2011

Nutrient Removal From Urban Stormwater Using Floating Treatment Wetland System

Md Kamrul Islam
University of Central Florida

STARS Citation

Islam, Md Kamrul, "Nutrient Removal From Urban Stormwater Using Floating Treatment Wetland System" (2011). *Electronic Theses and Dissertations, 2004-2019*. 1942.
https://stars.library.ucf.edu/etd/1942

NUTRIENT REMOVAL FROM URBAN STORMWATER USING FLOATING TREATMENT WETLAND SYSTEM

by

MD. KAMRUL ISLAM
B.Sc. Bangladesh University of Engineering and Technology, 2009

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Summer Term
2011

ABSTRACT

Despite the technology advancement, degradation of water quality due to stormwater continues to be a significant threat to the water and ecosystems due to the exponential growth of industries and agricultural enterprises that discharge stormwater. These anthropogenic activities are the sources of high nitrogen and phosphorus quantities in stormwater, which is responsible for eutrophication phenomena and deterioration of public health. Floating Treatment Wetlands (FTWs) are a potential solution to this problem. Both microcosm and mesocosm level studies were conducted for the effective removal of nutrients in stormwater wet detention ponds with different sorption media under varying nutrient concentrations and weather conditions. Water depth, percent area coverage of the FTWs and littoral zone emergent plants were varied in order to determine nutrient removal efficiency before implementing in an actual pond. Focus has also been placed on the observations of macrophyte-epiphyte-phytoplankton interactions in order to understand temporal characteristics of ecological phenomena. Water quality parameters included Total Nitrogen, Total Phosphorus, Orthophosphate, Nitrate-Nitrogen, and Ammonia-Nitrogen in addition to in-situ parameters such as pH, Dissolved Oxygen, Temperature and Chlorophyll-a. Results clearly indicate that an FTW filled with sorption media of 80% expanded clay and 20% tire crumb can significantly promote the biomass growth. Different levels of nutrient concentrations did affect the plants' growth and cold temperature in late winter was detrimental to growth. To make the system more viable irrespective of the seasonal weather conditions, the adoption of mixed vegetation is highly recommended in the FTWs implementation. It is also recommended that, the positioning of the floating wetlands should not be in the vicinity of the outlet of the pond as assimilated nutrient under the mat might increase the nutrient concentration in the discharged water. Finally, One-way ANOVA test is performed to check whether or not

these grouped microcosms and mesocosms with differing experimental setup can be deemed statistically significant.

ACKNOWLEDGMENTS

First and foremost, I would like to show my deepest gratitude to my advisor, Dr. Ni-Bin Chang, who has provided me constant valuable guidance in every stage of the writing of this thesis. Without his impressive kindness, illuminating instruction and patience, this thesis could not have reached its present form. His keen and vigorous academic observation enlightens me not only in this thesis but also in my future study.

Second, I would like to thank Dr. Martin Wanielista for providing his valuable time and comments in helping me to achieve my graduate degree as well as sitting on my committee. I am grateful to my committee member Dr. Husen Zhang for reviewing my thesis and for his valuable comments. I am greatly indebted to all my teachers who have helped me to develop the fundamental and essential academic competence. My sincere appreciation also goes to all research team members who participated in this study with great cooperation.

I am grateful for the financial support of this project provided by the Florida Department of Transportation (FDOT). I wish to thank Beeman’s Nursery for providing floating mats and plants. Assistance with experimental setup by Erik Stuart is also gratefully acknowledged.

Last but not least, I'd like to thank my family, especially my parents for their love, encouragement, and support in my life of studying abroad.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Overview

Nutrients, such as ammonia, nitrite, nitrate, and phosphorus, in stormwater effluents are common contaminants in water bodies that affect public health and ecosystem integrity with acute and chronic harmful outcomes directly or indirectly measured. For example, without proper treatment, ammonia in the wastewater effluents can stimulate phytoplankton growth, exhibit toxicity to aquatic biota, and exert an oxygen demand in surface waters (Beutel, 2006). Undissociated ammonia is extremely volatile and in aqueous solution either ionizes or volatizes. Ionized ammonia is very toxic for fish species (Tarazona et al., 2008). Fish mortality, health and reproduction can be affected by the presence of a minute amount of ammonia-N (Servizi and Gordon, 2005). Nitrate can cause human health problems such as liver damage and even cancers (Gabel et al, 1982; Huang et al., 1998). Nitrate can also bind with hemoglobin and create a situation of oxygen deficiency in an infant's body called methemoglobinemia (Kim-Shapiro et al., 2005). Nitrite can react with amines chemically or enzymatically to form nitrosamines that are very potent carcinogens (Sawyer et al., 2003).

Use of constructed wetlands have significantly increased for remediating nutrient-rich surface and subsurface flow (White et al., 2009; Baldwin et al., 2009; Belmont and Metcalfe, 2003), where various aquatic plants are used to purify both stormwater and wastewater (Iamchaturapatra et al., 2007). FTWs are one of the potential Best Management Practices (BMPs) where macrophytes remove pollutants by directly taking them up into their tissue, providing a suitable environment for microorganisms which also reduce the concentration of the pollutants (Breen, 1990; Billore and Sharma, 1996).

Stormwater runoff varies highly as storm events are erratic in terms of intensity and duration. Thus, sediment-rooted plants for conventional treatment wetlands would experience 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, or drought will affect plant growth, establishment and survival. Prolonged floods are stressful to some sediment-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 is definitely a limitation to their applicability. Floating Treatment Wetlands (FTWs) are an innovative variant on these systems and a possible solution to this problem. Plants grow on floating mats rather than rooted in the sediments (Figure 1). Therefore, water depth is not a concern and the mats are highly unlikely affected by fluctuations in water levels.

