the time from the end of a storm event to the sampling time, was measured to demonstrate the FTW’s performance in both ponds. It showed that the longer operating HRT generally led to higher removal efficiencies. HRT was a measure for the variability of holding time in a pond.

Based on pond measured influent and effluent concentration data, the increased removal of nitrogen and phosphorus (or credit for the use of a FTW) was calculated as 12% for each nutrient. This was estimated for Pond 4M, that had no additional loadings of nutrients. For Pond 5, there was an additional loading of nutrients from the mud at the bottom, which was presumably caused by a fountain. For this aerated condition, there was a higher removal by a FTW. Nevertheless, the effluent concentration for the aerated pond was higher than the non aerated one. As shown in some of the literature and in the mesocosm studies within this report, FTWs removed more dissolved pollutants with higher starting concentrations. This then indicated that in rare cases when stormwater concentrations increased the biological available concentrations, a FTW helped in reducing the concentrations even further than shown during average operation.

Removal of invasive plants in a FTW was suggested in the fall of each year and then replaced at the end of the winter season of the following year. During the fall, the runoff to the ponds decreased and this caused a decrease in pond nutrients as well. If invasive plants on the FTW were allowed to exist, the uptake of nutrients would be reduced by the invasive plants. Thus, the invasive plants were recommended to be replaced. Cyanobacteria in the pond also had limited nutrients and competed with the FTW plants for nutrients. This competition caused some of the Cyanobacteria to die and release toxins such as Microcystin (MC). This was documented by a positive correlation (0.83) and a negative correlation (-0.72) between Microcystin (MC) and TN concentrations found before and after the plant replacement. It is recommended that a FTW should be used in a wet detention pond during wet seasons to remove excess nutrients from stormwater runoff but during dry seasons the plants should be removed and replaced. This maintenance program will help limit the potential production of MC.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Nutrients, such as ammonia, nitrite, nitrate, and phosphorus, in stormwater effluents have been known to be common contaminants in water bodies that threaten public health and ecosystem integrity. This has caused acute and chronic outcomes, both directly and indirectly measured. For example, without proper treatment, ammonia in wastewater effluents has been shown to stimulate phytoplankton growth, exhibit toxicity to aquatic biota, and exert an oxygen demand in surface waters (Beutel, 2006). Furthermore, non-disassociated ammonia was found to be extremely volatile and became either ionized or volatized in aqueous solution. Ionized ammonia has actually been demonstrated to be very toxic for fish species. (Tarazona et al., 2008). Fish mortality, health, and reproduction have all been affected by the presence of a minute amount of ammonia-N (Servizi and Gordon, 2005). In addition to ammonia, nitrate has caused many health problems as well, particularly in humans. Nitrate has proven to be responsible for health issues such as liver damage and even some cancers (Gabel et al, 1982; Huang et al., 1998). Infants have also been affected by nitrate because nitrate binds with hemoglobin and creates a situation of oxygen deficiency in an infant's body called methemoglobinemia (Kim-Shapiro et al., 2005). Finally, it has also been discovered that when nitrite reacts with amines, chemically or enzymatically, it forms nitrosamines which are very potent carcinogens (Sawyer et al., 2003).

Conventional stormwater detention ponds were built essentially for providing aesthetic and recreational benefits, as well as flood and downstream erosion control. However, due to the increased human activity, many possible nutrient sources were infused into the ponds with the surface runoff including fertilizers, animal excrement, and organic debris. The excess nutrients that ponds cannot handle naturally have resulted in new environmental issues and concerns, such as eutrophication (coming from a Greek word meaning "overfed"). As a result of this harmful cycle for ponds, the algal blooms gradually covered the entire water surface and did not allow any sunlight to penetrate the water column (Figure 1). This became the catalyst that hindered the oxygen transfer and restrained a healthy aquatic ecosystem.

Figure 1: Algal bloom in a wet detention pond before the addition of a Floating Wetland

Use of constructed wetlands have significantly increased for remediating nutrient-rich surface and subsurface flow (Belmont and Metcalfe, 2003; White et al., 2009; Baldwin et al., 2009), where various aquatic plants were used to purify both stormwater and wastewater (Iamchaturapatra et al., 2007). FTWs were one of the most promising potential Best Management Practices (BMPs) because it is with them that macrophytes are known to remove pollutants by directly assimilating them into their tissue, provide a suitable environment for microorganisms to transform pollutants, and reduce their concentrations (Breen, 1990; Billore and Sharma, 1996).

Stormwater runoff was highly variable due to the erratic nature of storm events in both intensity and duration. Thus, sediment-rooted plants for conventional treatment wetlands experienced a range of water depths and periods of inundation (Greenway and Polson, 2007). The duration of inundation, the depth of water, the frequency of flooding, and droughts are known to affect plant growth, establishment, and survival. Long periods of flooding were stressful to some bottom-rooted wetland plants (Ewing, 1996; Headley et al., 2006). To manage this issue, wetland area might be increased to buffer against extremes during water level fluctuations or the high flows can be bypassed. In that case, a significant portion of incoming stormwater will not be treated (Headley et al., 2006). Besides, large land area requirement for installation was definitely a limitation to their applicability. Floating Treatment Wetlands (FTWs) were an innovative variant on these systems and a possible solution to this problem. Additionally, plants grew on floating mats rather than being rooted in the sediments (Figure 2). Therefore, water depth was not a concern and the mats are highly unlikely affected by fluctuations in water levels.

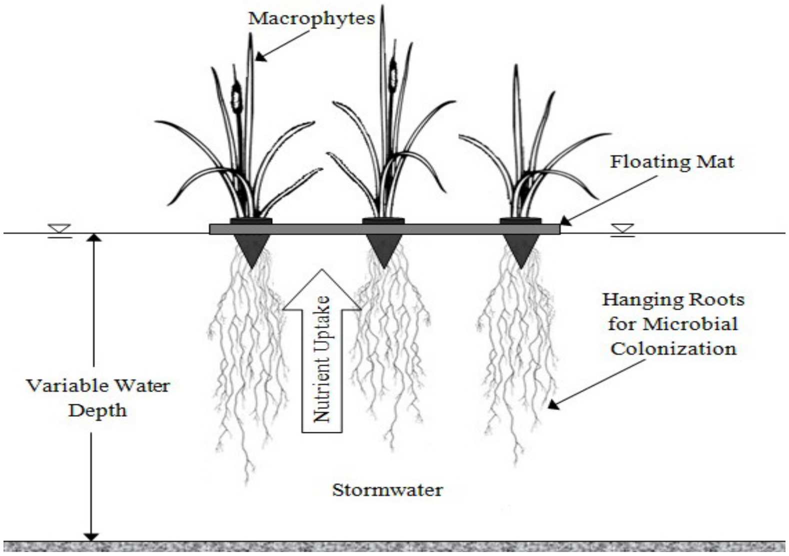


Figure 2: Cross section of a typical Floating Treatment Wetland

Biologically, aquatic macrophyte-based wastewater treatment systems were far more diverse than present-day mechanical treatment systems (Hammer, 1989; Moshiri, 1993). Free-floating macrophytes provided shading of the water column which resulted in a cooler habitat for fish and macroinvertebrates (Nahlik and Mitsch, 2006). The hanging roots provided a large surface area for denitrifying bacteria that created an anaerobic environment, which has the potential to remove nitrate by the denitrification process (Govindarajan, 2008); these roots entrapped fine suspended particulates that would otherwise remain in suspension in a conventional pond system (Headley and Tanner, 2006). Microbes that live on the surface of plant roots in a wetland removed ten times more nitrate than the plants themselves. (Adams, 1992). These microbes changed nitrate nitrogen (NO3-N) to ammonium nitrogen (NH4-N) in a process called dissimilatory nitrate reduction to ammonium, or DNRA. In floating wetlands, as the plants are not rooted in sediments, they are forced to acquire nutrition directly from the water column (Headley et al., 2006; Vymazal, 2007). Nutrient and other element uptake into biomass rate increased as physiological growth continued. Total nitrogen and phosphorus were removed when the plants were harvested regularly. Finally, algal toxins were not present in the pond as the lack of nutrients prevented them from growing back.

To date, little information has been published on FTWs. To further the advancements of FTW technologies, the addition of sorption media that may increase water holding capacity was expected to significantly improve the nutrient removal (Chang et al., 2007) and the production of plant biomass (Figge et al., 1995). In addition, it was also expected to improve tissue culture responses including somatic embryogenesis, organogenesis, adventitious shoot production and growth, and the rooting of micro-propagated tissues (Van Winkle and Pullman, 2005). As there was no soil in the rhizospheric zone of FTWs, the incorporation of sorption media promoted the attraction of sorption surface between the pollutant and the sorption media that caused the pollutants to leave the aqueous solution and simply adhere to the sorption media (Hossain et al., 2010). Thus, phosphorus was removed by both adsorption and absorption. Moreover, a biofilm formed on the surface of media particles to allow microbes to assimilate nitrogen species, although nitrogen was not able to be removed by sorption directly. It is indicative that sorption provided an amenable environment for subsequent nitrification and denitrification (Xuan, 2009). The use of these sorption media removed not only the nutrients, but also some other pollutants, such as heavy metals, pathogens, pesticides, and toxins (Chang et al., 2010).

1.2 OBJECTIVES

1.2.1 Pond 4M (1-year-old) study on-campus

A three-stage research plan was launched at a newly constructed wet detention pond, named Pond 4M, for assessing the interlocking foam FTW performance including small-scale (microcosm) and larger-scale (mesocosm) studies. The microcosm study emphasized the physical growth response of selected plants while limiting nutrients with various sorption media.

The mesocosm study helped evaluate decisions regarding FTW design and ecological consequences. The knowledge gained from both microcosm and mesocosm studies provided the support for implementation of FTWs in an actual wet detention pond.

1.2.1.1 Hypotheses: Microcosm Study

The authors hypothesize the following:

1) Geotextile filter will allow plant roots to penetrate through them while holding the sorption media in the rhizospheric zone.

2) Sorption media, mixture of expanded clay and tire crumb, should help nourish the plants in terms of stem height, root length, and overall biomass growth.

3) A sudden environmental impact may result in malnutrition of the plants and eventually they might die back to water resulting in an increase of nutrients in the water body.

4) Mixtures of plant species may be more effective than a monoculture due to the adverse effect of temperature on aquatic macrophytes.

1.2.1.2 Hypotheses: Mesocosm Study

For the mesocosm study the authors hypothesize that:

1) Variation of water depth examined in this work will not affect the nutrient removal efficiency of the floating macrophytes.

2) Area coverage of floating mat will have a significant impact on nutrient removal efficiency.

3) Existence of littoral zone should improve the water quality in terms of reducing turbidity, Chl-*a*, etc. and might change the nutrient removal efficiencies by acting either as a sink for pollutants or removing them.

4) Sorption media should enhance nutrient removal efficiency by both adsorption and absorption processes.

5) FTWs will be an alternate solution for common stormwater detention pond problems by suppressing unwanted species like algae, duckweeds, etc.

One-way ANOVA tests were used to show if water depth had any significant impact on nutrient removal efficiency. Effect of percent area coverage, littoral zone, and sorption media can be understood by regular monitoring of water quality parameters. Finally, temporal observation and unwanted plant species identification elucidated ecological evolution and interactions. A flowchart of the overall experiment illustrates in Figure 3 the relationships of the small-scale (microcosm), the large-scale (mesocosm), and actual pond studies.

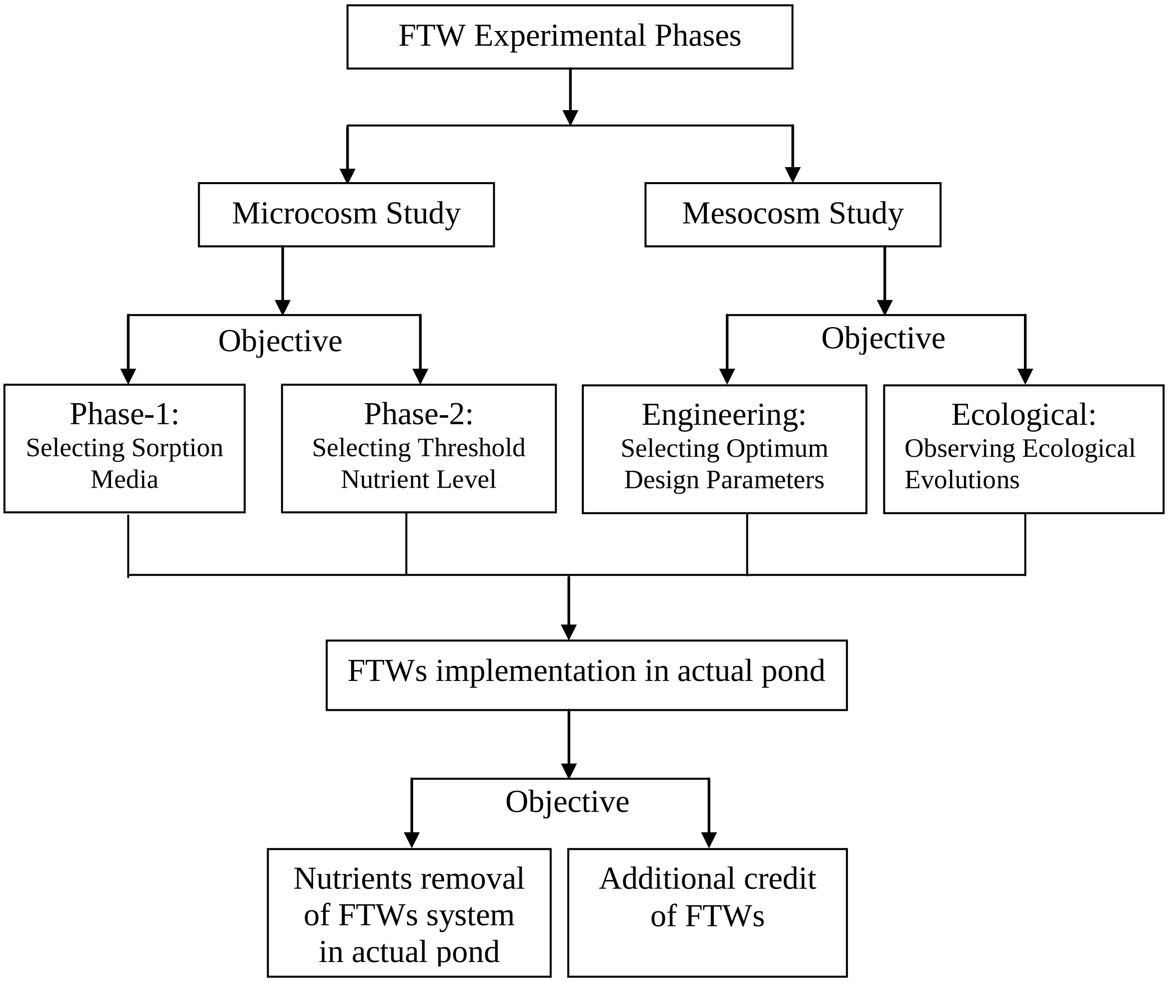


Figure 3: Flowchart of the overall experiment

1.2.2 Pond 5 (12-year-old) study off-campus

FTWs technology was also applied in an older pond serving in a community off-campus. The objectives of this study were to explore the engineering design strategies of floating wetlands and conduct research to determine the waste load reduction efficiencies of nutrients in a mature wet detention pond.

Similarly as what was studied in Pond 4M, it was hypothesized that (1) area coverage of floating mats would have a significant impact on nutrient removal efficiency; (2) existence of a littoral zone would improve the water quality in terms of reducing turbidity, Chl-*a*, and other components, and might change the nutrient removal efficiencies by acting either as a sink for pollutants or removing them; and (3) FTWs would be an alternate solution to improve the performance of stormwater wet detention ponds by suppressing unwanted species such as algae and duckweed. The effect of percent area coverage and the littoral zone were evaluated through regular monitoring of water quality parameters.

Distinguished from the Pond 4M, Pond 5 had a longer service time (12 years) in a community with smaller watershed area and pond size, where some emergent macrophyte had been acclimated along the bank of Pond 5 for years. There also had been a thick sediment layer formed at the bottom of the pond. To support a more harmonious landscape near the natural forest, fibrous matrix FTWs were applied in Pond 5. Furthermore, a fountain at the center of Pond 5 supported aeration and operated through the entire monitoring period. Temporal observation helped elucidate ecological evolution and interactions in an established ecosystem, and also provided the knowledge basis for application of FTWs in mature stormwater ponds.

CHAPTER 2 MICROCOSM STUDY

2.1 SELECTION OF PLANT SPEICES

Various species are found to be suitable for floating wetlands. Pioneer floating mat forming species include *Typha latifolia*, *T. angustifolia*, *Phragmites australis*, *Panicum hemitomon*, *Glyceria maxima*, *Carex lasiocarpa*, *Menyanthes trifoliate*, *Myrica gale,* and *Chamaedaphne calyculata* (Headley et al., 2006). Water hyacinths (*Eicchornea crassipes*) and duckweed species (*Lemna*, *Spirodela* and *Wolfiella*) are also regarded as the typical plant species for floating wetlands used in large-scale applications (Kadlec et al. 1996; DeBusk et al. 1995). Along with others, these are candidate plants being used by local nurseries in their promotion of floating islands. *T. japonica*, *E. crassipes,* and *P. stratiotes* achieved high nutrient removal efficiencies when nutrient removal rates were calculated via a biomass-based method; however they were not efficient when nutrient removal rates were calculated via an area-based method (White et al. 2009). *Canna flaccid*, *Juncus effussus,* and pickerelweed (*Pontederia cordata*) are indigenous to the wetlands of the south-eastern United States and these species have proven to be very effective at taking up nutrients (White et al. 2009; Cui et al. 2010). A grass species, *Agrostis alba,* is also known to be effective. Taking all of this into account, Canna, Agrostis, and Juncus were selected (Figure 4) for the Pond 4M microcosm and mesocosm studies. Juncus and pickerelweed were selected for the Pond 5 mesocosm study and some flowering plants were also initially used in Pond 4M.

Canna flaccida   *Juncus effusus*

Figure 4: Selected plant species (photo courtesy of Beeman's nursery)

2.2 SELECTION OF SORPTION MEDIA

Engineered, functionalized, and natural sorption media can be used to treat stormwater, wastewater, groundwater, landfill leachate, and sources of drinking water for nutrient removal via physicochemical and microbiological processes (Chang et al., 2010). The media may include, but are not limited to, sawdust, peat, compost, zeolite, wheat straw, newspaper, sand, limestone, expanded clay, wood chips, wood fibers, mulch, glass, ash, pumice, bentonite, tire crumb, expanded shale, oyster shell, and soy meal hull (Hossain et al., 2010).

A unique recipe of sorption media (Bold and Gold Stormwater™) was applied to support the current floating wetland study which was effective in reducing nitrogen (up to 47%) and phosphorus (up to 87%) from stormwater found in wet detention ponds. It did not become exhausted or saturated, and thus can be used without frequent replacement. Bold and Gold Stormwater™ (B&G) has an effective size of 0.150 mm (Wanielista et al., 2008) and is a tire crumb based media composition with varying mixtures for different applications. 60% expanded clay was mixed with 40% tire crumb (Figure 5) to create one mix examined in the Pond 4M study.

Expanded Clay

Tire Crumb

Figure 5: Main components of sorption media

2.3 EXPERIMENTAL DESIGN

Ecological systems do not have a single characteristic scale due to its embedded nonlinearity. Insightful research has been known to consider a range of different scales, including microcosms (Levin, 1992; Benton, 2007; Fraser and Keddy, 1997). In this research, water was collected from a wet detention pond for the microcosm study which was divided into three major phases. In the first phase, plant growth was monitored over 18 weeks for variation with respect to sorption media. Only one microcosm was used at this time for the growth of 24 plants (Table 1) and the growth was recorded biweekly.

Table 1: Plants and sorption media in the 1st phase (18th June 2010 to 30th October 2010)

Plant Species	No. of Plants	Sorption Media
Canna	4	No Media (Control)
Juncus	4	No Media (Control)
Canna	4	B & G
Juncus	4	B & G
Canna	4	Expanded Clay
Juncus	4	Expanded Clay

The second phase started at the end of the first phase and lasted for 12 weeks. As plants cannot survive in the extreme cold weather (during December), ambient temperature was recorded on a regular basis to determine the temperature at which plants become dormant. Three microcosms were used simultaneously in phase 2 with a descending amount of initial nutrients (Figure 6). The proportion of expanded clay was increased from 60% to 80% (with 20% tire crumb) at this time, as it might perform slightly better than in the first phase (this is discussed more in the results and discussion section). This phase used 24 plants in each microcosm. However, sorption media was intermittently arranged and nutrient dosing scheme was fixed. Plant species, sorption media, and initial nutrient levels in different microcosms are summarized in Table 2.

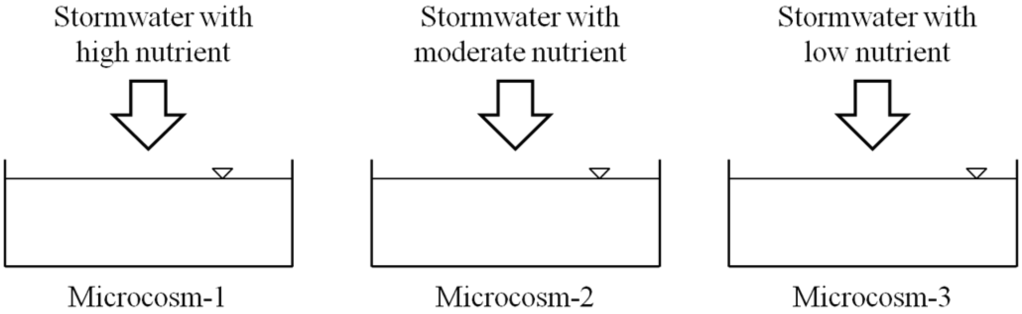


Figure 6: Nutrient dosing scheme in the microcosms (2nd phase)

Table 2: Plants, sorption media, and nutrient levels in the 2nd phase (30th October 2010 to 22nd January 2011)

Microcosms	Plant Species	No. of Plants	Sorption Media	Amount of Dosing**	Stormwater Quality
1	Canna	8	With Media	3 mg.L^{-1} NO_3-N 1 mg.L^{-1} PO_4-P	High Nutrient
	Canna	4	Without Media*		
	Juncus	8	With Media		
	Juncus	4	Without Media*		
2	Canna	8	With Media	1.5 mg.L^{-1} NO_3-N 0.5 mg.L^{-1} PO_4-P	Moderate Nutrient
	Canna	4	Without Media*		
	Juncus	8	With Media		
	Juncus	4	Without Media*		
3	Canna	8	With Media	0 mg.L^{-1} NO_3-N 0 mg.L^{-1} PO_4-P	Low Nutrient
	Canna	4	Without Media*		
	Juncus	8	With Media		
	Juncus	4	Without Media*		

*** Control Case**
**** Selected based on usual nutrient concentration of stormwater runoff in Florida stated by The National Stormwater Quality Database (NSQD) (Pitt et al., 2004)**

2.4 EXPERIMENTAL SETTING

Rectangular plastic tanks, each with a dimension of 2.4 m × 2 m × 0.5 m and a water holding capacity of 2,200 L, were used as microcosms. In order to get proper light, wind and seasonal variation microcosms were placed in the open field. Sufficient aeration due to wind, rainfall events, and evaporation ensured imitations of actual pond conditions. Rectangular tanks were calibrated (Appendix A) so that volume of water can be calculated from the water depth. Calculation of exact water volume was important for dosing purposes. Initially, the water level was kept at 40 cm with a clear cover of 10 cm so that it can accommodate additional water due to rainfall.

Buoyant interlocking foam mats were used to keep the plants floating. Puzzle cut mats (60 cm × 60 cm) (Figure 7a) were joined together by nylon connectors so that they can be assembled in any size or shape. After the mats were connected, plants were inserted into pre-cut holes found within perforated plastic pots (Figure 7a). Sorption media was then added in an innovative way so that they can float along with the plants. Mirafi® N-Series Nonwoven Polypropylene Geotextile (Figure 7a) was wrapped around (Figure 7b) those perforated pots in order to hold the sorption media (Figure 7c) inside. Each pot held about 60 g of media with the plant inside.

To mimic the worst case scenario, excess nutrients (3 $mg.L^{-1}$ of nitrate and 1 $mg.L^{-1}$ of phosphate for first phase) were dosed for the survival of the plants. Commonly used fertilizers, potassium nitrate (KNO_3) and monopotassium phosphate (KH_2PO_4), were used in this case.

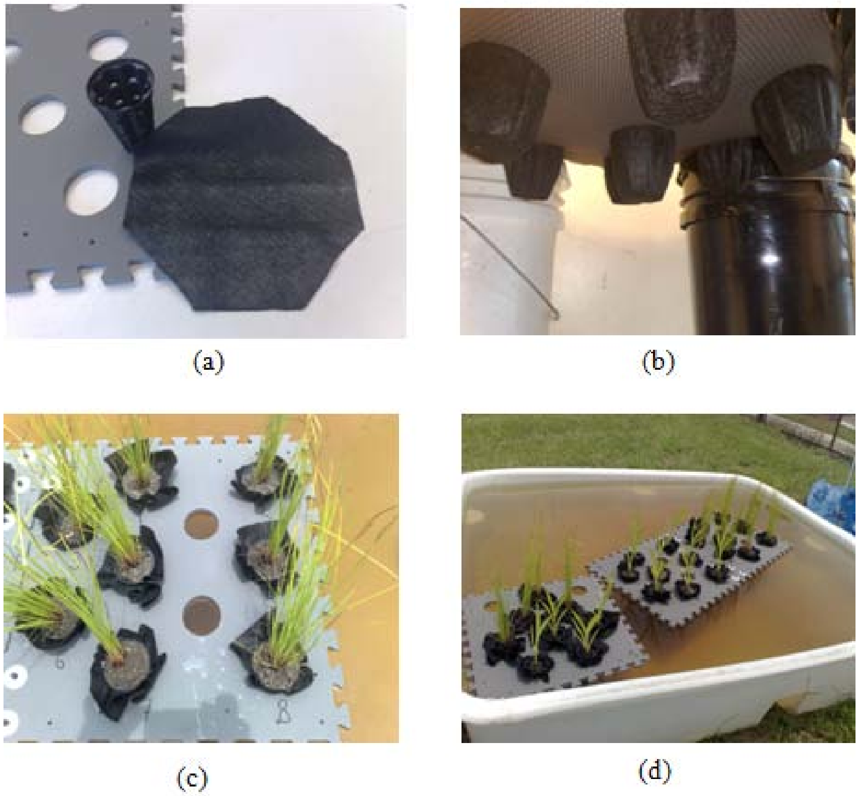


Figure 7: Experimental setup of microcosm study (a) Foam mat, perforated pot, and geotextile (b) Geotextile wrapping (c) Addition of sorption media (d) Plants in the microcosm

2.5 SAMPLING AND MEASUREMENTS

The study of plant root systems and root surface sorption zones required the knowledge of plant biomass (Raun 1997). However, the measurement of plant biomass via harvesting is known to be as destructive as plants when integrated with sorption media, geotextile, and perforated pots; therefore, increased biomass was not able to be measured during the experiment. Stem heights and root lengths were taken as the index of plant growth, decayed or dying, and only initial and final biomass was measured in order to substantiate other findings. For floating treatment wetlands, the length of the roots was important as they hung beneath the mat in the water column and influent water passed through them. Longer roots were desirable in this system for higher nitrate reductase activity (NRA), which is known to result in enhanced nutrient uptake (Cedergreen and Madsen 2003). Even with Canna and Juncus' stems, biomass increased as stem height increased. Eventually, average values, the standard deviation of stem heights, root lengths, and increases of biomass were all used for data interpretation.

In the second phase, as threshold nutrient level determination was the main focus, water quality and physical parameters were tested in all of the microcosms. Samples were collected from the four corner points of the rectangular tanks to make a composite sample which was a representative sample of the whole tank. For both phases, sampling was performed on a biweekly basis.

A DR 2800 Spectrophotometer was used to analyze nutrient concentrations. Total phosphorus was measured by Acid Persulfate Digestion Method (Hach Method 8190) and total nitrogen was measured by Persulfate Digestion Method Test 'N Tube™ Vials (Hach Method 10071). To maintain Quality Assurance/Quality Control (QA/QC) protocol, duplicate samples were collected from each microcosm and ran separately to verify analysis accuracy. Preservation was done with acidification when necessary and percent recovery was ensured within 80% to 120% each time.

2.6 RESULTS AND DISCUSSION

Root mobility appeared somewhat constricted by the geotextile; however, it was impossible to determine whether this restriction was due to the compacted sorption media beneath the geotextile or the geotextile itself. Visually, roots proliferated in the geotextile filter and grew out of the mats (Figure 8). After 18 weeks of observation (Appendix B & C) in the 1st phase, we discovered that the addition of expanded clay helped performance. Not only did the stems grow better in case of Canna (Figure 9), but the roots grew better in case of Juncus (Figure

10). Still, there were some cases where the control case looked better. With the inclusion of sorption media, however, there might be some inhibited growth of roots as compared to the control case.

Figure 8: Root penetrations through the geotextile filter

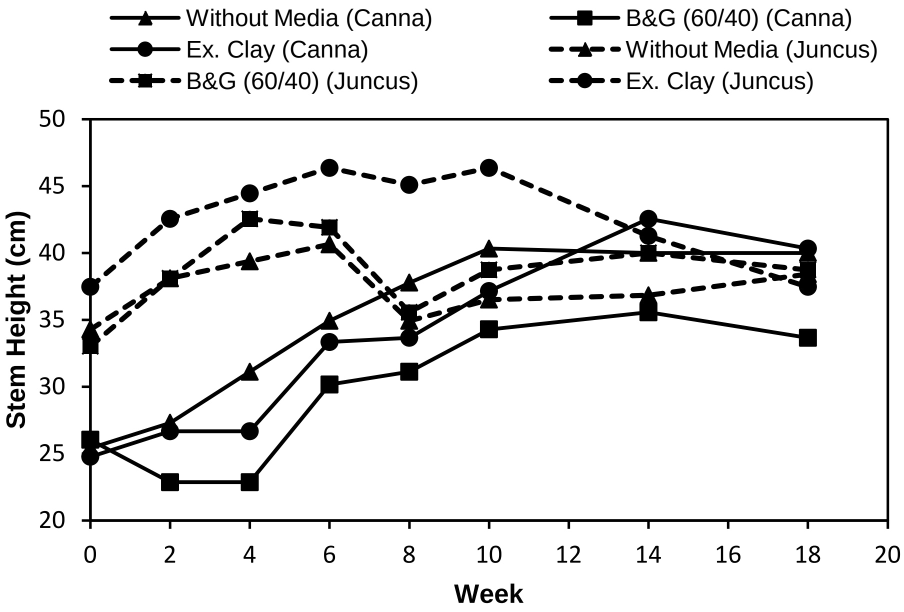


Figure 9: Effects of sorption media on stem growth

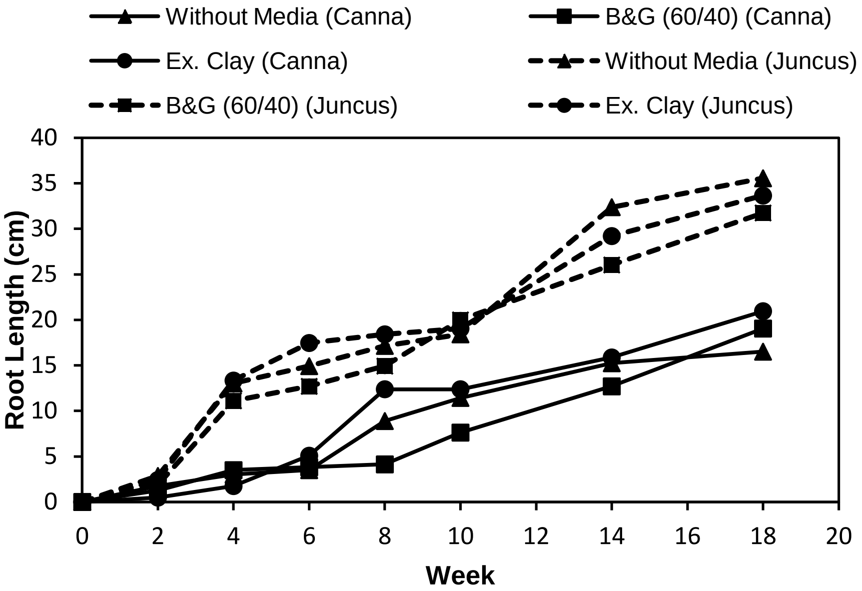


Figure 10: Effects of sorption media on root growth

In the 2nd phase of the study (Appendix D & E), sorption media performed better (Figures 11, 12 & 13), especially in stem growth. However, most of the time, plant growth in the other two microcosms were almost the same as that in the control case which can be explained by the aforementioned reason of inhibited growth. The addition of sorption media was not only for plant growth, but also for nutrient removal in FTWs. It is expected that the implementation of this new technology in on a large-scale pond will show many distinguishable results in the future. In the case of nutrient consumption (Appendix F), it was supposed to start from 3 mg.L^{-1} of total nitrogen and 1.5 mg.L^{-1} of total phosphorus according to the experimental design; however, it was reasonable to have slight deviation (Figures 11c, 12c and 13c) from those prescribed levels. Even with precise tank volume calculations, nutrient levels are known to fluctuate due to the residual nutrient levels in the actual wet pond water as it is being collected. Moreover, the plants have compost near the roots provided by the nursery that also contributed to such fluctuation. Therefore, it was normal for there to be an increase of nutrients in the aqueous solution. However, a decrease was also possible due to the rainfall event that had occurred as microcosms were placed in the open field.

With time, less nutrients were taken up by the plants (Figure 11c, 12c and 13c) and all of the microcosm plants experienced a drop in their nutrient levels; dwindled nutrient concentrations were likely responsible for this deficiency in nutrient uptake. Eventually, severe nutrient deficiency was encountered by the plants resulting in a reduction in stem height or death (Figure 13). The reason behind this was the temperature effect. It was evident that, at a specific temperature, plants went dormant in Microcosm-1. However, in Microcosm-2 and 3, plants started to reduce in height (dormancy induction) before this temperature occurred. It can then be inferred that nutrient limitation was the reason behind this phenomena.

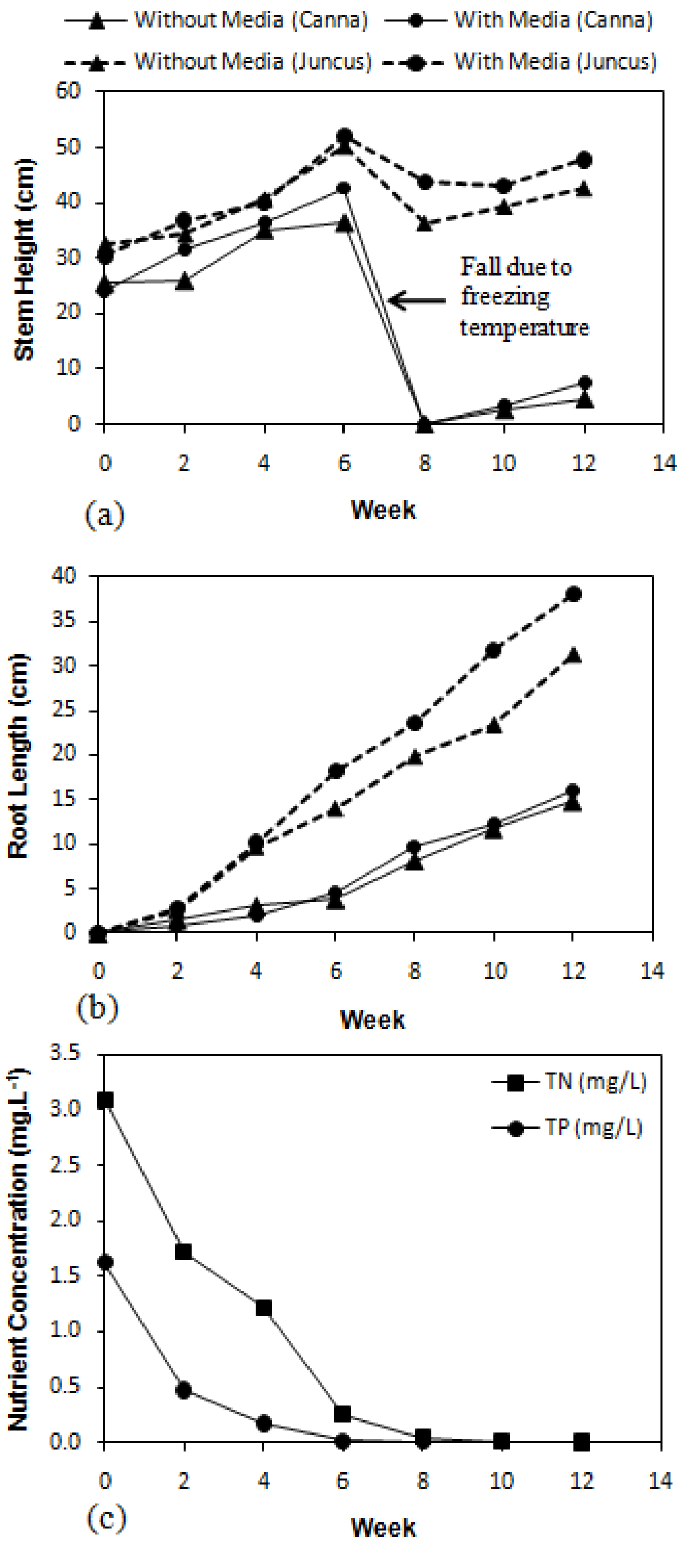


Figure 11: Plant growth and remaining nutrient level in Microcosm-1 (High initial nutrient)

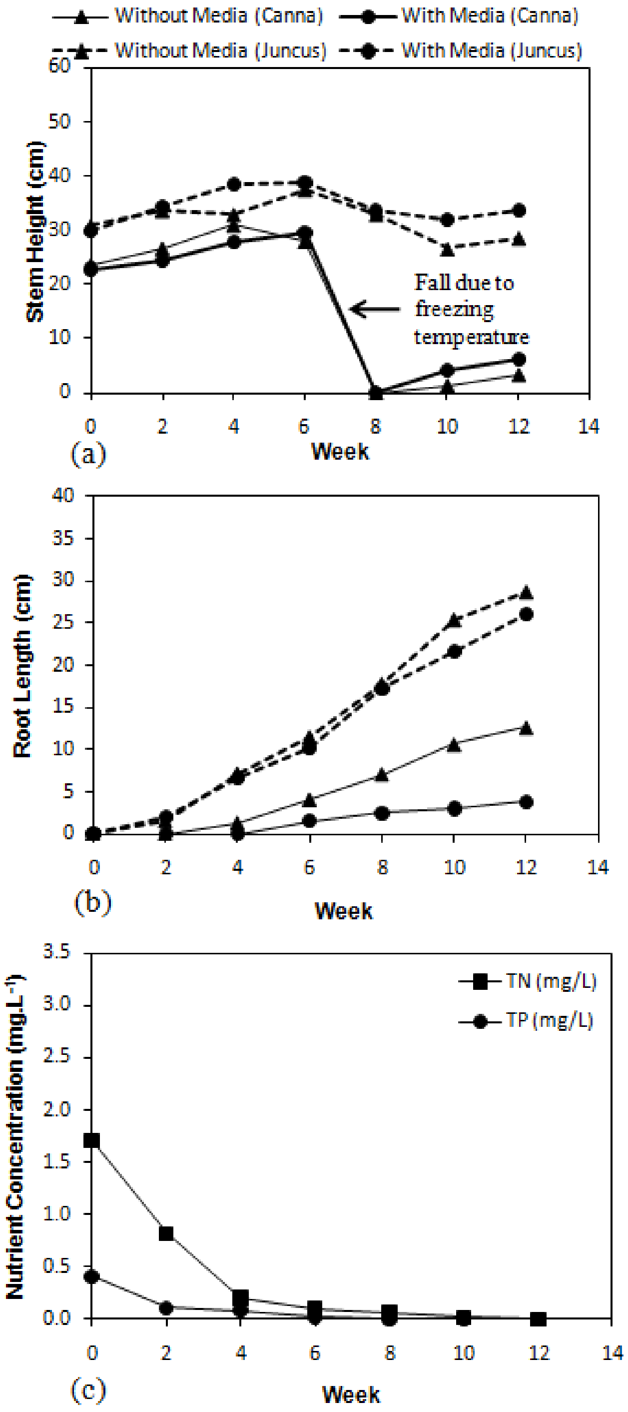


Figure 12: Plant growth and remaining nutrient level in Microcosm-2 (Moderate initial nutrient)

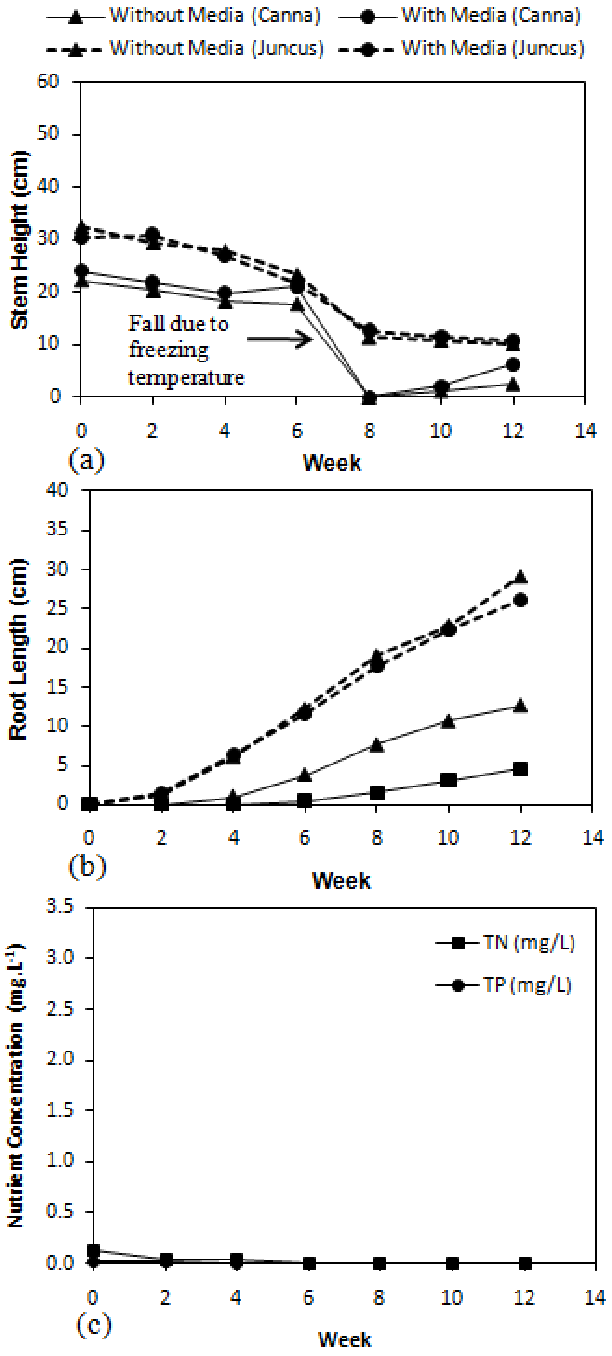
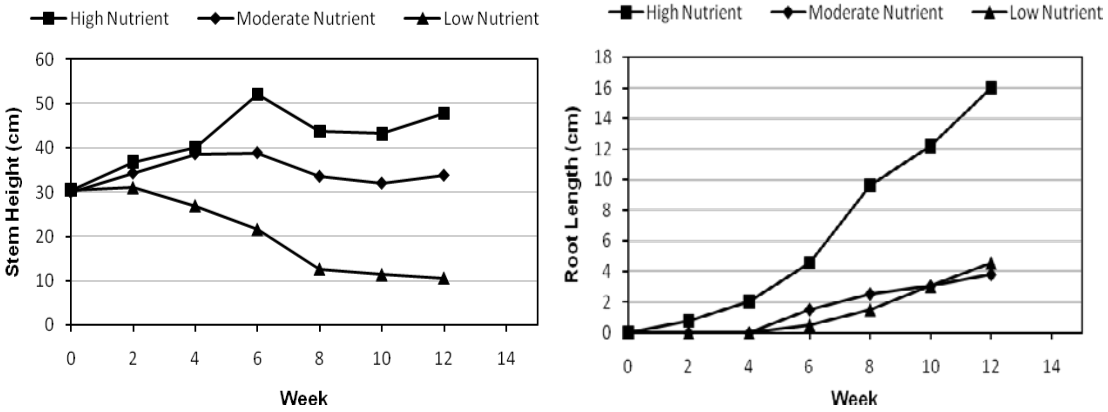


Figure 13: Plant growth and remaining nutrient level in Microcosm-3 (Low initial nutrient)

In order to determine the threshold nutrient level, separate graphs were plotted (Figure 14). These were the distinguishable results from several combinations. For stems, it was observed (Figure 14a) that plants of the microcosm with high nutrient levels kept growing due to the availability of the nutrients; however, they reduced in height during the 7th week due to cold weather instead of nutrient deficiency. Plants of microcosm with a moderate nutrient level stopped thriving before the arrival of the freezing temperature. It was inferred that there was a shortage of nutrients at that time because the plants had already consumed the supplied nutrients. In the microcosm with low nutrient levels, it was clear that just 2 weeks after the start date, their stems started to reduce and eventually, the top of the plant shoots became brown and died, falling into the water. The effects of nutrient levels were observed more clearly in the roots of Canna (Figure 14b), which grew much longer in the microcosm with high nutrient levels. For the floating wetlands, this root growth was deemed important for nutrient removal.