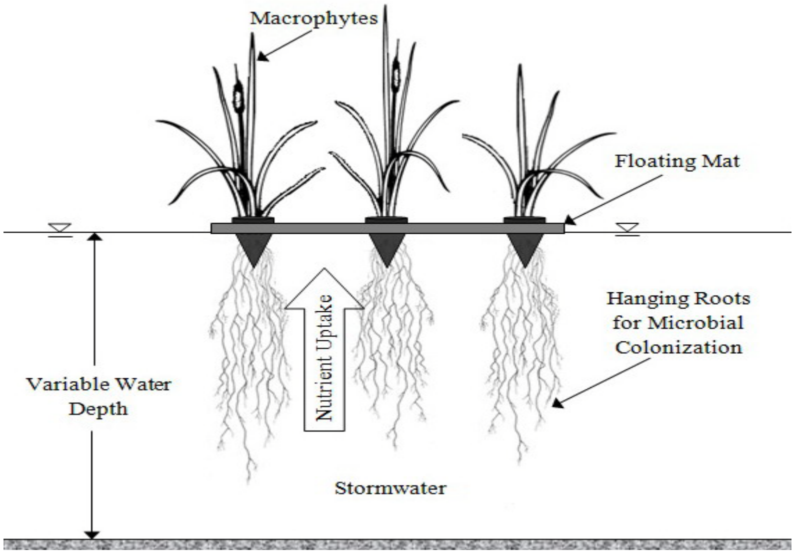


Figure 1: Cross Section of a Typical Floating Treatment Wetland

Biologically, aquatic macrophyte-based water treatment system is far more diverse than usual mechanical treatment systems (Hammer, 1989; Moshiri, 1993). Free-floating macrophytes provide shading of the water column resulting in a cooler habitat for aquatic life (Nahlik and Mitsch, 2006). Denitrifying bacteria can accumulate around the hanging roots which can be considered as an anaerobic zone, thus able to remove nitrate by denitrification process (Govindarajan, 2008), and these roots entrap fine suspended particulates that would otherwise remain in the water column in a conventional pond system (Headley and Tanner, 2006). Microbes that live on the surface of plant roots in a wetland remove ten times more nitrate than do the plants themselves (Adams, 1992). These microbes change nitrate nitrogen (NO_3-N) to ammonia nitrogen (NH_4-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 increase as physiological growth continues. Total nitrogen and phosphorus can be removed if the plants are harvested regularly. Finally, algal toxin can be avoided in the pond, as they cannot grow due to lack of nutrients.

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 is expected to significantly improve the nutrient removal (Chang et al., 2007) and the production of plant biomass (Figge et al., 1995). It also improves 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 is no soil in the rhizospheric zone of FTWs, the incorporation of sorption media may promote the attraction of sorption surface between the pollutant and the sorption media that causes the pollutants to leave the aqueous solution and simply adhere to the sorption media (Hossain et al., 2010). Thus, phosphorus may be removed by both adsorption and absorption. Moreover, a biofilm can be formed on the surface of media particles to allow microbes to assimilate nitrogen species although nitrogen cannot be removed by sorption directly. It is indicative that sorption provides an amenable environment for subsequent nitrification and denitrification (Xuan, 2007). The use of these sorption media remove not only the nutrients, but also some other pollutants, such as heavy metals, pathogens, pesticides and toxins (Chang et al., 2010).

1.2 Objectives

A flowchart of the overall experiment is shown in Figure 2 where both small-scale (microcosm) and large-scale (mesocosm) studies have been conducted. Microcosm study emphasizes on physical growth response of selected plants in limiting nutrient with variation of sorption media. On the other hand, mesocosm study helps taking engineering decisions and ecological consequences before implementation of FTWs in an actual pond. Experimental hypotheses have been discussed in the following sections:

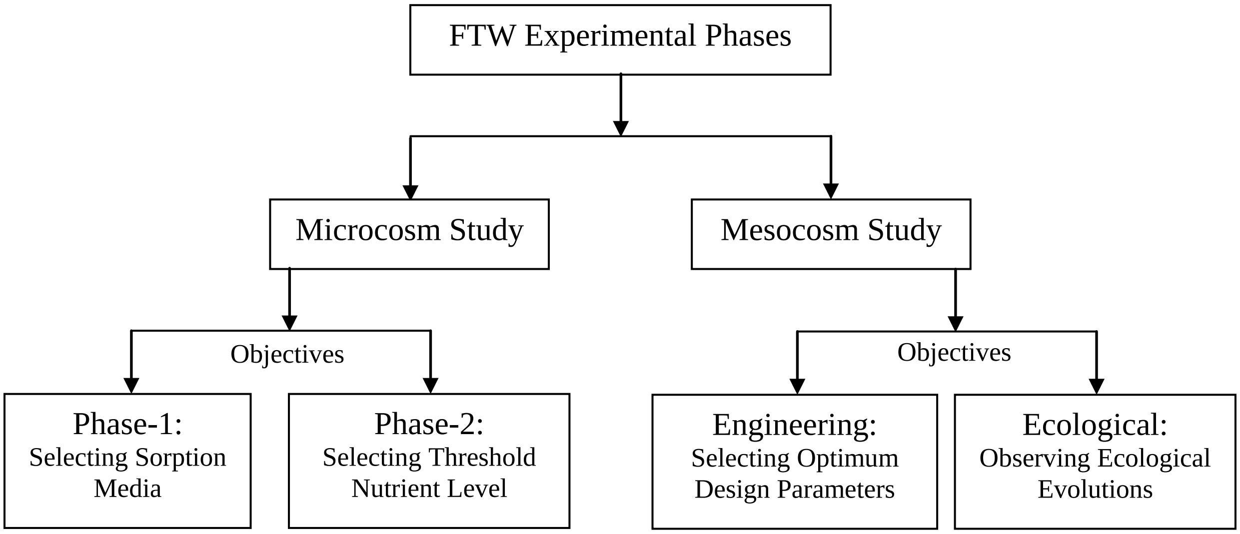


Figure 2: Flowchart of the Overall Experiment

1.2.1 Hypotheses: Microcosm Study

For the microcosm study the author hypothesizes that:

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.

Plant root lengths will be monitored as an index of successful penetration through the geotextile filter. Biweekly stem heights and total biomass increase will also be compared in order to understand the sorption media contribution. Nutrient limitation will be identified by regular analysis of water sample.

1.2.2 Hypotheses: Mesocosm Study

For the mesocosm study the author hypothesizes 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) There is an aggregation of nutrients near the rhizospheric zone resulting in a higher concentration beneath the floating mat.
6) FTWs will be an alternate solution for common stormwater detention pond problems by suppressing unwanted species like algae, duckweeds etc.

One-way ANOVA test will be able to show if water depth has any significant impact on nutrient removal efficiency or not. Effect of percent area coverage, littoral zone and sorption media can be understood by regular monitoring of water quality parameters and gradient of nutrient concentration can be measured by spatial sampling from the mesocosms. Finally, temporal observation and unwanted plant species identification can help elucidate ecological evolution and interactions.

1.3 Limitations

Budget constraints did not allow us to replicate the mesocosm. Flow of stormwater was not continuous too. Thus, our experiment best represented the non-tidal wetland phenomena. Nutrient concentration in the sediment was not incorporated considering that all mesocosms deposited equal amount of nutrients. Plant tissue nutrient concentrations were measured taking only one representative sample from each mesocosms which sometimes might be diversionary.

CHAPTER 2: LITERATURE REVIEW

2.1 Selection of Plant Species

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 wetland used in large-scale application (Kadlec et al. 1996; DeBusk et al. 1995). These are candidate plants along with others being used by local nurseries in their promotion of floating islands. *T. japonica*, *E. crassipes*, and *P. stratiotes* performed high nutrient removal efficiencies when nutrient removal rates were calculated by biomass-based method, while they were not efficient when nutrient removal rates were calculated by area-based method (White et al. 2009). Both *Canna flaccida* and *Juncus effussus* are indigenous to the wetlands of 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). There is another species *Agrostis alba* which is also effective but not native in Florida. Considering all these, Canna (Figure 3a) and Juncus (Figure 3b) are selected as the floating macrophytes of the microcosm and mesocosm study. On the other hand, Bulrush (*Scirpus californicus*) (Figure 3c) and Pickerelweed (*Pontederia cordata*) (Figure 3d) are selected in the mesocosms; as the emergent macrophytes of littoral zone as they are endemic flora of Florida.

(a) Canna **(b) Juncus**

(c) Bulrush **(d) Pickerelweed**

Figure 3: Selected Floating Macrophytes (a & b) and Emergent Macrophytes (c & d)

2.2 Selection of Sorption Media

Sorption media can increase water holding capacity resulting in significant improvement of nutrient removal efficiency (Chang et al. 2007) and the production of plant biomass (Figge et al. 1995). It also improves 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 is no soil in the rhizospheric zone of FTWs, the incorporation of sorption media may promote the attraction of sorption surface between the pollutant and the sorption media that causes the pollutants to leave the aqueous solution and simply adhere to the sorption media (Hossain et al. 2010). The use of these sorption media remove not only the nutrients, but also some other pollutants, such as heavy metals, pathogens, pesticides and toxins. Thus, phosphorus may be removed by both adsorption and absorption. Moreover, a biofilm can be formed on the surface of media particles to allow microbes to assimilate nitrogen species although nitrogen cannot be removed by sorption directly. It is indicative that sorption provides an amenable environment for subsequent nitrification and denitrification (Xuan 2007).

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™) is applied to support the current floating wetland study which is effective in reducing nitrogen (up to 47%) and phosphorus (up to 87%) from stormwater found in wet detention ponds. It does not become exhausted or saturated and thus can be used without frequent replacement. Bold and Gold Stormwater™ (B&G) is a tire crumb based media composition with varying mixture subject to different applications. Based on a previously performed microcosm study 60% Expanded Clay is mixed with 40% Tire Crumb (Figure 4).


Expanded Clay Tire Crumb

Figure 4: Components of Sorption Media

CHAPTER 3: MATERIALS AND METHODS

3.1 Experimental Design: Microcosm Study

Ecological systems do not have a single characteristic scale due to its embedded nonlinearity. Insightful research is likely 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 and the microcosm study was divided into three major phases. In the first phase, plant growth was monitored over 18 weeks for the variation of sorption media. Only one microcosm was used this time for growth of 24 plants (Table 1) and 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

Second phase started at the end of the first phase and lasts 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 descending amount of initial nutrients (Figure 5). Proportion of expanded clay increased to 80% (with 20% tire crumb) this time, as it might perform slightly better in the first phase (i.e., this is discussed more in the results and discussion section). This phase is also run for 24 plants in each microcosm. However, sorption media was intermittently arranged and nutrient dosing scheme was fixed in different microcosm. Plant species, sorption media and initial nutrient levels in different microcosm are summarized in Table 2.

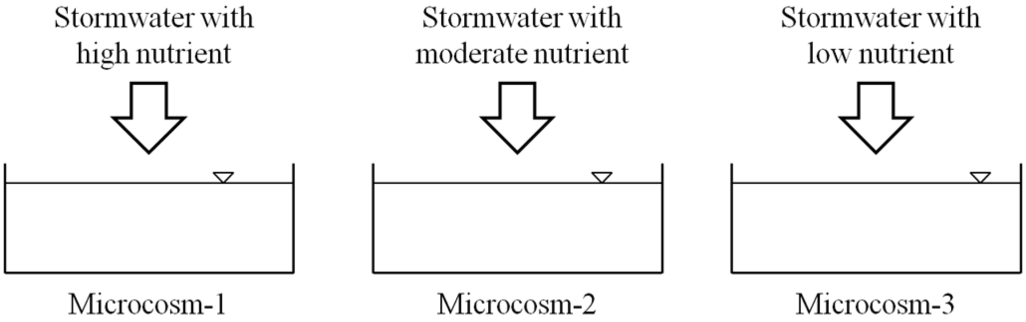


Figure 5: Nutrient Dosing Scheme in the Microcosms (2nd phase)

Table 2 Plants, sorption media and nutrient level 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 (Govindarajan 2008)**

3.2 Experimental Design: Mesocosm Study

Eleven scenarios have been created varying percent area coverage, littoral zone and water depth (Figure 6 and Table 3). Case-1 and Case-2 are without any floating macrophytes and performing as control cases. Sorption media has been used in all the cases except Case-7b which is control case in this regard. Considering feasibility of actual pond, percent area coverage has been limited to 10%. Two different water depths are 90 cm and 56 cm for which bottom sediment thickness is 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.