(a) **(b)**

Figure 14: Stem growths (a) in Juncus and Root growth (b) in Canna with media due to variation of nutrient level

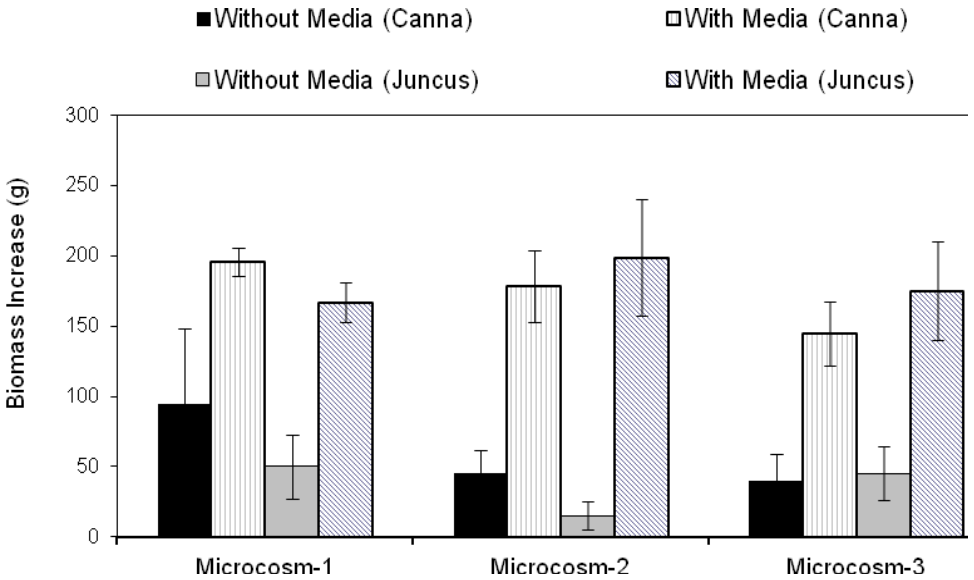


Figure 15: Comparative biomass increase

Although there was little effect of sorption media on the lengths of roots and shoots, there was a significant increase (Figure 15) in the plant biomass (Appendix G) for both Canna and Juncus. On the other hand, a variation of nutrients did not show commensurate changes in the biomass. Temperature might be a major issue during the winter season as it is known to influence the productivity of the aquatic plants by controlling the rate of chemical reactions, as well as nutrient acquisition (Simpson and Eaton 1986; Kirk 1994; Chapin 1980). In the 7th week of the study (2nd phase), the temperature was as low as 3.3 °C (Figure 16) and this low temperature was lethal for Canna (Figure 17b). All the leaves died due to frost during that week. Although Juncus did not die, their heights reduced during that time period.

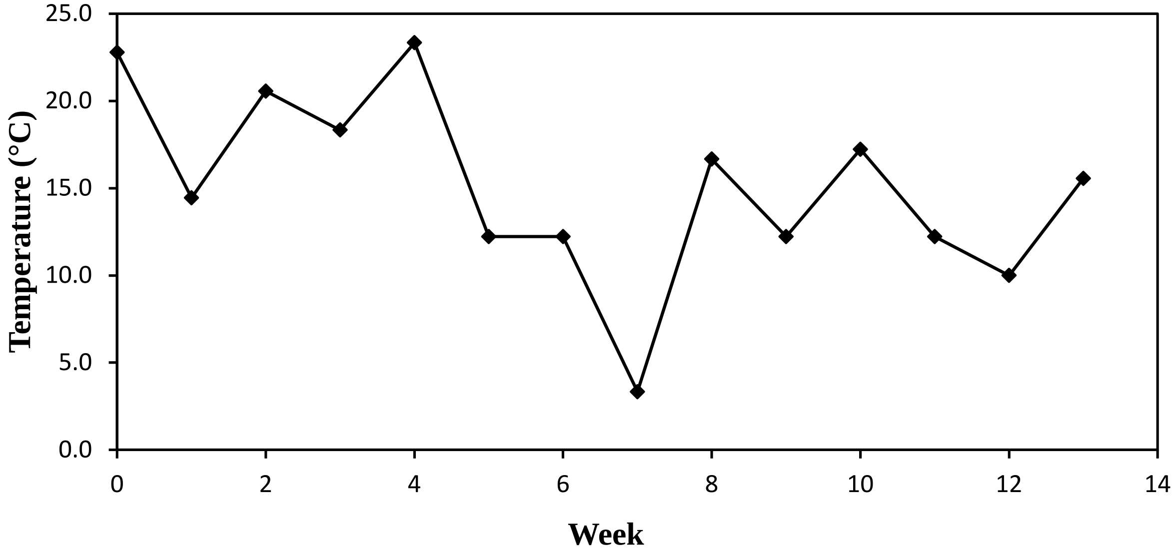


Figure 16: Variation of ambient temperature during 2nd phase

(a) **(b)**

Figure 17: (a) Microcosms at the end of 2nd phase (b) Canna and Juncus at freezing temperature

One-way ANOVA showed that sorption media had a significant effect on the plant biomass (for Canna: p= 0.008; for Juncus: p=0.001). For the most part, nutrient concentration did not have a significant effect on stem heights (Table 3), but it did have a salient effect on root length most of the time (Table 4). Although the one-way ANOVA study confirmed the credibility of this initial test, without the context of appropriately scaled field studies, microcosm experiments might become irrelevant and diversionary (Carpenter 1999; Carr et al. 1997; Chapin et al. 1986).

Table 3: ANOVA p-values for effect of nutrient concentration on stem heights

	Without Media (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
TN ($mg.L^{-1}$)	0.008	0.045	0.349	0.715
TP ($mg.L^{-1}$)	0.084	0.231	0.664	0.970

Table 4: ANOVA p-values for effect of nutrient concentration on root lengths

	Without Media (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
TN ($mg.L^{-1}$)	0.019	0.010	0.006	0.01
TP ($mg.L^{-1}$)	0.083	0.267	0.041	0.049

CHAPTER 3 MESOCOSM STUDY

3.1 SELECTION OF LITTORAL ZONE PLANTS

A littoral zone is known as the portion of a lake that is less than 15 feet in depth. It extends from the shoreline of a lake and continues to the depth where sufficient light for plant growth reaches the sediments and bottom of the lake. Bulrush (*Scirpus californicus*) (Figure 18a) and Pickerelweed (*Pontederia cordata*) (Figure 18b) were selected as the emergent macrophytes of the littoral zone in both mesocosm studies of Pond 4M and Pond 5, as they are endemic in Florida.

(a) Bulrush **(b) Pickerelweed**

Figure 18: Selected emergent macrophytes (Photo courtesy of Beeman's nursery)

3.2 EXPERIMENTAL DESIGN

3.2.1 Interlocking foam FTWs

Eleven scenarios were created with varying percent area coverage, littoral zones, and water depths (Figure 19 and Table 5; Chang et al., 2012a). Case-1 and Case-2 were without any floating macrophytes and performed as control cases. Sorption media was used in all of the cases, except Case-7b which was the control case in this regard. Considering feasibility of an actual pond, percent area coverage was limited to 10%. There were two different water depths, 90 cm and 56 cm, for which bottom sediment thickness was 50 cm and 30 cm, respectively. A slope of 1:5 was maintained toward the center of the cylindrical mesocosms for the bottom sediment layer.

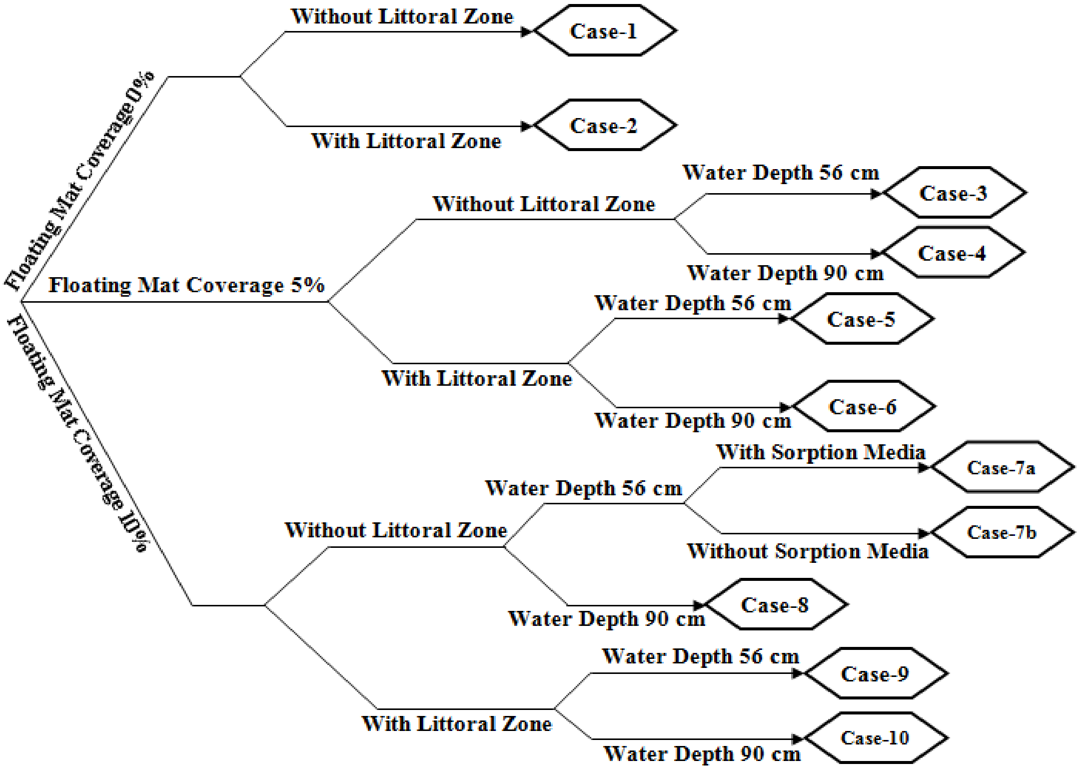


Figure 19: A schematic diagram of the mesocosm setup for interlocking foam FTWs study

Table 5: Component of the mesocosms for interlocking foam FTWs study

Scenario	Area Coverage	Littoral Zone	Water Depth (cm)	Mesocosm Diameter (m)
Case-1*	0%	No	90	5
Case-2*	0%	Yes	90	5
Case-3	5%	No	56	3
Case-4	5%	No	90	5
Case-5	5%	Yes	56	3
Case-6	5%	Yes	90	5
Case-7a	10%	No	56	3
Case-7b	10%	No	56	3
Case-8	10%	No	90	5
Case-9	10%	Yes	56	3
Case-10	10%	Yes	90	5

* Control Case

3.2.2 Fibrous matrix FTWs

Ten scenarios were created with varying percent area coverage, littoral zones, and plant species (Figure 20 and Table 6). Case-1 and Case-2 had no floating macrophytes and served as control cases. Considering feasibility in an actual pond, percent area coverage was limited to 10%. A slope of 1:5 was maintained toward the center of the cylindrical mesocosms for the bottom sediment layer (Chang et al., 2012b).

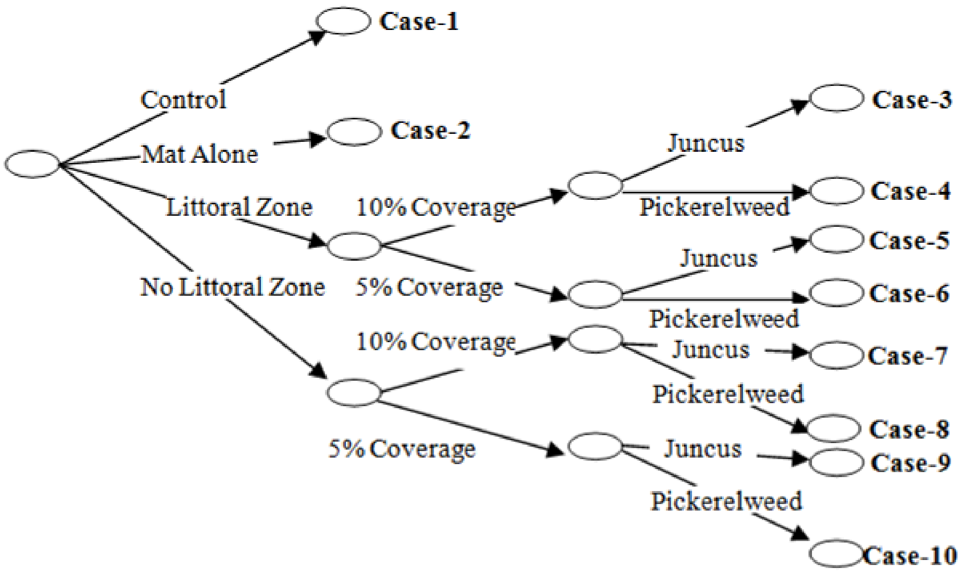


Figure 20: Schematic diagram of the mesocosm setup for fibrous matrix FTWs study

Table 6: Component of the mesocosms for fibrous matrix FTWs study

Scenario	Littoral Zone	Area Coverage	Plant Species
Case-1*	No	0%	N/A
Case-2*	No	10%	N/A
Case-3	Yes	10%	Juncus
Case-4	Yes	10%	Pickerelweed
Case-5	Yes	5%	Juncus
Case-6	Yes	5%	Pickerelweed
Case-7	No	10%	Juncus
Case-8	No	10%	Pickerelweed
Case-9	No	5%	Juncus
Case-10	No	5%	Pickerelweed

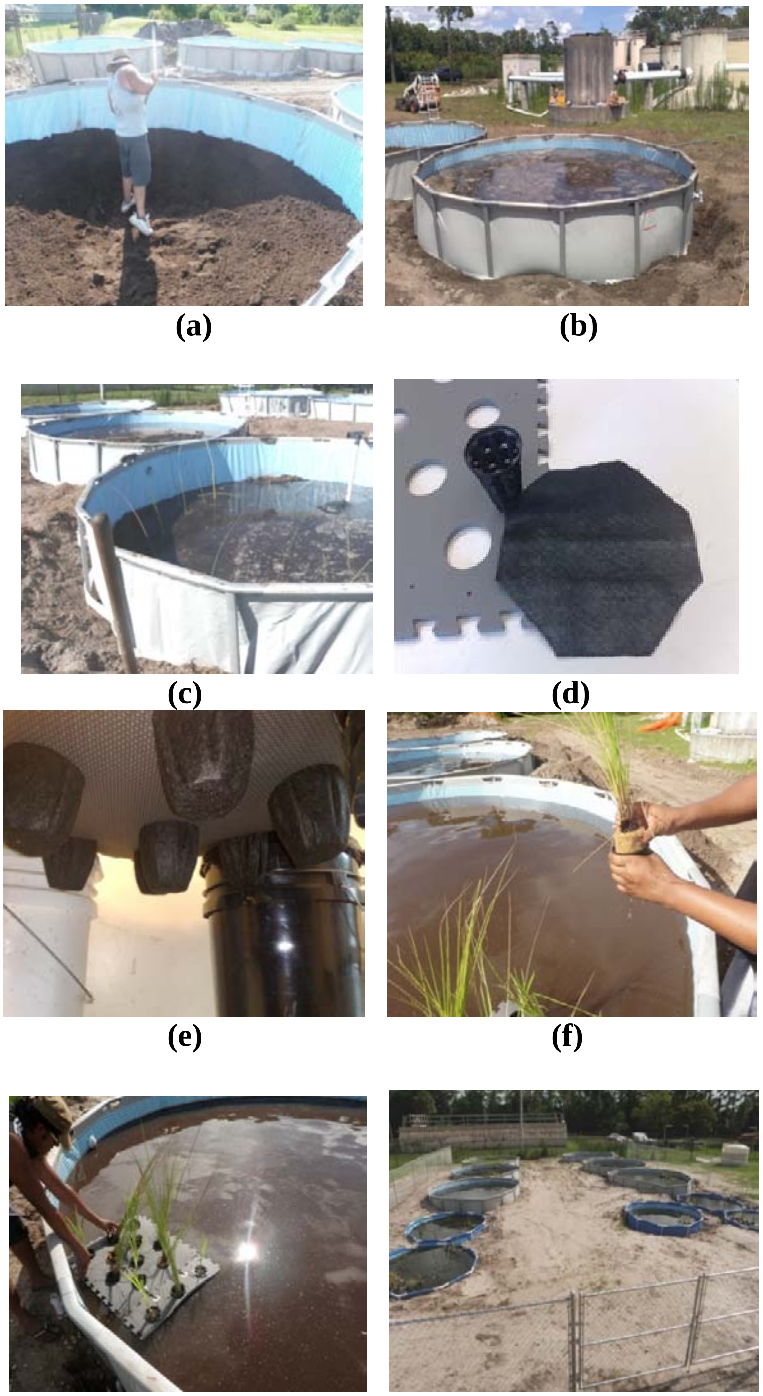
* Control Case

3.3 EXPERIMENTAL SETTING

3.3.1 Interlocking foam FTWs

Cylindrical plastic tanks with the dimensions of 5 m × 1.2 m and 3 m × 0.8 m and a water holding capacity of 18,000 L and 4,000 L, respectively, were used as mesocosms. Bottom soil was collected from an actual pond and placed (Figure 21a) under all the mesocosms for planting emergent littoral zone plants (Figure 21c). Even where there was not a littoral zone, sediment was placed in order to mimic an actual pond environment. Light, wind, and seasonal variations were achieved by placing mesocosms in the open field (Figure 21h). Sufficient aeration due to wind, rainfall events, and evaporation ensured almost perfect imitation to an actual pond.

Buoyant interlocking foam mats were used to keep the plants floating. Puzzle cut mats (60 cm × 60 cm) (Figure 21d) were joined together by nylon connectors so that they can be assembled in any size or shape. After the mats were connected, plants were inserted into pre-cut holes within perforated plastic pots (Figure 21d). Sorption media was added in an innovative way so that they can float along with the plants. Mirafi® N-Series Nonwoven Polypropylene Geotextile (Figure 21d) was wrapped around (Figure 21e) those perforated pots in order to hold the sorption media inside. With the plant inside, each pot held about 60 g of media. For the control case, where there was no sorption media, inert coconut fiber was used to hold the plants upright.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 21: Experimental setup of mesocosm study (a) Placement of bottom sediment (B) Mesocosms with stormwater (C) Plantation in the littoral zone (D) Foam mat, perforated pot, and geotextile (E) Geotextile wrapping (F) Coconut fiber in the control case (G) Floating mats in the mesocosm (H) Set of mesocosms

3.2.2 Fibrous Matrix FTWs

The same sizes of cylindrical plastic tanks were used for the Mesocosm study of fibrous matrix FTWs. Bottom soil was collected from an actual pond and placed under all mesocosms for planting emergent littoral zone plants. Sediment was also placed under mesocosms with no littoral zone to mimic an actual pond environment. For proper light, wind, and seasonal variation, mesocosms were placed in an open field (Figure 22b) to mimic actual pond conditions of aeration due to wind, rainfall events, and evaporation.

FTW treatments consisted of fibrous matrix mats which were injected with expanded polyurethane to provide buoyancy. The center of the mats were filled with a growth medium (8 cm deep) consisting of sand, peat, and compost (1:2:1); 100% Canadian peat was used around the root zone as sorption media.

(a) (b)

Figure 22: Experiment setting: (a) floating mat and (b) all mesocosms after setup.

3.4 SAMPLING AND MEASUREMENTS

Like the microcosm study, nutrients (3 $mg.L^{-1}$ of nitrate and 1 $mg.L^{-1}$ of phosphate) were dosed for determining nutrient removal efficiency in the mesocosm study. Commonly used fertilizers, potassium nitrate (KNO_3) and monopotassium phosphate (KH_2PO_4), were used in this case. Dosing and the addition of new stormwater took place once every 30 days, which imitated a natural rainfall event and mimicked nutrient-rich surface runoff. Furthermore, samples were collected on a bi-weekly basis over a three month period. Finally, samples collected from five different points were mixed to form a composite sample deemed representative of the entire mesocosm.

A DR 2800 Spectrophotometer was used to analyze nutrient concentrations. A variety of methods used in chemical analyses can be summarized in Table 7. In order to maintain Quality Assurance/Quality Control (QA/QC) protocol, duplicate samples were analyzed every ten samples. Preservation was done with acidification when necessary and percent recovery was ensured within 80% to 120% each time.

Table 7: Chemical analysis methods

Parameter	Method
pH	Hach HQ40d
Conductivity	Hach HQ40d
Dissolved Oxygen	Hach HQ40d
Turbidity	Turbidimeter
Chl-*a*	Aquafluor™ Handheld Fluorometer
Total Nitrogen	Persulfate digestion method (Hach Method 10071)
NH_4^+	Salicylate method (Hach Method 8155)
Nitrate	Cadmium reduction method (Hach Method 8192, 8171)
Total Phosphorus	Acid persulfate digestion method (Hach Method 8190)
Orthophosphate	PhosVer 3 (Ascorbic Acid) method (Hach Method 8048)

3.5 RESULTS AND DISCUSSION

3.5.1 Interlocking Foam FTWs

Due to a different bottom mud compaction and a corresponding change in water volume, it was difficult to maintain a constant initial nutrient loading in our experiment. Therefore, a small amount of deviation from the usual stormwater quality was observed in the initial nutrient concentrations. Tables 8, 9, and 10 present both influent and effluent concentrations over a three month period (Sept. –Nov 2010) for various parameters, which indicated the efficacy of the FTW system. Although the control case (Case-1) was supposed to show a very little amount of nutrient removal, growth of undesirable plant species, like duckweed (*Lemna minor*) and algae, hampered our comparison. In other cases, effluent concentrations were satisfactorily low. Actually, the absence of plants in the control case allowed them to grow and cover the whole surface, resulting in a significant amount of nutrient removal. Duckweeds are known to require many nutrients to grow, so typically they were found in nutrient-rich environments. A surface layer of duckweeds prevented sunlight from reaching the deeper parts of the water column. This resulted in a significant reduction in photosynthesis and oxygen production of underwater plants and algae, which can greatly stress or even kill fish.

Table 8: GroupWise effluent concentration after 30 days of floating wetland treatment
(September 2010**)**

Scenario	Total Phosphorus		Orthophosphate		Total Nitrogen		Nitrate-Nitrogen	
	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})
Case-1	1.523	0.556	1.183	0.061	4.161	1.251	0.778	0.072
Case-2	2.858	1.476	2.560	1.386	4.300	0.768	0.896	0.099
Case-3	3.156	0.589	2.215	0.345	5.567	0.768	0.942	0.072
Case-4	2.189	0.909	1.379	0.063	3.885	2.072	1.119	0.099
Case-5	3.649	0.909	2.413	0.336	3.724	1.348	0.642	0.072
Case-6	3.361	0.692	2.086	0.559	3.217	0.092	0.815	0.079
Case-7a	2.313	0.742	2.001	0.462	3.447	1.348	0.916	0.065
Case-7b	2.807	0.398	2.253	0.210	4.253	0.816	1.030	0.057
Case-8	2.846	0.692	2.528	0.728	3.516	0.913	0.522	0.079
Case-9	3.034	0.409	2.403	0.338	2.594	0.961	0.754	0.072
Case-10	2.327	0.809	2.270	0.781	4.000	1.106	1.312	0.099

Table 9: GroupWise effluent concentration after 30 days of floating wetland treatment (Oct. 2010)

Scenario	Total Phosphorus		Orthophosphate		Total Nitrogen		Nitrate-Nitrogen	
	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})
Case-1	1.713	0.502	1.014	0.228	2.073	0.000	0.974	0.029
Case-2	4.298	1.048	3.028	0.635	2.798	0.000	2.578	0.095
Case-3	1.819	0.484	0.888	0.103	1.554	0.000	1.034	0.057
Case-4	2.037	0.648	1.875	0.017	2.798	0.000	1.696	0.000
Case-5	2.552	0.676	0.846	0.187	1.658	0.000	0.557	0.057
Case-6	2.725	0.526	2.312	0.274	2.176	0.000	1.975	0.000
Case-7a	1.668	0.264	0.767	0.137	1.969	0.000	0.661	0.133
Case-7b	1.841	0.664	0.844	0.214	1.244	0.000	0.840	0.010
Case-8	5.912	1.536	3.596	0.722	1.917	0.000	1.351	0.095
Case-9	1.360	0.426	0.998	0.125	1.917	0.000	1.036	0.237
Case-10	3.941	0.664	2.673	0.817	3.679	0.000	2.092	0.000

Table 10: GroupWise effluent concentration after 30 days of floating wetland treatment (November 2010)

Scenario	Total Phosphorus		Orthophosphate		Total Nitrogen		Nitrate-Nitrogen	
	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})
Case-1	1.561	1.061	0.983	0.283	3.186	0.828	0.919	0.004
Case-2	1.909	0.793	1.399	0.489	1.953	0.000	0.640	0.000
Case-3	0.911	0.466	0.765	0.112	2.547	0.000	0.867	0.015
Case-4	3.076	0.000	1.154	0.000	4.860	0.000	0.799	0.015
Case-5	2.744	0.034	0.835	0.028	1.744	0.000	0.506	0.010
Case-6	1.296	0.063	0.759	0.010	2.400	0.077	0.431	0.033
Case-7a	3.538	1.228	1.127	0.100	2.895	0.316	0.565	0.034
Case-7b	3.816	0.849	1.347	0.567	2.889	0.122	0.464	0.065
Case-8	2.590	0.094	0.919	0.056	1.500	0.000	0.593	0.067
Case-9	3.100	0.091	1.057	0.067	3.023	0.000	0.505	0.098
Case-10	1.588	0.850	0.968	0.457	2.863	0.000	0.460	0.000

3.5.1.1 Effect of water depth

Several mesocosms were set up with varying depths of water column under the floating mat. A One-way ANOVA test was performed by Minitab software to check if there was a significant impact of water depth on the removal efficiency. It was seen that although for total nitrogen and nitrate, removal efficiency increased with larger water column depths, total phosphorus and orthophosphate decreased. ANOVA test p-values (for total nitrogen 0.459, total phosphorus 0.114, nitrate 0.464, and orthophosphate 0.377) indicated that the distinction of water column depth was not statistically significant across the relevant mesocosms.

3.5.1.2 Effect of percent area coverage

Excluding the control case, nutrient removal efficiency was not significantly different (Figure 23 & 24) between mesocosms with 5% and 10% floating macrophyte coverage. Although average nutrient removals with 10 % coverage were to some extent higher than those with 5% coverage (i.e., Case-10 vs. Case-6 in Figure 23 and Case-8 vs. Case-4 in Figure 24), the differences are statistically insignificant due to the high standard deviations. It can be inferred that, even without the presence of a littoral zone, 5% coverage was enough for a significant amount (53.82% TP, 48.06% OP, 31.84% TN and 48.21% nitrate) of nutrient removal in just 15 days. Moreover, in an actual pond it might not be feasible to go over 5% floating mat coverage for the requirement of large surface area, which would have inhibited sunlight to reach the bottom of the pond.

Although algae are big nutrient consumers in the aquatic ecosystem, their growth was limited due to the fact that they had to compete with floating plants. With the increase of percent area coverage of floating macrophytes, a decrease in Chl-*a* value was observed (Figure 23), which was an indicator of decreased algae. Without the littoral zone, however, this relationship was not salient.

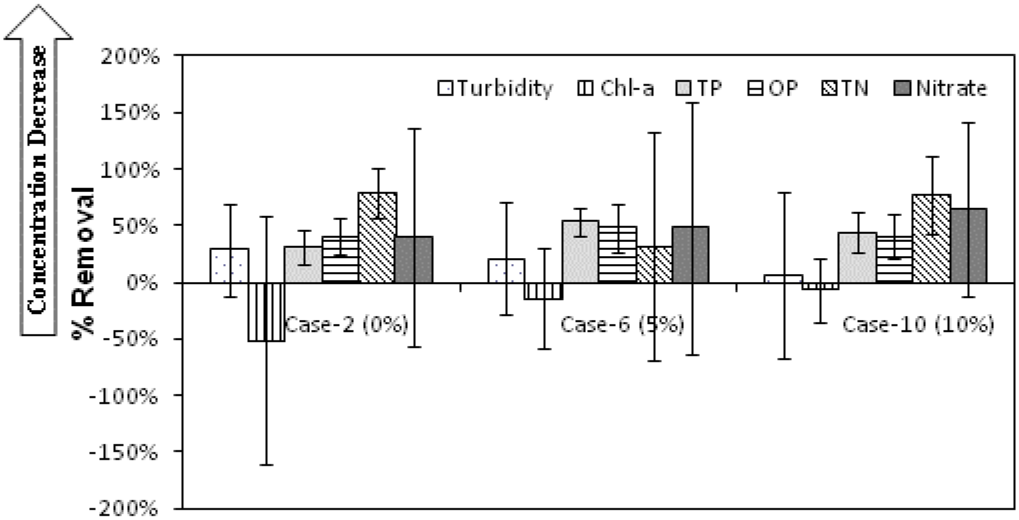


Figure 23: Effect of percent area coverage with a littoral zone (15 days removal efficiency)

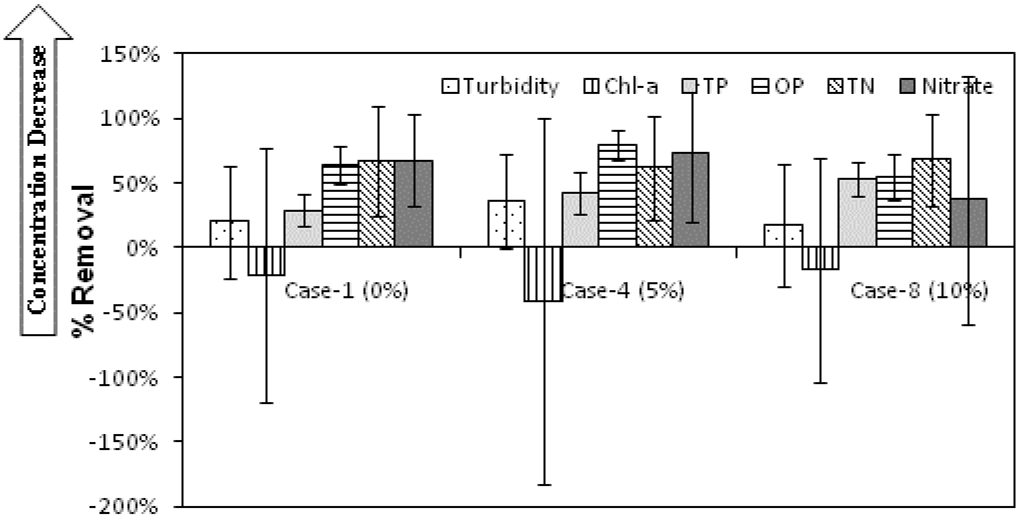


Figure 24: Effect of percent area coverage without a littoral zone (15 days removal efficiency)

3.5.1.3 Effect of littoral zone

Wetland littoral zones involve an interaction of aquatic plants, microorganisms, and physical/chemical processes, such as adsorption, precipitation, and sedimentation (Gersberg et al. 1986). This area may act as either a sink for pollutants, removing them from incoming water, or as a source, adding them to the water (Mickle & Wetzel 1978a, b; van der Valk et al. 1979; Carpenter & Lodge 1986). In Figure 25, we see that when Case-3 is compared to Case-5, the effect of the littoral zone was prominent on Chl-*a* and turbidity, as they both decreased significantly due to the presence of the littoral zone. However, nutrient removal efficiency was almost the same in both cases. Comparison of other specific cases also showed the effect of a littoral zone, but for aforementioned reasons, it was not possible to decide the value of littoral zones in terms of nutrient removal efficiencies in these experiments.

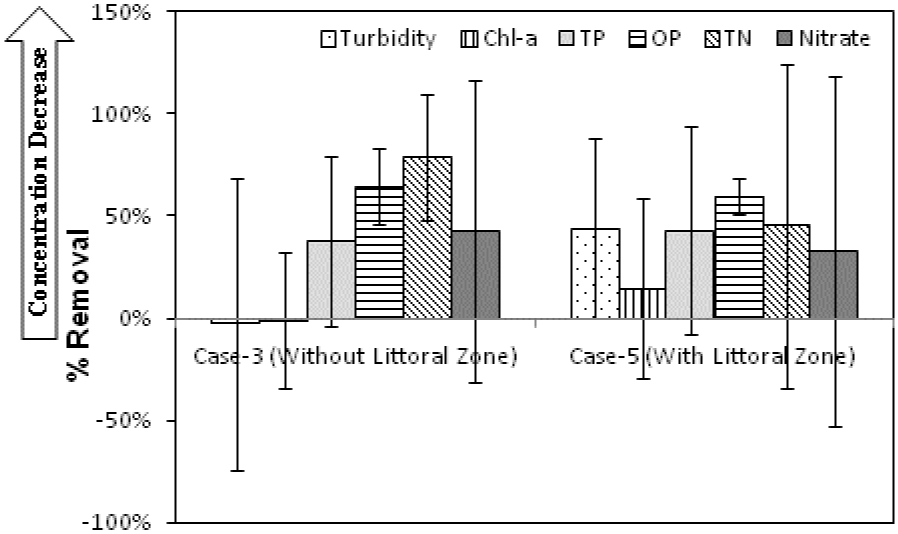


Figure 25: Effect of a littoral zone on removal efficiencies (15 days removal efficiency)

3.5.1.4 Effect of sorption media

Total phosphorus and orthophosphate removal was much better (Figure 26) in the mesocosm with sorption media. However, total nitrogen and nitrate removal was better in the mesocosm without any media. Phosphorus might have been removed by both adsorption and absorption. Moreover, a biofilm formation was possible on the surface of the sorption media particles which allowed microbes to assimilate.

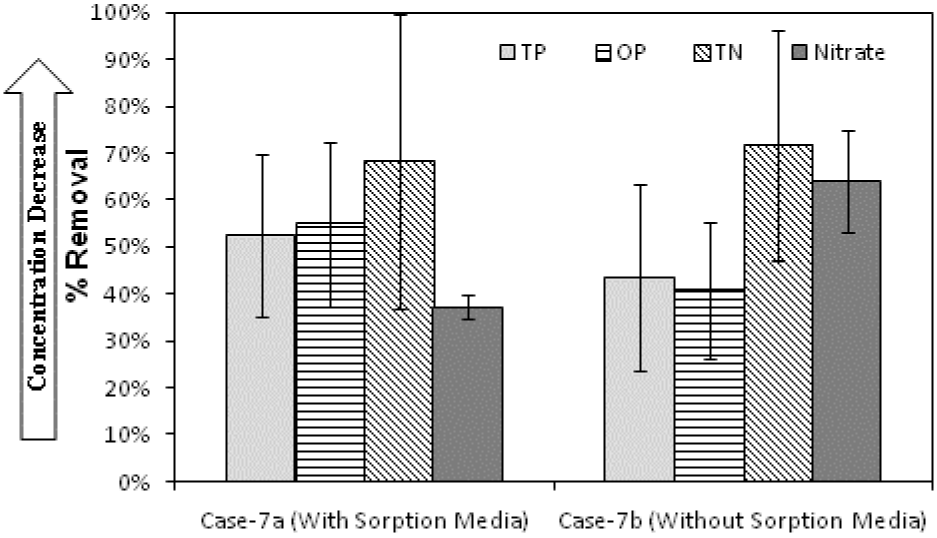


Figure 26: Effect of sorption media on removal efficiencies

3.5.1.5 Tissue nutrient concentrations

After three months of observation on water quality, representative plant samples (floating macrophyte) from each mesocosm were analyzed to determine their tissue nutrient concentrations in the roots and shoots. Results were expressed (Figure 27) as the percentage of their dry weights. It is seen that roots and shoots have taken close to an equal amount of nutrients. However, nitrogen uptake was much higher than that of phosphorus, which was commensurate with the amount of dosing. Considering plant species, Canna was better than Juncus in both shoots and roots. Assuming all the plants in a mesocosm have taken the same amount of nutrients as the representative sample, daily nutrient uptake per unit area of floating mat had been calculated for each mesocosm. On average, the nitrogen uptake rate was 36.39 mg/m^2/day and the phosphorus uptake rate was 1.48 mg/m^2/day for FTW systems with only 5% to 10% coverage. For FTW systems with 100% coverage, different rates would have been determined (White, 2010).

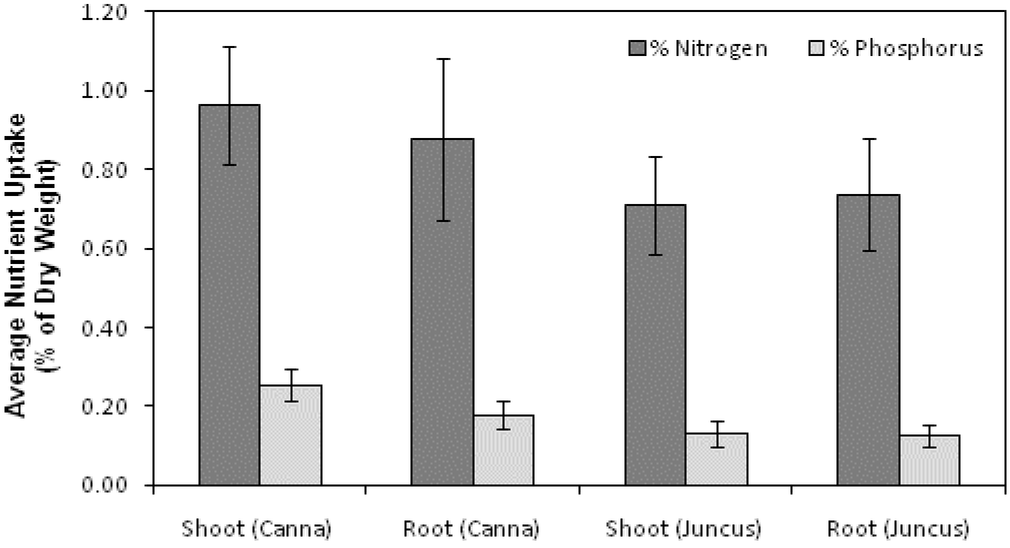


Figure 27: Average tissue nutrient concentrations (% of Dry Weight)

3.5.1.6 Efficacy of FTWs based on macrophyte-epiphyte-phytoplankton competition

Fertilizer was dosed on a monthly basis for the nutritive importance of the macrophytes. As time passed, various weeds and algae began to grow. The most visible one was duckweed (Lemna minor). Duckweeds are free-floating plants that completely covered the surface of a pond. These plants are known to require a lot of nutrients (nitrogen and phosphorus) to grow, so typically they are found in nutrient-rich environments. Table 11 shows almost all the ecological findings in a sequential manner. After 3 months, the control case (Case-1) became infested (100%) with duckweeds due to the absence of macrophytes. Some other mesocosms also had partial duckweed coverage. Although they had floating macrophytes or a littoral zone, somehow there were redundant nutrients for duckweeds.

Algae and duckweeds are natural competitors. As soon as duckweeds were removed from the mesocosms, algal growth was noticed (After 5 months). Again the control case was the most vulnerable one; as it was covered 100% by filamentous blue-green algae (Cyanophyceae).

This algae was tested in the laboratory and identified that a majority of the samples had Oscillatoria. There were also another two species, Microcystis and Ankistrodemus. After 7 months, there were not only duckweeds and algae, but also a significant amount of other plant species near the floating plant roots. In the control cases, there were no floating plants and for this reason, no other plants were able to grow.

From the above observations on temporal ecological changes, it was evident that FTWs can suppress algae and duckweed growth significantly, especially when compared with the control cases. Other weeds (Alligator weed, Dogfennel, False hop sedge, Bladderwort, Goosefoot, etc.) which were found after 7 months, might have been beneficiary for the system as they grew on the floating mats with Canna and Juncus, and it was possible for them to take up nutrients. At this stage, few mesocosms showed a significant amount of duckweeds, algae, or other weeds, despite the presence of sufficient macrophytes. This might be the reason that littoral zone plants were not merely an inert substratum for algal attachment but rather a nutrient source that significantly influenced epiphyte P metabolism throughout the growing season. Bottom sediments might have also been the possible contributor of this extra nutrient source, as they were getting old.

Table 11: GroupWise proportion of epiphytes and phytoplankton

Scenario	After 3 Months (November 2010)	After 5 Months (January 2011)		After 7 Months (March 2011)		
	Epiphyte	Epiphyte	Phytoplankton	Epiphyte		Phytoplankton
	Duckweed	Duckweed	Algae	Duckweed	Other[#]	Algae
Case-1*	100%	0%	100%	40%	-	20%
Case-2*	1%	0%	100%	20%	-	35%
Case-3	25%	15%	2%	0%	Type-3	15%
Case-4	2%	2%	0%	80%	Type-1, 2, 3	50%
Case-5	60%	5%	0%	10%	Type-4	5%
Case-6	1%	0%	10%	20%	Type-1, 2	18%
Case-7a	0%	10%	0%	0%	Type-1, 2, 5	75%
Case-7b	0%	25%	0%	1%	-	3%
Case-8	30%	5%	5%	90%	Type-1	10%
Case-9	8%	0%	10%	3%	Type-1, 2	50%
Case-10	3%	0%	5%	2%	Type-1	5%

* Control Case
[#] Type-1: Alligator weed (*Alternanthera philoxeroides*)
Type-2: Dogfennel (*Eupatorium capillifolium*)
Type-3: False hop sedge (*Carex lupuliformis*)
Type-4: Bladderwort (*Utricuaria species*)
Type-5: Goosefoot (*Chenopodium glaucum*)

To better understand the impact of epiphytes and phytoplankton, nutrient removal efficiency and monthly average consumption data were presented in Table 12. For comparison purposes, nutrient consumption was shown instead of effluent concentration. Increased nutrient removal efficiencies were observed over the period of time that epiphytes and phytoplankton were growing. In the control case, the first 3 months of observations showed nutrient removal by only duckweeds as there were no macrophytes. The results during the 4th and 5th months indicated that the nutrient removal was by algae only, as no duckweeds were present during these months. Furthermore, in the last two months, nutrient removal from the water column was the lowest (20.42% TP and 74.74% TN). During this time, both duckweeds and algae were present in a much smaller proportion because some had died off, which resulted in less nutrient consumption. This observation of the control case demonstrated the demand of duckweeds and algae for nutrients, which should have a significant impact on other mesocosms with floating and emergent macrophytes.

Comparing nutrient consumption data between Case-1 and Case-2 (Table-12), we can see that there were more in Case-2, which was probably due to the presence of a littoral zone. In other cases, most of the time nutrient removal efficiencies and consumptions increased due to the presence of epiphytes and phytoplankton.

Table 12: Nutrient removal efficiencies in association with ecological changes

	(September, October, November 2010)		After 5 Months (December 2010-January 2011)		After 7 Months (February-March 2011)	
Scenario	TP	TN	TP	TN	TP	TN
Case-1	63.49% (0.967)*	69.93% (2.910)	70.70% (1.211)	100% (2.073)	32.03% (0.500)	74.74% (2.358)
Case-2	48.37% (1.382)	82.14% (3.532)	75.61% (3.250)	100% (2.798)	58.47% (1.116)	100% (1.953)
Case-3	81.32% (2.567)	86.20% (4.799)	73.40% (1.335)	100% (1.554)	48.85% (0.445)	100% (2.547)
Case-4	58.48% (1.280)	46.65% (1.813)	68.16% (1.388)	100% (2.798)	100% (3.076)	100% (4.860)
Case-5	75.09% (2.740)	63.81% (2.376)	73.52% (1.876)	100% (1.658)	98.76% (2.710)	100% (1.744)
Case-6	79.40% (2.669)	97.15% (3.125)	80.69% (2.199)	100% (2.176)	95.14% (1.233)	96.80% (2.323)
Case-7a	67.91% (1.571)	60.90% (2.099)	84.18% (1.404)	100% (1.969)	65.26% (2.310)	89.09% (2.579)
Case-7b	85.83% (2.409)	80.80% (3.437)	63.95% (1.178)	100% (1.244)	77.75% (2.967)	95.78% (2.767)
Case-8	75.68% (2.154)	74.03% (2.603)	74.01% (4.375)	100% (1.917)	96.37% (2.496)	100% (1.500)
Case-9	86.52% (2.625)	62.94% (1.633)	68.69% (0.934)	100% (1.917)	97.06% (3.009)	100% (3.023)
Case-10	65.24% (1.518)	72.34% (2.894)	83.16% (3.277)	100% (3.679)	46.46% (0.738)	100% (2.863)

* Monthly average nutrient consumption in mg.L^{-1}

3.5.1.7 Acclimation of FTWs in an aquatic environment

There was not a significant change in temperature or pH during the three months of observations (Figure 28). In Case-4, Chl-*a* was higher (6.88 µg.L-1) than the others which could be due to some sort of contaminate in this mesocosm. It was also observed that there was a decrease in turbidity, as the use of FTWs increased (Table 13). For example, without any FTWs, the control case (Case-1) showed the highest turbidity (26.69 NTU), Case-2 was more transparent (18.56 NTU) with the presence of a littoral zone, and Case-10 was the most transparent, with both a littoral zone and 10% floating mat coverage. This is reasonable as both, sediment rooted and floating plants are known to reduce the amount of sediments that accumulate within the system by retaining biosolids within the root mass.

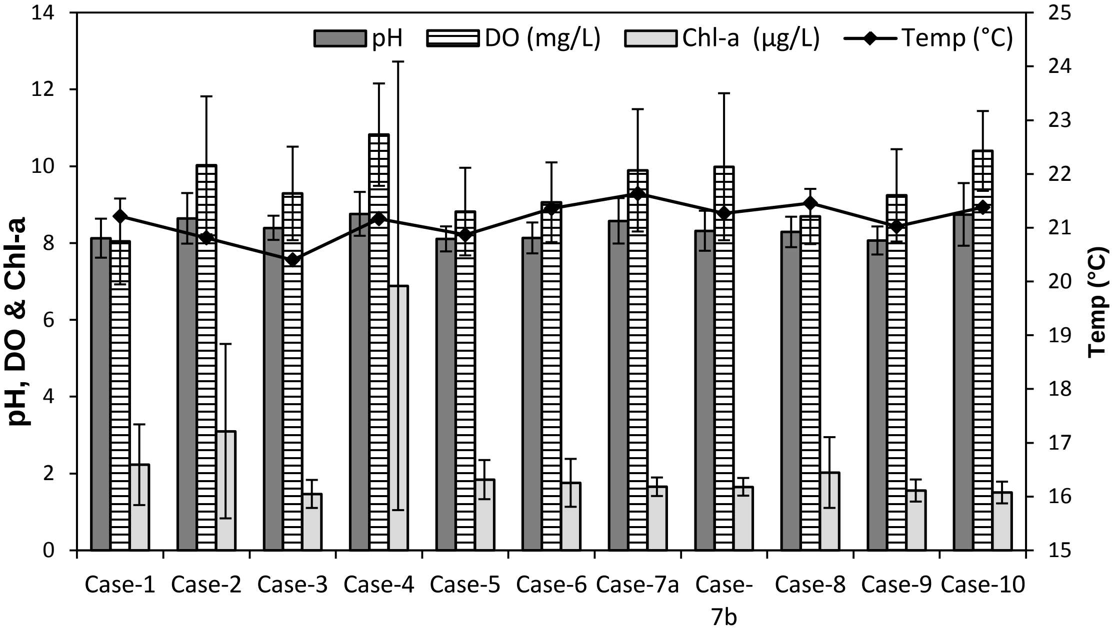


Figure 28: Variation of pH, DO, Chl-a, and Temperature

Table 13: Average turbidity decrease with increasing vegetation

Scenario	Average Turbidity (NTU)
Case-1	26.69
Case-2	18.56
Case-3	8.38
Case-4	22.36
Case-5	24.09
Case-6	10.15
Case-7a	17.05
Case-7b	16.41
Case-8	9.85
Case-9	7.45
Case-10	7.44

It is already known that during photosynthesis plants release oxygen into the water, while during respiration, plants remove oxygen from the water. In addition, it has also been shown that bacteria and fungi use oxygen as they decompose dead organic matter in the stream, and these types of organisms (plant, bacteria, fungi, etc.) affect the DO concentration in a water body. When many plants are present, water has been known to become supersaturated with DO during the day, as photosynthesis had taken place. Meanwhile, concentrations of oxygen are known to decrease significantly during the night, due to respiration. DO concentrations are usually highest in the late afternoon because photosynthesis had been occurring all day. In our mesocosms, the same phenomena were observed (Figure 29). It was sometimes oversaturated at noon and dissolved oxygen was lowest (8.04 $mg.L^{-1}$) in the control case, which was due to the lack of FTWs. However, on average, DO was 9.48 $mg.L^{-1}$ in all the mesocosms, which is known to be needed for aquatic health.

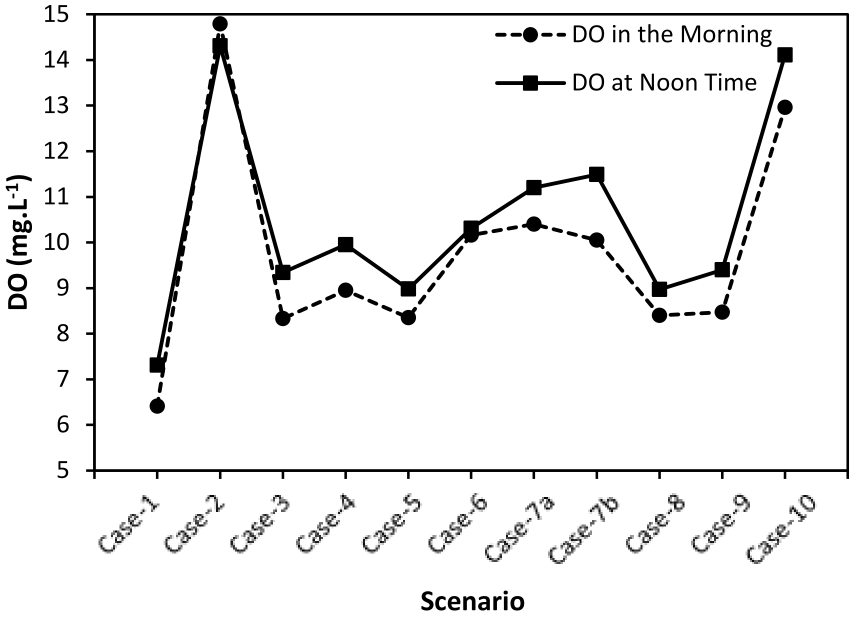


Figure 29: Day to night variation of DO

Duckweed and algae are known to quickly cover the surface of a pond or small lake, often blowing toward the downwind side. In addition to making a pond or lake unsightly and not very appealing for swimming, the thick growths of these plants have prevented sunlight from reaching the deeper parts of the water body. The sub-surface plants then have a reduced ability to photosynthesize and produce oxygen, which have been known to cause the levels of dissolved oxygen to decrease below the acceptable levels required for a healthy fish population. Figure 30 showed a decrease in DO in two months when duckweeds, algae, and other weeds grew from the 5th to the 7th month. The left axis showed the summation of percent area coverage of the mesocosms by algae and duckweeds. Most of the time they were seen overlapped on each other. Therefore, the summation was sometimes more than 100%. The right axis showed the change in DO in two months. For example, in Case-4, DO decreased significantly (7 mg.L^{-1}) when there was 80% duckweeds and 50% algae. Except for a couple of exceptions, the DO change was prominent with the amount of duckweeds and algae.

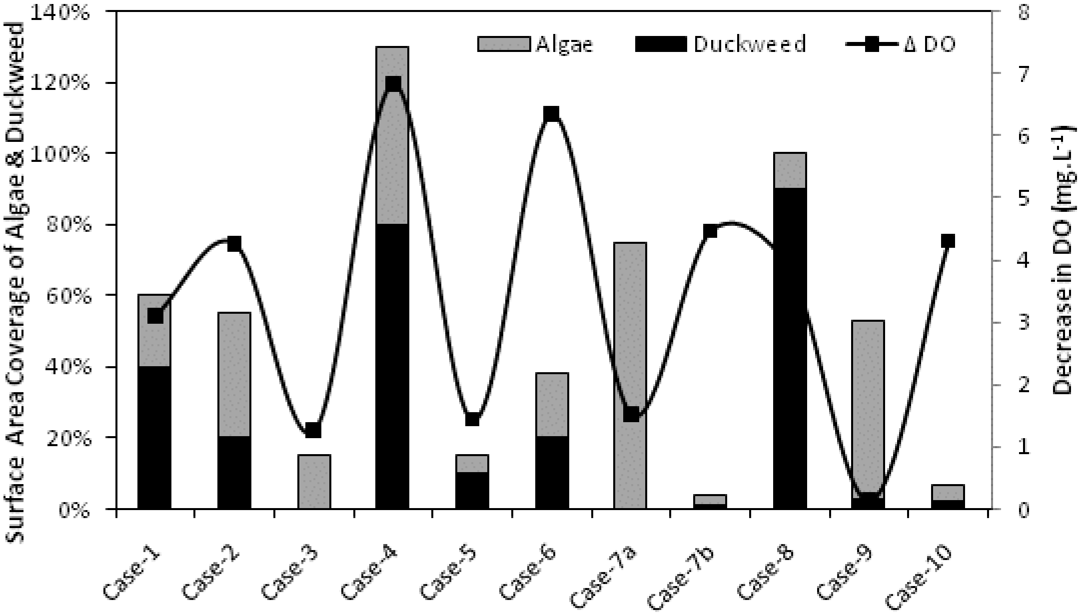


Figure 30: Effects of Epiphyte and Phytoplankton on DO level

3.5.2 Fibrous matrix FTWs

Due to differences in bottom mud compaction and corresponding changes in water volume, it was difficult to maintain constant initial nutrient loading in our experiment; therefore, a small deviation from the usual stormwater quality was observed in the initial nutrient concentrations. Both influent (0 Day) and effluent (15 and 30 Days) concentrations of various nutrients (Tables 14–18) indicated the efficacy of the fibrous matrix FTW system. More water quality constituents of concern are listed in Tables 19-24.

Table 14: Bi-weekly total phosphorus concentrations (in mg.L−1)

	Month-1			**Month-2**			**Month-3**		
Scenario	**0* Day**	**15 Days**	**30 Days**	**0* Day**	**15 Days**	**30 Days**	**0* Day**	**15 Days**	**30 Days**
Case-1	3.476	2.659	1.156	2.460	1.921	0.719	2.664	0.698	0.329
Case-2	3.506	1.205	0.673	1.980	1.122	0.661	1.333	0.673	0.417
Case-3	2.058	0.506	0.265	1.648	0.987	0.694	0.801	0.383	0.358
Case-4	2.053	1.949	0.821	2.188	1.562	0.983	2.097	1.457	0.393
Case-5	1.826	0.624	0.442	1.562	0.871	0.394	2.220	0.321	0.000
Case-6	3.063	2.013	0.932	3.194	2.591	1.348	0.462	0.417	0.092
Case-7	3.383	1.723	1.122	2.166	1.349	0.719	1.289	0.737	0.432
Case-8	2.737	1.531	0.713	1.481	0.781	0.305	1.181	0.489	0.220
Case-9	3.191	0.979	0.742	1.190	0.882	0.290	1.161	0.737	0.240
Case-10	3.659	0.891	0.595	2.029	1.031	0.482	0.806	0.353	0.191

* Nutrients were dosed in liquid form

Table 15: Bi-weekly orthophosphate concentrations (in mg.L−1)

	Month-1			Month-2			Month-3		
Scenario	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days
Case-1	1.380	1.073	0.504	1.783	1.231	0.411	1.010	0.422	0.274
Case-2	1.838	0.551	0.263	1.652	0.783	0.328	0.792	0.242	0.128
Case-3	1.105	0.227	0.156	1.229	0.674	0.451	0.593	0.367	0.043
Case-4	1.777	0.927	0.648	1.898	1.149	0.542	0.843	0.811	0.172
Case-5	1.414	0.392	0.281	1.115	0.657	0.118	0.589	0.304	0.000
Case-6	2.079	1.337	0.806	2.569	1.980	0.882	0.394	0.299	0.000
Case-7	1.963	0.938	0.752	1.887	0.768	0.651	0.970	0.162	0.135
Case-8	1.824	0.642	0.469	0.992	0.439	0.102	0.874	0.462	0.130
Case-9	1.523	0.386	0.253	0.722	0.561	0.023	0.559	0.075	0.000
Case-10	1.682	0.390	0.319	1.864	0.720	0.182	0.589	0.227	0.067

Table 16: Bi-weekly total nitrogen concentrations (in mg.L−1)

	Month-1			Month-2			Month-3		
Scenario	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days
Case-1	4.783	3.032	2.664	4.032	2.078	1.693	4.599	4.184	3.954
Case-2	3.078	2.433	2.341	3.277	1.739	0.966	3.862	3.585	3.078
Case-3	3.862	2.341	2.018	2.202	1.938	0.849	3.631	2.802	2.387
Case-4	3.954	2.111	1.972	3.129	2.131	1.513	5.244	3.816	3.585
Case-5	3.677	2.111	1.972	3.387	2.271	1.345	3.355	3.171	2.249
Case-6	3.263	2.249	2.065	2.251	2.025	1.554	4.046	3.217	2.479
Case-7	3.124	2.203	2.203	4.057	2.010	0.882	3.954	3.447	2.479
Case-8	3.908	2.295	2.249	3.528	1.773	0.816	3.539	3.401	3.032
Case-9	3.309	2.618	2.018	3.220	1.460	0.973	4.230	3.124	2.387
Case-10	3.862	2.341	2.065	3.115	2.090	1.082	4.829	2.618	2.387

Table 17: Bi-weekly nitrate-nitrogen concentrations (in mg·L−1)

Scenario	Month-1			Month-2			Month-3		
	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days
Case-1	1.032	0.193	0.236	1.341	0.114	0.029	0.575	0.068	0.034
Case-2	1.106	0.055	0.002	0.976	0.024	0.011	0.975	0.000	0.006
Case-3	1.488	0.098	0.032	1.105	0.037	0.028	0.731	0.020	0.061
Case-4	1.718	0.075	0.018	0.793	0.064	0.034	0.453	0.022	0.052
Case-5	1.028	0.052	0.006	1.169	0.267	0.089	0.453	0.013	0.000
Case-6	0.984	0.036	0.036	1.040	0.046	0.031	0.487	0.004	0.018
Case-7	1.732	0.068	0.041	1.014	0.024	0.019	0.575	0.025	0.043
Case-8	1.233	0.239	0.064	1.014	0.036	0.027	1.021	0.142	0.050
Case-9	1.900	0.087	0.004	1.407	0.023	0.016	0.623	0.002	0.000
Case-10	1.847	0.202	0.038	1.418	0.239	0.100	0.855	0.015	0.011

Table 18: Bi-weekly ammonia-nitrogen concentrations (in mg.L−1)

Scenario	Month-1			Month-2			Month-3		
	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days	0 Day	15 Days	30 Days
Case-1	0.216	0.147	0.000	0.127	0.023	0.000	0.066	0.065	0.029
Case-2	0.081	0.090	0.000	0.070	0.017	0.000	0.101	0.079	0.037
Case-3	0.141	0.086	0.000	0.187	0.031	0.000	0.088	0.082	0.030
Case-4	0.051	0.099	0.000	0.086	0.042	0.000	0.126	0.090	0.052
Case-5	0.075	0.093	0.000	0.157	0.030	0.000	0.114	0.016	0.037
Case-6	0.079	0.084	0.000	0.107	0.017	0.000	0.105	0.050	0.034
Case-7	0.085	0.097	0.000	0.114	0.084	0.000	0.061	0.072	0.047
Case-8	0.148	0.161	0.000	0.129	0.013	0.000	0.104	0.038	0.024
Case-9	0.134	0.085	0.000	0.068	0.068	0.000	0.074	0.039	0.009
Case-10	0.107	0.082	0.000	0.096	0.055	0.000	0.130	0.069	0.040

Table 19: pH values over the observation period

Scenario	0 Day	15 Days	30 Days	45 Days	60 Days	75 Days	90 Days
Case-1	7.36	7.80	8.01	7.98	8.00	7.50	7.71
Case-2	7.48	8.95	8.81	8.60	8.45	7.99	8.30
Case-3	7.45	8.03	8.05	8.20	7.85	8.02	8.04
Case-4	7.51	8.02	8.09	8.08	7.64	7.33	7.53
Case-5	7.42	7.76	8.04	8.09	7.88	8.10	8.03
Case-6	7.45	8.52	8.08	8.34	8.78	8.22	8.95
Case-7	7.66	8.50	8.35	8.26	8.03	8.11	8.09
Case-8	7.60	8.20	7.90	7.54	8.13	8.47	8.12
Case-9	7.34	7.76	8.00	7.80	8.31	8.01	8.06
Case-10	7.52	8.17	8.28	8.29	8.57	8.90	8.85

Table 20: Electrical conductivity (in µS.cm−1) over the observation period

Scenario	0 Day	15 Days	30 Days	45 Days	60 Days	75 Days	90 Days
Case-1	129.1	150.7	169.1	170.5	200.6	167.3	145.9
Case-2	156.0	159.8	177.5	166.4	206.6	162.8	161.5
Case-3	194.1	208.7	229.0	232.3	237.0	204.9	194.4
Case-4	152.8	152.2	160.1	147.8	170.6	129.7	121.7
Case-5	153.2	143.5	135.4	113.6	147.5	118.1	103.1
Case-6	202.5	191.3	209.9	187.5	227.0	190.2	171.9
Case-7	153.5	152.6	149.6	165.4	180.8	153.8	155.1
Case-8	218.0	217.6	228.0	210.5	253.0	215.4	201.3
Case-9	157.2	160.9	165.4	160.3	182.1	115.3	143.2
Case-10	141.8	148.0	170.1	188.2	197.2	165.8	159.3

Table 21: Temperature (in °C) over the observation period

Scenario	0 Day	15 Days	30 Days	45 Days	60 Days	75 Days	90 Days
Case-1	29.5	26.2	25.7	30.1	29.9	29.0	30.8
Case-2	28.5	25.9	26.1	30.0	30.2	29.8	29.9
Case-3	28.3	24.8	25.1	29.8	30.0	29.0	30.2
Case-4	28.4	26.2	25.6	29.9	29.8	29.3	31.7
Case-5	29.3	26.1	26.1	30.0	30.1	28.4	30.1
Case-6	26.8	26.9	26.2	30.2	30.3	28.7	29.8
Case-7	28.7	27.1	27.7	30.2	30.1	30.4	30.0
Case-8	28.7	25.7	25.2	30.5	30.0	29.9	29.3
Case-9	29.4	25.8	25.4	29.7	30.4	28.7	30.3
Case-10	29.0	27.1	26.7	30.8	31.0	30.3	30.4

Table 22: Dissolved oxygen (in mg.L−1) over the observation period

Scenario	0 Day	15 Days	30 Days	45 Days	60 Days	75 Days	90 Days
Case-1	6.72	5.81	6.22	7.03	7.29	7.24	6.29
Case-2	5.43	8.70	8.39	9.23	10.16	11.60	5.15
Case-3	3.48	6.28	5.52	5.16	5.99	6.23	7.14
Case-4	7.76	7.88	7.82	7.86	7.70	6.57	5.84
Case-5	5.60	7.08	6.77	6.87	6.90	8.68	9.36
Case-6	6.02	8.27	Out of Range	8.32	5.18	9.49	8.43
Case-7	5.87	7.12	7.01	7.35	8.06	9.70	6.10
Case-8	5.83	5.70	2.01	4.09	4.47	6.36	5.82
Case-9	5.45	5.57	4.91	3.28	2.78	7.86	7.89
Case-10	7.73	4.93	6.37	6.61	6.14	8.16	9.01

Table 23: Turbidity (in NTU) over the observation period

Scenario	0 Day	15 Days	30 Days	45 Days	60 Days	75 Days	90 Days
Case-1	28.00	39.00	34.00	22.56	17.60	14.70	5.10
Case-2	3.00	7.00	5.00	7.41	8.33	7.35	3.35
Case-3	93.00	21.00	12.00	11.20	10.20	9.83	8.28
Case-4	15.00	4.00	4.00	5.51	6.36	4.79	5.49
Case-5	2.00	5.00	6.00	4.88	3.99	5.23	1.44
Case-6	4.00	3.00	5.00	4.25	1.63	2.99	2.16
Case-7	5.00	6.00	5.00	5.79	5.29	6.35	5.00
Case-8	6.00	6.00	3.00	11.61	27.10	11.60	5.56
Case-9	7.00	4.00	2.00	2.19	2.21	8.78	6.96
Case-10	31.00	4.00	4.00	3.78	3.85	2.72	3.46

Table 24: Chlorophyll-*a* (in µg.L−1) over the observation period

Scenario	0 Day	15 Days	30 Days	45 Days	60 Days	75 Days	90 Days
Case-1	4.46	4.36	2.26	3.19	4.38	1.65	2.23
Case-2	0.92	1.30	0.95	0.81	1.42	1.32	1.49
Case-3	2.03	2.01	2.74	1.82	1.78	1.76	1.66
Case-4	1.81	1.46	1.81	3.77	5.02	1.81	5.77
Case-5	1.28	1.48	1.32	2.01	2.39	2.03	1.58
Case-6	1.43	1.23	1.51	1.49	1.56	1.82	1.63
Case-7	1.53	1.57	2.04	4.67	4.36	4.72	2.47
Case-8	2.02	1.61	1.67	2.01	2.06	1.87	1.67
Case-9	1.12	1.37	1.47	1.39	1.20	2.66	2.89
Case-10	1.86	1.06	1.14	1.92	1.30	0.93	2.42

Although the control case (Case-1) was expected to show little nutrient removal, growth of undesirable plant species like duckweed (*Lemna minor*) and algae hampered our comparison. In other cases, effluent concentrations were satisfactorily low. The absence of macrophyte plantings in the control case allowed duckweed to grow and cover the surface, which resulted in a significant amount of nutrient removal. Duckweed is known to require a lot of nutrients to grow, so typically it is found in nutrient-rich environments. The surface layer of duckweeds prevented sunlight from reaching the deeper parts of the water column so that underwater plants and algae can no longer photosynthesize and produce oxygen. This had been widely understood in the past and is taught to greatly stress or even kill fish.

Most ecological findings were reported in a sequential manner (Table 25). After 1 month, the control case (Case-1) became infested (40%) with duckweed due to the absence of macrophytes. Other mesocosms also had partial duckweed coverage and although they had floating macrophytes or a littoral zone, they somehow had redundant nutrients for duckweed.

Algae and duckweed are natural competitors. As soon as duckweed was removed from the mesocosms, algal growth was noticed. The growth was near complete within 2 months after removal of the duckweed and consisted of mostly filamentous blue-green algae (*Cyanophyceae*). Laboratory tests identified that the majority of samples contained *Oscillatoria,* as well as some *Microcystis* and *Ankistrodemus*. After 3 months, an increase in the proportion of epiphytes and phytoplankton were noted, and the existence of fish and frogs were observed over time.

From the above observations over these temporal ecological changes, it was evident that FTWs can significantly suppress algae and duckweed growth, especially when compared with the control cases. A few mesocosms showed a significant amount of duckweeds or algae despite the presence of sufficient macrophytes. This might be why littoral zone plants were not merely an inert substratum for algal attachment, but rather served as a nutrient source that significantly influenced epiphyte P metabolism throughout the growing season. Bottom sediments might have also periodically released extra nutrients as they were saturated.

Table 25: GroupWise evolution and proportion of epiphytes, phytoplankton, and other fauna.

	After Month-1		After Month-2			After Month-3		
	Epiphyte (Duckweed)	Phytoplankton (Algae)	Epiphyte (Duckweed)	Phytoplankton (Algae)	Fauna	Epiphyte (Duckweed)	Phytoplankton (Algae)	Fauna
Case-1	40%	-	1%	30%	Frog	40%	5%	-
Case-2	-	60%	1%	80%	-	2%	85%	-
Case-3	5%	-	10%	-	-	10%	5%	-
Case-4	3%	-	5%	1%	Frog	2%	-	Frog
Case-5	1%	-	5%	-	Frog	-	90%	Fish
Case-6	-	10%	1%	20%	Fish	5%	15%	-
Case-7	-	-	-	-	-	-	-	-
Case-8	-	-	-	-	-	80%	-	-
Case-9	15%	-	25%	2%	-	7%	-	-
Case-10	-	-	-	3%	-	-	7%	-

Average nutrient removal efficiencies (Figure 31) showed the efficacy of FTWs more clearly and helped us select optimum design components for the actual pond implementation. The TP diagram shows that Case-5, which has both littoral zone plants and 5% floating mat coverage, performed better. Orthophosphate (OP) concentration, Case-9, had a better removal efficiency with 5% *Juncus* coverage and no littoral zone. With the same coverage, TN, NO_3-N, and NH_3-N also had good removal efficiencies in Cases 5, 7, 9, and 10. From this observation, we concluded that 5% floating mat coverage may suffice for the actual pond.

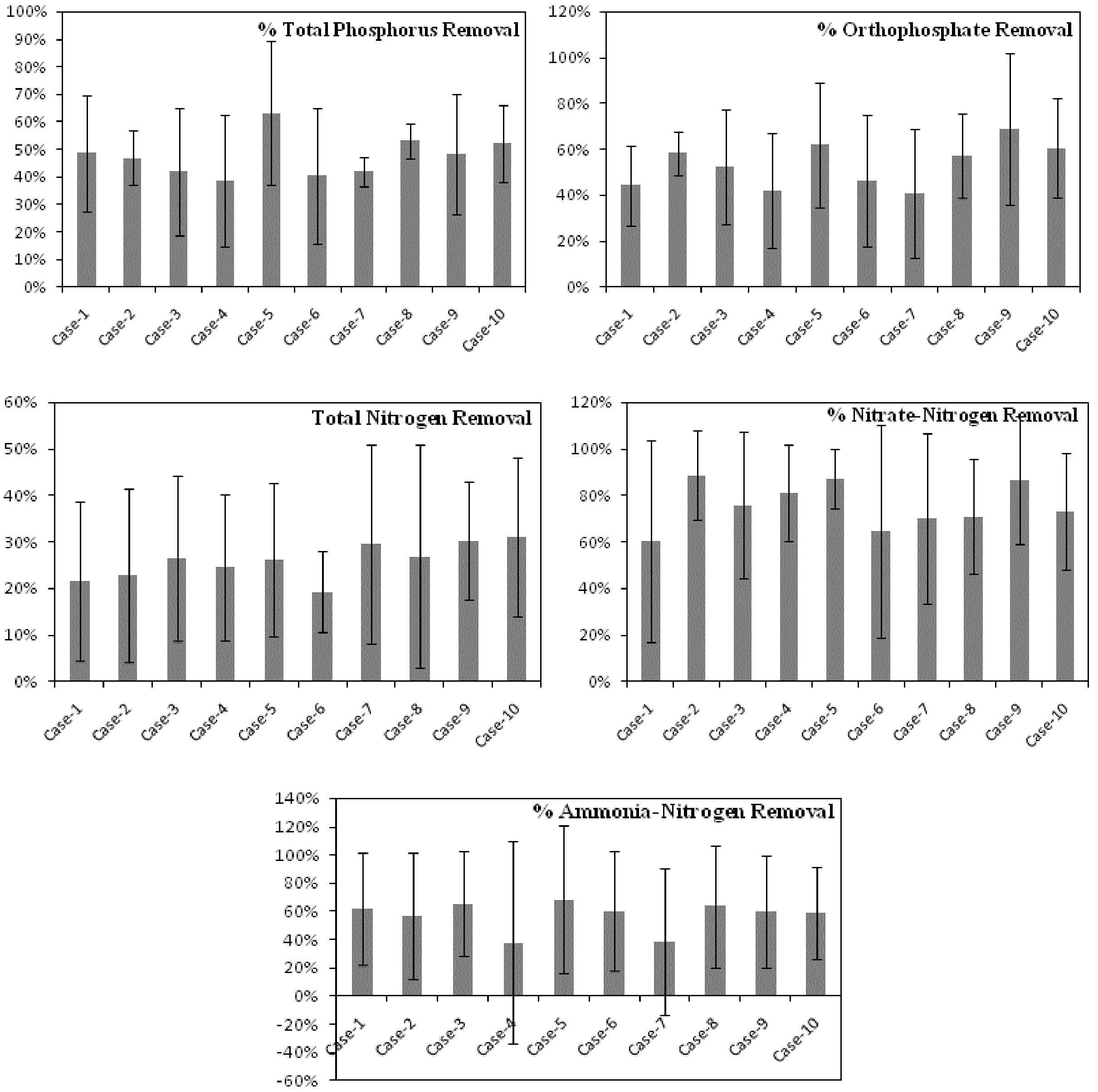


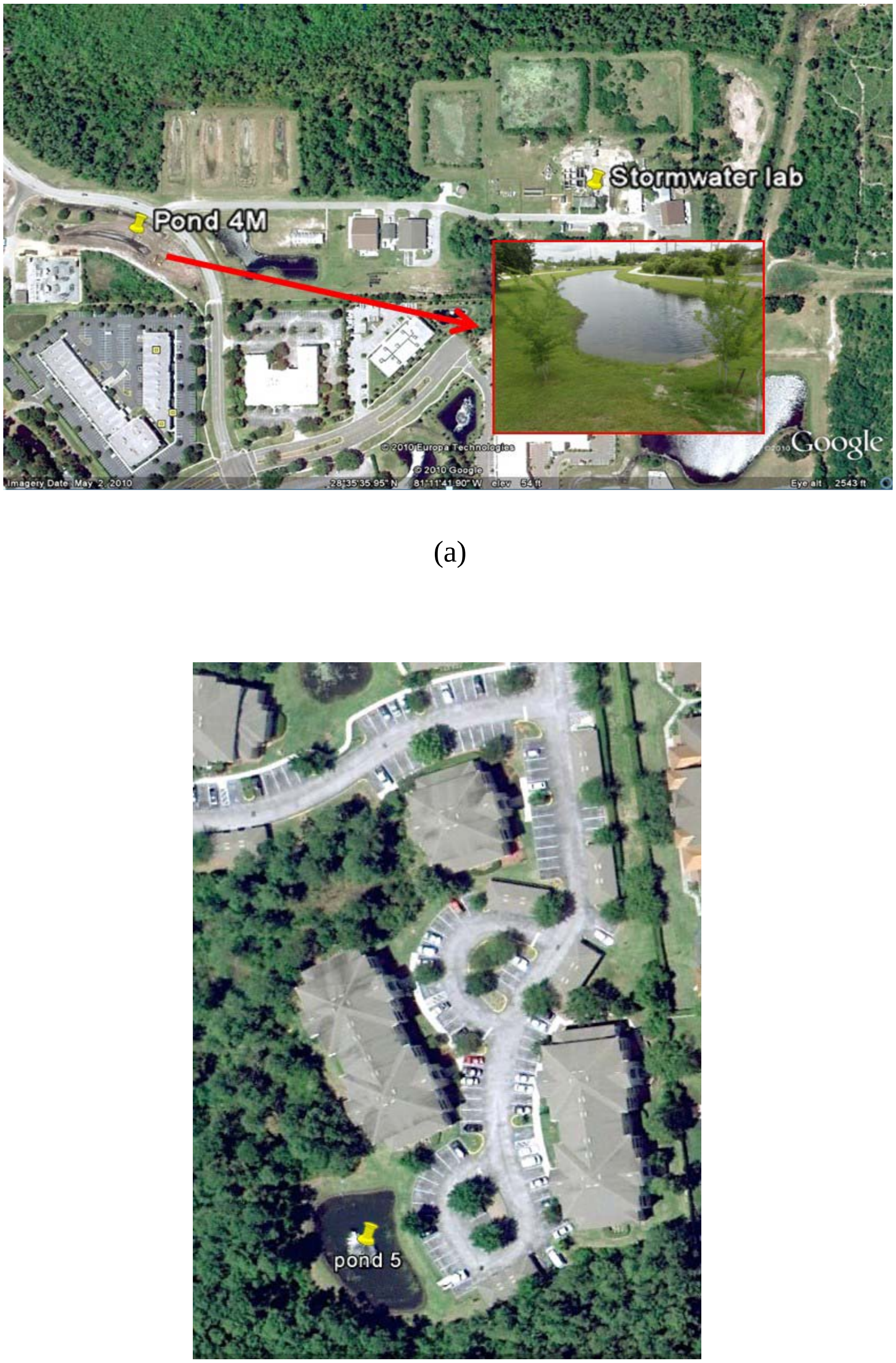
Figure 31: Average bi-weekly nutrient removal efficiencies.

CHAPTER 4 FIELD POND STUDY

4.1 EXPERIMENTAL DESIGN

Adjacent to the UCF Stormwater Management Academy Laboratory, a newly-built detention pond, Pond 4M (Figure 32a), was selected as our actual pond for the interlocking foam FTWs study. The pond had a surface area of 0.69 acres at discharge control elevation and a bottom area of 0.18 acres. The permanent pond volume provided was around 3.73 ac-ft (4601 m^3).

A stormwater detention pond located in a community near the UCF main campus in Orlando, Florida, Pond 5 in this study, was used to investigate the potential of fibrous matrix FTWs. The pond had a surface area around 3,700 ft^2 at discharge control elevation (75.5 ft) and a watershed of about 1.64 acres (Figure 32b). In-flow and out-flow pipes were both constructed at the elevation of 72.5 ft. A concrete structure at 71.75 ft in the adjacent wetland received the out-flow discharge from the pond. It had a 1.25 inch-diameter orifice at 75.5 ft and a fiberglass skimmer top at 76.75 ft, so that when the water level in Pond 5 rose over 76.75 ft, the flood water can spill away from the top of the concrete structure directly toward the nearby wetland.



(a)

(b)

Figure 32: Location of the (a) Pond 4M on campus and (b) Pond 5 off campus

4.1.1 Hydrology and Water Balance

A storm event based water balance for the pond included the following terms:

∆Storage = Direct Rainfall + In-flow – Out-flow – Evaporation – Infiltration

4.1.1.1 Pond 4M

4.1.1.1.1 Water level

For Pond 4M, the storage was represented in the form of water level data. The water level sensor (Global Water WL400, figure 33) was installed outside of the outlet concrete structure. Data logger (Global Water GL500-2-1) was connected with the water level sensor and had been set to record the water level data at intervals of 10 minutes. The data can be exported via its USB port to a laptop computer as an Excel compatible file (.CSV file)

Figure 33: Water level sensor

4.1.1.1.2 Rainfall

During the pre-analysis, rainfall (the direct amount falling to the pond) was read from the rain gauge on site. Since late January 2011, the real-time (5-minute intervals) rainfall data has been observed from the newly established UCF Green Roof Weather Station on the roof of the Physical Science building: (https://www.hobolink.com), only 0.6 mile away from the site. It provided more accurate and reliable data, as well as more appropriate time for sampling. The rainfall was characterized by calculating total rainfall, duration, rainfall intensity, and runoff coefficient using the following criteria:

Rainfall: rainfall amounts for each event, in.
Duration: periods of active rainfall, hr.
Intensity: total event rainfall / duration, in. /hr.
Runoff ratio: inflow amount / rainfall amount, unit less;

4.1.1.1.3 In-flow

Surface runoff is considered the principal component of the in-flow volume. It is known as the water flow that occurs when the soil reaches its full water capacity. Therefore, the amount of runoff depended on the area of the watershed that contributed to Pond 4M. One method of runoff estimation was to use rainfall values multiplied by the efficiency of the watershed. However, the truth was that not all storms produced runoff. What's more is that there was another factor which is also known to contribute to the in-flow volume during a storm event, but it is usually neglected from calculations. That factor was groundwater supplement, the water in-flow from the surrounding, fully saturated soil matrix during the storm. Therefore, the sum of runoff and groundwater supplement was used as gross in-flow. When other terms were measured or estimated from the water balance equation, the gross in-flow was then easily calculated as this was the only unknown term.

4.1.1.1.4 Out-flow

A concrete box was constructed at the outlet of the 4M pond. Its inner dimension was 1.37 m (54-inch) long, 0.91 m (36-in) wide and 2.18 m (86-in) deep (Figure 34). There was a 4-inch-diameter out-flow pipe on the outlet structure (about 22-inch below the top of the structure). Since it was highly probably the water level in Pond 4M would rise over this elevation and the pond water would start to discharge, a flow meter unit (Georg Fischer Signet 2551 Magmeter Flow Sensor) was installed inside the outlet structure to record the amount of water that was discharged from the pond (Figure 34).

Figure 34: Outlet structure and the flow meter unit inside

4.1.1.1.5 Evaporation

Evaporation is known as the amount of water lost to the atmosphere from the pond water surface. Evaporation rates are found to be dependent on many different factors, such as temperature, wind, atmospheric pressure, etc. In our study, an evaporation pan (Figure 35) located in the UCF stormwater lab was used to measure evaporation rate, which was further converted to the pond evaporation rate by multiplying a coefficient of 0.7.

Figure 35: Evaporation pan

4.1.1.1.6 Infiltration

The infiltration from the pond, as well as to the groundwater table from the pond, was calculated from a mass balance of the pond. During the pre-analysis, there was a one-month gap without any storm events before the first storm was sampled in early December 2010. During that time interval, the pond water level was much lower than the level of out-flow pipe on the concrete structure. Therefore, direct rainfall, in-flow, and out-flow can be considered as zero, and then the water balance equation can be simplified as below:

ΔStorage = – Evaporation – Infiltration

That is, infiltration can be calculated as the water level loss after subtracting the evaporation amount. For simplification, the infiltration rate was considered as a constant for the water balance calculation. Once infiltration was determined, the in-flow in the water balance equation could be calculated.

4.1.1.2 Pond 5

4.1.1.2.1 Water level

The storage for Pond 5 was represented by water level data and recorded by the same water level sensor model (Global Water WL400; Figure 33) installed at the mouth of the circular outlet culvert (i.e., 0 ft in raw water level data is equivalent to 72.5 ft). The data logger (Global Water GL500-2-1) was connected with the water level sensor and set to record the water level data at 10-minute intervals

4.1.1.2.2 Rainfall

During the experiment period, rainfall (the direct amount falling into the pond) was measured and read from a 6-inch Tipping Bucket rain gauge (Figure 36: RG200, Global Water) on site. The radar rainfall data from The St. Johns River Water Management District was used as a backup rainfall data source when the rain gauge was not functioning due to some unpredictable factors.

Figure 36: Rain gauge.

4.1.1.2.3 In-flow

The amount of surface runoff, considered the principal component of the in-flow, depended on the land size of the watershed that produced runoff flowing into Pond 5. Due to budget limitations, there was no flowmeter installed at the inlet. Instead, the rational runoff was used to estimate the in-flow amount. The watershed area and the runoff coefficient used for the Pond 5 were summarized (Table 26):

Rational Equation: Q = ciA, where Q = Peak discharge, in cfs; c = Rational method runoff coefficient; i = Rainfall intensity, in inch/hour; and A = Drainage area, in acres.

Table 26: Watershed area and runoff coefficient used for Pond 5

	Runoff coefficient (RC) range	RC, used value	Watershed Area (acre)	weighted runoff fraction
Lawns	0.05-0.35	0.20	0.1950	0.024
Roofs	0.75-0.95	0.85	0.5957	0.309
Concrete streets	0.7-0.95	0.83	0.7615	0.386
Pond	1.00	1.00	0.0849	0.052
Total			1.6371	0.771

4.1.1.2.4 Evaporation

For Pond 5, the same evaporation pan (Figure 35) located in the UCF stormwater lab was used to measure evaporation rate, which was further converted to the pond evaporation rate by multiplying by a coefficient of 0.7.

4.1.1.2.5 Infiltration

It was not feasible to directly measure the infiltration to the groundwater table with time for the whole pond area; therefore, a period of time when the water level was lower than the level of orifice on the concrete structure was selected to estimate the infiltration amount. Like the principle we used for the Pond 4M study, infiltration was calculated as the water level loss after subtracting the evaporation amount. For simplification, the infiltration rate was considered a constant for the water balance calculation. Once infiltration was determined, the outflow (the unknown term in the Pond 5 study) in the water balance equation could be calculated.

4.1.1.2.6 Out-flow

A concrete structure was constructed at 71.75 ft., which connected Pond 5 to the adjacent wetland. The structure had a 1.25 inch-diameter orifice at 75.5 ft. and a fiberglass skimmer on the top at 76.75 ft. We knew that when the water level in Pond 5 rose over 75.5 ft., out-flow would have discharged, and when the water level was higher than 76.75 ft, the flood water would have spilled away from the top of the concrete structure directly toward the nearby wetland.

4.1.2 Nutrients removal evaluation of FTWs

4.1.2.1 Temporal and spatial nutrients distribution in stormwater pond

4.1.2.1.1 Pond 4M

Table 27 presents the water quality analysis plan for capturing at least seven storm events before the floating wetland deployment (December 2010 to April 2011). The observation and monitoring during pre-analysis provided the background value of stormwater quality and self-purification capacity of the stormwater pond. The non-storm events monitoring effort was conducted by Prof. Patrick Bohlen at UCF Urban Landscape and Natural Resources (ULNR) Lab.