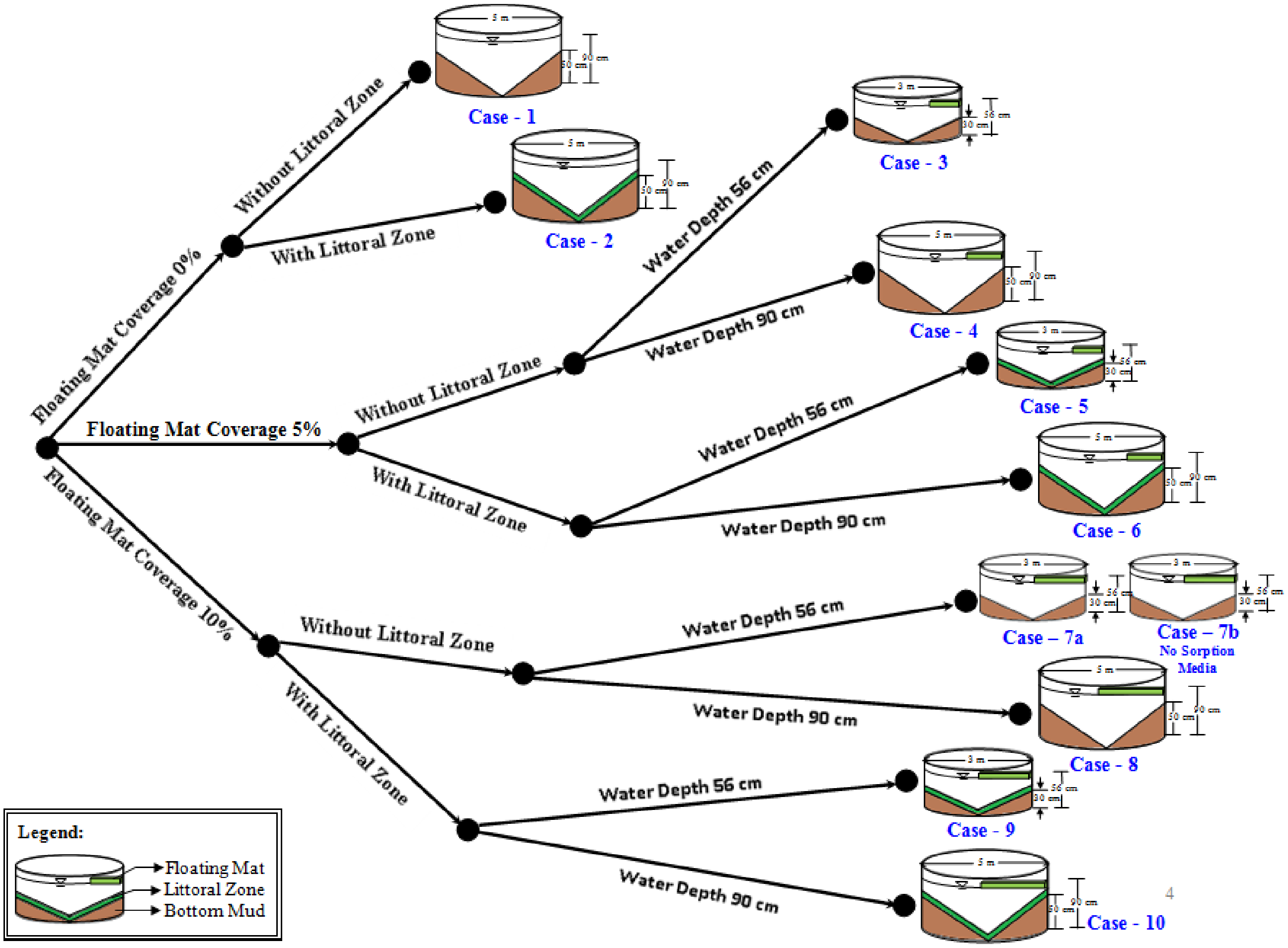


Figure 6: A Schematic Diagram of the Mesocosm Setup

Table 3 Component of the mesocosms

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

3.3 Sampling and Measurements

Study of plant root systems and root surface sorption zones requires knowledge of plant biomass (Raun 1997). However, measurement of plant biomass via harvesting is destructive as plants are integrated with sorption media, geotextile and perforated pot; therefore, increased biomass cannot not be measured during the experiment. Stem heights and root lengths were taken as the index of plant growth, decay or dying and only initial and final biomass was measured in order to substantiate other findings. For floating treatment wetlands, root lengths are important as they hang beneath the mat in the water column and influents pass through them. Longer roots are desirable in this system for higher nitrate reductase activity (NRA) resulting in enhanced nutrient uptake (Cedergreen and Madsen 2003). Even in case of stems of Canna and Juncus, biomass increases with the increase of stem height. Eventually average values as well as the standard deviation of stem heights and root lengths and increase of biomass are used for data interpretation of the microcosm study.

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

In mesocosm study, water was collected from an actual stormwater pond on the University of Central Florida campus and the background study of the pond showed a very low nutrient concentration (0.40 mg•L^{-1} TN and 0.008 mg•L^{-1} TP). Therefore, nutrients (3 mg•L^{-1} of Nitrate and 1 mg•L^{-1} of Phosphate) were dosed for determining nutrient removal efficiency. Commonly used fertilizers Potassium Nitrate (KNO_3) and Monopotassium Phosphate (KH_2PO_4) were used in this case. Dosing and addition of new stormwater were performed once in every 30 days which imitate natural rainfall event and consequent nutrient-rich surface runoff. Samples were collected on a bi-weekly basis over three months. Samples collected from five different points were mixed together in order to get a composite sample which is deemed as the representative sample over the whole mesocosm.

3.4 Chemical Analysis

DR 2800 Spectrophotometer was used to analyze nutrient concentrations. The methods used in chemical analyses can be summarized in Table 4. In order to maintain Quality Assurance/Quality Control (QA/QC) protocol, duplicate samples were analyzed in every ten samples. Preservation was done with acidification when necessary and percent recovery was ensured within 80% to 120% each time. All water sampling equipments were acid-rinsed followed by flushing in distilled water prior to sampling of each tank.

Table 4 Chemical analysis methods

Parameter	Method
pH	Hach sensION156 (Product #: 5465014)
Conductivity	Hach sensION156 (Product #: 5465014)
Dissolved Oxygen	Hach sensION156 (Product #: 5465014)
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 Experimental Setup: Microcosm Study

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

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

Water is collected from an actual pond, background study of which showed very low nutrient concentration (0.40 mg•L^{-1} TN and 0.008 mg•L^{-1} TP). Therefore, nutrients (3 mg•L^{-1} of Nitrate and 1 mg•L^{-1} of Phosphate for first phase) are dosed for the survival of the plants. Commonly used fertilizers Potassium Nitrate (KNO_3) and Monopotassium Phosphate (KH_2PO_4) are used in this case.

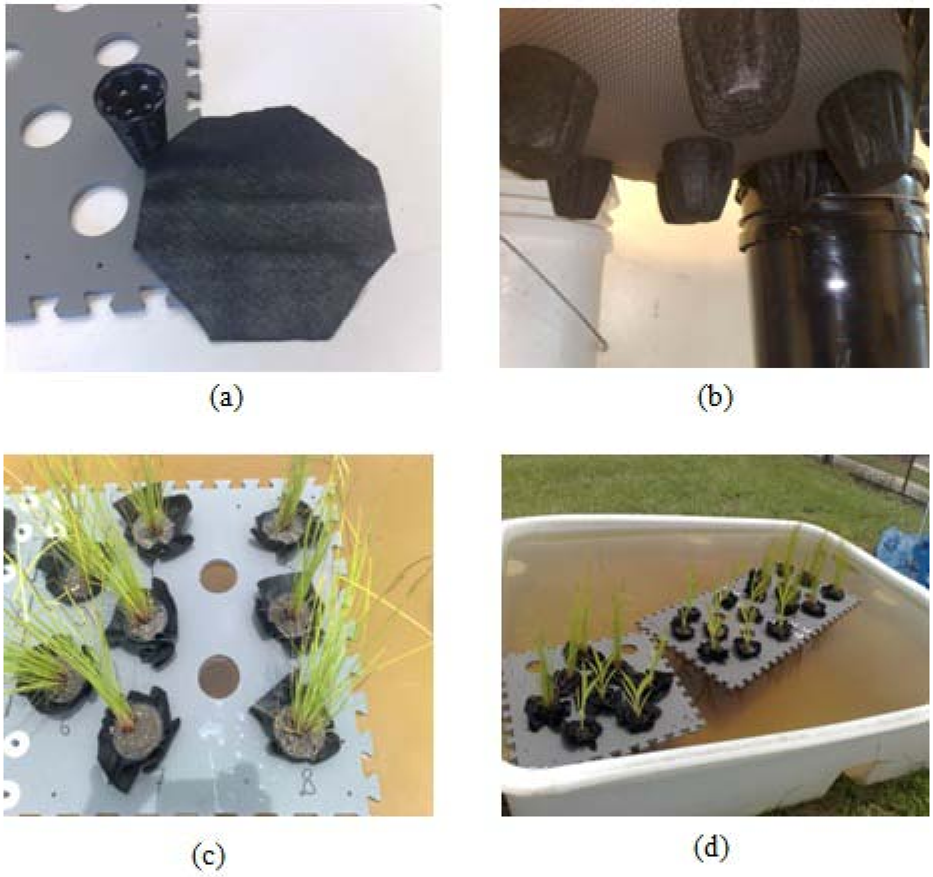

(a) (b) (c) (d)

Figure 7: (a) Foam Mat, Perforated Pot And Geotextile (b) Geotextile Wrapping (c) Addition Of Sorption Media (d) Plants In The Microcosm

3.6 Experimental Setup: Mesocosm Study

Cylindrical plastic tanks with the dimension 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 are used as mesocosms. Bottom soil was collected from an actual pond and placed (Figure 8a) under all the mesocosms for planting emergent littoral zone plants (Figure 8c). Even where there is no littoral zone, sediment is placed in order to mimic actual pond environment. For proper light, wind and seasonal variation, mesocosms are placed in the open field (Figure 8h). Sufficient aeration due to wind, rainfall events and evaporation ensured almost perfect imitation to actual pond.