To explore the seasonal nutrient removal efficiency of FTWs, the floating wetland study at Pond 4M would be carried out within a one-year time frame after the floating wetland deployment. The concentration reduction percentage (CRP) results for nutrient levels at the inlet and outlet were monitored to calculate the nutrient removal effectiveness of the FTW systems. Tables 28 and 29 present the water quality analysis plan for a one-year experimental period, which was known as post-analysis. It was divided into two parts, monthly-based and event-based. Monthly-based analysis was used to produce a monthly estimate of nutrient distribution throughout the pond and a nutrient reduction between inlet and outlet. Since in-flow and out-flow are generated during the storm events, the event-based data was used to estimate removal. Seven event-based sampling efforts were done in parallel with the monthly sampling campaign.

$$CRP = \frac{C_{inlet} - C_{outlet}}{C_{inlet}} \times 100\%$$

Table 27: Water quality analysis plan for pre-analysis

Parameter	Event #1	Event #2	Event #3	Event #4	Event #5	Event #6	Event #7
Total Nitrogen	5	5	5	5	5	5	5
Nitrite + Nitrate	5	5	5	5	5	5	5
Ammonia	5	5	5	5	5	5	5
Total Phosphorus	5	5	5	5	5	5	5
Orthophosphate	5	5	5	5	5	5	5

Table 28: Water quality analysis plan for monthly-based analysis

Parameter	04/ 11	05/ 11	06/ 11	07/ 11	08/ 11	09/ 11	10/ 11	11/ 11	12/ 11	01/ 12	02/ 12	03/ 12	04/ 12
Total Nitrogen	5	5	5	5	5	5	5	5	5	5	5	5	5
Nitrite + Nitrate	5	5	5	5	5	5	5	5	5	5	5	5	5
Ammonia	5	5	5	5	5	5	5	5	5	5	5	5	5
Total Phosphorus	5	5	5	5	5	5	5	5	5	5	5	5	5
Orthophosphate	5	5	5	5	5	5	5	5	5	5	5	5	5

Table 29: Water quality analysis plan for event-based analysis

Parameter	Event #1	Event #2	Event #3	Event #4	Event #5	Event #6	Event #7
Total Nitrogen	6+5*	6+5	6+5	6+5	6+5	6+5	6+5
Nitrite + Nitrate	6+5	6+5	6+5	6+5	6+5	6+5	6+5
Ammonia	6+5	6+5	6+5	6+5	6+5	6+5	6+5
Total Phosphorus	6+5	6+5	6+5	6+5	6+5	6+5	6+5
Orthophosphate	6+5	6+5	6+5	6+5	6+5	6+5	6+5

* 6+5: 6 Individual sub-samples of inflow and composite samples from 5 sampling locations

4.1.2.1.2 Pond 5

As a pre-analysis, water quality analysis was conducted for three storm events and three non-storm events in the first half of July 2011. Non-storm event analysis was used to produce an instantaneous snapshot of nutrient distribution throughout the pond and a nutrient reduction between inlet and outlet. Event-based sampling efforts were done in parallel with the non-storm events sampling campaign.

To estimate removal efficiencies using fibrous matrix FTWs, a post-analysis at Pond 5 was conducted for 9 months after the floating wetland deployment. Water quality parameters were monitored to calculate the nutrient removal efficiencies of the FTWs. The post-analysis was further divided into two parts, non-storm-based and event-based. The data in post-analysis was used to calculate the additional water quality improvement due to the fibrous matrix FTWs.

4.1.2.2 Operating hydraulic residence time (HRT) and removal efficiencies.

Design HRT is the ratio of the pond volume and the inflow rate:

$$\mathrm{HRT} = V/Q$$

Where:

HRT = hydraulic residence time, d;
V = pond volume, m^3;
Q = inflow rate, m^3/d.

Removal efficiency is known to be related to holding or reaction time and is thus primarily dependent on the pond’s HRT at a particular moment in time. However, the operating HRT is not equivalent to a constant HRT value because influent flow varies over time and the rate never became steady, so there is a need to define the operating HRT in another way.

Forty (40) studies were selected for inclusion in a data base to identify runoff event mean concentration (EMC) values for single land use categories in Florida (Harper, 2011). The geometric means of 1.068 $mg.L^{-1}$ for TN and 0.179 $mg.L^{-1}$ for TP (particulate plus dissolved) for a Low Density Commercial (LDC) watershed were used for Pond 4M. LDC is defined as a commercial area with low traffic and where cars are parked for extended periods. This would include schools, offices, and small shopping centers. For Pond 5, the geometric means of 2.102 $mg.L^{-1}$ for TN and 0.497 $mg.L^{-1}$ for TP (particulate plus dissolved) were used for multi-family residential runoff, as well as the initial nutrient concentration in the runoff. Since the event-based sampling efforts were carried out in parallel with the monthly sampling campaign, the operating HRT can be defined as (1) the time interval between the occurrence of the storm and the time of sampling (which was converted to a daily basis as a matter of convenience) and (2) it is the time interval on the daily basis between the end of last storm event and the time of the subsequent non-storm sampling. Therefore, the event-based data revealed how much of the nutrients were removed by the physical sedimentation process within a short HRT (event- based) and the monthly-based data implied how much of the nutrients were removed by the biological treatment during a long HRT. Removal efficiency varied with different operating HRT. Thus, a plot of operating HRT vs. removal efficiencies was formed to provide another perspective of nutrient removal performance of FTWs.

4.1.2.3 Credit of floating wetlands

Besides the self-purification capacity via a natural process, floating wetlands were introduced to further improve the water quality, which is known to be essential to quantify additional credit for floating wetlands in terms of (1) assumed value based (outlet value vs. assumed runoff value) and (2) inlet value based (outlet value vs. inlet value) nutrient control. It should be recognized that particulates are known to settle out during a short HRT and therefore, floating islands hardly help remove particulates. However, over a long period of time via biological processes, the mostly dissolved fraction of nitrogen and phosphorus can be removed. The procedure for assessing the performance credit of floating wetlands is described below.

(1) Runoff concentration based:

A) Short-term settling dominated removal efficiency (RE_S);

$$RE_S = \frac{C_{assumed} - \overline{C_{I-S}}}{C_{assumed}} \times 100\%$$

Note: Assume input of TN is 1.068 mg/L and TP is 0.179 mg/L for Pond 4M; 2.102 mg.L^{-1} of TN and 0.497 mg.L^{-1} of TP for Pond 5; $\overline{C_{I-S}}$ **:** Geometric mean of nutrients concentration at the inlet for the storm events

B) Overall removal efficiency (RE$_O$);

$$RE_O = \frac{C_{assumed} - \overline{C_{O-N}}}{C_{assumed}} \times 100\%$$

Note: $\overline{C_{O-N}}$ **:** Geometric mean of nutrients concentration at the **outlet** in the **non-storm** events

C) Long-term biologically dominated removal efficiency (RE$_B$);

$$RE_B = RE_O - RE_S = \left(\frac{C_{assumed} - \overline{C_{O-N}}}{C_{assumed}} - \frac{C_{assumed} - \overline{C_{I-S}}}{C_{assumed}} \right) \times 100\%$$

$$= \frac{\overline{C_{I-S}} - \overline{C_{O-N}}}{C_{assumed}} \times 100\%$$

RE$_B$ in terms of TN and TP were calculated for both pre-analysis (without FTWs) and post-analysis (with FTWs) for two types of FTWs. A marginal concentration-based improvement was used to estimate the credit of floating wetlands as RE$_B$ (with FTWs) – RE$_B$ (without FTWs).

(2) Pond concentration based:

$$\frac{\overline{C_{I-S}} - \overline{C_{O-N}}}{\overline{C_{I-S}}} \times 100\%$$

4.2 EXPERIMENTAL SETTING

4.2.1 FTWs deployment in Pond 4M

The floating wetlands were deployed in Pond 4M on April 8, 2011 with area coverage at about 5%. It was expected that since Pond 4M was a kidney-shaped pond, algae species would probably aggregate at the two ends of the pond. Thus, two pieces of floating mats were deployed at both ends of the pond and the third one was deployed close to the outlet to achieve a better out-flow quality (Figure 37). Thousands of seedlings (including Canna and Juncus), flowers, and grass were planted on three integrated floating mats (Figure 37). The information about the N/P content in plant tissue was listed in the Appendix H. The sorption media was added in each seedling container. The floating islands were expected to work as a kidney of nature, providing a beautiful and peaceful habitat for birds and animals.

Canna *Juncus*

Flower *Grass*

Figure 37: Floating Wetland Plants (4/8/2011)

4.2.2 FTWs deployment in Pond 5

The Fibrous matrix FTWs were deployed at Pond 5 on July 15, 2011. Each of the four floating islands was an 80 ft^2 mat that occupied collectively around 5% of the pond surface area at the highest water level to ensure coverage if the fountain re-suspended nutrients. The mats were tied together in a ring surrounding the fountain, away from the inlet and outlet (Figures 38). Plant species were the same as in the mesocosm study and pots in the mat were filled with peat moss as the plant substrate.

Figure 38: Deployment of floating wetland (7/15/2011)

4.2.3 Plants replacement for the FTWs in Pond 4M

Nitrogen in the FTWs system is known to present a complex biogeochemistry circulation and it mainly exists in the form of organic nitrogen in pond water. At the same time, some forms of inorganic nitrogen, such as ammonia and nitrate, which is the essential material needed during the plant growth process, can be directly used through plant uptake. The newly-planted vegetation might perform a considerable N removal efficacy during the growing season, which might descend when the plants become fully matured. Besides, the FTWs and wet ponds often suffer from the overgrowth of exotic invasive plants, which could deteriorate the nutrient uptake. In our study, primrose willow was found spreading over the FTWs and cattail was colonizing at the shore of the pond (Figure 39). Therefore, the maintenance in terms of wetland plants replacement and aquatic plants control in winter was required as a means of nitrogen and carbon removal for a prolonged operation of FTWs. Also, the plant replacement in winter somewhat reduced shock to the reestablished vegetation due to the lack of storms.

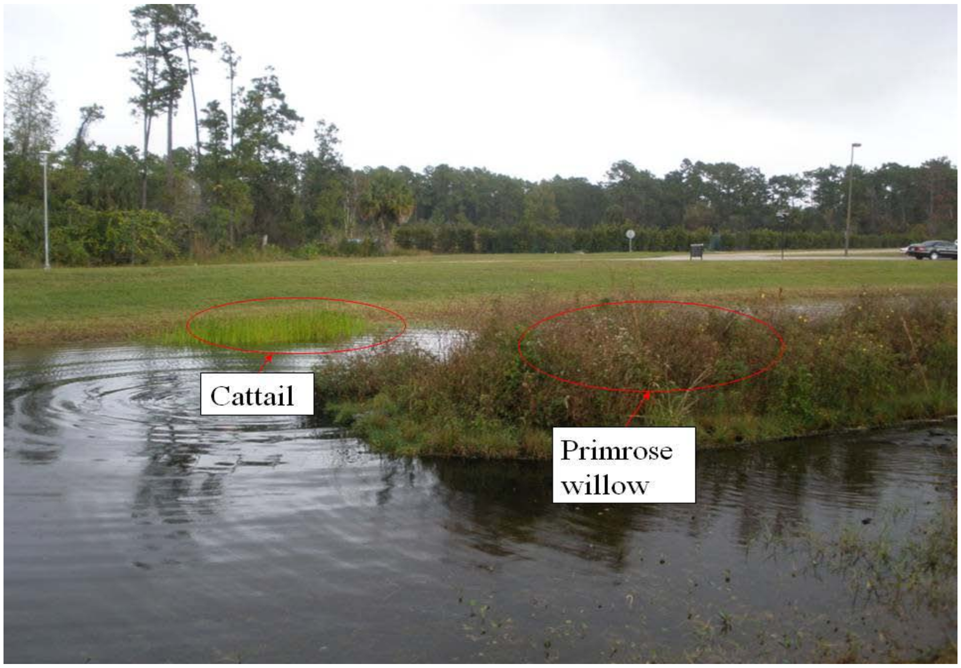


Figure 39: Invasive plants found at Pond 4M: Primrose willow on the wetland mats and Cattail at the shore of the pond

There were a few issues to consider for the plant replacement. First of all, all plant material should be the indigenous wetland plant species. Second, the vegetation for the replacement should be nursery grown plants, which is healthy and free of disease and pests. Third, plant material should be planted as soon as possible after delivery. Replacement of the plant species on the floating mats were carried out on December 12, 2011. The plants including Canna and Juncus, along with the grass from Beeman's Nursery, were replaced on three integrated floating mats. The comparison between the new vegetation replacement from Beeman's Nursery and the old vegetation pulled out of wetland mats (Figure 40) demonstrated the significant biomass growth of the three species of wetland plants (Canna, Juncus, and Agrostis Grass) used in Pond 4M during the 8-month experimental period, especially in their root systems. Overall, the observation implied that the buoyant interlocking foam mats with the perforated plastic cup design and sorption media, promoted high physiological activity of wetland plants and supported a highly efficient plant replacement effort (Figure 41).

(a) Canna (b) Juncus (c) Grass

Figure 40: Comparison between new vegetation for replacement (left) and the old vegetation (right) pulled out of floating mats

(a) Before (b) After

Figure 41: FTWs before and after the plants replacement (12/12/2011)

4.3 SAMPLING AND MEASUREMENTS

4.3.1 Pond 4M

For each storm event during the pre-analysis, pond water samples were collected about 5 inches below the water surface from 5 points in Pond 4M (Figure 42). Points 1 and 5 were located at the inlet and the outlet of the Pond 4M, respectively. Point 4 was picked at the other end of the pond. Point 2 was at the middle point between Points 1 and 5. Point 3 was at the middle point between Points 1 and 4. For each point, 6 evenly distributed sub-samples were collected at 15-minute intervals and finally composited to a half-gallon polypropylene bottle. The composite samples were transported at 4 °C to a NELAC certified Environmental Research & Design (ERD) lab for nutrient analysis. Due to the different methods of TN measurement used by the ERD lab and UCF ULNR lab, duplicate samples collected on February 15, 2012 were sent to both labs for comparison. The ULNR results (non-storm monitoring before the deployment of interlocking foam FTWs) would be adjusted for consistency when they have the similar trend as ERD results, but different in numbers.

During the post-analysis period, for monthly-based sampling, grab samples were collected from 5 sampling points once a month. For event-based sampling, flow weighted composite samples from 5 sampling points were taken over the storm hydrograph with the aid of real-time rainfall data from the new established UCF Green Roof Weather Station. In addition, the 6 sub-samples collected from the inlet were saved individually to see the variability of the influent over time during a runoff event and to estimate the traveling time of runoff to the pond. Thus, for each storm event, a total of eleven samples were transported to the ERD lab at 4 °C for analysis and quality control. Table 30 shows the chemical analysis methods of nutrients that ERD used.

Table 30: Outline of analysis methods

Parameter	Analytical Method
TN	SM21 4500-N C
NO_2+NO_3	EPA 353.2 / SM21 4500-NO3 F
NH_3	EPA 350.1 / SM21 4500-NH3 G
TP	EPA 365.1 / SM21 4500-P B
OP	EPA 365.1 / SM21 4500-P F

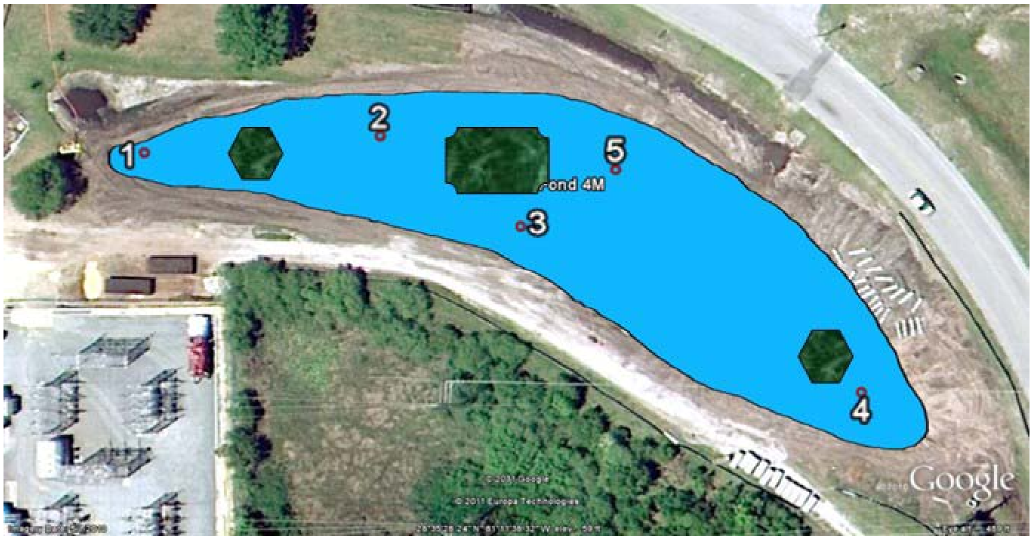


Figure 42: Sampling locations in Pond 4M

4.3.2 Pond 5

During storm and non-storm events, water samples were collected in triplicate close to the inlet and the outlet at Pond 5, and then mixed as composite samples (Figure 43). All the composite samples were stored at 4 °C and delivered to the ERD lab for chemical analysis of nutrients using various methods (Table 30). Note that the fountain in Pond 5 operated throughout the entire monitoring period.

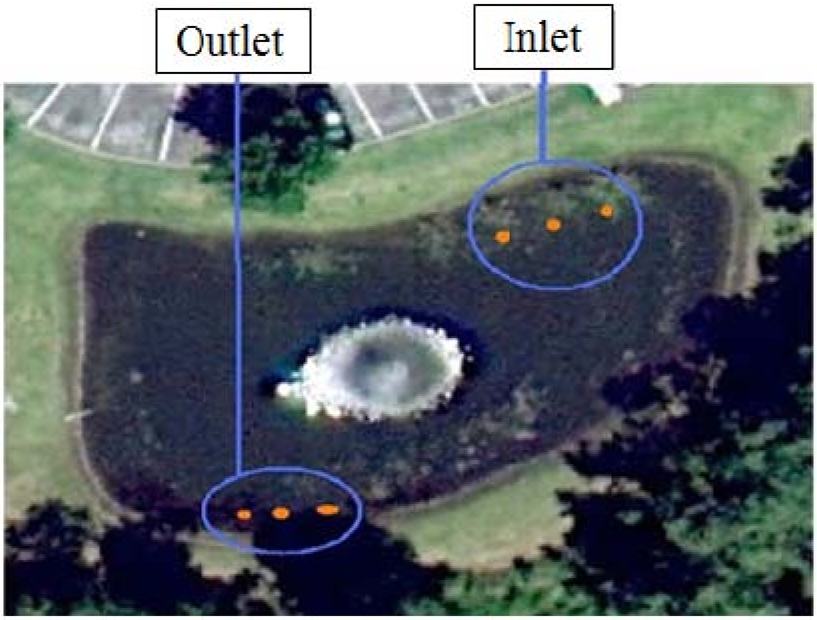


Figure 43: Sampling locations in Pond 5.

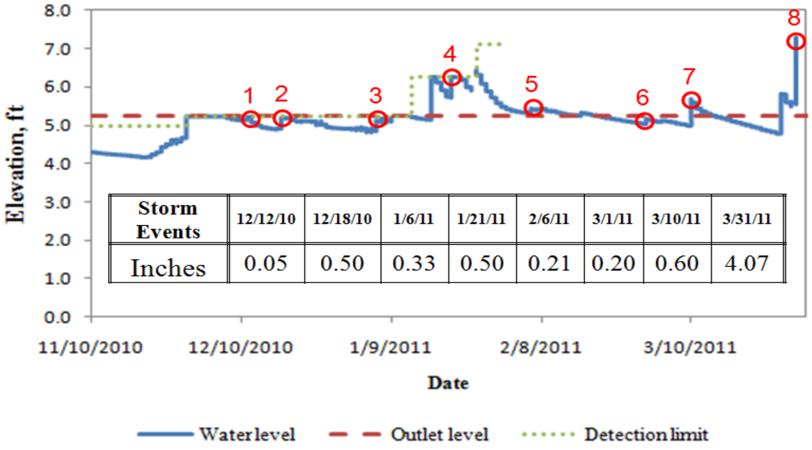
4.4 RESULTS AND DISCUSSION

4.4.1 Temporal and spatial nutrients distribution in stormwater ponds

4.4.1.1 Pond 4M

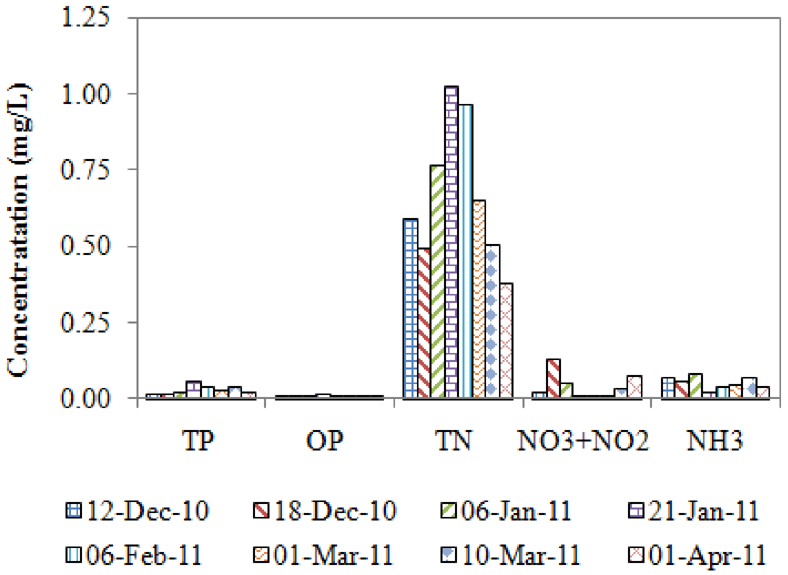
4.4.1.1.1Pre-analysis

Both hydrological and water quality parameters were monitored over 4 months before the floating wetland deployment. The data of water level, rainfall, and evaporation data used to make a water balance calculation for the pond are shown in Figure 44 and Appendix I. Figure 45 and Table 31 summarized the ERD results concerning the nutrient's level of the influent and effluent during the pre-analysis. It can be seen that after each storm event, inflow and runoff mixed with the pond water rapidly in Pond 4M, which caused almost the same nutrient concentration at inlet and outlet. Very low concentration of NH_3 and NO_2+NO_3 indicated that the dominant N form was organic nitrogen. The 4th (1-21-11) and 5th (2-6-11) storm events introduced more TN to the pond. The leaching from dead plant detritus and soils in late winter could be the main reason for the peak of N. UCF ULNR results and the concentration adjustment were also recorded and are shown in Appendix J & K.

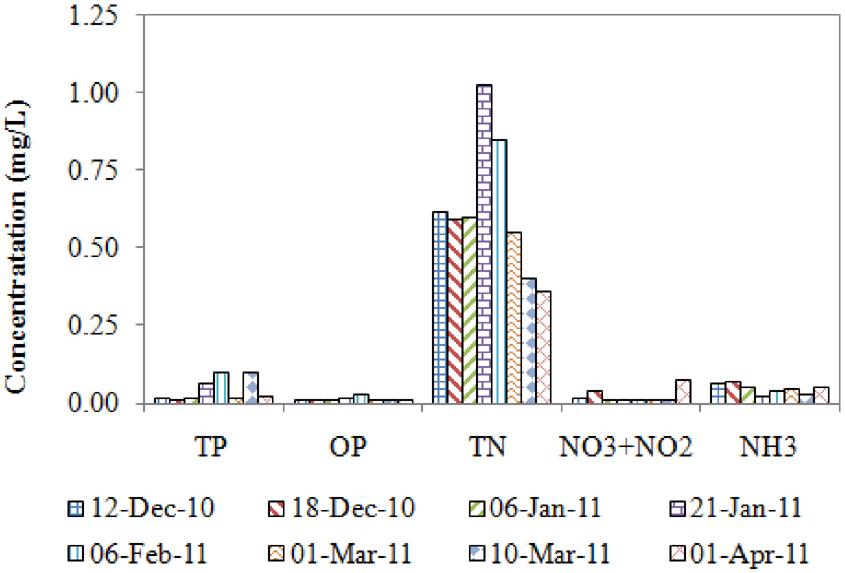


Storm Events	12/12/10	12/18/10	1/6/11	1/21/11	2/6/11	3/1/11	3/10/11	3/31/11
Inches	0.05	0.50	0.33	0.50	0.21	0.20	0.60	4.07

Figure 44: Hydrological data before deployment
(The level of concrete box inner bottom was set as 0 ft)



a) Influent



b) effluent

Figure 45: Water quality data before deployment

Table 31: Water quality summary of pre-analysis (n = 8)

	Average		Standard deviation	
	Influent (mg.L^{-1})	Effluent (mg.L^{-1})	Influent (mg.L^{-1})	Effluent (mg.L^{-1})
TN	0.669	0.620	0.231	0.220
NO_2+NO_3	0.040	0.019	0.042	0.024
NH_3	0.051	0.044	0.020	0.017
TP	0.029	0.040	0.015	0.039
OP	0.004	0.006	0.004	0.009

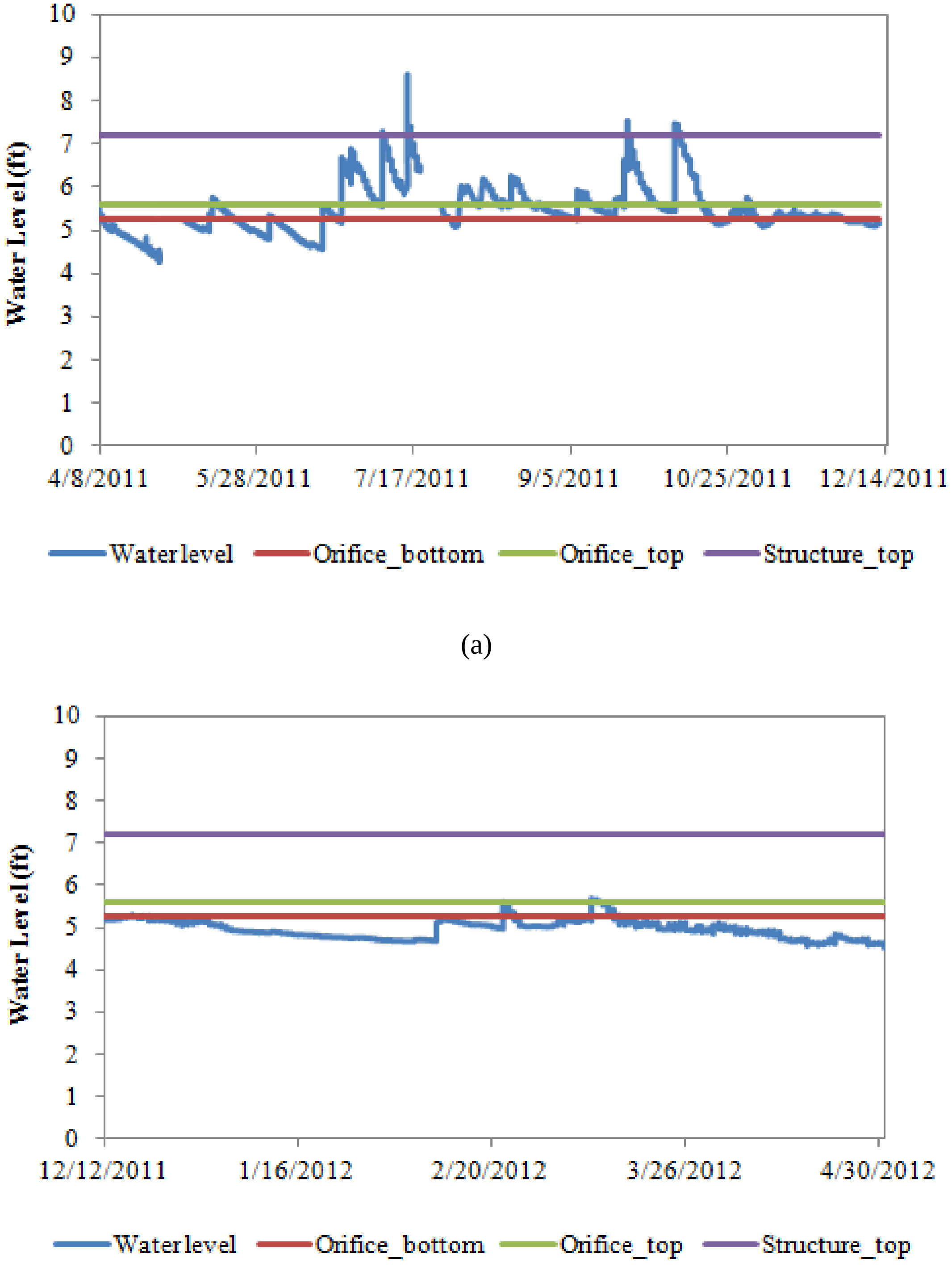
4.4.1.1.2 Post-analysis

Both hydrological and water quality parameters were continuously monitored after the floating wetland deployment. The hydrology of the Pond 4M was characterized by recording rainfall (Table 32) and measuring the surface water level (Figure 46). Rainfall data included storm volume, time interval volume, storm duration, rainfall intensity, and runoff coefficient and is listed as:

Rainfall: rainfall volume for each event, in.
Duration: periods of active rainfall, hr.
Intensity: total event rainfall / duration, in/hr.
Runoff ratio: inflow amount / rainfall amount, unit less;

Table 32: Rainfall monitored after deployment of floating wetlands

Event	**5/14/11**	**6/24/11**	**10/8/11**	**10/29/11**	**10/31/11**	**12/11/11**	**2/22/12**
Rainfall, in.	0.54	1.68	7.12	0.34	0.72	0.12	0.87
Duration, hr.	3.0	3.8	22.7	3.7	4.7	0.58	1.5
Intensity, in./hr.	0.18	0.44	0.31	0.09	0.15	0.21	0.58
Runoff ratio	9.3	10.0	6.2	8.1	8.0	0.08	4.01



(a)

(b)

Figure 46: Water level after deployment of floating wetlands: (a) Before the replacement of plants (b) After the replacement of plants (the elevation between red and green line represents the diameter of the outlet pipe)

4.4.1.1.2.1 Monthly-based

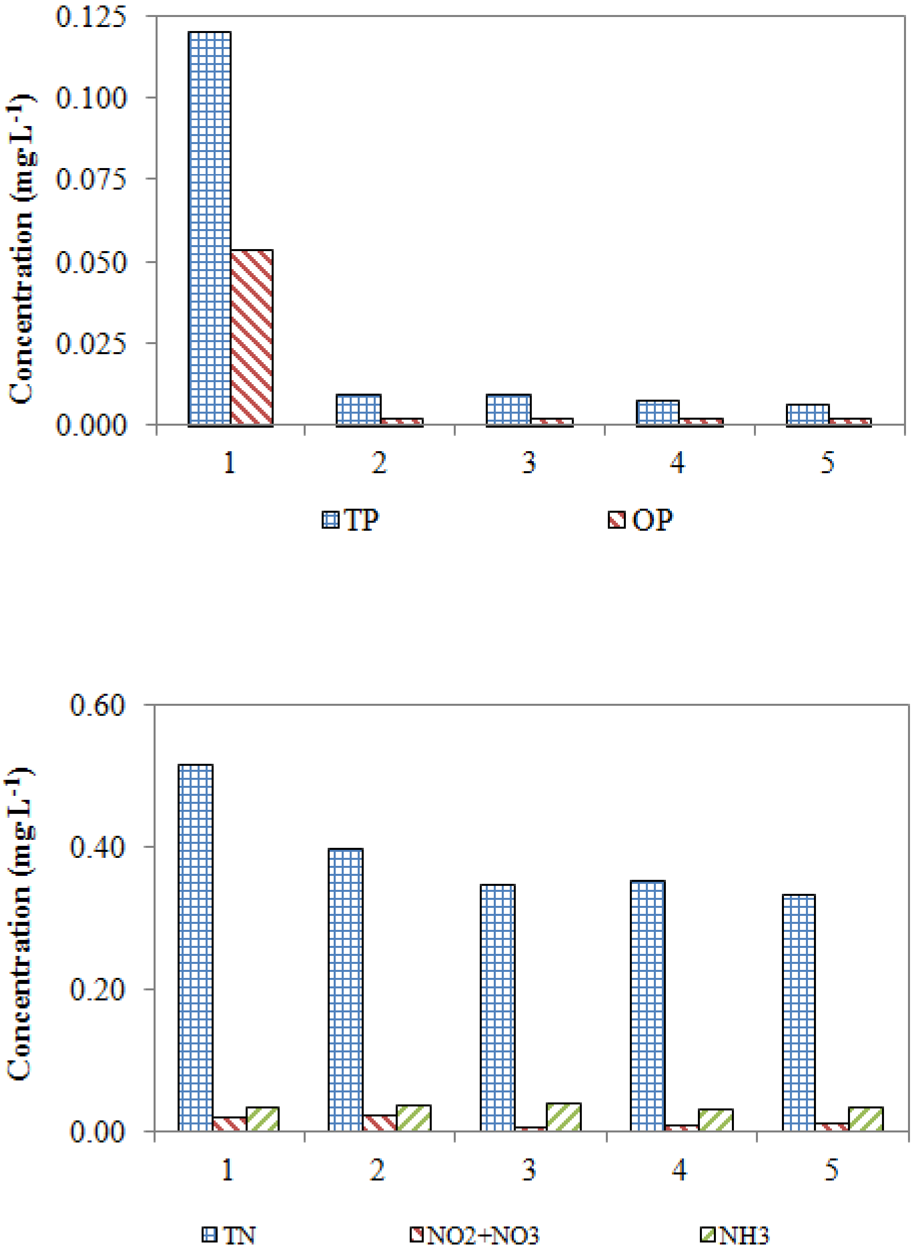
The first monthly-based sampling was carried out on April 15, one week after the field implementation when the plants on FTWs had been acclimated in the new environment during the rapidly growing season. From this point forward, grab samples were collected near the middle of every month at the 5 locations throughout the pond (Table 33). There were two typical spatial patterns of nutrient concentrations observed throughout the pond, gradient pattern and uniform pattern. The nutrient gradient pattern (Figure 47a) indicated that the floating wetland close to the inlet successfully performed as a barrier to block the nutrient-rich in-flow near the inlet, which no longer dispersed throughout the entire pond as quickly as usual. About 90% TP was removed, which was most likely due to the adsorption of sorption media in the floating wetland. Both ammonia and nitrite + nitrate concentrations looked unified among different sampling points. However, they just accounted for about 10% of TN, while 30% of TN was removed. Our sorption media had been proven efficient enough to treat the ammonia-rich water. Therefore, in this case, ammonification (i.e. convert organic N to ammonia) should be promoted for a better N removal. In May, the spatial distribution presented a uniform pattern (Figure 47b). Both TN and TP concentrations from 5 sampling locations kept similar values to the concentration at the outlet in April. Figure 47c shows the spatial nutrient results in June. The phosphorus species concentration was still at the very low level except at location 4. However, the nitrogen species concentration throughout the pond increased significantly, especially at location 3. In July, the distinctively higher phosphorus concentration appeared at location 2 (Figure 47d). From Figure 38e-38m, the spatial distribution of TN presented a relatively uniformed pattern, except at location 2 in October. As for the spatial distribution of TP, there were still some higher results found intermittently at other sampling locations though (like location 2 in July, September, and November, and at location 4 in June and October) probably due to the re-suspension of sediment caused by sampling disturbance. Overall, the TP concentration at both the inlet and outlet stayed at quite a low level (below 0.04 mg L^{-1}). Figure 48 shows the comparison between the inlet and outlet in terms of the time-series monthly-based nutrient results. TN showed an obvious seasonal pattern with two peaks in June and November 2011. There were two extreme storms before both periods, which implied that it might take 1-2 months for microbes to decompose the organic debris that poured into the pond with the runoff via a biological process. Since the settlement was the main approach for TP removal and the process is much shorter (by about a couple of days), TP variability was more stable after April-2011, when the floating wetlands were deployed. Organic N was the dominant form of TN. Since there were almost no storms (i.e. N source from runoff) in winter, the inorganic N: NH_3 and NO_2+NO_3 kept near-zero due to the uptake by newly-planted vegetation. This has accelerated the growth since February 2012 in a warmer environment and made the TN concentration drop below 0.3 mg L^{-1}.

Although the concentration difference between the inlet and outlet kept decreasing with time due to the uniform pattern in a later period, the overall average of the monthly TN concentration reduction (April 2011-April 2012) still reached 15.04% and there was a considerable 42.51 % decrease in TP. The concentration reduction from the inlet to outlet in terms of OP, NO_2+$NO_{3,}$ and NH_3 were 54.65, 17.51, and 27.66 %, respectively (Table 34 and Figure 49).

Table 33: Non-storm events results of spatiotemporal nutrients distribution (mg.L^{-1})

	Location	TP	OP	TN	NO_2+NO_3	NH_3
Apr-11	1	0.120	0.053	0.514	0.019	0.034
	2	0.009	0.002	0.397	0.020	0.036
	3	0.009	0.002	0.344	0.005	0.038
	4	0.007	0.002	0.352	0.008	0.029
	5	0.006	0.002	0.332	0.010	0.034
May-11	1	0.015	0.004	0.393	0.006	0.037
	2	0.012	0.006	0.363	0.006	0.040
	3	0.014	0.000	0.405	0.003	0.038
	4	0.014	0.002	0.426	0.003	0.048
	5	0.017	0.003	0.401	0.003	0.040
Jun-11	1	0.019	0.005	0.938	0.000	0.080
	2	0.016	0.000	0.915	0.000	0.096
	3	0.021	0.007	1.262	0.000	0.215
	4	0.049	0.008	0.774	0.009	0.030
	5	0.012	0.004	0.743	0.001	0.021
Jul-11	1	0.037	0.003	0.613	0.008	0.151
	2	0.090	0.002	0.258	0.013	0.136
	3	0.027	0.003	0.276	0.007	0.166
	4	0.023	0.003	0.231	0.011	0.125
	5	0.033	0.002	0.208	0.004	0.098
Aug-11	1	0.014	0.003	0.480	0.009	0.345
	2	0.010	0.002	0.426	0.007	0.143
	3	0.011	0.003	0.506	0.009	0.196
	4	0.010	0.002	0.501	0.013	0.153
	5	0.014	0.003	0.461	0.012	0.295
Sep-11	1	0.016	0.005	0.328	0.033	0.082
	2	0.051	0.006	0.384	0.034	0.062
	3	0.029	0.006	0.337	0.035	0.127
	4	0.012	0.007	0.347	0.038	0.114
	5	0.007	0.006	0.388	0.038	0.033
Oct-11	1	0.005	0	0.311	0.008	0.066
	2	0.022	0.002	0.456	0.005	0.075
	3	0.007	0.002	0.262	0.004	0.033
	4	0.037	0.004	0.274	0.003	0.105
	5	0.005	0	0.213	0.011	0.050
Nov-11	1	0.009	0.001	0.908	0.003	0.040
	2	0.028	0.001	0.966	0.003	0.078
	3	0.025	0.001	0.784	0.003	0.046
	4	0.010	0.001	0.775	0.003	0.031
	5	0.003	0.001	0.791	0.003	0.036
Dec-11	1	0.012	0.001	0.444	0.007	0.007
	2	0.013	0.001	0.423	0.004	0.007

	3	0.011	0.001	0.448	0.001	0.004
	4	0.009	0.002	0.418	0.001	0.005
	5	0.015	0.001	0.434	0.001	0.003
Jan-12	1	0.014	0.003	0.512	0.030	0.056
	2	0.013	0.003	0.494	0.005	0.043
	3	0.016	0.004	0.490	0.007	0.036
	4	0.024	0.002	0.537	0.004	0.021
	5	0.016	0.002	0.513	0.009	0.039
Feb-12	1	0.008	0.003	0.525	0.006	0.023
	2	0.006	0.004	0.478	0.009	0.013
	3	0.005	0.003	0.495	0.004	0.043
	4	0.007	0.004	0.469	0.007	0.020
	5	0.011	0.008	0.455	0.039	0.020
Mar-12	1	0.009	0.005	0.226	0.046	0.111
	2	0.008	0.005	0.275	0.001	0.057
	3	0.008	0.008	0.269	0.003	0.050
	4	0.032	0.025	0.272	0.023	0.069
	5	0.014	0.006	0.281	0.011	0.064
Apr-12	1	0.009	0	0.249	0.002	0.049
	2	0.011	0.002	0.252	0	0.060
	3	0.012	0.001	0.251	0.042	0.046
	4	0.019	0.002	0.252	0.001	0.050
	5	0.012	0.001	0.252	0.004	0.049
Average	1	0.022	0.007	0.495	0.014	0.083
	2	0.022	0.003	0.468	0.008	0.065
	3	0.015	0.003	0.471	0.009	0.080
	4	0.019	0.005	0.433	0.010	0.062
	5	0.013	0.003	0.421	0.011	0.060
Stdev	1	0.030	0.014	0.222	0.014	0.088
	2	0.024	0.002	0.224	0.010	0.041
	3	0.008	0.002	0.279	0.013	0.070
	4	0.013	0.006	0.180	0.010	0.047
	5	0.008	0.002	0.182	0.013	0.074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2
3
4
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OP
Concentration (mg L^{-1})
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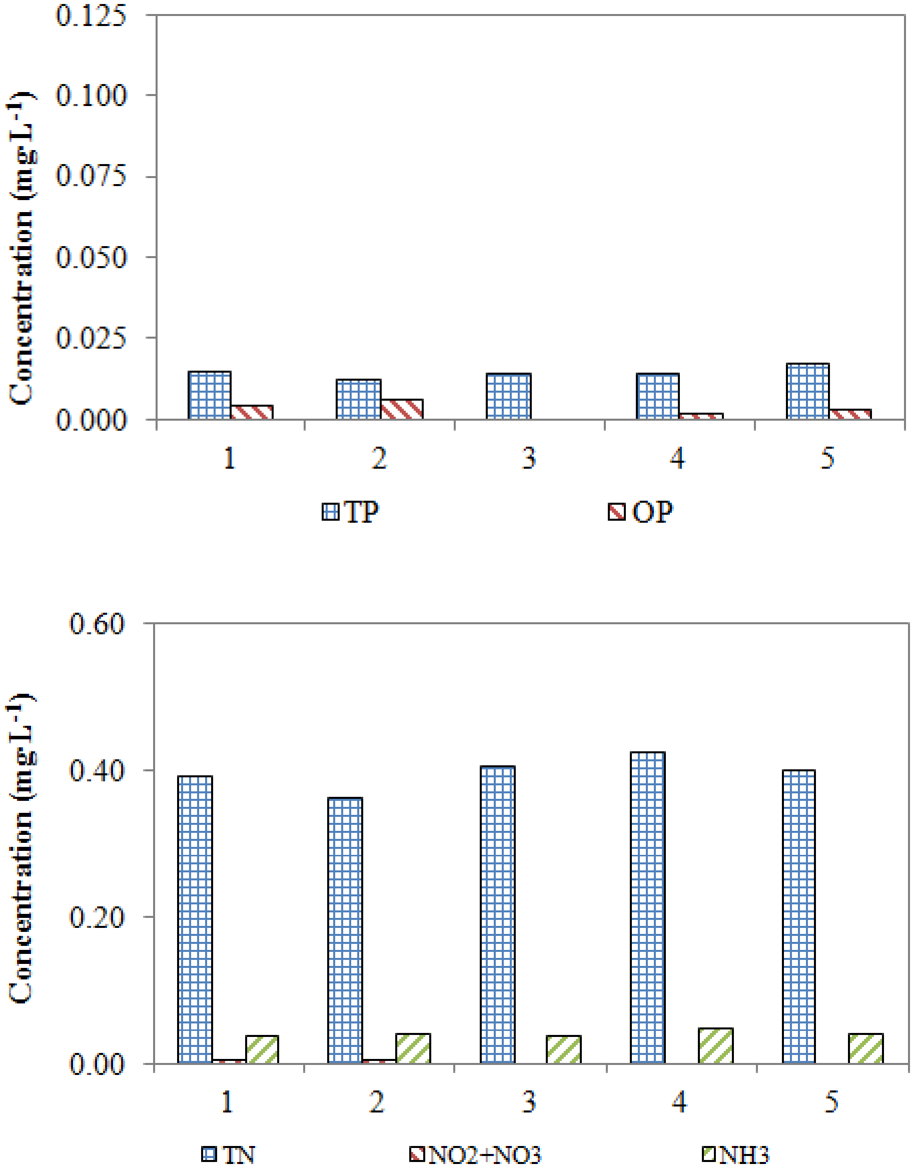
3
4
5
TN
NO2+NO3
NH3

a) Apr-15-11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▦ TN
▧ NO2+NO3
▨ NH3

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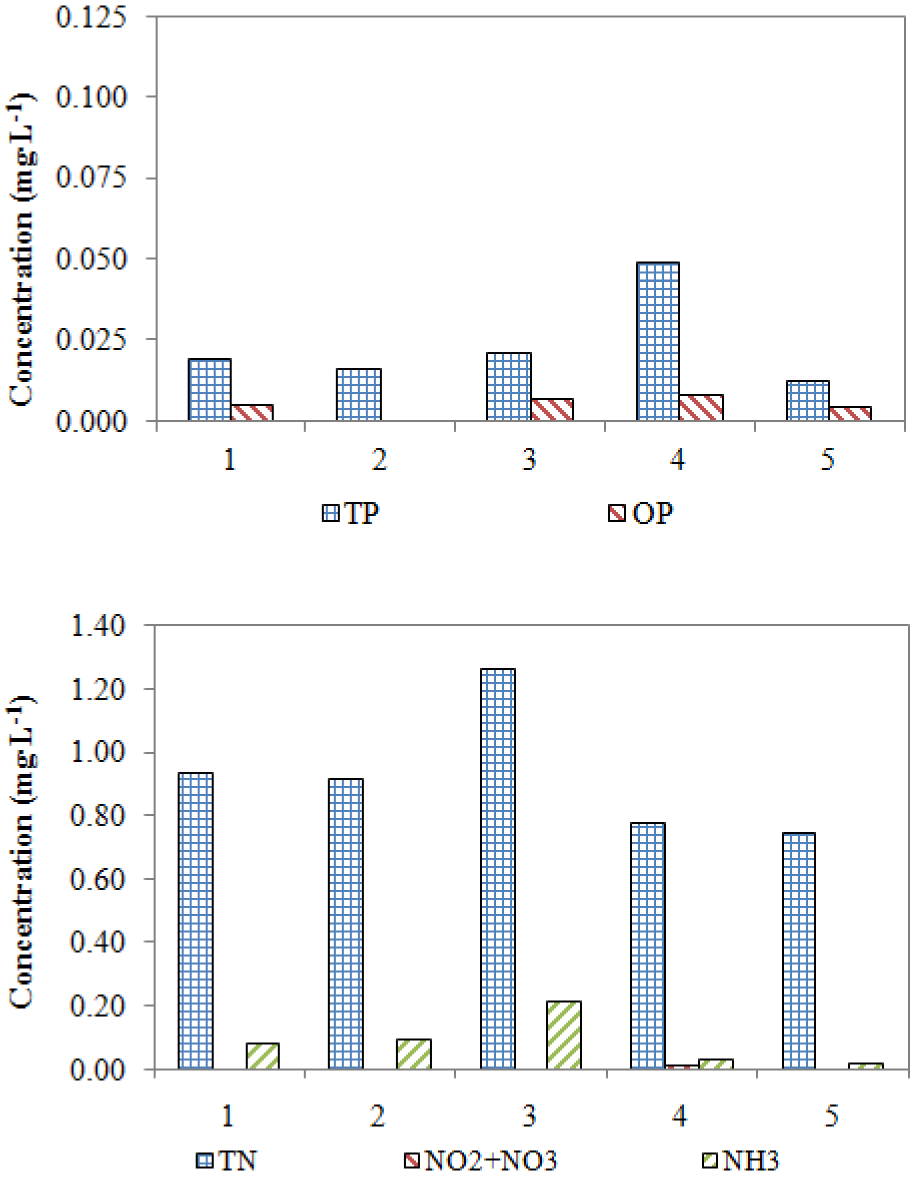
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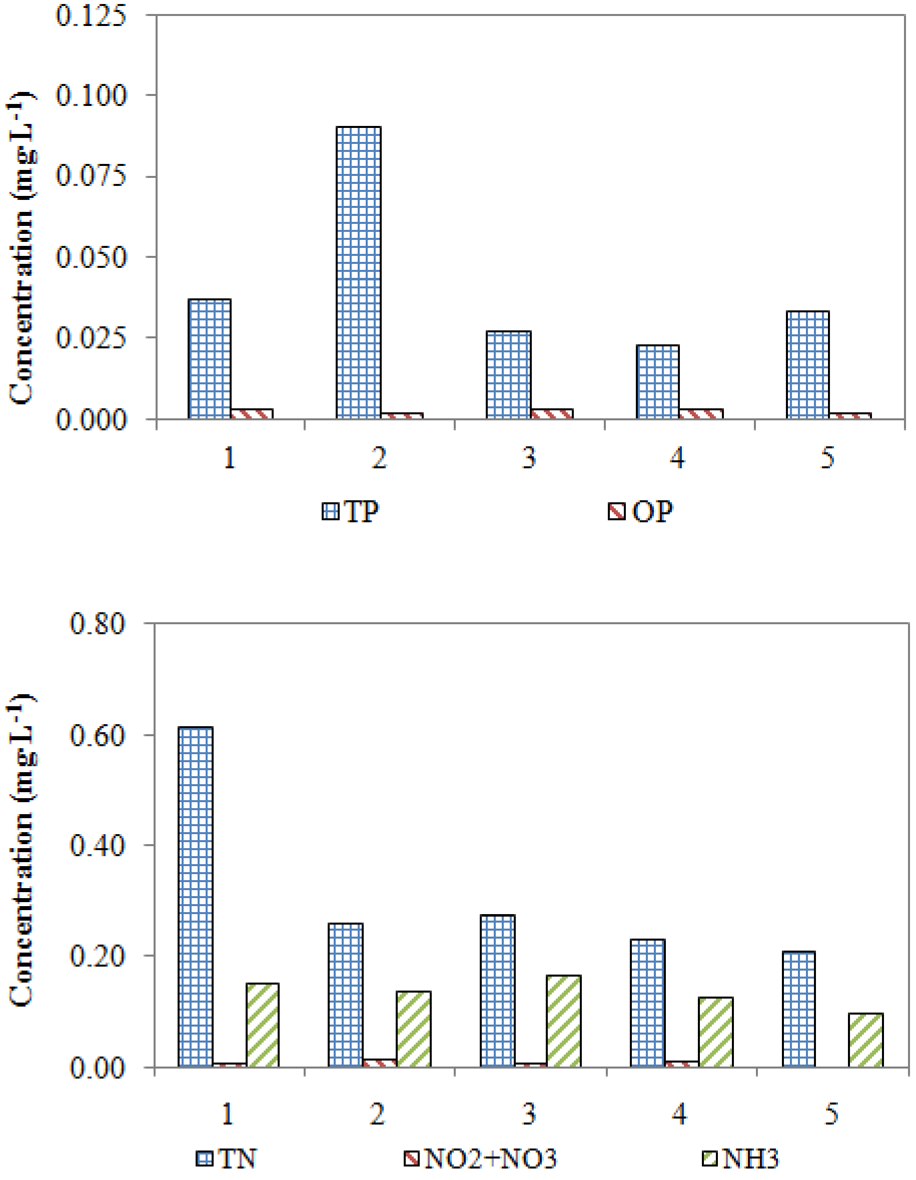
NO2+NO3
NH3

c) June-15-11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Concentration (mg L-1)
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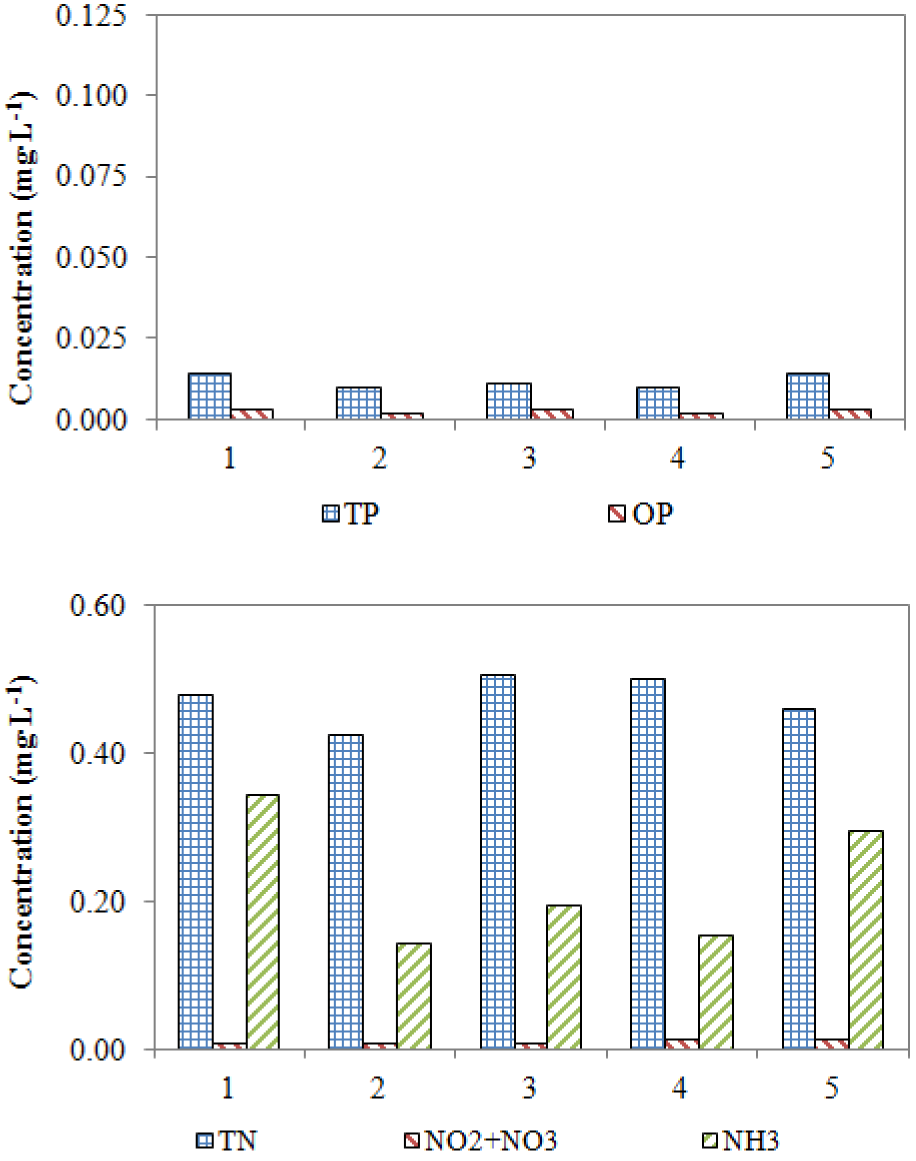
4
5
TN
NO2+NO3
NH3

d) July-17-11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Concentration (mg·L-1)
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4
5
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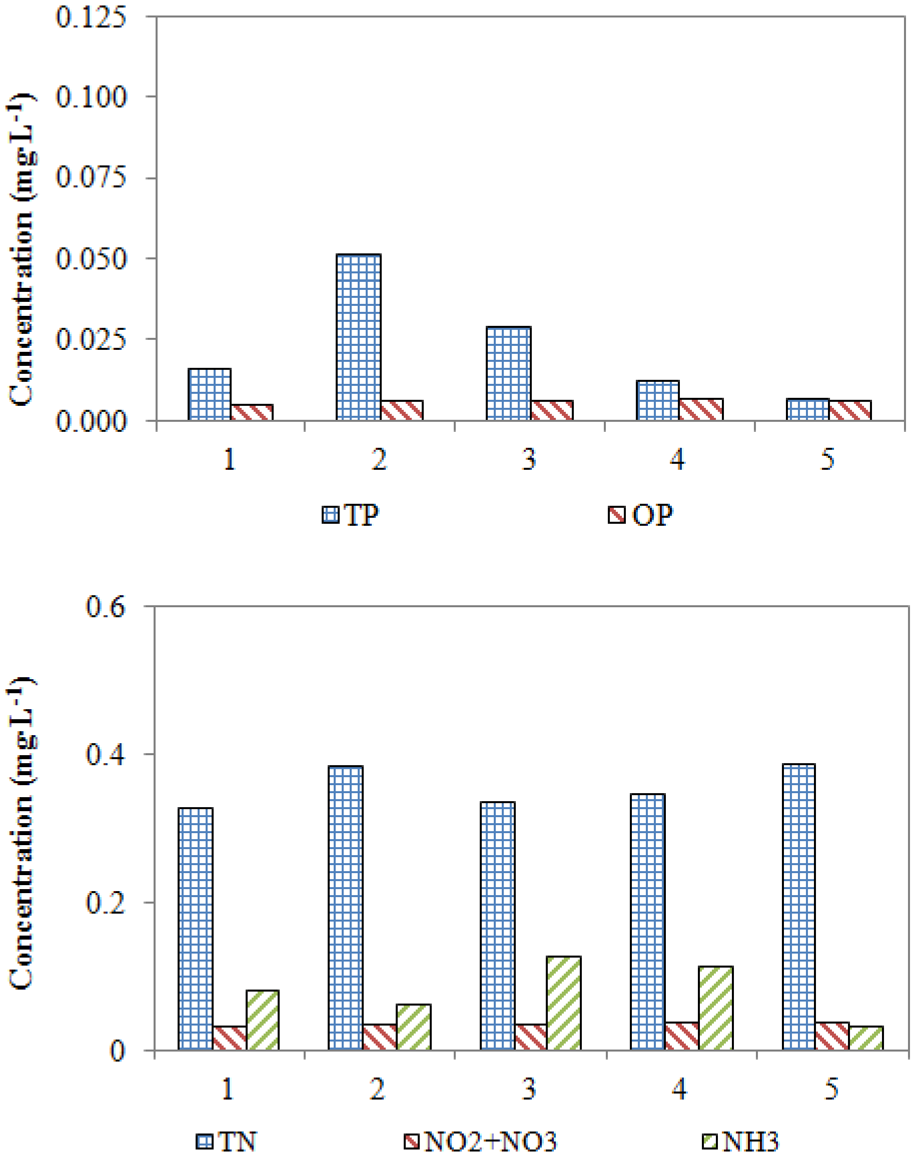
▧ NO2+NO3
▨ NH3

e) Aug-16-11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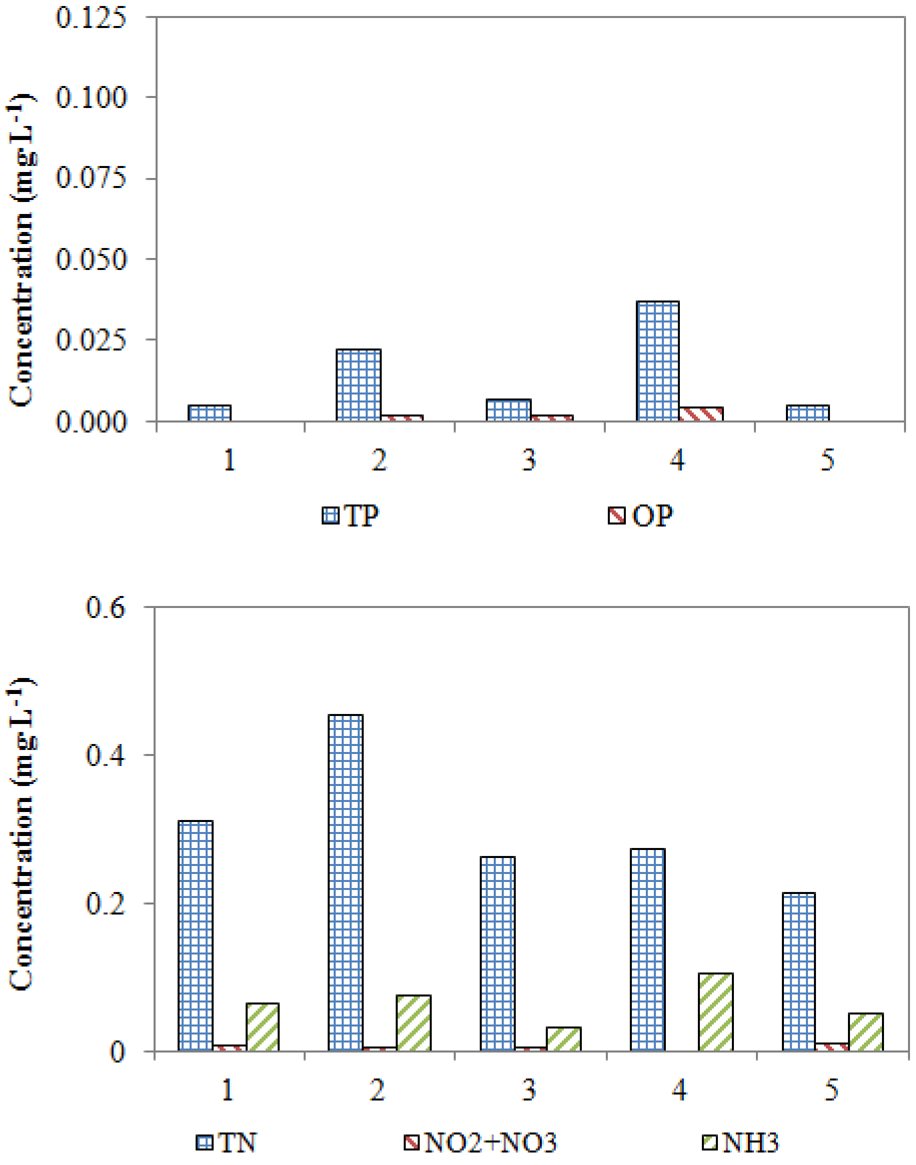
f) Sept-15-11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OP
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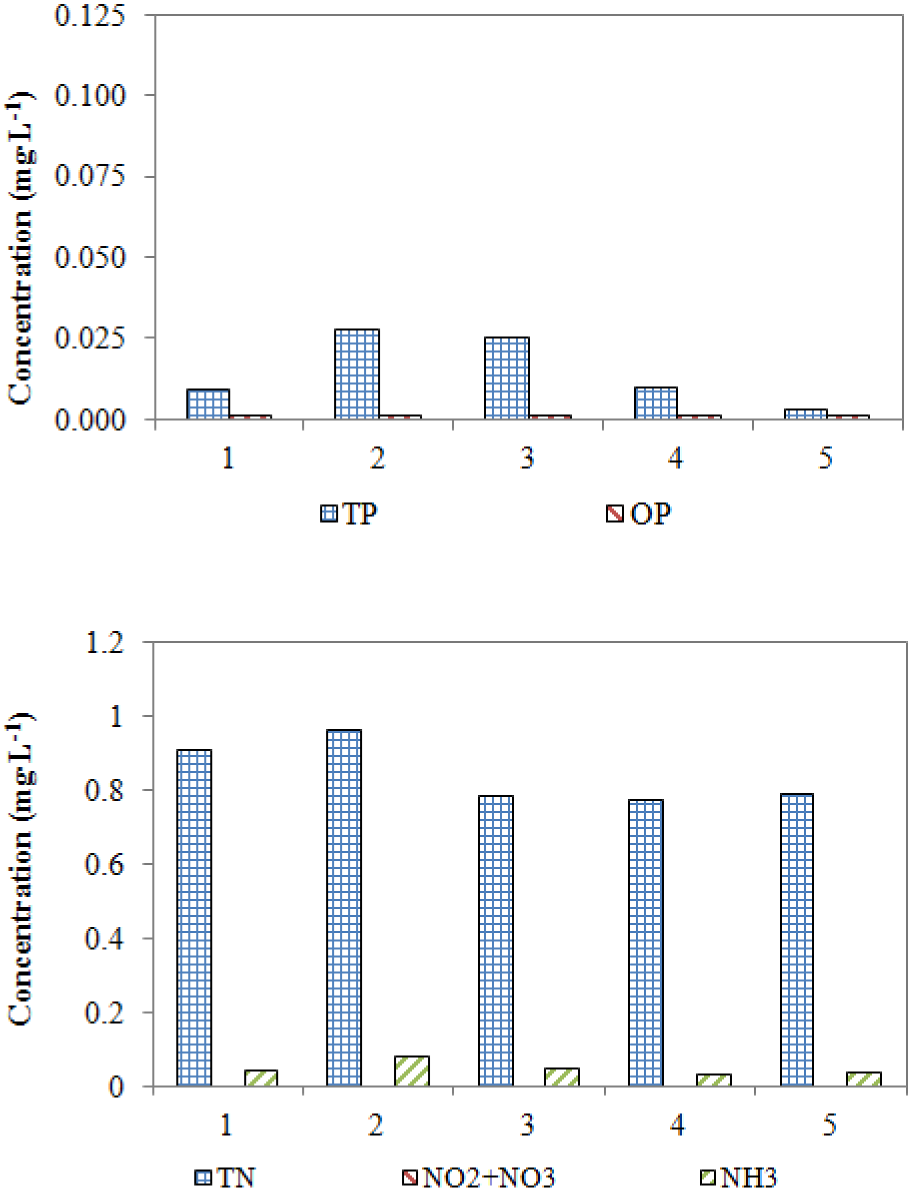
TN
NO2+NO3
NH3

g) Oct-17-11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OP
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0.4
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3
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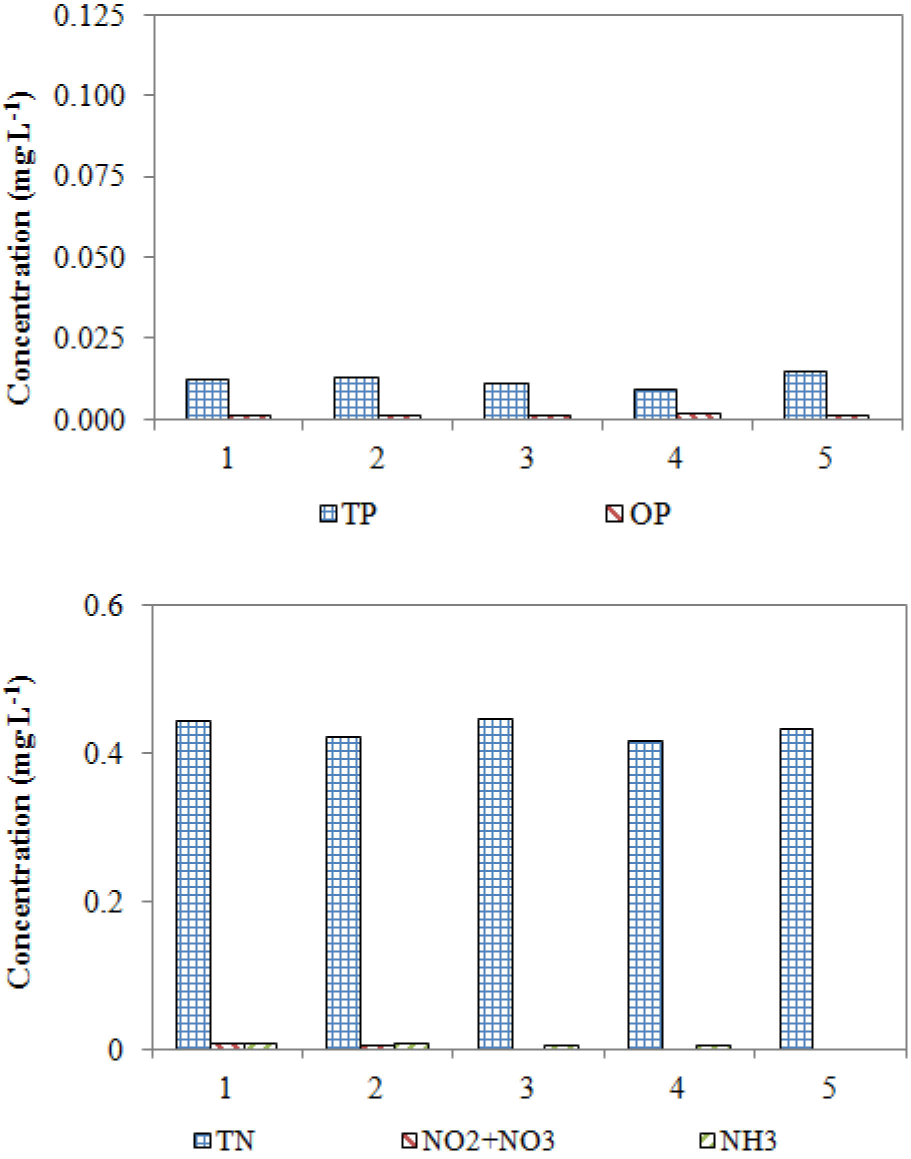
5
TN
NO2+NO3
NH3

h) Nov-16-11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TP
OP
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Concentration (mg L-1)
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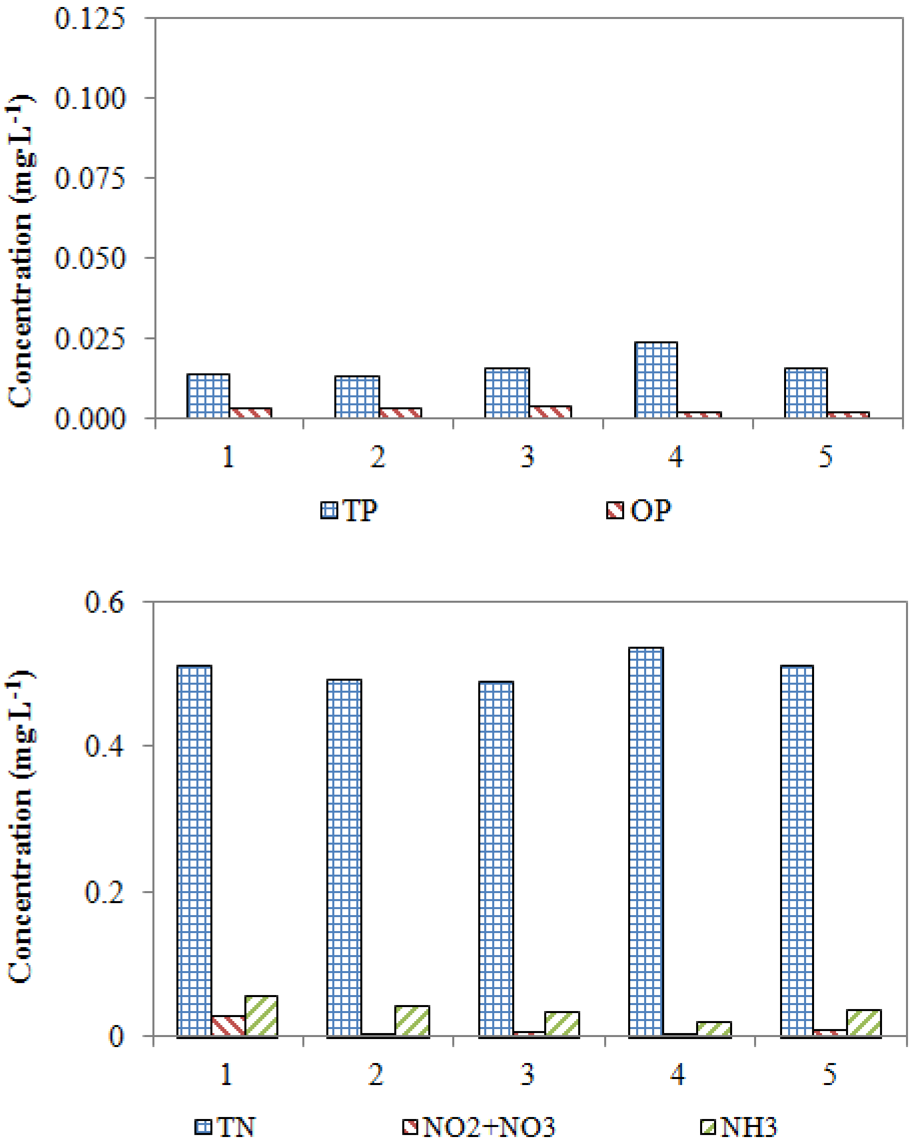
TN
NO2+NO3
NH3

i) Dec-16-11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OP
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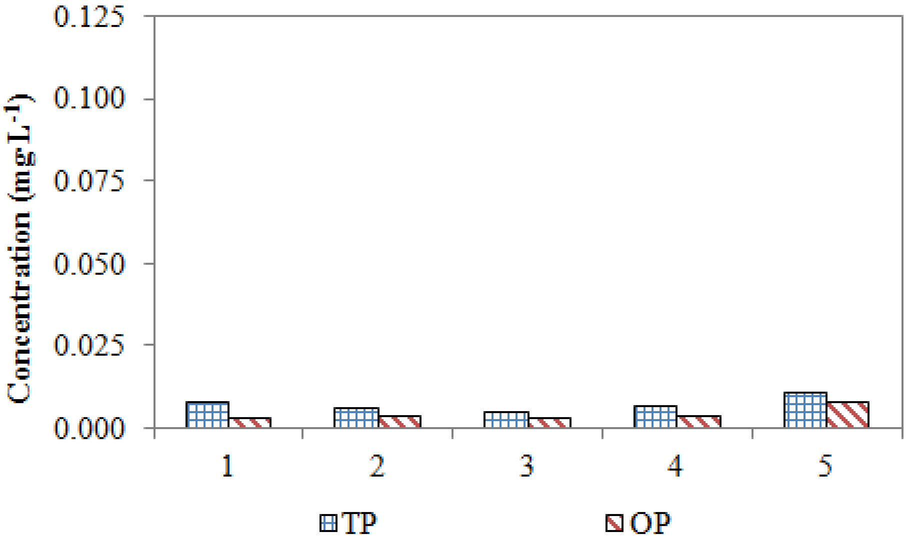
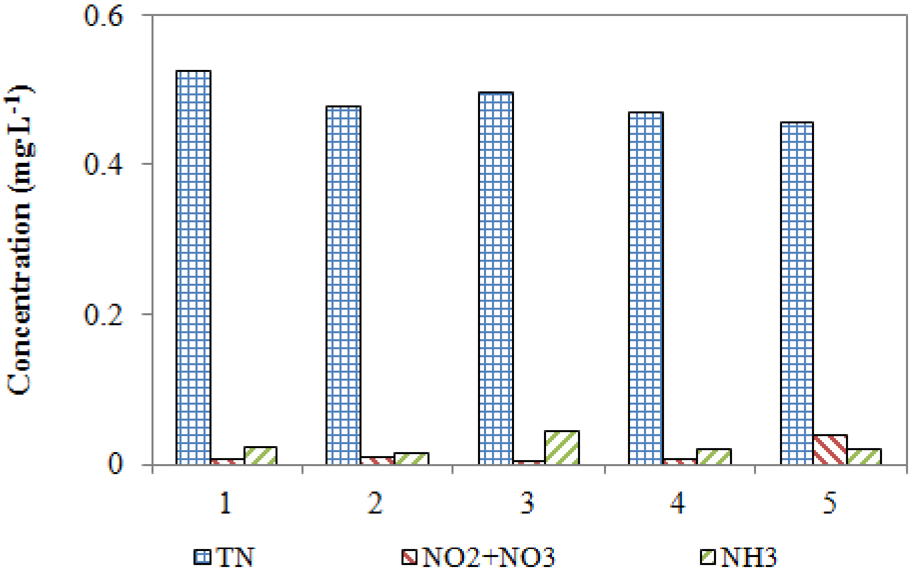
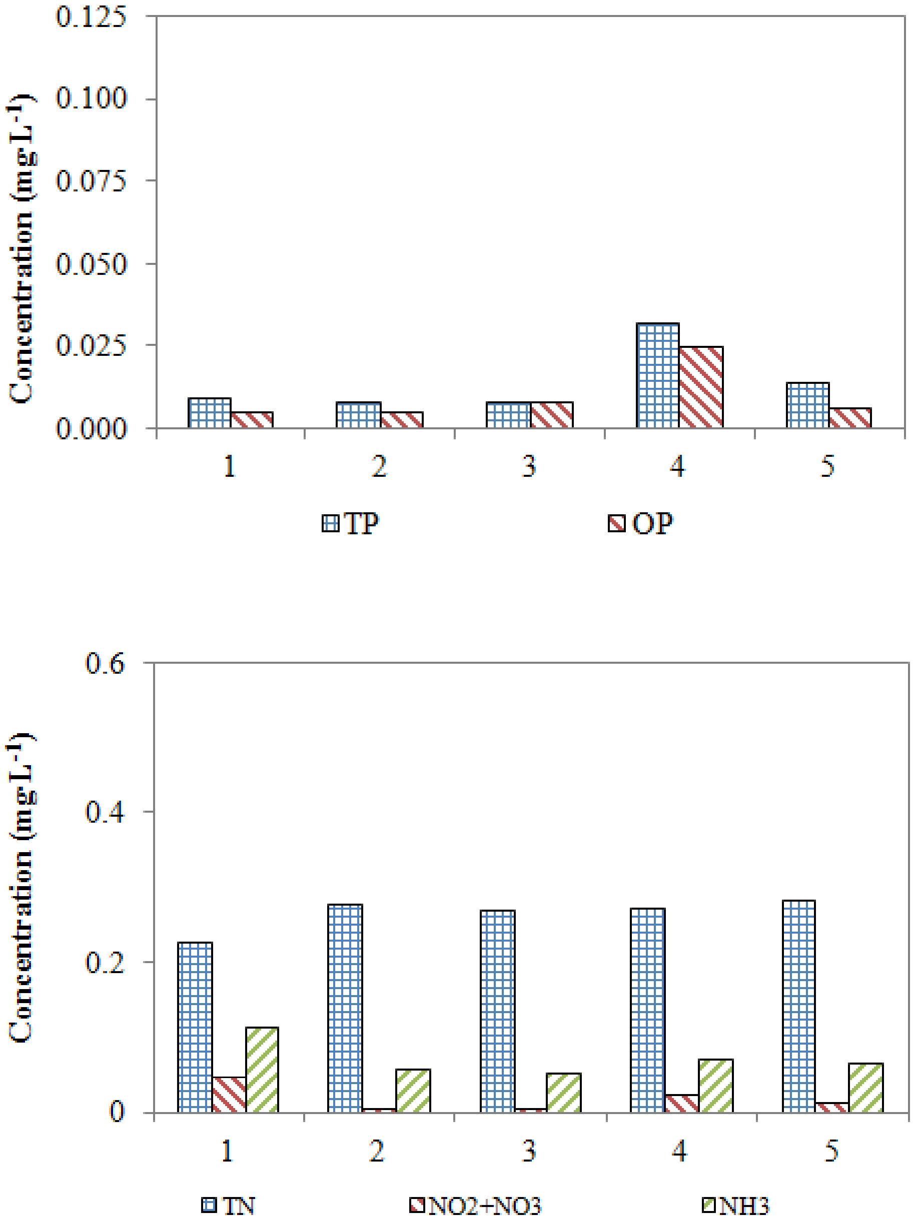
0.4
0.2
0
1
2
3
4
5
TN
NO2+NO3
NH3

j) Jan-18-12

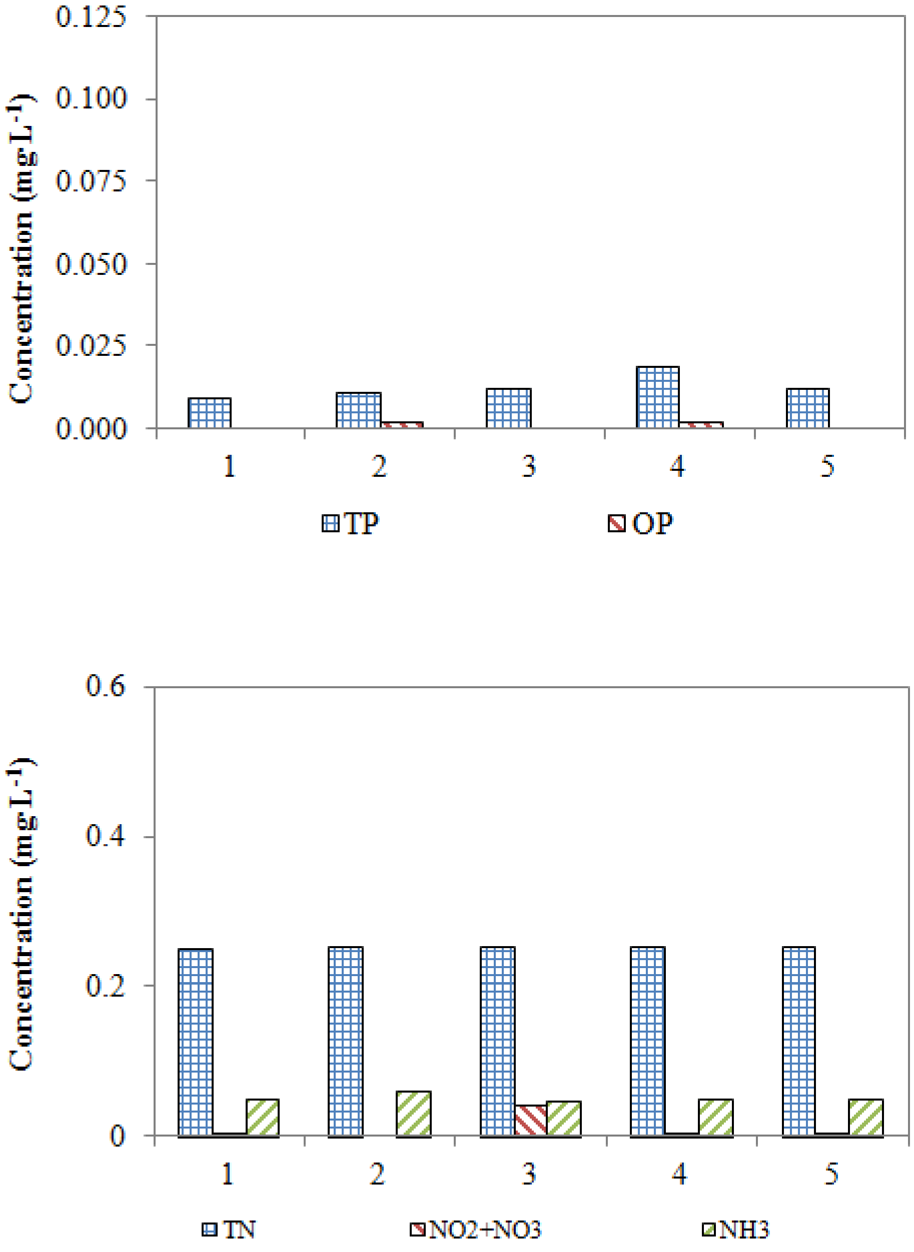

Concentration (mg L-1)
0.125
0.100
0.075
0.050
0.025
0.000
1
2
3
4
5
TP
OP


Concentration (mg L-1)
0.6
0.4
0.2
0
1
2
3
4
5
TN
NO2+NO3
NH3

k) Feb-14-12


Concentration (mg·L-1)
0.125
0.100
0.075
0.050
0.025
0.000
1
2
3
4
5
TP
OP
Concentration (mg·L-1)
0.6
0.4
0.2
0
1
2
3
4
5
TN
NO2+NO3
NH3

l) Mar-19-12



m) Apr-18-12

Figure 47: Monthly-based results of spatial nutrients distribution

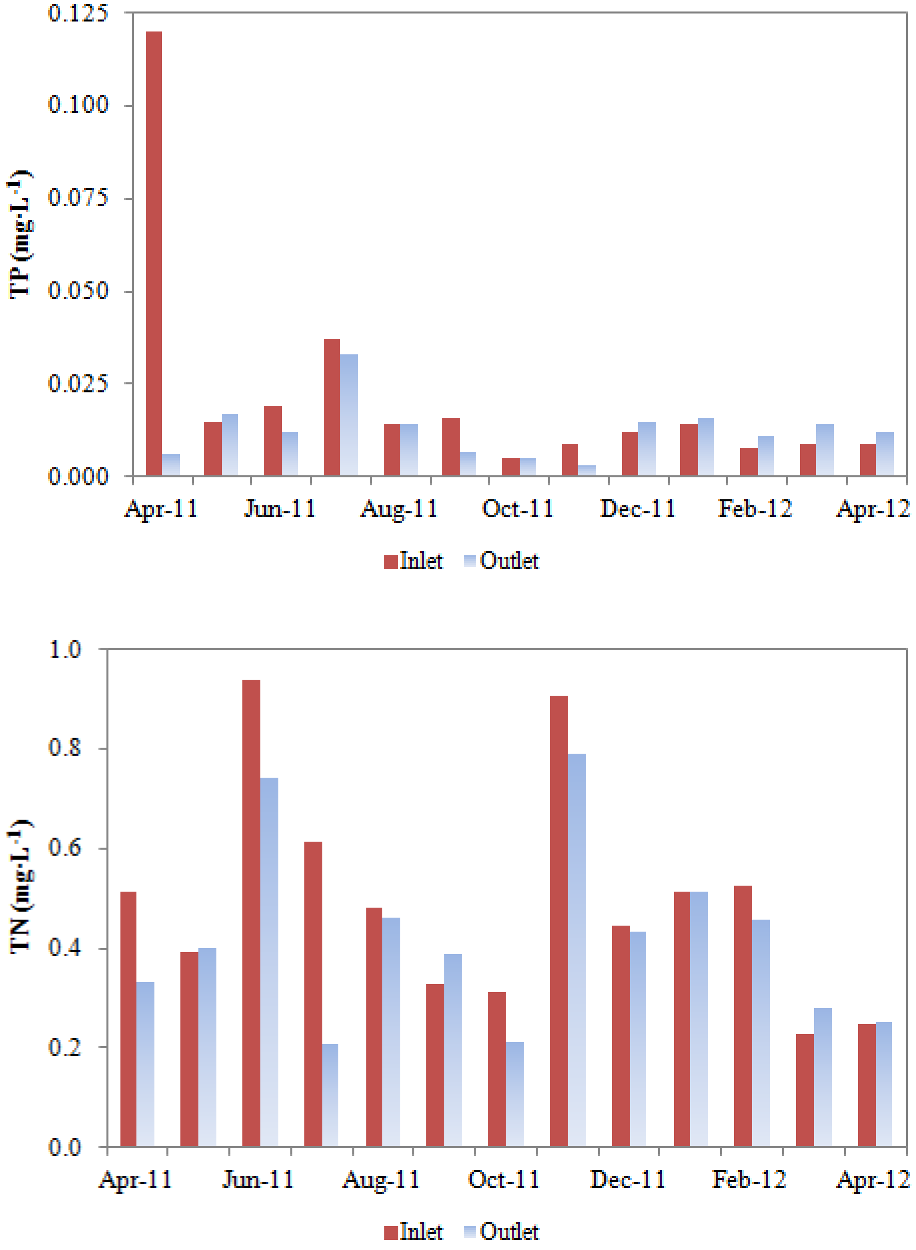


Figure 48: Time-series monthly-based nutrients results

Table 34: Nutrients concentration for non-storm events during post-analysis at Pond 4M ($mg.L^{-1}$).