Buoyant interlocked foam mats are used to keep the plants floating. Puzzle cut mats (60 cm × 60 cm) (Figure 8d) joined together by nylon connectors so that they can be assembled in any size or shape. After the mats are connected, plants are inserted into pre-cut holes within perforated plastic pots (Figure 8d). Sorption media is added in an innovative way so that they can float along with the plants. Mirafi® N-Series Nonwoven Polypropylene Geotextile (Figure 8d) is wrapped around (Figure 8e) those perforated pots in order to hold the sorption media inside. With the plant inside each pot can hold about 60 g of media. For the control case, where there is no sorption media, inert coconut fiber is used to hold the plants upright.

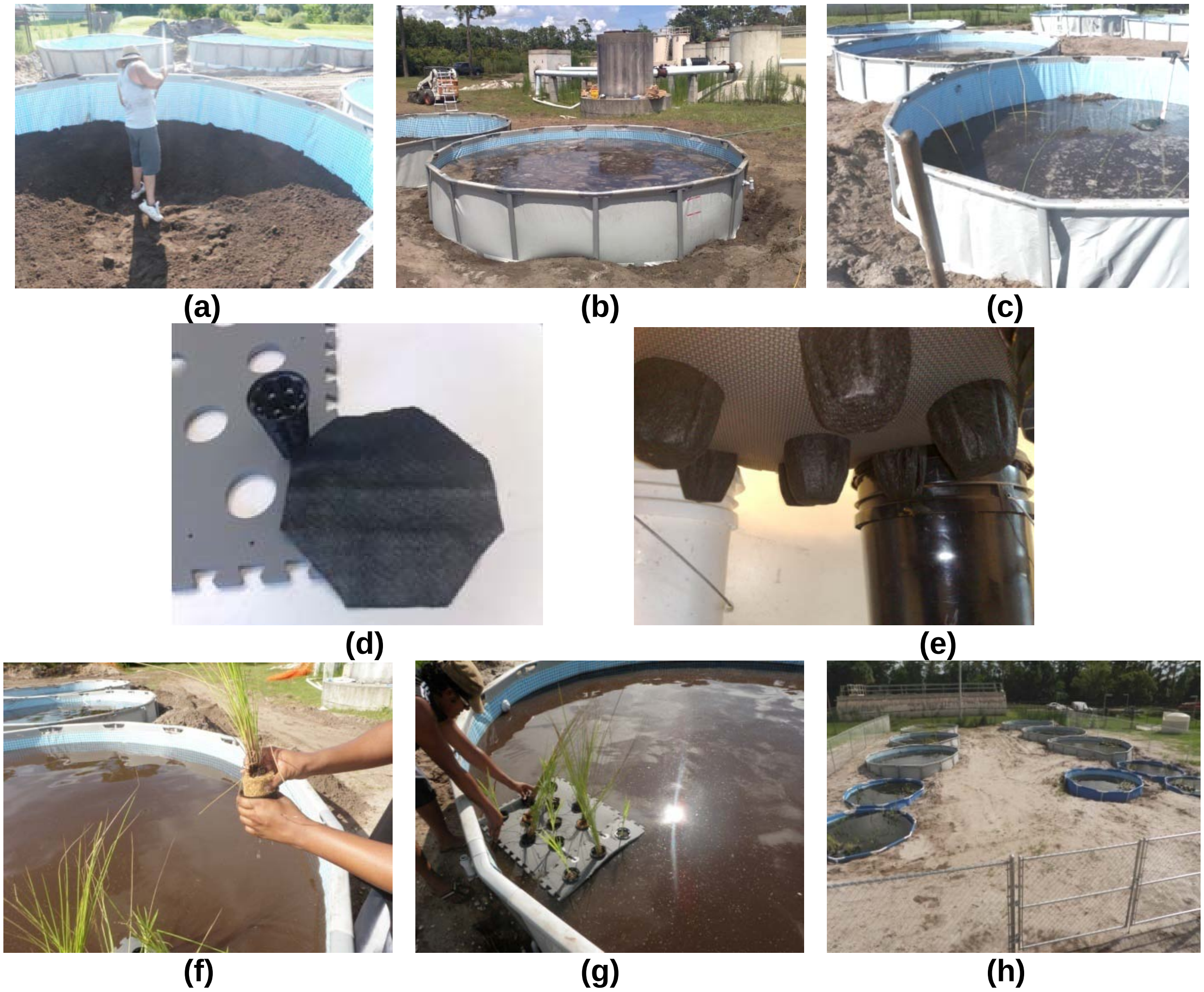


Figure 8: (a) Placement of Bottom Sediment (b) Mesocosms With Stormwater (c) Plantation In The Littoral Zone (d) Foam Mat, Perforated Pot And Geotextile (e) Geotextile Wrapping (f) Coconut Fiber In The Control Case (g) Floating Mats In The Mesocosm (h) Set of Mesocosms

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Microcosm Study

Root mobility appeared somewhat constricted by the geotextile; however, it is impossible to determine whether this restriction is 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 9). After 18 weeks of observation (Appendix B & C) in the 1st phase, we see that the addition of expanded clay performs better. While stems grow better in case of Canna (Figure 10), growth of root is better in case Juncus (Figure 11). In some cases, control case looks better; though. With the inclusion of sorption media, however, there might be some inhibited growth of roots as compared to the control case.

Figure 9: Root Penetrations through the Geotextile Filter

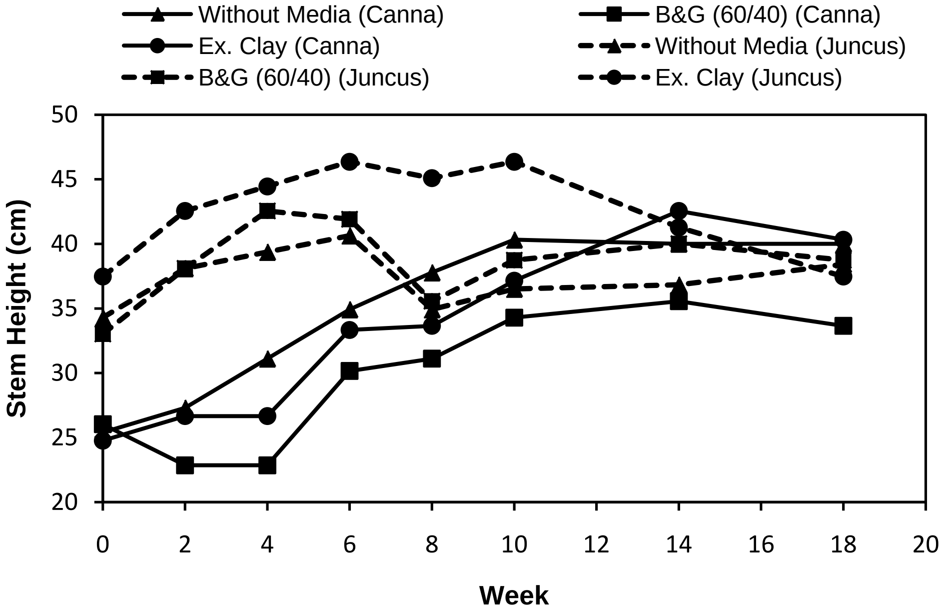


Figure 10: Effects of Sorption Media on Stem Growth

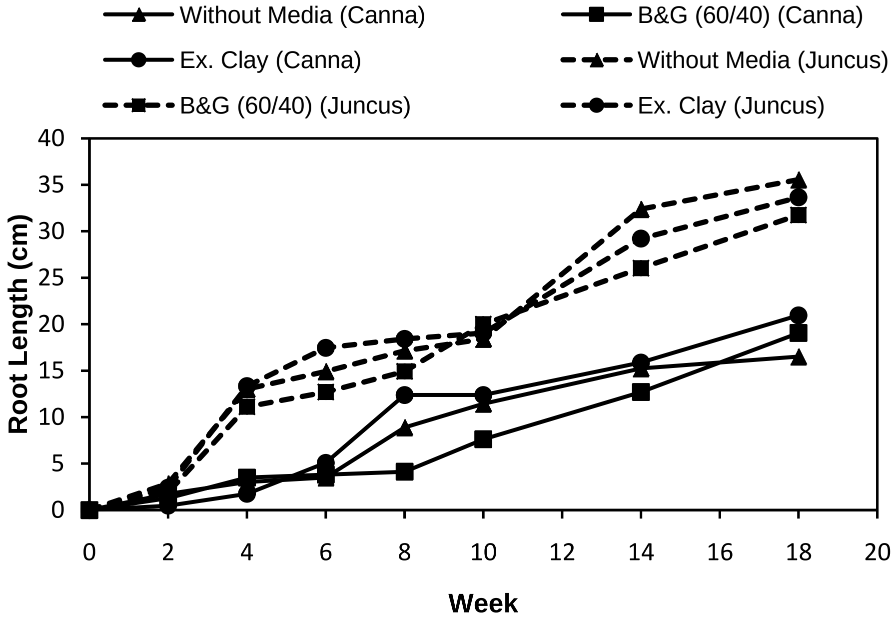


Figure 11: Effects of Sorption Media on Root Growth

In the 2nd phase of the study (Appendix D & E), sorption media performs better (Figures 12, 13 & 14) especially in stem growth. However, most of the time, plant growth in the other two microcosms is almost the same as that in control case which can be explained by the aforementioned reason of inhibited growth. The addition of sorption media is not only for plant growth but also for nutrient removal in FTWs. It is expected that the implementation of this new technology on a large-scale pond will show much distinguishable results in the future. In case of nutrient consumption (Appendix F), although it is supposed to start from 3mg•L^{-1} Total Nitrogen and 1.5 mg•L^{-1} Total Phosphorus according to the experimental design; it is reasonable to have slight deviation (Figures 12c, 13c and 14c) from those prescribed levels. Even with precise tank volume calculation, nutrient level may fluctuate due to the residual nutrient level in the actual wet pond water while collecting it. Moreover, the plants have compost near the roots provided by the nursery that also contributed to such fluctuation. Therefore, it is normal for nutrients to be increased in the aqueous solution. A decrease is also possible due to the rainfall event as microcosms are placed in the open field.

With time, nutrient was taken up by the plants (Figures 12c, 13c and 14c) and all the microcosms experienced a drop of nutrient level and dwindled nutrient concentration causes the deficiency of nutrient uptake. Eventually, plants died or reduced in stem height before encountering the severe nutrient deficiency (Figure 14). The reason behind it is the temperature effect as discussed later. It is evident that in a specific temperature plants went dormant in Microcosm-1. However, in Microcosm-2 and 3, plants started to reduce in height (dormancy induction) before the minimum temperature appears. It can be inferred that, nutrient limitation is the reason behind this phenomena.