Date	TP		OP		TN		NO_2+NO_3		NH_3	
	In	Out	In	Out	In	Out	In	Out	In	Out
Apr-11	0.120	0.006	0.053	0.002	0.514	0.332	0.019	0.010	0.034	0.034
May-11	0.015	0.017	0.004	0.003	0.393	0.401	0.006	0.003	0.037	0.040
Jun-11	0.019	0.012	0.005	0.004	0.938	0.743	0	0.001	0.080	0.021
Jul-11	0.037	0.033	0.003	0.002	0.613	0.208	0.008	0.004	0.151	0.098
Aug-11	0.014	0.014	0.003	0.003	0.480	0.461	0.009	0.012	0.345	0.295
Sep-11	0.016	0.007	0.005	0.006	0.328	0.388	0.033	0.038	0.082	0.033
Oct-11	0.005	0.005	0	0	0.311	0.213	0.008	0.011	0.066	0.050
Nov-11	0.009	0.003	0.001	0.001	0.908	0.791	0.003	0.003	0.040	0.036
Dec-11	0.012	0.015	0.001	0.001	0.444	0.434	0.007	0.001	0.007	0.003
Jan-12	0.014	0.016	0.003	0.002	0.512	0.513	0.03	0.009	0.056	0.039
Feb-12	0.008	0.011	0.003	0.008	0.525	0.455	0.006	0.039	0.023	0.020
Mar-12	0.009	0.014	0.005	0.006	0.226	0.281	0.046	0.011	0.111	0.064
Apr-12	0.009	0.012	0	0.001	0.249	0.252	0.002	0.004	0.049	0.049
Average	0.022	0.013	0.007	0.003	0.495	0.421	0.014	0.011	0.083	0.060
CRP, %	42.5		54.7		15.0		17.5		27.7	

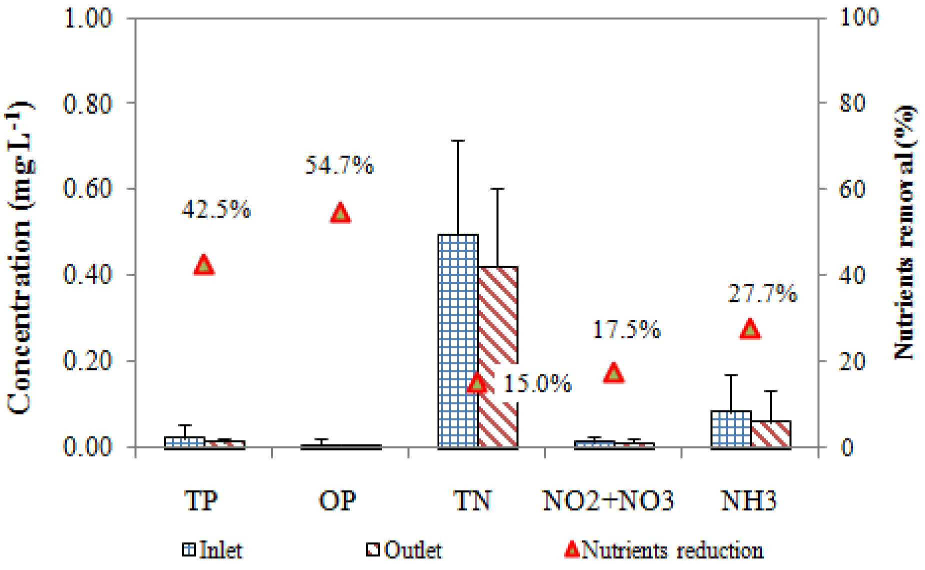
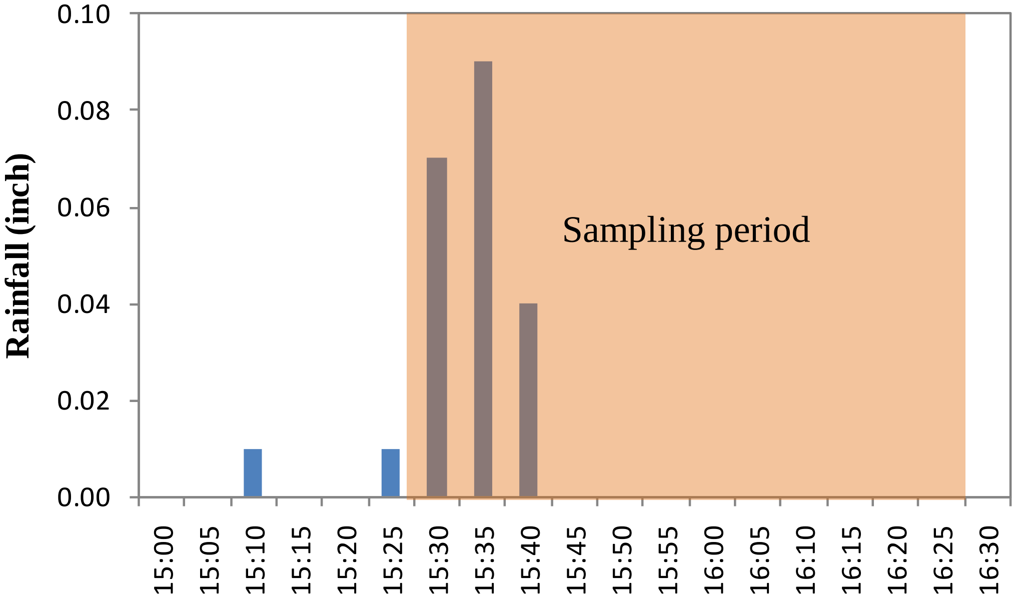


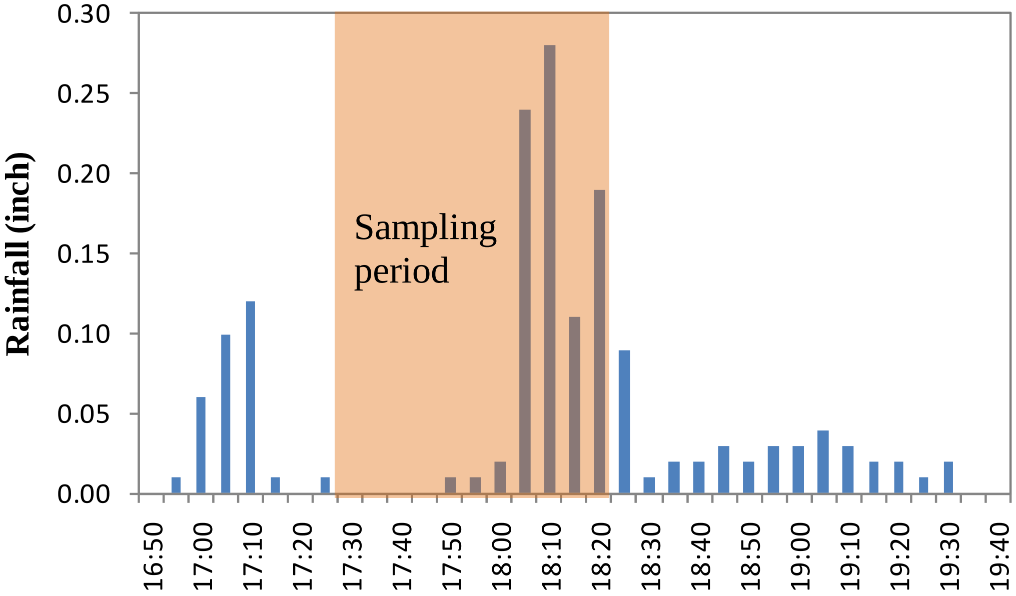
Figure 49: Nutrients reduction of the average monthly-based nutrients results

4.4.1.1.2.2 Event -based

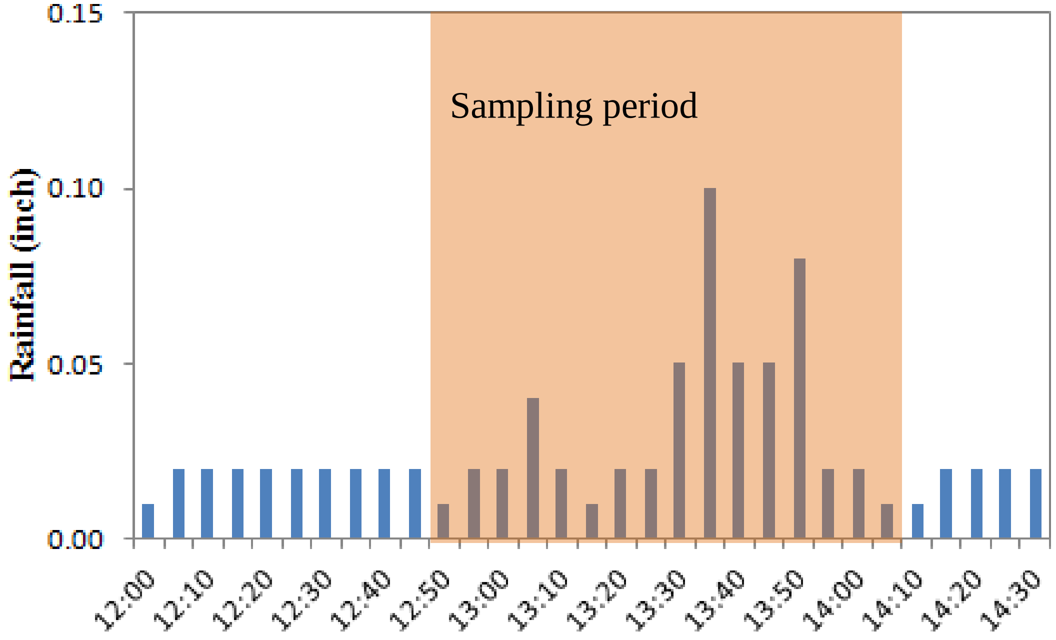
In addition to the monthly-based analysis, six storm events were monitored on May 14, June 24, October 8, October 29, October 31, December 11, 2011, and February 22, 2012. Figure 50 presents the storm hydrograph and sampling period for these storm events. Figure 51 displays that the variability of TN and TP over time was generally constant during a runoff event and the event-based temporal nutrient trend was highly consistent with the storm hydrograph pattern. In addition, by comparing those figures, the lag time between them was found to be about 15 minutes, which means that for Pond 4M the highest influent nutrient concentration appears approximately 15 minutes after the peak rainfall. As for the spatial nutrients distribution of both storm events (figure 52), relatively low concentration was often observed in location 4, which was the furthest sampling location from the inlet. The only exception occurred on October 8 due to an overflow. Because of the short duration of the storm on December 11, the sampling period did not cover the time when the pond received the peak volume of runoff (Fig. 50f). Thus, the event-based temporal nutrients distribution looked quite stable during the sampling period (Fig. 51f). As for the event-based spatial nutrients distribution, it was easier for the TP concentration to be influenced by the stormwater runoff, as it fluctuated throughout different locations in the pond (Fig. 51g).



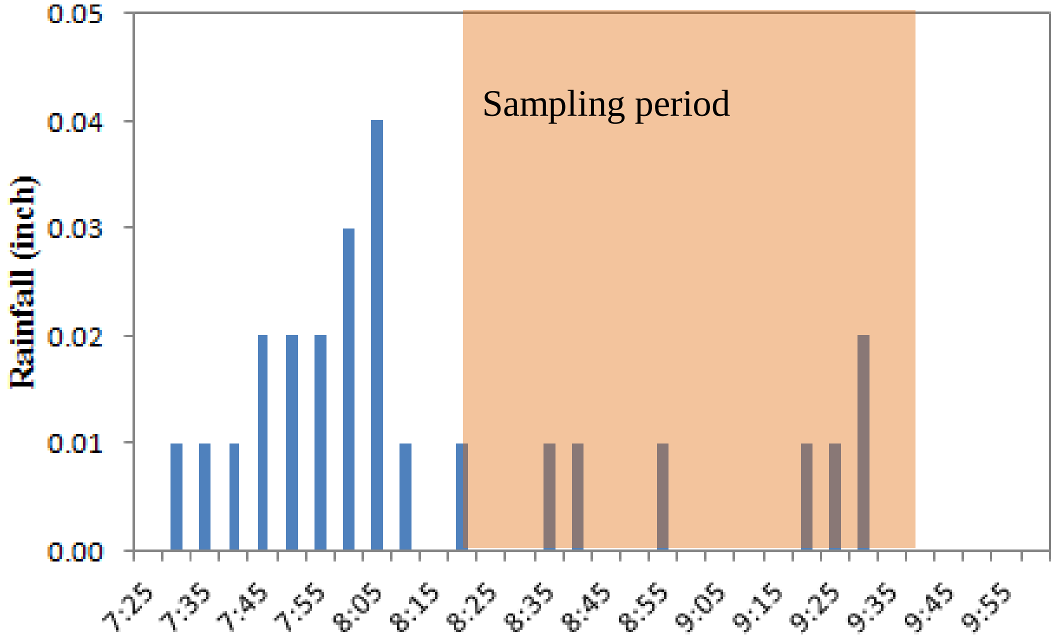
a) May-14-11



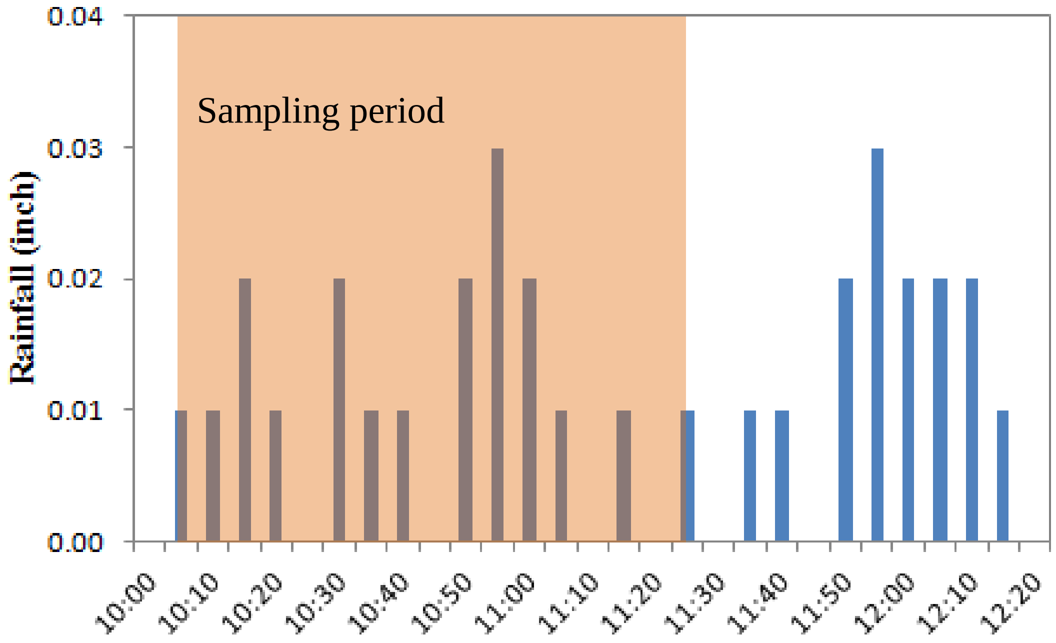
b) June-24-11



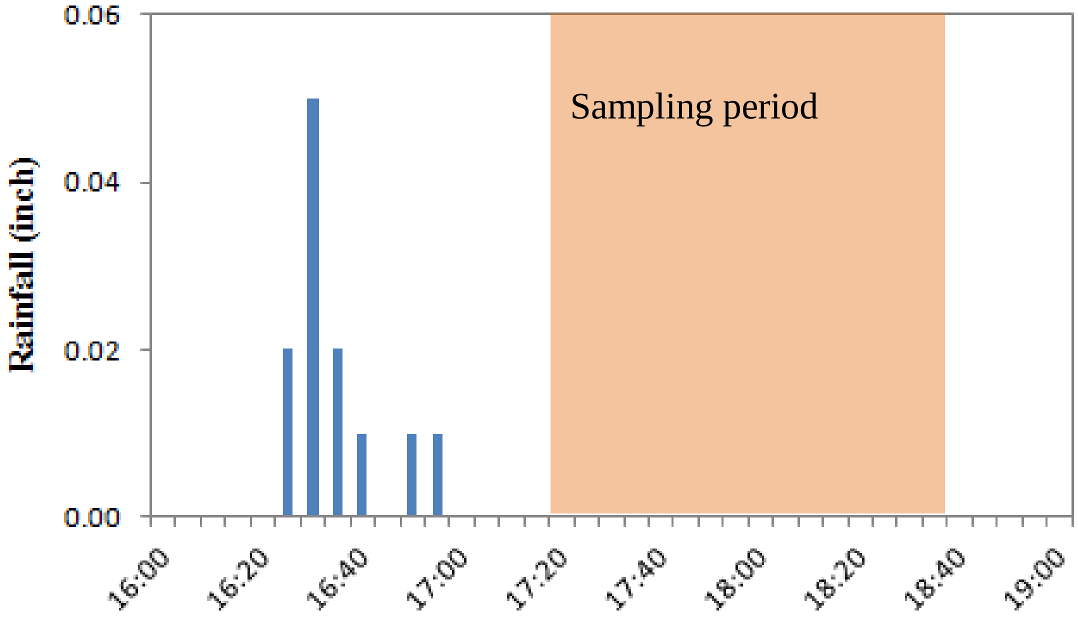
c) Octorber-8-11



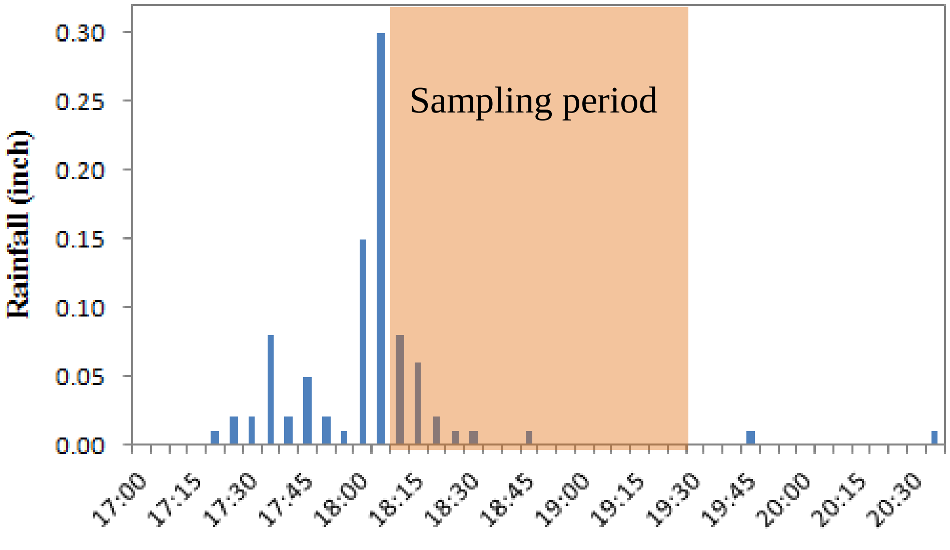
d) Oct-29-11



e) Oct-31-11

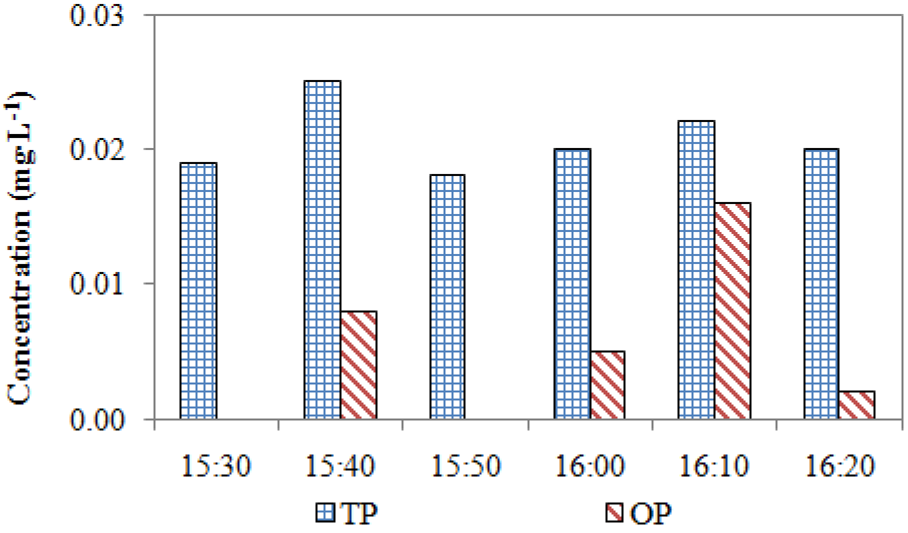


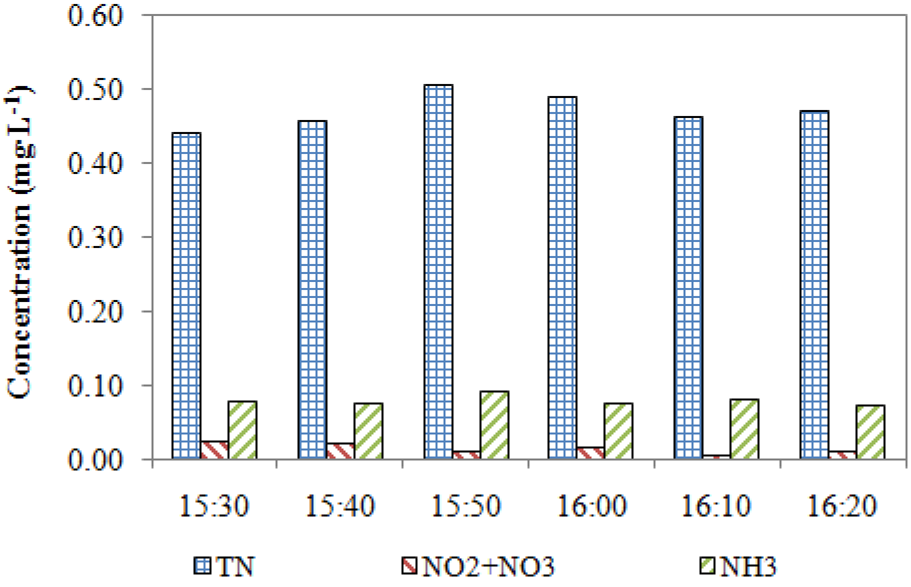
f) Dec-11-11



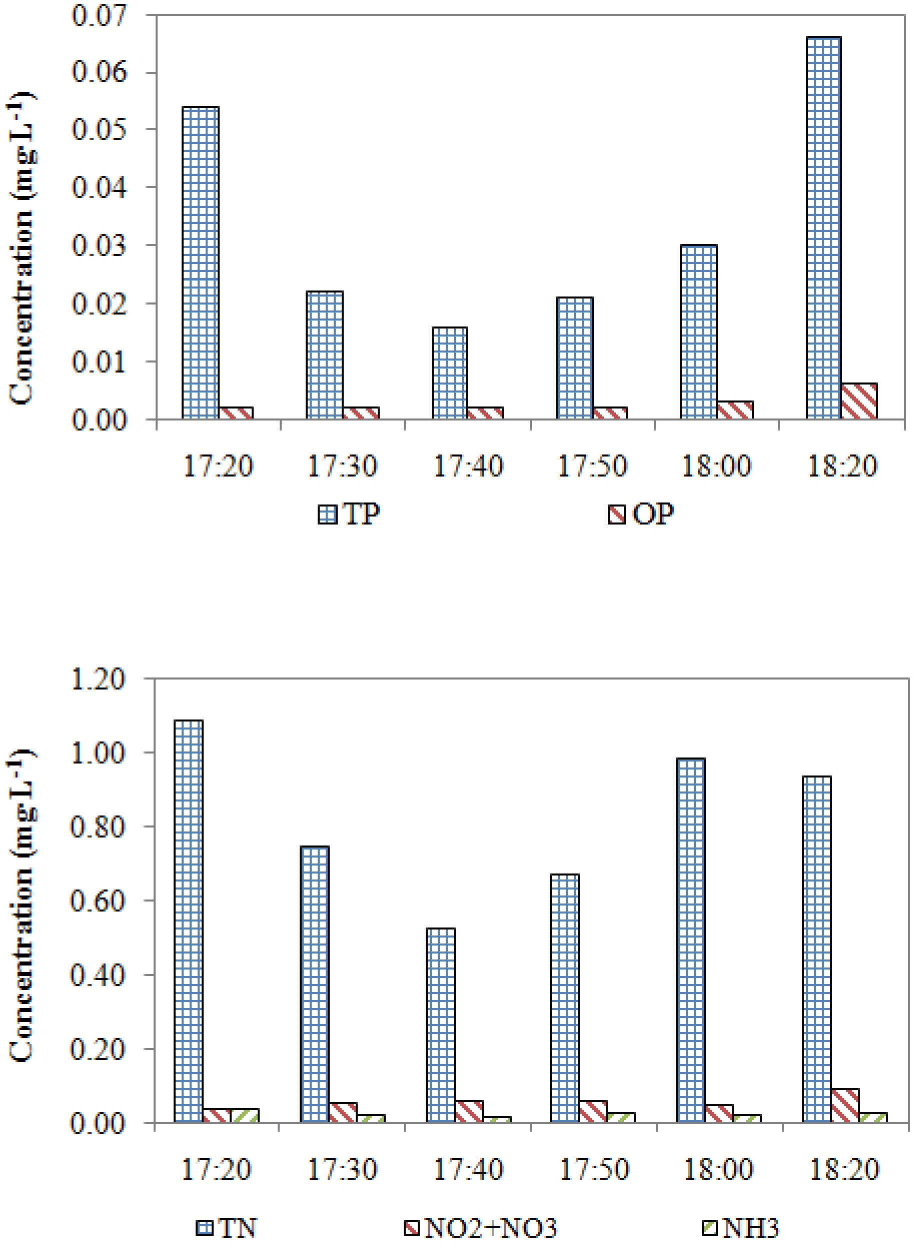
g) Feb-22-12

Figure 50: Storm hydrograph and sampling period

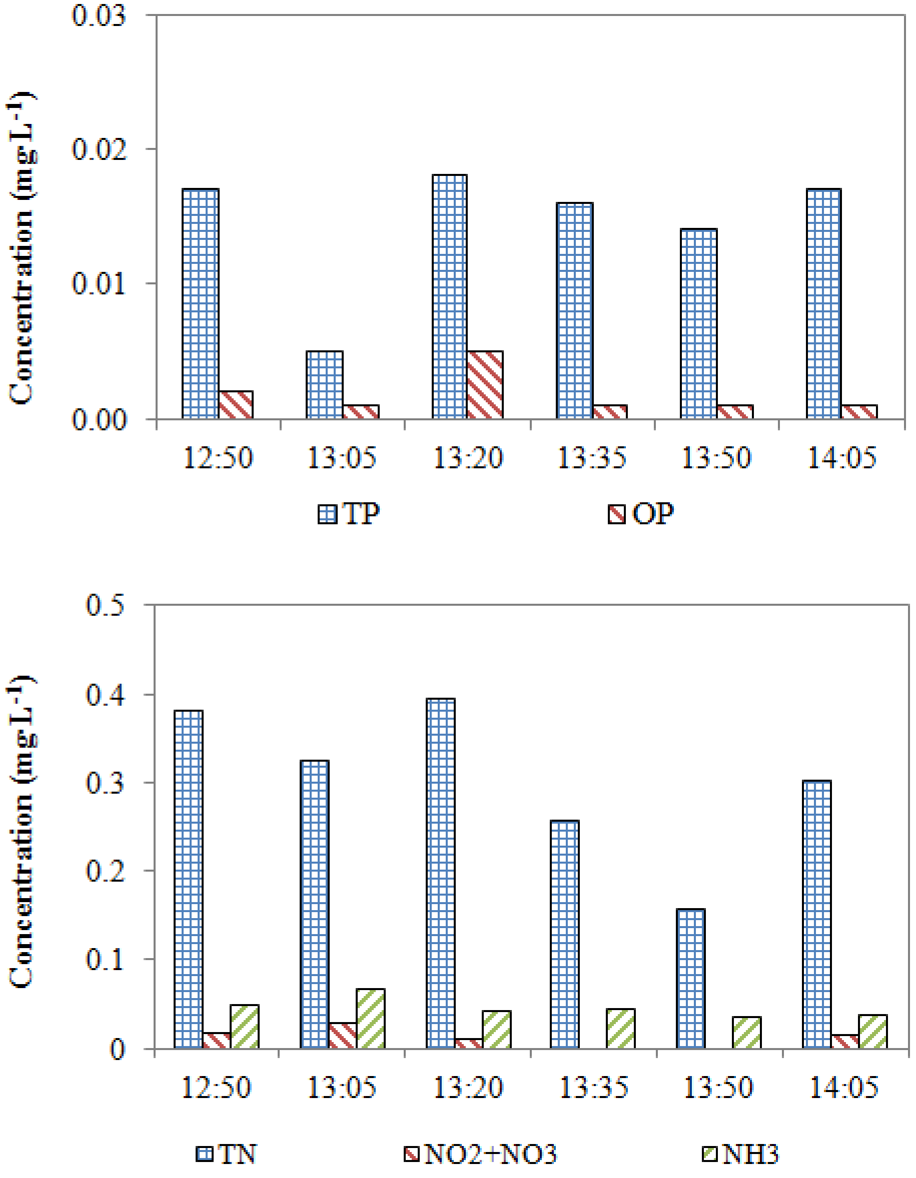

0.03
0.02
0.01
0.00
Concentration (mg·L-1)
15:30
15:40
15:50
16:00
16:10
16:20
TP
OP


0.60
0.50
0.40
0.30
0.20
0.10
0.00
Concentration (mg·L-1)
15:30
15:40
15:50
16:00
16:10
16:20
TN
NO2+NO3
NH3

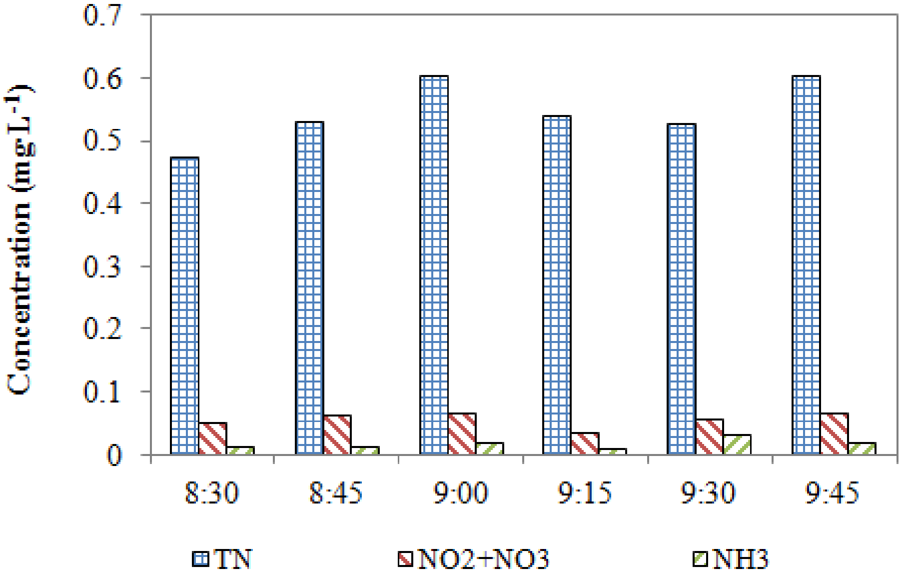
a) May-14-11

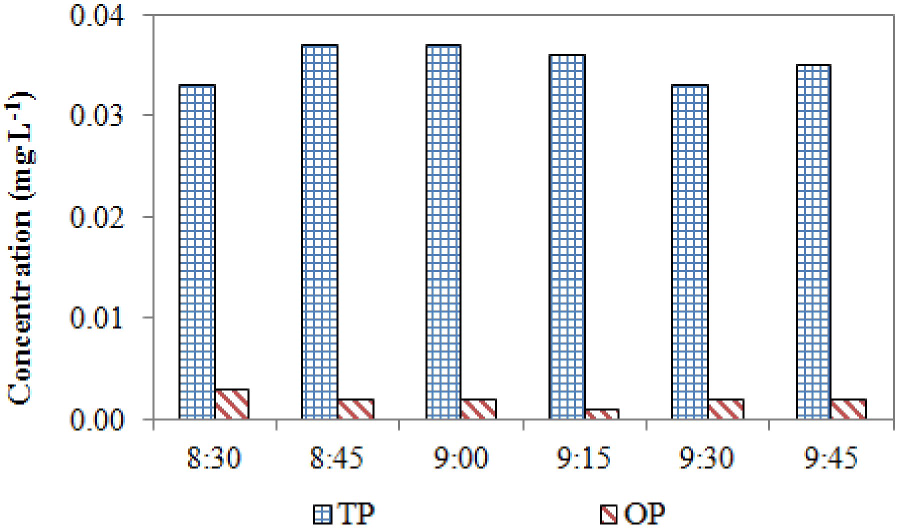

0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Concentration (mg L-1)
17:20
17:30
17:40
17:50
18:00
18:20
TP
OP
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Concentration (mg L-1)
17:20
17:30
17:40
17:50
18:00
18:20
TN
NO2+NO3
NH3

b) June-24-11

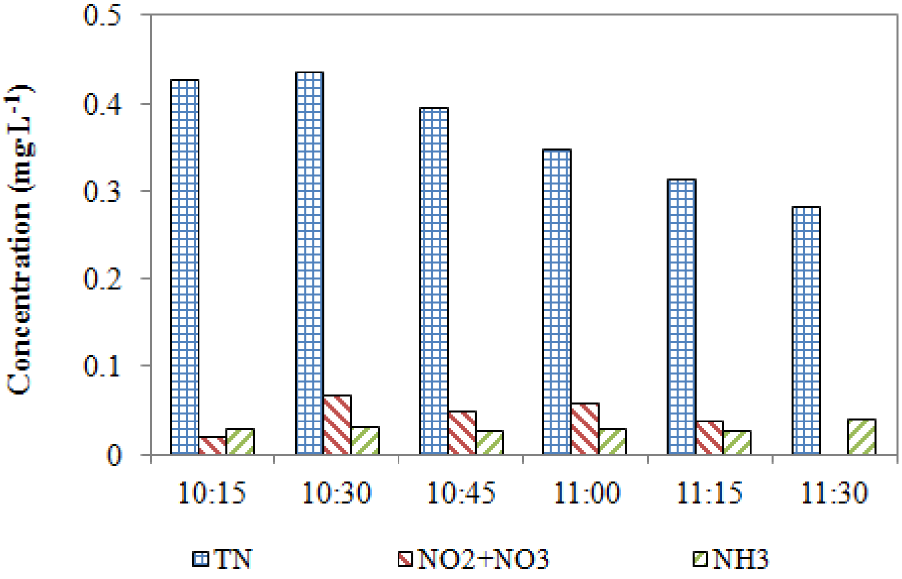


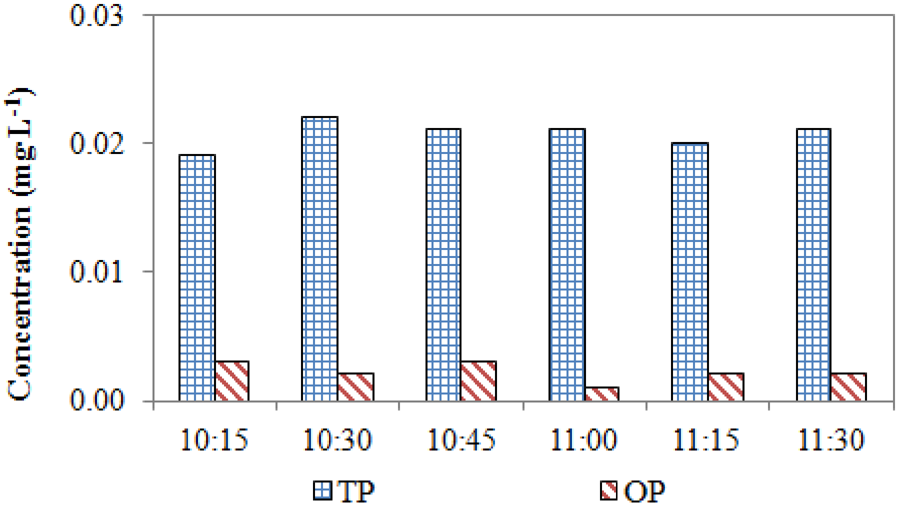
c) Octorber-8-11


Concentration (mg L-1)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
8:30
8:45
9:00
9:15
9:30
9:45
TN
NO2+NO3
NH3

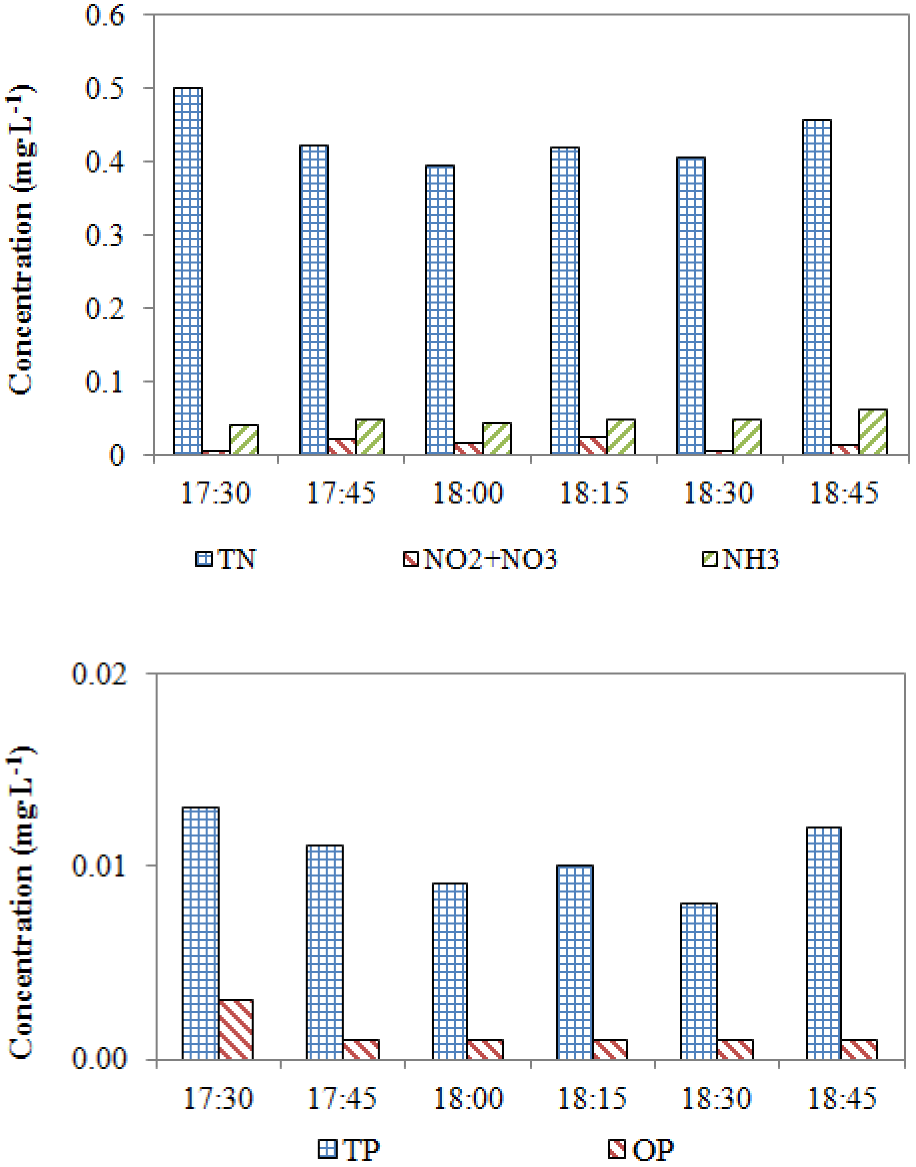

Concentration (mg L-1)
0.04
0.03
0.02
0.01
0.00
8:30
8:45
9:00
9:15
9:30
9:45
TP
OP

d) Oct-29-11

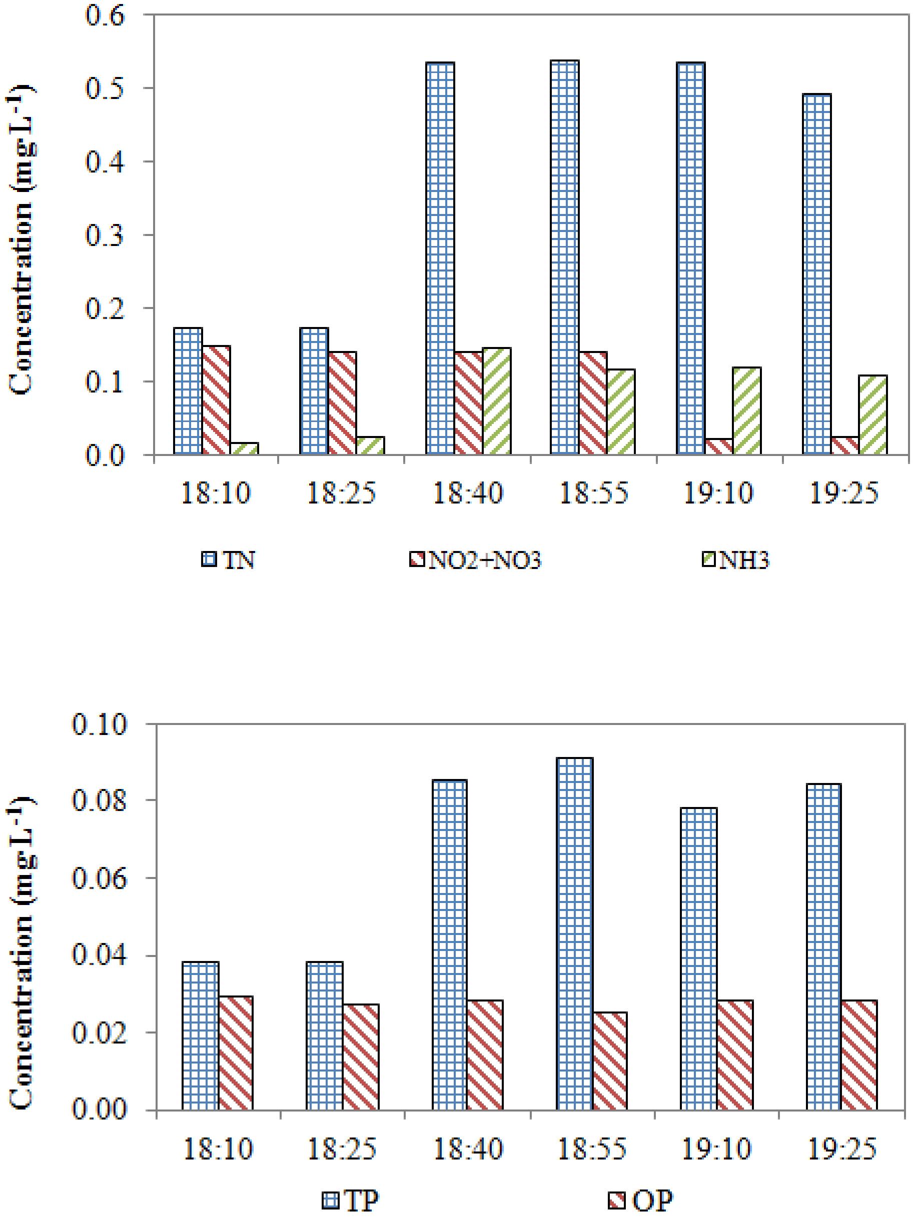

Concentration (mg L-1)
0.5
0.4
0.3
0.2
0.1
0
10:15
10:30
10:45
11:00
11:15
11:30
TN
NO2+NO3
NH3


Concentration (mg L-1)
0.03
0.02
0.01
0.00
10:15
10:30
10:45
11:00
11:15
11:30
TP
OP

e) Oct-31-11

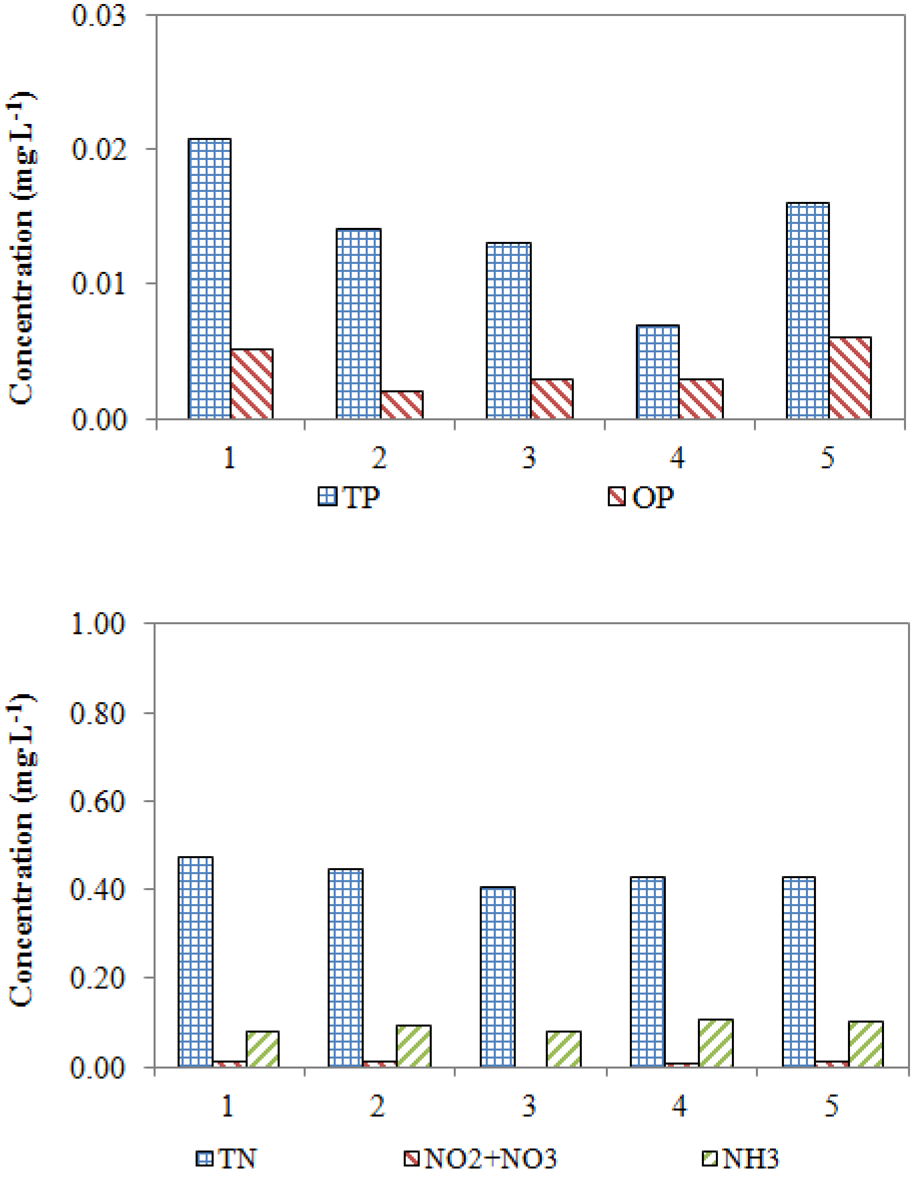


f) December-11-11

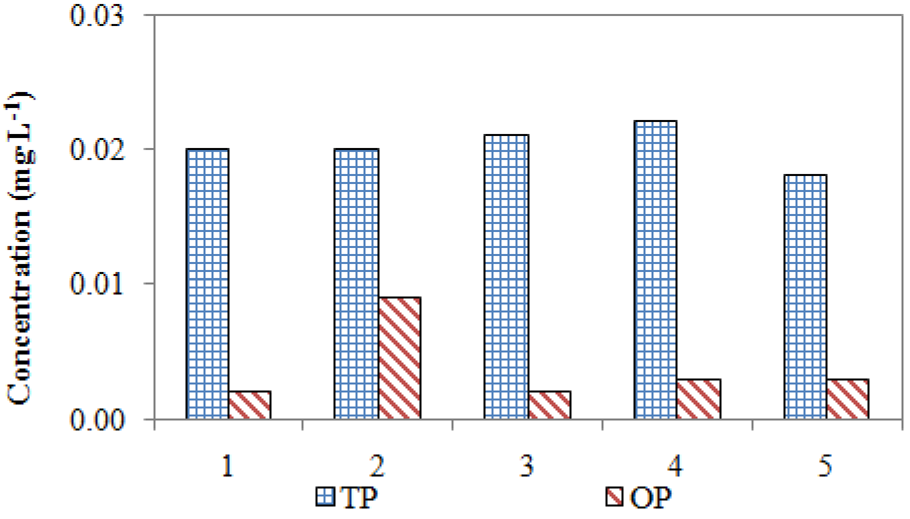


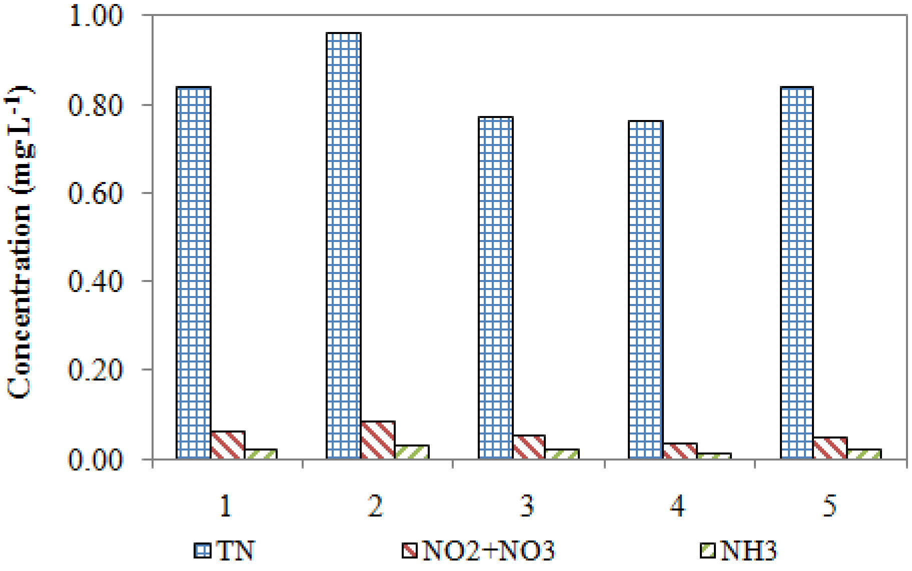
g) February-22-12

Figure 51: Event-based temporal nutrients distribution

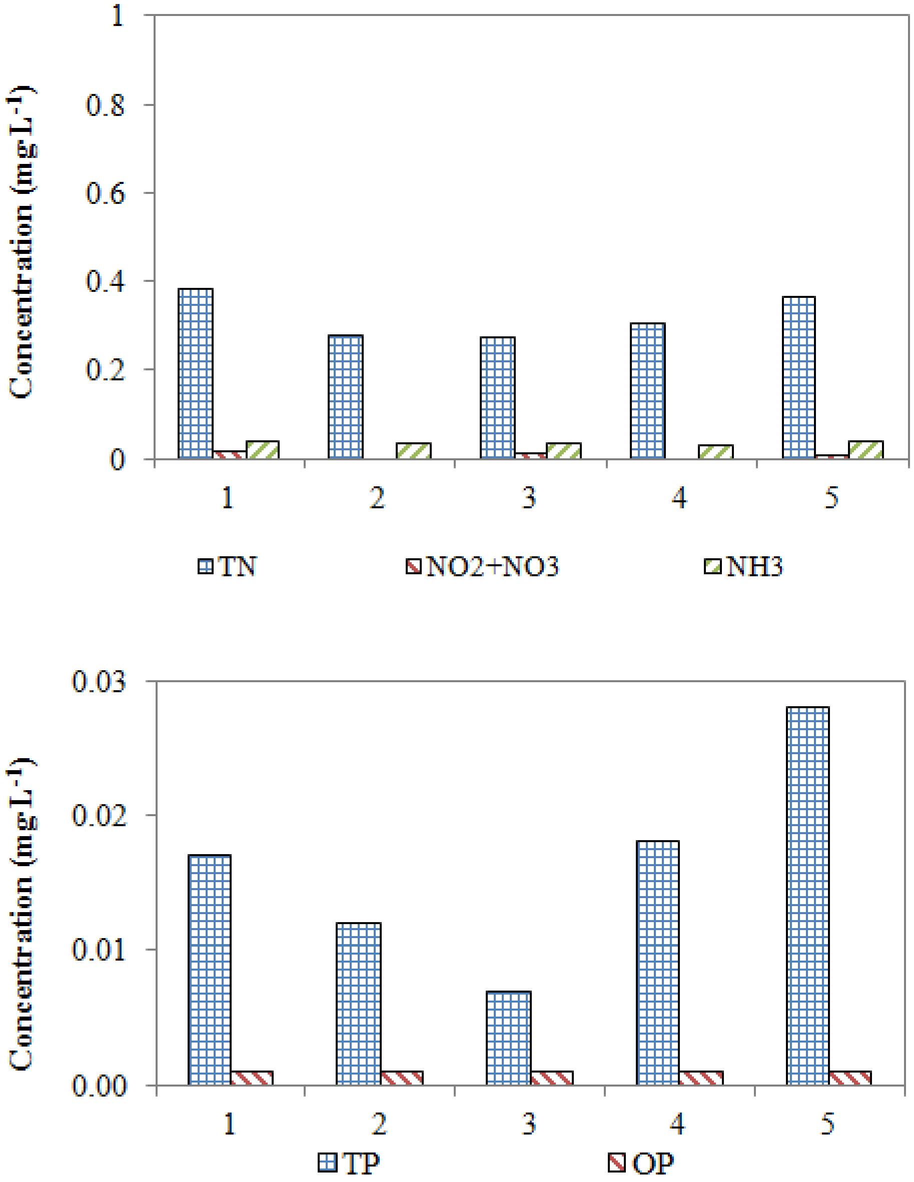

Concentration (mg L^{-1})
0.03
0.02
0.01
0.00
1
2
3
4
5
TP
OP
Concentration (mg L^{-1})
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
TN
NO2+NO3
NH3

a) May-14-11

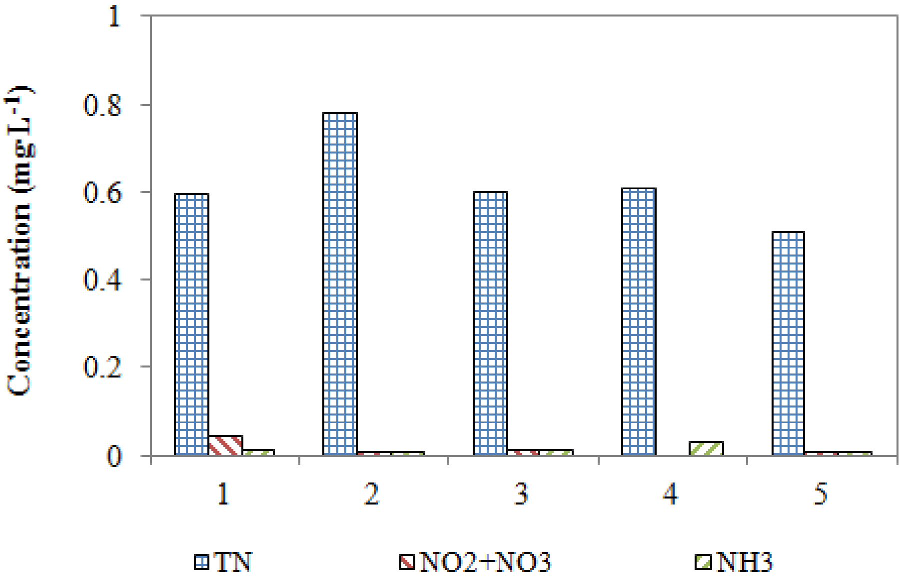

0.03
0.02
0.01
0.00
Concentration (mg L-1)
1
2
3
4
5
TP
OP

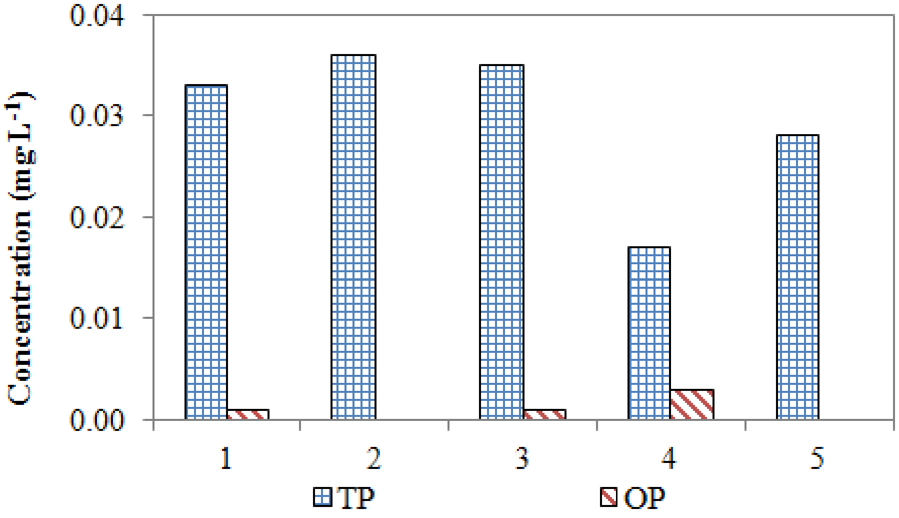

1.00
0.80
0.60
0.40
0.20
0.00
Concentration (mg L-1)
1
2
3
4
5
TN
NO2+NO3
NH3

b) June-24-11

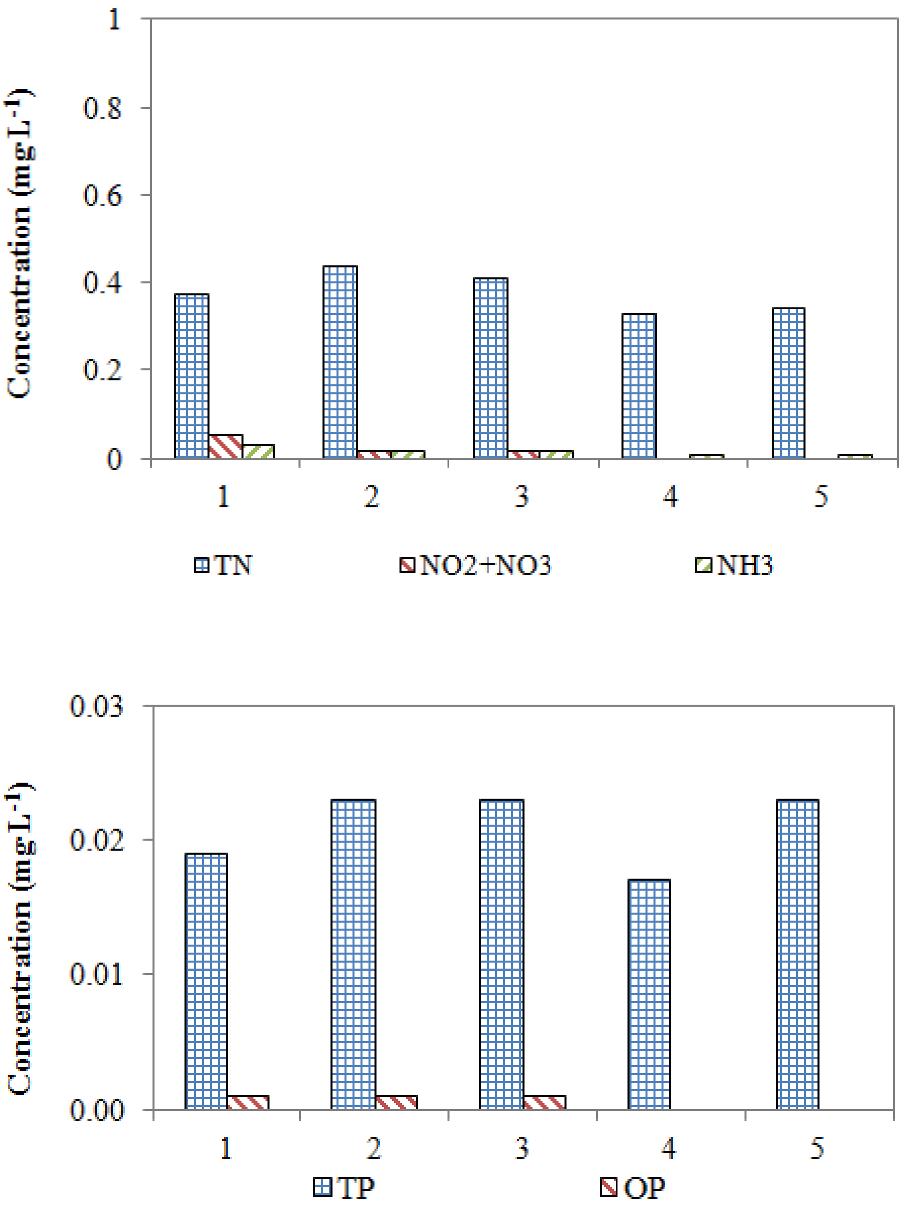


c) October-8-11

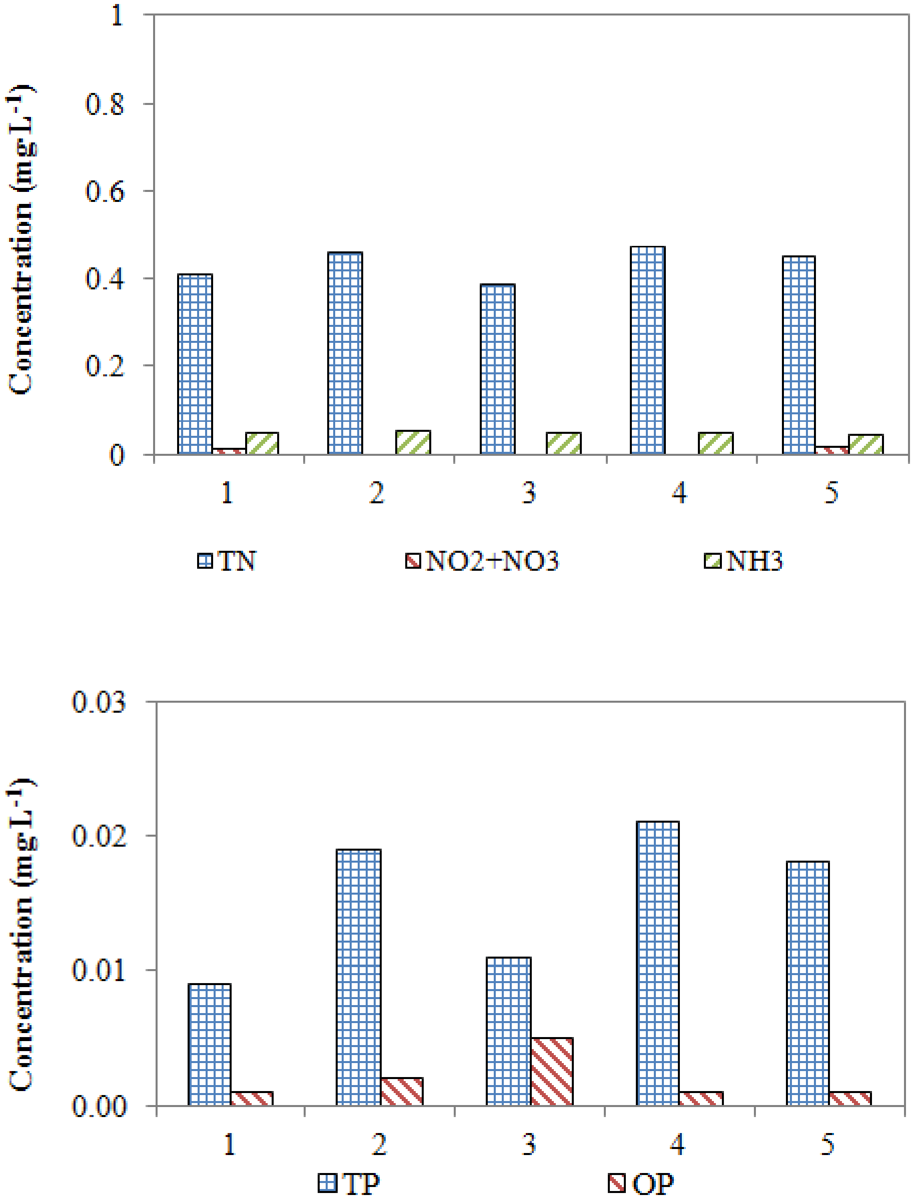




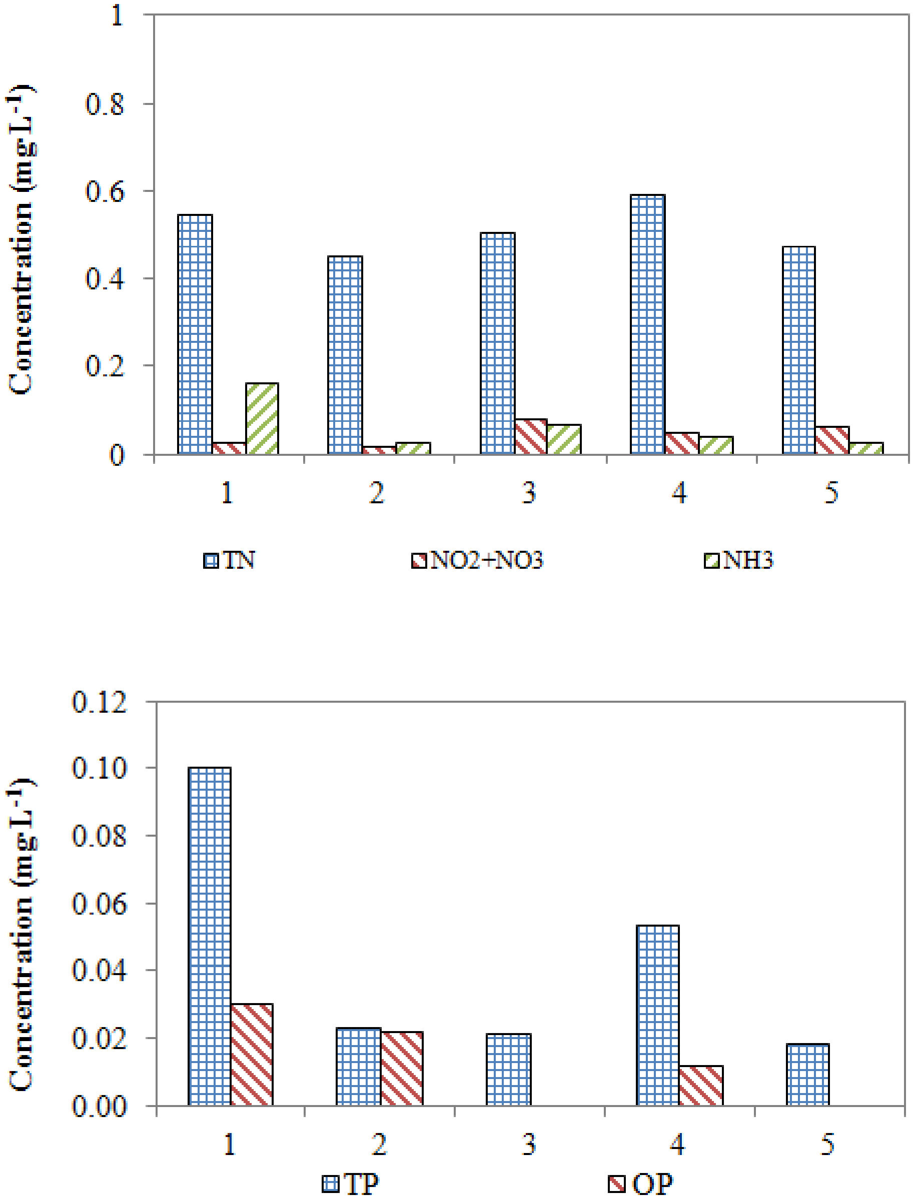
d) October-29-11



e) October-31-11



f) December-11-11



g) February-22-12

Figure 52: Event-based spatial nutrients distribution

4.4.1.2 Pond 5

4.4.1.2.1 Pre-analysis

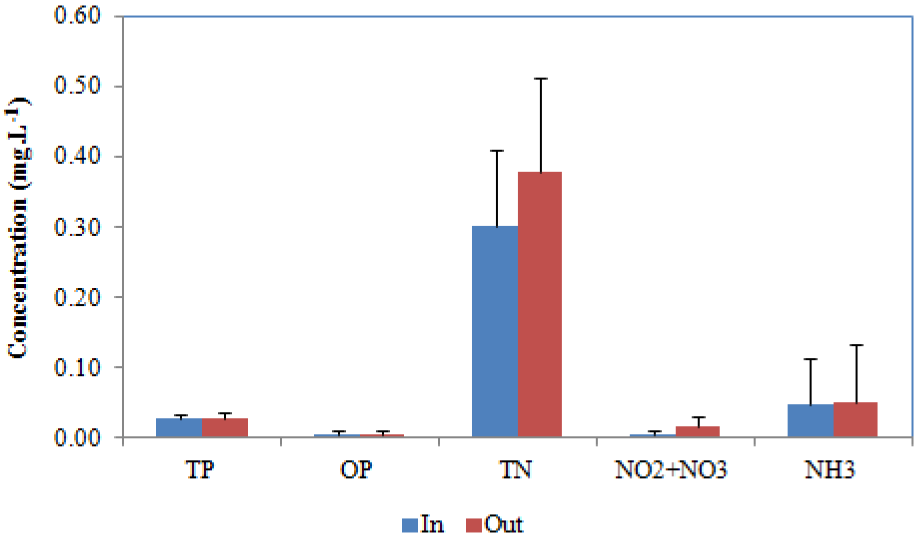
The pre-analysis period was defined as the study period before the deployment of the floating wetland. Within the pre-analysis period, three storm and three non-storm events were investigated in the first half of July to determine the background of this pond. The CRP results for nutrient levels at the inlet and outlet (Figure 55 and Table 36) showed that for storm events, the nutrient levels for TP and OP in in-flow and out-flow were almost the same (Table 35). Three forms of nitrogen in the out-flow were even higher than those in the in-flow. Low concentrations of NH_3 and NO_2+NO_3 indicated that the dominant N form was organic nitrogen. Yet, the smaller difference in TN levels between the inlet and outlet, along with a positive CRP of TP, OP, NH_3, and nitrite-nitrogen + nitrate-nitrogen (NO_2-N +NO_3-N), indicated that a moderate self-purification occurred in Pond 5. In non-storm events, organic nitrogen was partially converted to NH_3, which led to the increase of NO_2+NO_3 due to the aeration by the fountain, when compared to the counterparts in storm events.

Table 35: Nutrients concentration for storm events during pre-analysis (mg.L^{-1}).

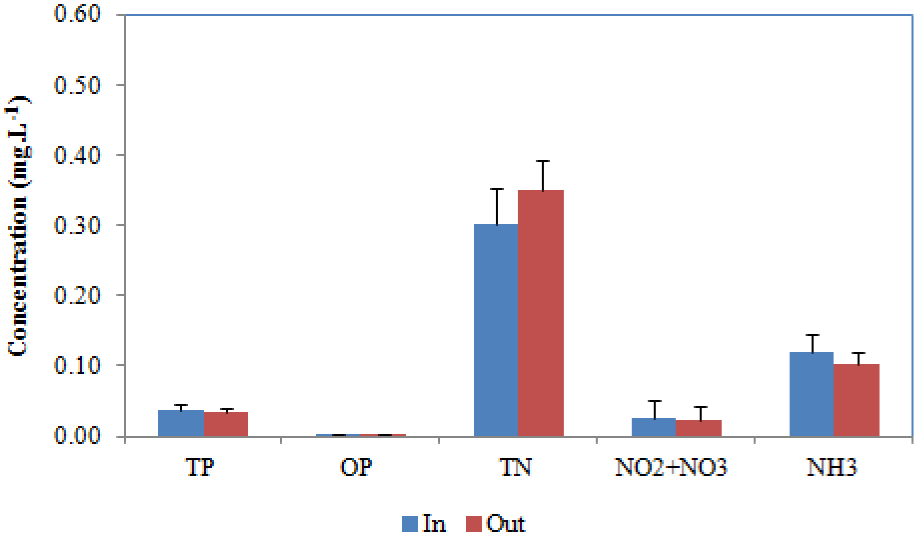
Date	TP		OP		TN		NO_2+NO_3		NH_3	
	In	Out	In	Out	In	Out	In	Out	In	Out
7/2/11	0.032	0.034	0.008	0.008	0.223	0.332	0.011	0.032	0.012	0.009
7/7/11	0.030	0.032	0.009	0.009	0.427	0.528	0.003	0.017	0.008	0.001
7/12/11	0.023	0.016	0.001	0.001	0.251	0.272	0.005	0.003	0.123	0.146
Average	0.028	0.027	0.006	0.006	0.300	0.377	0.006	0.017	0.048	0.052
CRP, %	3.5		0.0		-25.6		-173.7		-9.1	

Table 36: Nutrients concentration for non-storm events during pre-analysis (mg.L^{-1}).

Date	TP		OP		TN		NO_2+NO_3		NH_3	
	In	Out	In	Out	In	Out	In	Out	In	Out
7/8/11	0.044	0.038	0.003	0.002	0.362	0.388	0.054	0.045	0.149	0.114
7/9/11	0.040	0.036	0.004	0.002	0.265	0.302	0.007	0.016	0.114	0.110
7/11/11	0.026	0.027	0.001	0.001	0.281	0.358	0.015	0.006	0.100	0.086
Average	0.037	0.034	0.003	0.002	0.303	0.349	0.025	0.022	0.121	0.103
CRP, %	8.2		37.5		-15.4		11.8		14.6	



a) Storm events



b) Non-storm events

Figure 53: Nutrients concentration during pre-analysis.

4.4.1.2.2 Post-analysis

The post-analysis period is defined as the study period after the deployment of the floating wetland. During the post-analysis period, in-situ data for water quality analysis at Pond 5 was monitored continuously to test if the deployment would function as we expected in the two scenarios, storm versus non-storm events. Water samples in four storm and four non-storm events were collected, and nutrient samples were delivered to the same certified laboratory off campus for chemical analysis. The overall performance of the fibrous matrix FTWs between storm and non-storm events were investigated and compared between the pre-analysis and post-analysis conditions. Attention was still placed upon the performance differentiation of the fibrous matrix FTWs between storm and non-storm events.

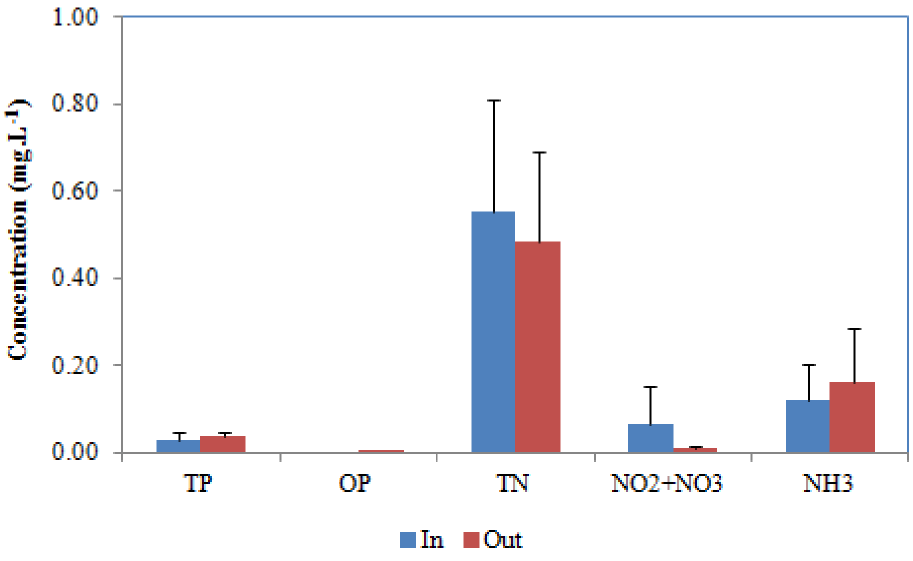
In 2011, six storm events were monitored after the deployment on August 16 and 28, September 19, and October 8 and 29, and in 2012 on April 6. The nutrient levels in runoff during post-analysis (Table 37) were much higher than those during pre-analysis (Table 35); even though a high removal of TN and NO_2+NO_3 was observed (Figure 56a), which confirmed the credit of the floating wetland performance. In addition to the analysis for storm events, sampling for seven non-storm events were carried out in 2011 on July 27, August 23, September 2, November 17, and December 14, and in 2012 on February 2 and March 27. Positive removal was observed in terms of all forms of nutrients (Figure 56b). The overall CRP of phosphorus was substantial: 46.3% TP and 79.5% OP were removed, probably by the combination of adsorption through peat moss in the floating wetlands and sedimentary process in the pond. The overall reduction of TN, NO_2+NO_3, and NH_3 reached 16.9, 16.7, and 53.0%, respectively. In short, significant improvements were found in post-analysis (Tables 37 and 38).

Table 37: Nutrients concentration for storm events during post-analysis at Pond 5 ($mg.L^{-1}$).

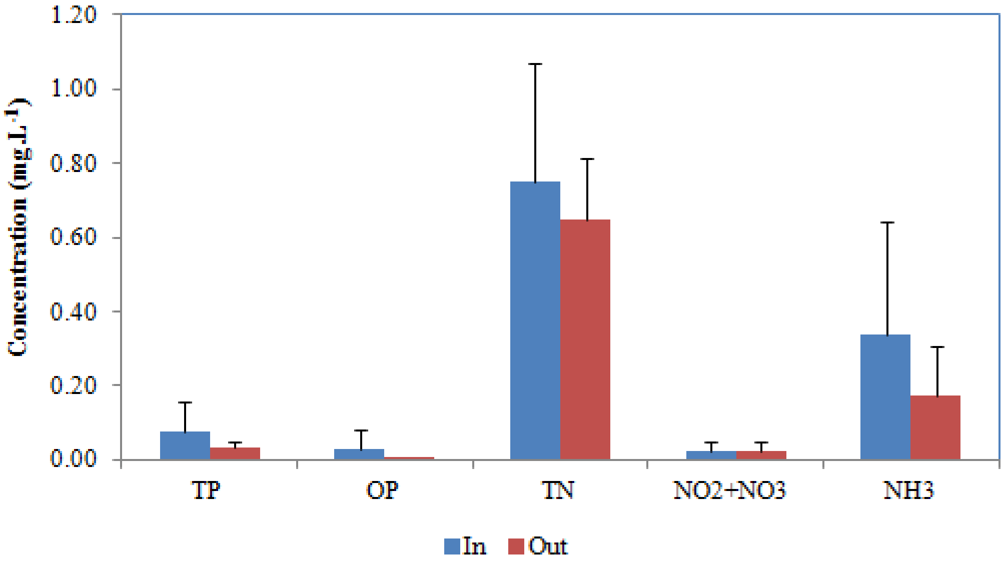
Date	TP		OP		TN		NO_2+NO_3		NH_3	
	In	Out	In	Out	In	Out	In	Out	In	Out
8/16/11	0.052	0.035	0	0.001	0.853	0.645	0.194	0.017	0.186	0.325
8/28/11	0.015	0.046	0	0.001	0.638	0.431	0	0.003	0.194	0.159
9/19/11	0.004	0.027	0	0.002	0.465	0.649	0.006	0.007	0.073	0.143
10/8/11	0.053	0.055	0.028	0.027	0.324	0.320	0.056	0.049	0.044	0.043
10/29/11	0.035	0.038	0	0.001	0.253	0.215	0.054	0.01	0.034	0.026
4/6/12	0.160	0.060	0.094	0.036	0.941	0.455	0.008	0.004	0.092	0.003
Average	0.053	0.042	0.020	0.010	0.579	0.505	0.053	0.020	0.104	0.100
CRP (%)	21.3		51.5		12.7		62.3		3.3	

Table 38: Nutrients concentration for non-storm events during post-analysis at Pond 5 ($mg.L^{-1}$).

Date	TP		OP		TN		NO_2+NO_3		NH_3	
	In	Out	In	Out	In	Out	In	Out	In	Out
7/27/11	0.196	0.033	0.112	0.001	1.154	0.481	0.028	0.02	0.468	0.137
8/23/11	0.031	0.028	0.002	0.004	0.514	0.542	0	0	0.169	0.176
9/2/11	0.093	0.054	0.039	0	0.841	0.751	0.014	0	0.447	0.348
11/17/11	0.017	0.02	0.001	0.001	0.47	0.827	0.061	0.063	0.017	0.029
12/14/11	0.052	0.037	0.025	0.011	0.780	0.512	0.032	0.043	0.183	0.022
2/2/12	0.030	0.028	0.019	0.016	0.737	0.611	0.012	0.014	0.011	0.009
3/27/12	0.018	0.013	0.000	0.000	0.151	0.150	0.094	0.060	0.017	0.016
Average	0.057	0.030	0.023	0.005	0.666	0.553	0.034	0.029	0.224	0.105
CRP (%)	46.3		79.5		16.9		16.7		53.0	



a) storm event



b) non-storm event

Figure 54: Nutrients concentration during post-analysis.

4.4.2 Operating HRT and removal efficiencies

4.4.2.1 Pond 4M

Removal efficiency was primarily dependent on the operating HRT. As mentioned in the section 4.1.2.2, the operating HRT is defined as the contact time spanning (1) from the time when each storm begins to the sampling time for event-based data and (2) from the date when the latest storm took place to the sampling date for monthly-based data. 1.068 mg.L^{-1} of TN and 0.179 mg.L^{-1} of TP were used as the initial nutrient concentrations in the runoff received by the stormwater pond. The event-based data and the monthly-based data then revealed how much of the nutrients were removed by the physical sedimentation process within a short HRT and by the biological treatment during a long HRT, respectively.

Tables 39 and 40 summarize the operating HRT associated with nutrient removal efficiencies during the post-analysis. Generally speaking, the apparent trend shown in Figures

53 and 54 demonstrated that longer operating HRT leads to higher removal efficiencies. Noted in 4.4.2.1, there were two extreme storms in April and October 2011. It might take 1-2 months for microbes to decompose the organic debris which poured into the pond with the runoff via a biological process. This led to the TN peak in the monthly data of June and November (i.e. a higher final value), and then further resulted in two, pretty low numerical removal efficiencies. One more outlier of TN removal efficiency was seen on January 18th, 2012. At that time, the new-replaced plants had not been functioning due to the low temperature in winter. Therefore, these three values were omitted for the formula fitting. Since the removal of TP was more subjected to sedimentation, the removal efficiencies of both event-based and monthly-based are mostly over 80%. The outlier in February 2012 was primarily caused by the disturbance of flowing runoff received at the inlet.

Table 39: Operating HRT associated with TN removal at Pond 4M with a FTW

	Sampling date (dd-mm-yy)	Operating HRT, d	TN, mg L^{-1}	Removal % Ci = 1.068	Removal % Ci = 0.725
Event-based	14-05-11	0.03	0.472	55.8	34.9
	24-06-11	0.05	0.410	61.6	43.4
	08-10-11	0.53	0.383	64.1	47.2
	29-10-11	0.13	0.375	64.9	48.3
	31-10-11	0.27	0.594	44.4	18.1
	11-12-11	0.07	0.839*		
	22-02-12	0.06	0.544	49.1	25.0
Monthly-based	17-05-11	3	0.401	62.5	44.7
	15-06-11	14	0.743*		
	17-07-11	2	0.208	80.5	71.3
	16-08-11	2	0.461	56.8	36.4
	15-09-11	5	0.388	63.7	46.5
	17-10-11	9	0.213	80.1	70.6
	16-11-11	16	0.791*		
	16-12-11	5	0.434	59.4	40.1
	18-01-12	37	0.513	52.0	29.2
	14-02-12	4	0.455*		
	19-03-12	11	0.281	73.7	61.2
	18-04-12	18	0.252	76.4	65.2

* This data was omitted from the formula fitting and average.
Average removal beyond 2 days HRT = 67% for Ci=1.068 mg/l and 52% for Ci = 0.725 mg/L

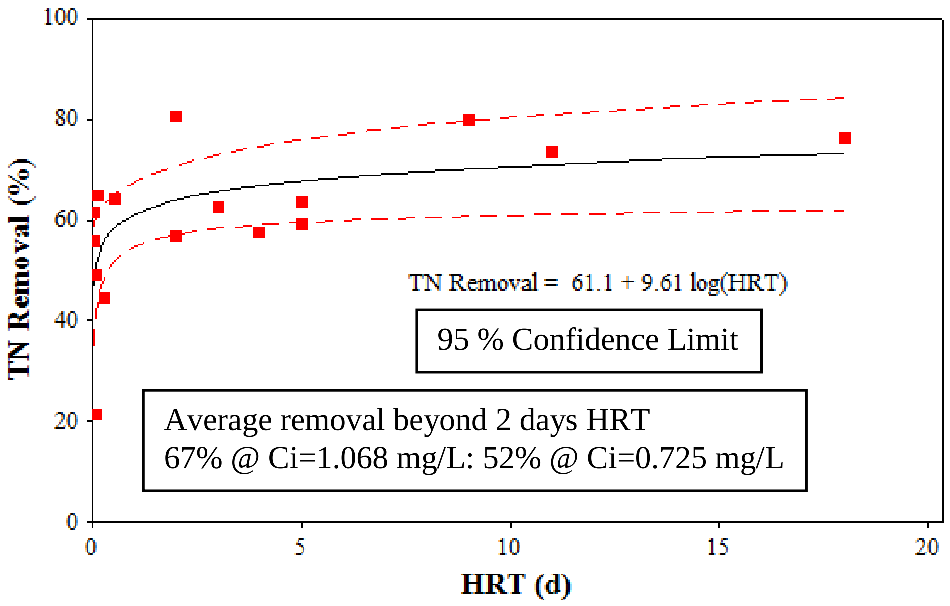


Figure 55: Operating HRT vs. TN removal efficiencies (Ci=1.068 mg/L) at Pond 4M

Table 40: Operating HRT associated with TP removal at Pond 4M with a FTW

	Sampling date (dd-mm-yy)	Operating HRT, d	TP, mg L^{-1}	Removal % Ci = 0.179	Removal % Ci = 0.100
Event-based	14-05-11	0.03	0.021	88.5	79.0
	24-06-11	0.05	0.009	95.0	91.0
	08-10-11	0.53	0.017	90.5	83.0
	29-10-11	0.13	0.019	89.4	81.0
	31-10-11	0.27	0.033	81.6	67.0
	11-12-11	0.07	0.020	88.8	80.0
	22-02-12	0.06	0.100	44.1	0.0*
Monthly-based	17-05-11	3	0.017	90.5	83.0
	15-06-11	14	0.01	93.3	90.0
	17-07-11	2	0.033	81.6	67.0
	16-08-11	2	0.01	92.2	90.0
	15-09-11	5	0.007	96.1	93.0
	17-10-11	9	0.005	97.2	95.0
	16-11-11	16	0.003	98.3	97.0
	16-12-11	5	0.015	91.6	85.0
	18-01-12	37	0.016	91.1	84.0
	14-02-12	4	0.011	93.9	89.0
	19-03-12	11	0.014	92.2	86.0
	18-04-12	18	0.012	93.3	88.0

* This data point was omitted from the average.

Average removal beyond 2 days HRT = 93% for Ci=0.179 mg/l and 87% for Ci = 0.100 mg/L

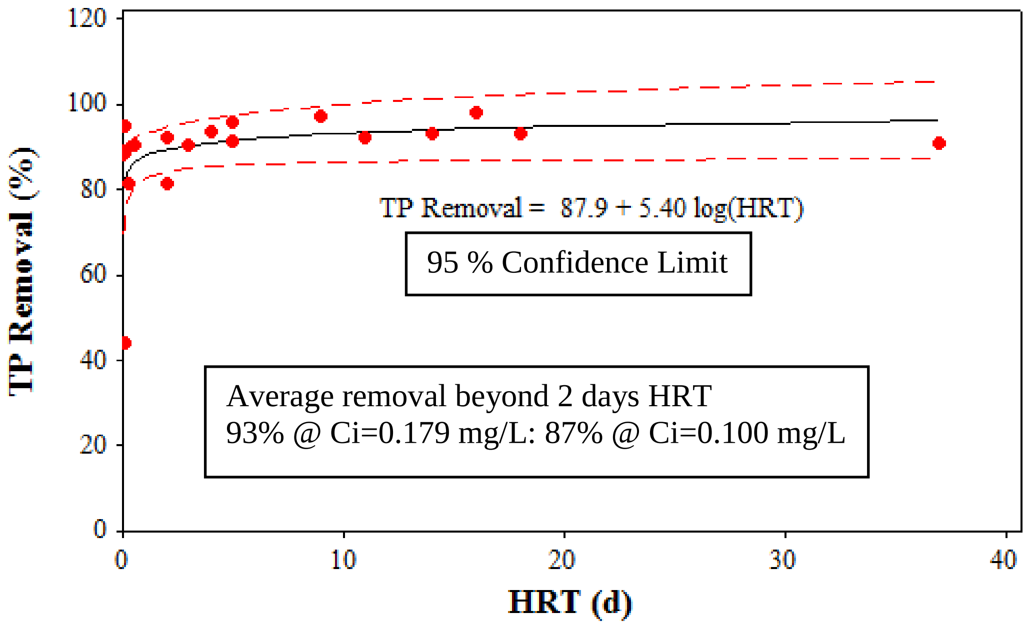


Figure 56: Operating HRT vs. TP removal efficiencies (Ci=0.179 mg/L) at Pond 4M

4.4.2.2 Pond 5

Tables 41 and 42 summarize the operating HRT associated with nutrient removal efficiencies during the post-analysis for the Pond 5 study. Similarly, the logarithmic trend in Figures 57 and 58 made it apparent that longer operating HRT leads to higher removal efficiencies. During post-analysis, TP removal was stable over 68% when the operating HRT was longer than a few hours. In comparison, TN removal was a more complicated dynamic process due to the involvement of nitrogen and denitrification processes. Furthermore, the operation of the fountain introduced more dissolved oxygen, interrupting denitrification and sedimentation, both of which influence the removal of TN. This then led to the decreased removal efficiencies with a longer operating HRT.