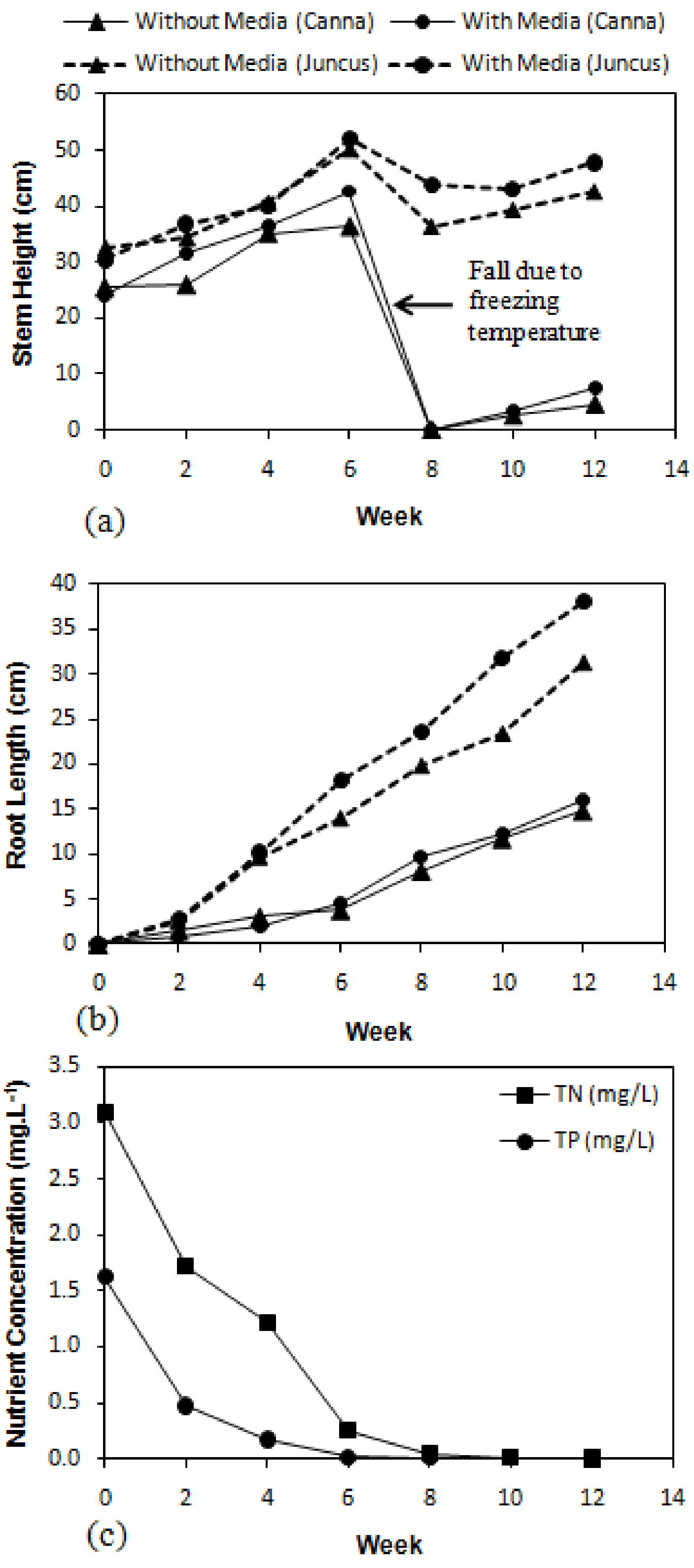


Figure 12: Plant Growth and Remaining Nutrient Level in Microcosm-1

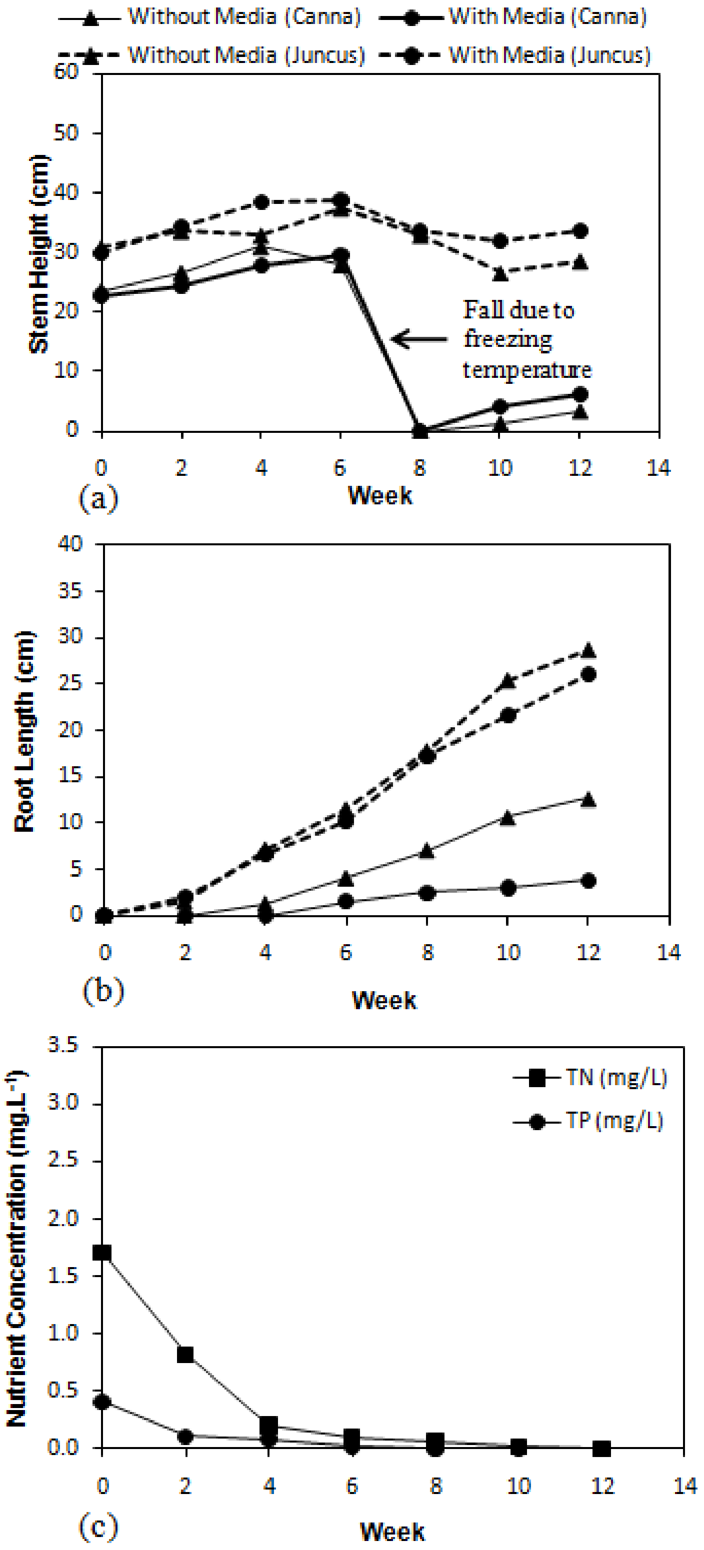


Figure 13: Plant Growth and Remaining Nutrient Level in Microcosm-2

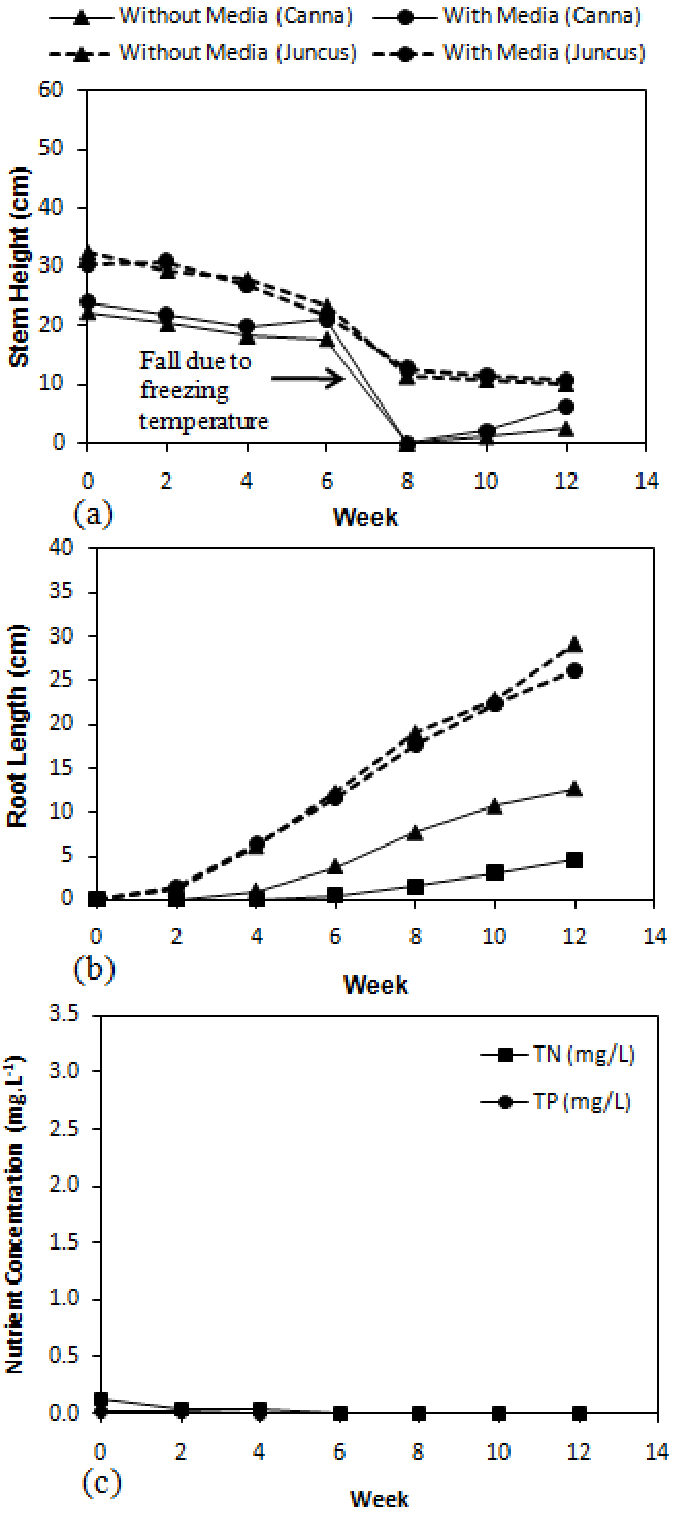
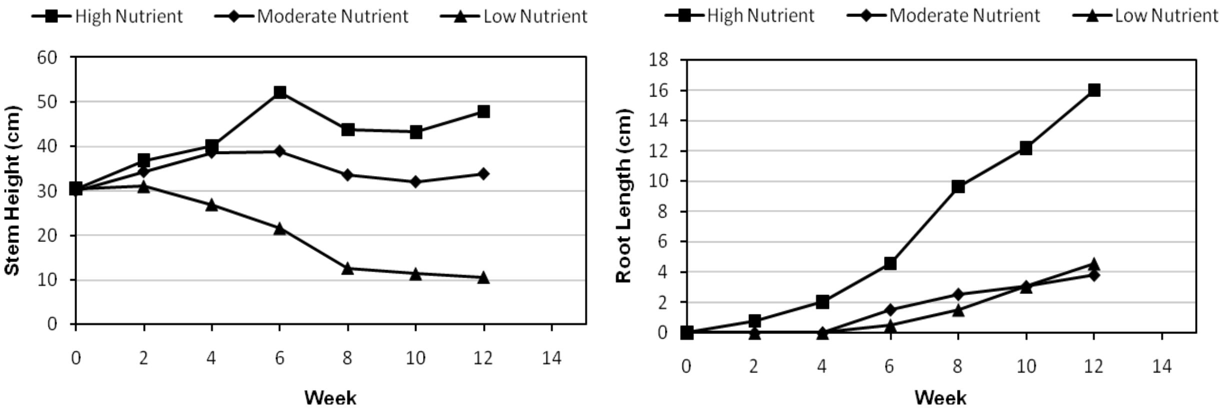


Figure 14: Plant Growth and Remaining Nutrient Level in Microcosm-3

In order to determine the threshold nutrient level, separate graphs are plotted (Figure 15). Those are the distinguishable results from several combinations. For stems, it is observed (Figure 15a) that, plants of the microcosm with high nutrient level kept growing due to the availability of the nutrients, but reduced in height during 7th week due to cold weather instead of nutrient deficiency. Plants of microcosm with moderate nutrient level stopped thriving before the arrival of the freezing temperature. We can infer that, there was shortage of nutrients at that time and before that plants already consumed supplied nutrients. In the microcosm with low nutrient level, it is clear that after just 2 weeks of the start date, their stems started to reduce and eventually top of the plant shoots became brown and died back to water. Effect