Table 41: Operating HRT associated with TN removal at Pond 5 with a FTW

	Sampling date (dd-mm-yy)	Operating HRT, d	TN, mg L^{-1}	Removal, %
Event-based	16-08-11	0.06	0.853	59.4
	28-08-11	N/A*	0.638	69.6
	19-09-11	N/A*	0.465	77.9
	08-10-11	N/A*	0.324	84.6
	29-10-11	0.43	0.253	88.0
	06-04-12	0.02	0.941	55.2
Monthly-based	27-07-11	4	0.481	77.1
	23-08-11	4	0.542	74.2
	02-09-11	2	0.751	64.3
	17-11-11	17	0.470	77.6
	14-12-11	27	0.512	75.6
	02-02-12	37	0.611	70.9
	27-03-12	16	0.150	92.9

*This data was omitted for formula fitting due to the missing rainfall data

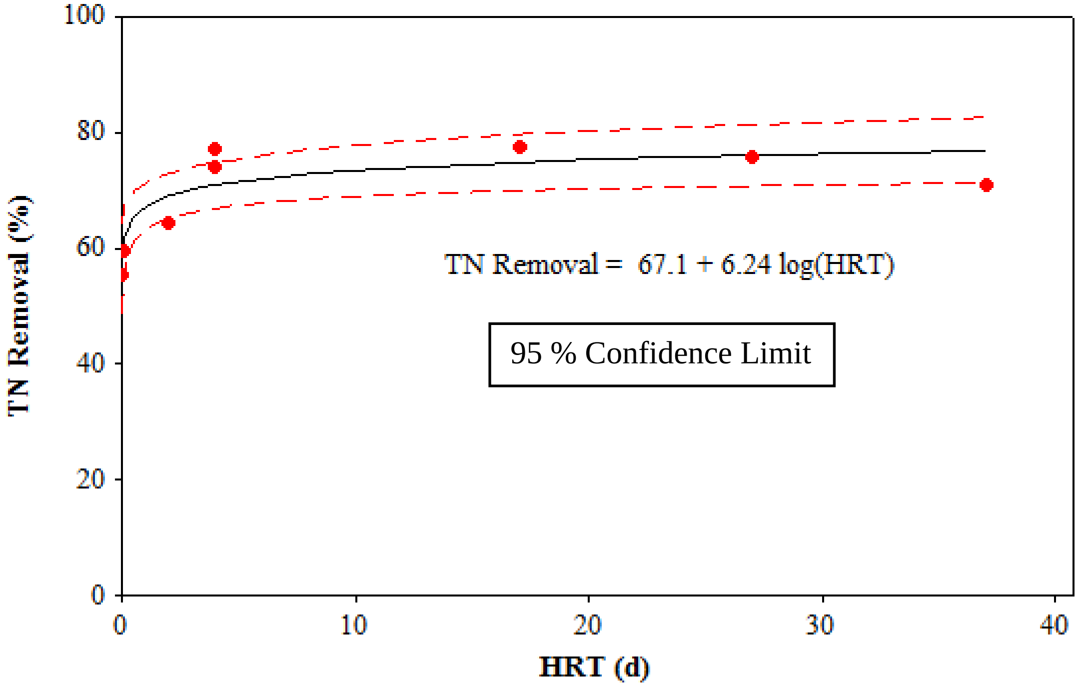


Figure 57: Operating HRT vs. TN removal efficiencies at Pond 5

Table 42: Operating HRT associated with TP removal at Pond 5 with a FTW

	Sampling date (dd-mm-yy)	Operating HRT, d	TP, mg L^{-1}	Removal, %
Event-based	16-08-11	0.06	0.052	89.5
	28-08-11	N/A*	0.015	97.0
	19-09-11	N/A*	0.004	99.2
	08-10-11	N/A*	0.053	89.3
	29-10-11	0.43	0.035	93.0
	06-04-12	0.02	0.16	67.8
Monthly-based	27-07-11	4	0.033	93.4
	23-08-11	4	0.028	94.4
	02-09-11	2	0.054	89.1
	17-11-11	17	0.02	96.0
	14-12-11	27	0.037	92.6
	02-02-12	37	0.028	94.4
	27-03-12	16	0.013	97.4

*This data was omitted for formula fitting due to the missing rainfall data

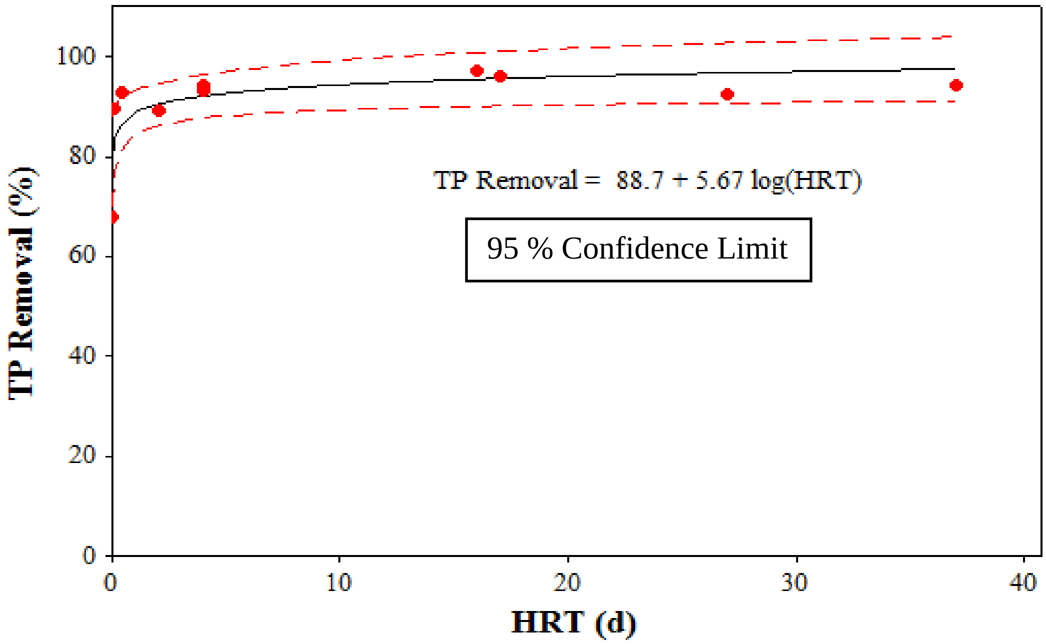


Figure 58: Operating HRT vs. TP removal efficiencies at Pond 5

4.4.3 Credit of floating wetland

In addition to flood control and downstream erosion prevention, nutrient removal is also a major function of a wet detention pond. Besides its self-purification capacity via a natural process, floating wetland technology was introduced to further improve the water quality. It was noted in the sampling of the influent that the type of sampling minimizes the inclusion of particulate material. This is done so that it is recognized that particulates will most likely settle out and floating islands do not remove particulates, but only a dissolved fraction of nitrogen and phosphorus. Tables 43 and 44 summarize the credit estimation for both interlocking foam FTWs and fibrous matrix FTWs. According to the assumed value based evaluation, the additional credit of interlocking foam FTWs and fibrous matrix FTW were almost the same. However, since aeration introduced re-suspension of sediment, less TN was removed by the settling effect at Pond 5, which caused the inlet value based credit of fibrous matrix FTWs to be greater than that of interlocking foam FTWs. Additionally, compared to the Mesocosm system with a fixed surface area, natural ponds had a variable surface area. A smaller pond size usually results in a greater variation of surface area, given similar input flow rates. The fibrous matrix FTWs were applied at Pond 5 with 5% coverage in July when the pond level was at its highest. Since Pond 5 was relatively small, the coverage percentage increased proportionally to the drop of water level over time, which might be another reason for the higher removals with the fibrous matrix FTWs as compared to the interlocking foam FTWs. The data in Table 45 compared Pond 4M with Pond 5.

Table 43: Credit of interlocking foam FTWs in Pond 4M without aeration

		TN		TP	
		No FTW	With FTW	No FTW	With FTW
$\overline{C_{I-S}}$		0.635	0.497	0.024	0.024
$\overline{C_{O-N}}$		0.570	0.388	0.014	0.011
Runoff Concentration based*	RE_B (%)**	6.10 (4.32 – 8.60)	10.29 (7.30 – 14.51)	5.65 (4.03 – 7.90)	7.11 (5.08 – 9.95)
	Credit (%)	4.19 (2.97 – 5.91)		1.46 (1.05 – 2.05)	
Pond Concentration based	RE (%)	10.3	22.1	42.2	54.2
	Credit (%)	11.8		12.0	

* Low Intensity Commercial Land Use

** Geometric Average and (± 1 Standard Deviation)

Table 44: Credit of fibrous matrix FTWs in Pond 5 with aeration

		TN		TP	
		Without FTW	With FTW	Without FTW	With FTW
$\overline{C_{I-S}}$		0.288	0.519	0.028	0.031
$\overline{C_{O-N}}$		0.347	0.498	0.033	0.028
Runoff Concentration based*	RE_B (%)**	-2.83 (-1.78 – -4.49)	0.99 (0.63 – 1.58)	-1.06 (-0.76 – -1.46)	0.65 (0.47 – 0.90)
	Credit (%)	3.82 (2.41 – 6.06)		1.71 (1.23 – 2.37)	
Pond Concentration based	RE (%)	-20.6	4.0	-18.7	10.4
	Credit (%)	24.6		29.1	

* Multi-Family Residential Land Use

** Geometric Average and (± 1 Standard Deviation)

Table 45: Comparison between Pond 4M and Pond 5 studies

	Pond 4M		**Pond 5**	
Adjacent land use	Parking lot, low intensity commercial		Multi-family residential	
Watershed size	12.97 acres		1.64 acres	
Pond age	1-2 years		12-13 years	
Pond size	0.63 acre		0.085 acre	
FTWs	Interlocking foam		Fibrous matrix	
Aeration	None		Pond fountain	
Exp. duration	18-month		10-month	
Exp. design	Microcosm and Mesocosm		Mesocosm	
Plants	Canna, Juncus, and Agrostis		Juncus, Pickerelweed	
Media	Sorption media		Peat moss mix	
Credit	TN	TP	TN	TP
Assumed runoff conc. based	4.19 % **(4%)**	1.46 % **(1%)**	3.82 % **(4%)**	1.71 % **(2%)**
Pond conc. based	11.8 % **(12%)**	12.0 % **(12%)**	24.6 % **(25%)**	29.1 % **(29%)**

CHAPTER 5 ALGAL TOXINS STUDY

5.1 OBJECTIVE OF ALGAL TOXIN STUDY

It is believed that Cyanobacteria have existed on Earth for 3.5 billon years. They are one of the most adaptable organisms, even found in extreme environments ranging from hot springs to partially-frozen Antarctic lakes (Whitton, 1992). Classified as photoautotrophs, the vast majority of Cyanobacteria require only light, carbon dioxide, water, and inorganic nutrients for their life processes (WHO, 1999). Some genera of Cyanobacteria are capable of producing Cyanotoxin that bring a lethal effect on human and animal life, which was first discovered in an Australian lake back in 1878 (Francis, 1878), and then further realized as a health problem worldwide in freshwater ecosystems (Carmichael, 2008).

Since Cyanobacteria are able to exist in shallow, warm, slow-moving or still water, the subtropical climate of Florida associated with nutrient-rich stormwater runoff, caused by expanding urban development, stimulate Cyanobacteria growth in many stormwater wet detention ponds throughout the state. As the most frequently isolated cyanotoxin in freshwater bodies, Microcystins (MC) have been detected not only in a variety of the larger water bodies found in Florida including rivers, natural lakes, and reservoirs (Burns et al, 2002; Abbott et al, 2009), but also in various sized stormwater ponds associated with watersheds of different land uses and concentrations ranging from 0.04 to 1.56 μg/L (Wanielista et al, 2006). In addition, O'Reilly et al, (2010) showed that in a saturated flow condition and in sandy soils, toxins get transported into the groundwater. When one comes into contact with MC-rich water, serious health problems can arise. First of all, it has been known to have an adverse effect on rapid blinding and skin irritation. Also, it was evident that Microcystin *does* accumulate in the liver. In fact, long-term drinking of such contaminated water due to the presence of MC may even trigger liver cancer (Fleming et al., 2002). Microcystin-LR (MC-LR) is the most acute and toxic compound of MC. It is very stable in water, and resistant to pH and temperature extremes (Wannemacher, 1989). The World Health Organization has set a provisional guideline of 1 μg/L for MC-LR in drinking water. Such a cruel situation of stormwater pond management, in terms of ecological sustainability and human health, calls for an eco-friendly solution to not only improve the water quality of the pond but also to maintain the aesthetic value of the pond.

Currently, there is little information published on FTWs that relate nutrient levels to MC concentrations. Also, limited literature was found to delineate the ecological response of MC concentration associated with the plant replacement of FTWs. In this study, the interaction between MC and nutrients in the pond were observed for improving the understanding of signatures associated with biological and ecological dynamics when using FTWs in stormwater wet detention ponds.

5.2 SAMPLING AND MEASUREMENTS

50 mL water samples were taken during inter-event times at Pond 4M. They were then transferred into a 60 mL vial and preserved at -40 $^{\circ}$C after being filtered by 0.45-micrometer glass-microfiber filters (47mm, Whatman, Kent, UK). Filtered water samples, which were thawed and brought to room temperature prior to running the experiment, were quantitatively analyzed. This was done using enzyme-linked immunosorbent assay (ELISA) with a VERSAmax Tunable Microplate Reader (Molecular Devices Corporation, Sunnyvale, CA) and commercially available 96-well microplate kits (Microcystin-ADDA Microtiter Plate, Product No. 520011, Abraxis, Warminster, PA) with the detection limit of 0.1 μg L^{-1} (ppb). ELISA experiments were

performed at the UCF Department of Civil, Environmental, and Construction Engineering Organic Chemistry Laboratory according to the manufacturer's kit instructions. All samples were evaluated in duplicate and against standards (also provided by ELISA kits). Absorbance as the surrogate for concentration was averaged before computing the MC concentration via the standard curve. The standard curve was developed by relating relative absorbance (absorbance of sample divided by the absorbance at zero standard value and at 450 nanometers) to MC-LR concentration (Wanielista et al, 2006).

5.3 RESULTS AND DISCUSSION

5.3.1 Algal toxin results

To discover the temporal and spatial abundance of algal toxin using pond water from Pond 4M with the FTWs system, algal toxin was monitored simultaneously with the water quality analysis. From Figure 59, algal toxin roughly showed an "up and down" pattern during the monitoring period. After June (0.137 ppb), MC concentration dropped to near-zero until January 2012, with an exception in November 2011 (0.052 ppb). Two higher MC values in June and November were coincident with two peaks of TN concentration. As mentioned in the previous chapter, TN was mainly ON, which provided the main carbon and nitrogen source for the growth of Cyanobacteria, when inorganic nitrogen was limiting. Starting from January 2012, there was an apparent rise of MC concentration leading toward the highest value in April 2012 (0.437 ppb). There may have been another factor to dominate the whole process during the later stage, which will be discussed in detail in the next section. Spatially, MC concentration at location 4 was about twice as high as it was at the other four sampling locations (Figure 60). Different from the nutrient gradient, MC concentration showed a gradient increase with the distance from the inlet (i.e. the farther from the inlet, the higher MC concentration observed).

Sampling location 4 was at the other end of the pond, where less runoff turbulence is found. The lack of turbulence agreed with the theory that slower water movement may cause more Cyanobacteria, and therefore a higher MC concentration. This finding could have implications to the design of pond shape and size, as the concern for MC control may become a focus in stormwater reuse.

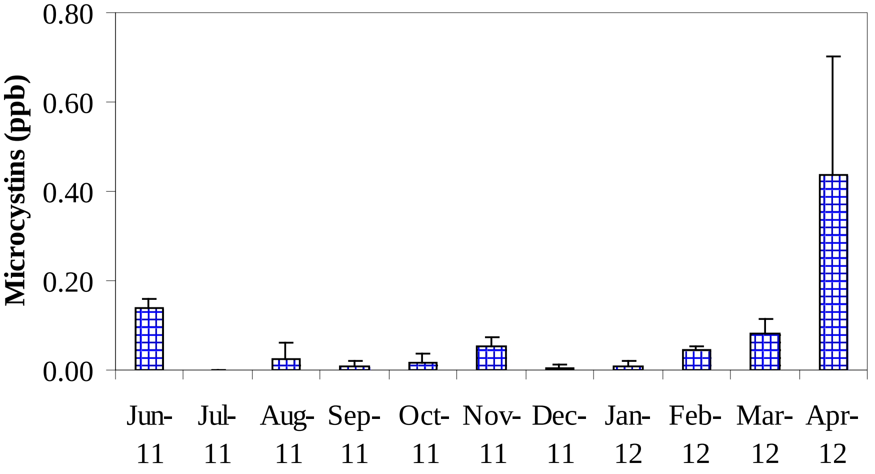


Figure 59: Time-series monthly-based MC results (n = 5)

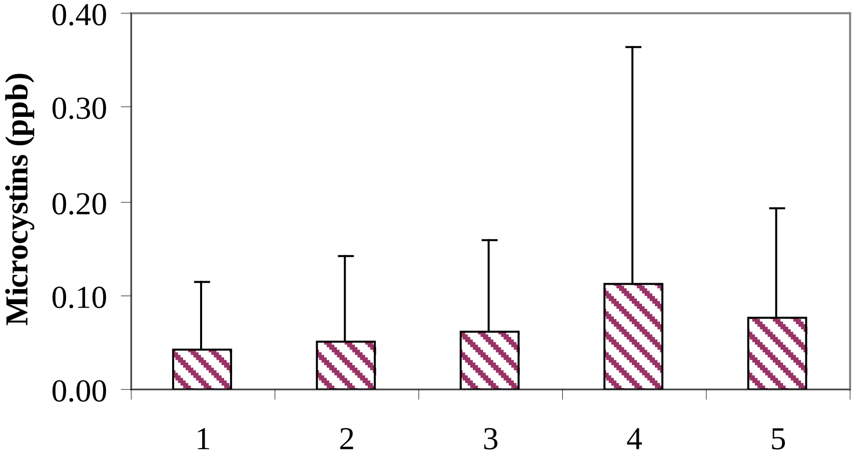


Figure 60: Spatial monthly-based MC results (n = 11)

5.3.2 Interactions between MC and nutrients

To explain the interaction between nutrient concentration and possible influence by plant replacement on the Cyanobacteria growth, the monitoring period was divided into two parts: before plant replacement and after plant replacement. An interesting discovery emerges from this segmentation. A substantial positive correlation (0.83) and a strong negative correlation (-0.72) between MC and TN concentrations were found before and after the plant replacement, respectively (Figures 61 and 62). Meanwhile, average TN was decreased from 0.55 to 0.39 mg L^{-1}. From this, it was apparent that nitrogen availability played a critical role in varying MC concentrations.

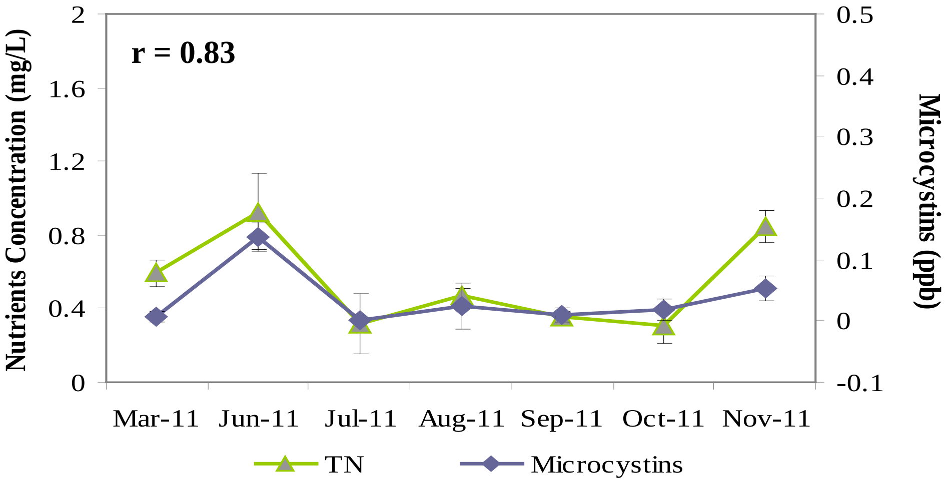


Figure 61: Positive correlation between MC and TN concentrations before plant replacement

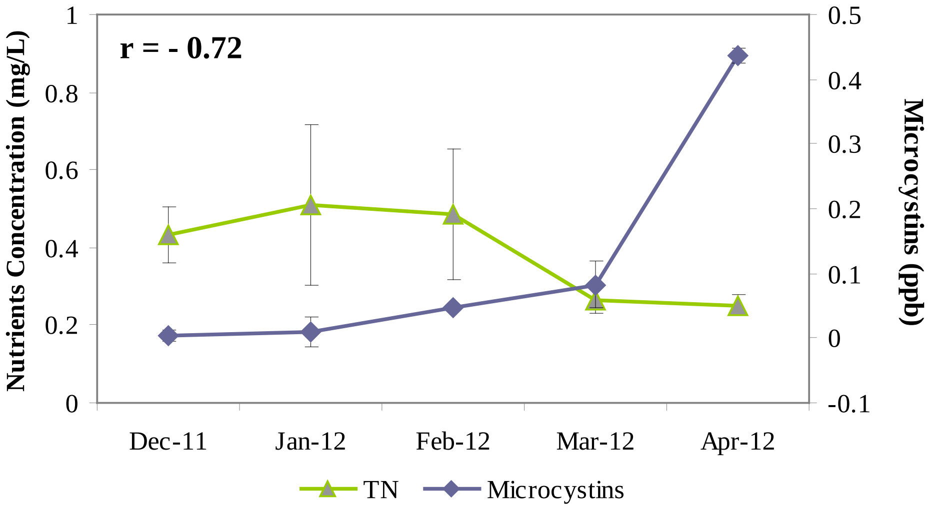


Figure 62: Negative correlation between MC and TN concentrations after the plant replacement

Since MC is produced by Cyanobacteria when they die, strictly speaking, the MC concentration represents an amount of dead Cyanobacteria, while algal bloom represents an amount of living Cyanobacteria. When TN level is higher than a threshold (a minimum requirement is needed to maintain the normal metabolism of Cyanobacteria), they die proportionally (i.e. constant ratio of dead to living Cyanobacteria). Thus, MC concentration appears to be proportional to nutrient concentration; which explains why we found that the MC concentration had a positive correlation with TN concentration before the plant replacement (April – November 2011). Although a considerable amount of nutrients were removed by plant uptake, nutrient level was still relatively high due to more nutrient influx introduced by frequent storm events. However, the positive correlation may no longer be valid when the nutrient level is lower than that threshold. There were less storm events after the plant replacement (December 2011 – April 2012), and the nutrient concentrations were trending lower and lower, while new plants kept using the limited nutrients. Consequently, the remaining Cyanobacteria massively died due to a lack of nutrients and they released more MC, which caused an increase in MC concentration, and this is exactly what was observed (i.e., MC concentration has a negative correlation with TN concentration) after December 2011.

For maintenance concerns, FTWs should be used in wet ponds during wet seasons to remove excess nutrients from stormwater runoff. During dry seasons, the FTW should be removed from the wet pond to maintain a certain level of nutrients available for Cyanobacteria; otherwise, they will die and potentially cause a high production of MC.

Notwithstanding, the minimum requirement of the nutrient level for keeping the MC concentration low could not be constant all of the time. It may vary with time and be determined by many other environmental and hydrological effects, such as temperature, dissolved oxygen, wind speed, water level, etc. They all need to be considered in future studies to develop a function of the minimum requirement for MC control.

5.4. FINAL REMARKS

A plankton bloom was observed on March 15, 2011, before the deployment of FTWs. A water sample was evaluated for algae identification. Based on certified lab results, the dominant algal species in Pond 4M during the plankton bloom was microflagellate sp., which is another species of plankton that do not produce MC (Figure 63). Instead, there was a competition between microflagellate and Cyanobacteria. Thus, the presence of microflagellate even sped up the degradation of Cyanobacteria. After the deployment of FTWs, the competition would take place among floating plants, Cyanobacteria, and microflagellate. A system dynamics model may be developed in the future to illuminate the nutrient allocation for different species. Moreover, another threshold, which could trigger plankton bloom, would be determined.

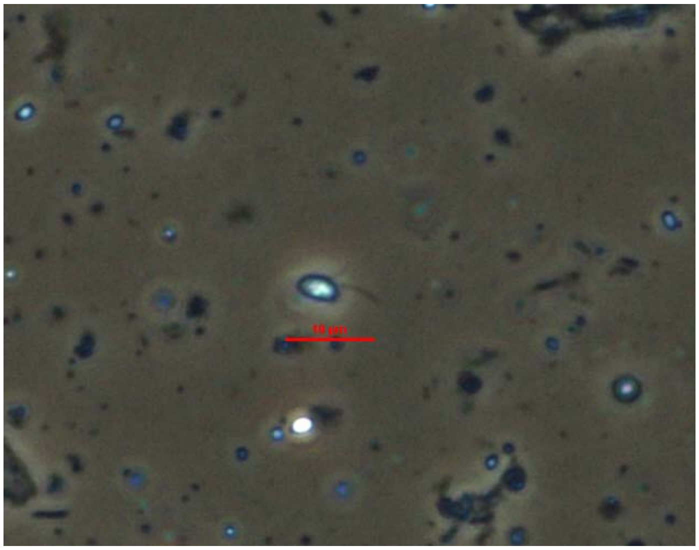


Figure 63: Dominant algal species during the plankton bloom in Pond 4M: microflagellate sp. (scale bar = 10 µm)

CHAPTER 6 CONCLUSION

The performance of two types of FTWs, interlocking foam FTW and fibrous matrix FTW, were investigated in terms of small-scale (microcosm) operation, large-scale (mesocosm) operation, and actual pond performance. From the microcosm study, a significant increase in plant biomass was observed when a mixture of 80% Expanded Clay and 20% Tire Crumb was used. It was also noted that cold temperatures were one environmental factor which constrained the growth of macrophytes. From the mesocosm study, it was concluded that varying water depth used in the experimental mesocosms was not a concern in terms of treatment efficiency of nutrient removal in FTWs, which might be affected by fluctuations in seasonal water levels. Within the feasible limit of floating mat coverage (from a 5%-10% increase), there was not a significant increase in the system removal efficiency for specific concentrations of nutrients. More area coverage would not be suitable from a cost effective perspective and might inhibit the sunlight to reach the bottom of the actual pond. Furthermore, the existence of a littoral zone increased transparency of the water column by reducing turbidity and Chl-*a*. With the addition of sorption media in plant holding cups in the mesocosm study, TP and OP had a significantly higher removed than without sorption media. From an ecological point of view, FTWs suppressed algae and duckweed growth significantly. Also the placement of the FTW should be near calm water because moving water has the potential to remove nutrients in the particulate and dissolved form from the root zones of the plants. Thus a FTW should not be located near the influent and effluent structures.

FTWs in wet detention ponds were evaluated in terms of effectiveness. The size of a FTW was limited to 5% of the pond area and was based on the performance data from the small-scale (microcosm) and large-scale (mesocosm) studies. Additionally, both hydrological and water quality parameters were monitored before and after the FTW deployment. Very low concentrations of NH_3 and NO_2+NO_3 indicated that the dominant N form was organic nitrogen and the dissolved form was being used by the FTW. In Pond 4M, the TN concentration reduction reached 15.04% and there was a considerable 42.51% decrease in TP concentration. The concentration reduction from the inlet to the outlet in terms of OP, NO_2+NO_3, and NH_3 were 54.65%, 17.51%, and 27.66%, respectively. On the other hand, the overall removal of TP, OP, TN, NO_2+NO_3, and NH_3 reached 46.3%, 79.5%, 16.9%, 16.7%, and 53.0 %, respectively in Pond 5. The FTW in pond 5 had higher removals because there was greater concentration of N and P in the water column, presumably because of the Fountain. The operating HRT was calculated to demonstrate the FTWs performance in both ponds. The longer operating HRT generally led to higher removal efficiencies. According to the pond concentration measurements, the credit for the use of a FTW was 12% for nitrogen and phosphorus. The credit was calculated based on operating data from the wet detention pond before and after the introduction of a FTW. Since fountain aeration introduced re-suspension of nutrients, more removal by a FTW can be expected with higher concentrations, as demonstrated in Pond 5. However, for this pond location and water fountain, the effluent concentration was higher for both nitrogen and phosphorus.

Finally, a positive correlation (0.83) and a negative correlation (-0.72) between MC and TN concentrations were found before and after the plants replacement. For maintenance reasons, FTWs were suggested to be used in wet ponds during wet seasons to remove excess nutrients from stormwater runoff, and removed during dry seasons in order to maintain a certain level of nutrients available for Cyanobacteria to suppress the potential production of MC.

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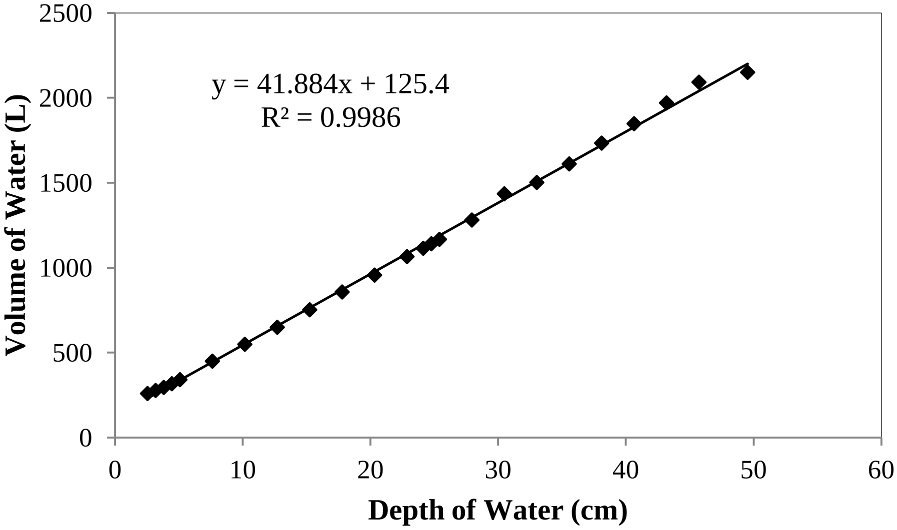
APPENDIX

Appendix A: Tank calibrations for calculating water volume



Appendix B: Average stem height (Phase-1)

Week	Canna (cm)			Juncus (cm)		
	Without Media	B&G	Ex. Clay	Without Media	B&G	Ex. Clay
0	25.4	26.0	24.8	34.3	33.0	37.5
2	27.3	22.9	26.7	38.1	38.1	42.5
4	31.1	22.9	26.7	39.4	42.5	44.5
6	34.9	30.2	33.3	40.6	41.9	46.4
8	37.8	31.1	33.7	34.9	35.6	45.1
10	40.3	34.3	37.1	36.5	38.7	46.4
14	40.0	35.6	42.5	36.8	40.0	41.3
18	40.0	33.7	40.3	38.4	38.7	37.5

Appendix C: Average root length (Phase-1)

Week	Canna (cm)			Juncus (cm)		
	Without Media	B&G	Ex. Clay	Without Media	B&G	Ex. Clay
0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.7	1.3	0.5	2.9	1.9	2.4
4	3.0	3.5	1.7	13.0	11.1	13.3
6	3.5	3.8	5.1	14.9	12.7	17.5
8	8.9	4.1	12.4	17.1	14.9	18.4
10	11.4	7.6	12.4	18.4	20.0	19.1
14	15.2	12.7	15.9	32.4	26.0	29.2
18	16.5	19.1	21.0	35.6	31.8	33.7

Appendix D: Average stem height (Phase-2)

Microcosm-1

	Canna (cm)		Juncus (cm)	
Week	Without Media	With Media	Without Media	With Media
0	25.4	24.13	32.512	30.48
2	25.908	31.75	34.29	36.83
4	35.052	36.322	40.64	40.132
6	36.322	42.672	50.292	52.07
8	0	0	36.322	43.688
10	2.54	3.302	39.37	43.18
12	4.572	7.62	42.672	47.752

Microcosm-2

	Canna (cm)		Juncus (cm)	
Week	Without Media	With Media	Without Media	With Media
0	23.622	22.86	30.988	29.972
2	26.67	24.384	33.782	34.29
4	30.988	27.94	33.02	38.608
6	27.94	29.464	37.592	38.862
8	0	0	33.02	33.528
10	1.27	4.064	26.67	32.004
12	3.302	6.35	28.702	33.782

Microcosm-3

	Canna (cm)		Juncus (cm)	
Week	Without Media	With Media	Without Media	With Media
0	22.352	24.13	32.512	30.48
2	20.32	21.844	29.464	30.988
4	18.288	19.812	27.94	26.924
6	17.78	21.082	23.368	21.59
8	0	0	11.43	12.7
10	1.27	2.032	10.922	11.43
12	2.54	6.35	10.16	10.668

Appendix E: Average root length (Phase-2)

Microcosm-1

	Canna (cm)		Juncus (cm)	
Week	Without Media	With Media	Without Media	With Media
0	0	0	0	0
2	1.524	0.762	2.54	2.794
4	3.048	2.032	9.652	10.16
6	3.81	4.572	13.97	18.288
8	8.128	9.652	19.812	23.622
10	11.684	12.192	23.368	31.75
12	14.732	16.002	31.242	38.1

Microcosm-2

	Canna (cm)		Juncus (cm)	
Week	Without Media	With Media	Without Media	With Media
0	0	0	0	0
2	0	0	1.524	2.032
4	1.27	0	7.112	6.604
6	4.064	1.524	11.43	10.16
8	7.112	2.54	17.78	17.272
10	10.668	3.048	25.4	21.59
12	12.7	3.81	28.702	26.162

Microcosm-3

Week	Canna (cm)		Juncus (cm)	
	Without Media	With Media	Without Media	With Media
0	0	0	0	0
2	0	0	1.27	1.524
4	1.016	0	6.096	6.35
6	3.81	0.508	12.192	11.684
8	7.62	1.524	19.05	17.78
10	10.668	3.048	22.86	22.352
12	12.7	4.572	29.21	26.162

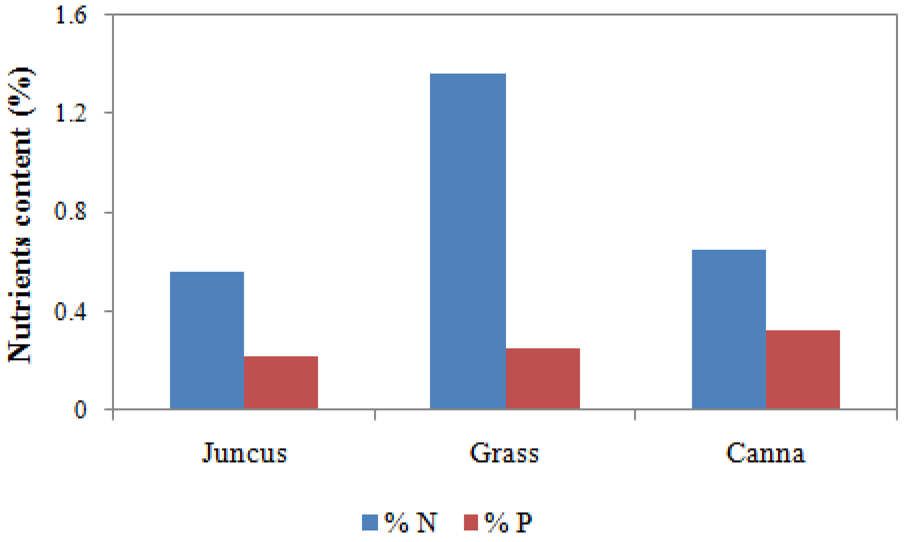
Appendix F: Remaining Nutrient Level (Phase-2)

	Microcosm 1		Microcosm 2		Microcosm 3	
Week	TN (mg/L)	TP (mg/L)	TN (mg/L)	TP (mg/L)	TN (mg/L)	TP (mg/L)
0	3.095	1.623	1.710	0.409	0.129	0.021
2	1.715	0.472	0.820	0.103	0.027	0.010
4	1.220	0.172	0.199	0.079	0.026	0.006
6	0.249	0.016	0.102	0.016	0.007	0.002
8	0.044	0.008	0.058	0.002	0.000	0.000
10	0.005	0.010	0.014	0.000	0.001	0.000
12	0.001	0.011	0.003	0.001	0.000	0.001

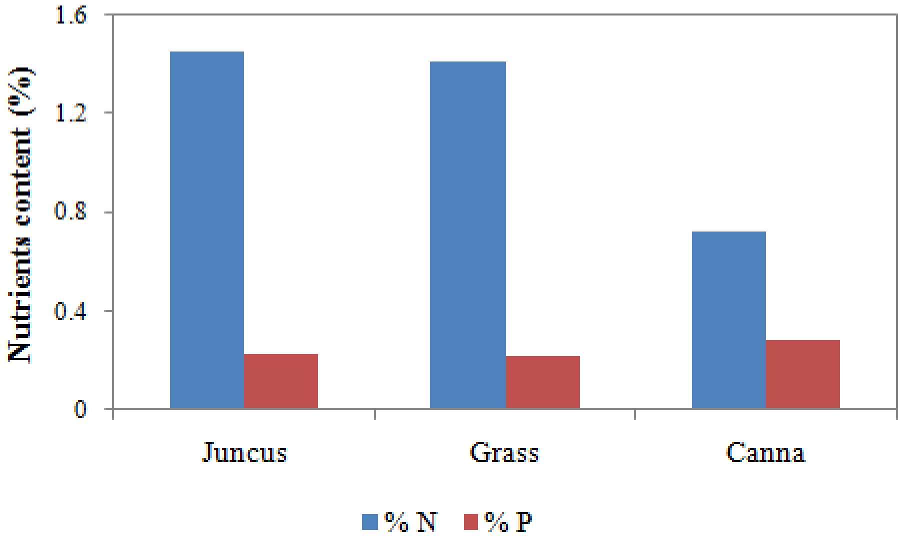
Appendix G: Plant biomass increase in grams (Phase-2)

	Without Media	With Media	Without Media	With Media
Microcosm-1	95	195.71	50	167.14
Microcosm-2	45	178.57	15	198.57
Microcosm-3	40	145	45	175

Appendix H: Nutrients content in different plants tissues



a) Leaf



b) Root

Appendix I: Storm Event Base Water Balance for Pond 4M in pre-analysis

Note: Volume-base data was the product of level-base data and an assumed constant surface area of 0.69 acres.

Dec. 12 – Dec 18., 2010		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	2.64 (-)	0.05	0.35	0.09	0.17	0.65
Volume-base (10^3 Gallon)	49.56(-)	0.94	6.57	1.75	3.15	12.16

Note: About 40,000 gallons water was transfer from Pond 4M to Mesocosm pools during this period.

Dec. 18 – Dec. 25, 2010		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	2.28	0.50	2.73	0	0.20	0.76
Volume-base (10^3 Gallon)	42.80	9.39	51.28	0	3.68	1.42

Jan. 6 – Jan. 10, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration

Level-base (inch)	3.12	0.33	3.33	0	0.11	0.43
Volume-base (10^3 Gallon)	58.57	6.19	62.58	0	2.10	8.11

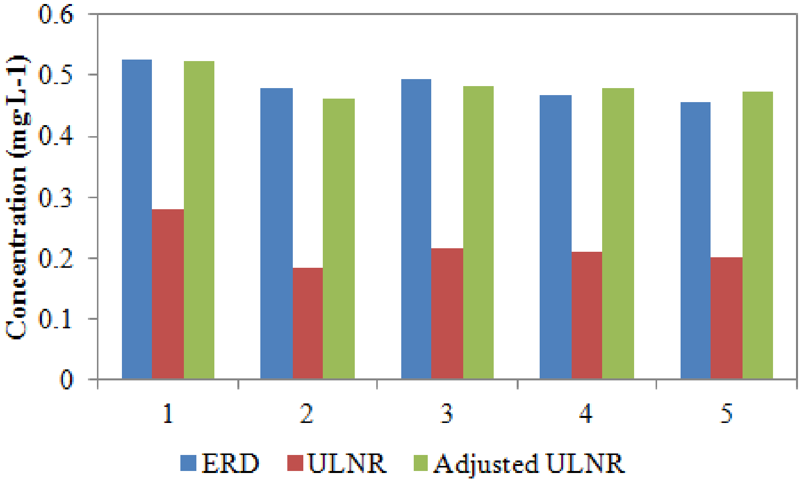
Jan. 21 – Jan. 25, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	2.28	1.26	11.50	9.90	0.12	0.46
Volume-base (10^3 Gallon)	42.80	23.71	215.83	185.76	2.26	8.72

Feb. 6 – Feb. 11, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	0.72	0.21	4.14	3.18	0.13	0.32
Volume-base (10^3 Gallon)	13.52	3.94	77.81	59.63	2.52	6.08

Mar. 1 – Mar. 4, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	0.60	0.2	2.02	0	0.14	0.33
Volume-base (10^3 Gallon)	11.26	3.75	16.40	0	2.61	6.28

Mar. 10 – Mar. 14, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	3.24	0.60	6.43	3.11	0.25	0.43
Volume-base (10^3 Gallon)	60.82	11.26	120.77	58.38	4.73	8

Appendix K: Comparison of ERD and ULNR results



Adjusted ULNR = 0.624 × ULNR + 0.349

Appendix L: Adjustment of ULNR results

Sample Date	Time	TN (mg.L^{-1})	Adjusted TN (mg.L^{-1})
12/2/2010	12:25	0.412	0.606
1/13/2011	14:40	0.603	0.725
2/15/2011	9:13	0.211	0.480
3/15/2011	12:03	0.392	0.593
4/7/2011	11:30	0.212	0.481

Appendix J: Storm Event Base Water Balance for Pond 4M in post-analysis

May. 14 – May. 20, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	0	0.54	5.04	4.22	0.77	0.59
Volume-base (10^3 Gallon)	0	10.14	94.67	79.2	14.45	11.15

Jun. 24 – Jun. 27, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	10.8	1.68	16.87	6.90	0.53	0.32
Volume-base (10^3 Gallon)	202.7	31.54	316.7	129.6	9.85	6.08

Oct. 8 – Oct. 14, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	10.2	7.18	44.29	40.27	0.35	0.65
Volume-base (10^3 Gallon)	191.5	134.8	831.4	756.0	6.57	12.16

Oct. 29 – Oct. 31, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	0.72	0.34	2.76	2.13	0.09	0.16
Volume-base (10^3 Gallon)	13.52	6.38	51.78	39.96	1.64	3.04

Oct. 31 – Nov. 1, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	2.76	0.72	5.74	3.45	0.09	0.16
Volume-base (10^3 Gallon)	51.81	13.52	107.8	64.81	1.64	3.04

Dec. 11 – Dec. 11, 2011		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	0.12	0.12	0.01	0	0	0.01
Volume-base (10^3 Gallon)	2.25	2.25	0.17	0	0	0.17

Feb. 22 – Feb. 25, 2012		+		-		
Terms	ΔStorage	Rainfall	Inflow	Outflow	Evaporation	Infiltration
Level-base (inch)	1.08	0.87	3.50	2.77	0.20	0.32
Volume-base (10^3 Gallon)	20.3	16.33	65.74	52.02	3.70	6.08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