of optimum nutrient level is observed more clearly in the roots of Canna (Figure 15b) where roots in the microcosm with high nutrient level grew much longer. For the floating wetlands, this root growth is deemed important for nutrient removal.



(a) **(b)**

Figure 15: Stem Growths (a) In Juncus and Root Growth (b) In Canna with Media Due To Variation of Nutrient Level

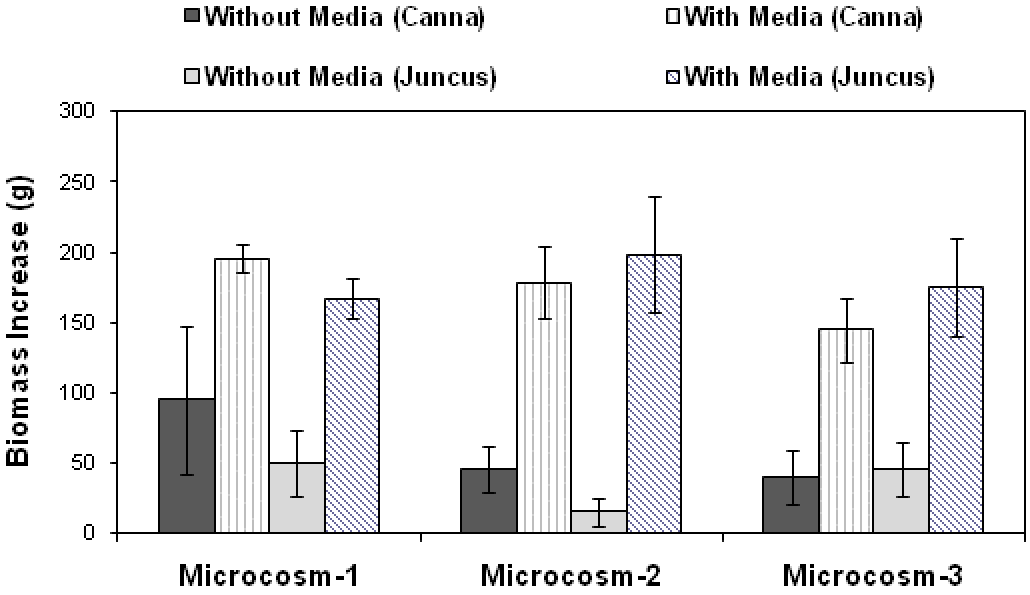


Figure 16: Comparative Biomass Increase

Although there is less effect of sorption media on lengths of roots and shoots, there is a significant increase (Figure 16) in the plant biomass (Appendix G) for both Canna and Juncus. On the other hand, variation of nutrients does not show commensurate changes in the biomass. Temperature might be a major issue during the winter season as it influences the productivity of the aquatic plants by controlling the rate of chemical reactions as well as nutrient acquisition [33-35]. In the 7th week of the study (2nd phase) temperature was as low as 3.3 °C (Figure 17) and this low temperature is lethal for Canna (Figure 18b). All the leaves died due to frost during that week. Although Juncus did not die, their heights reduced during that time period.

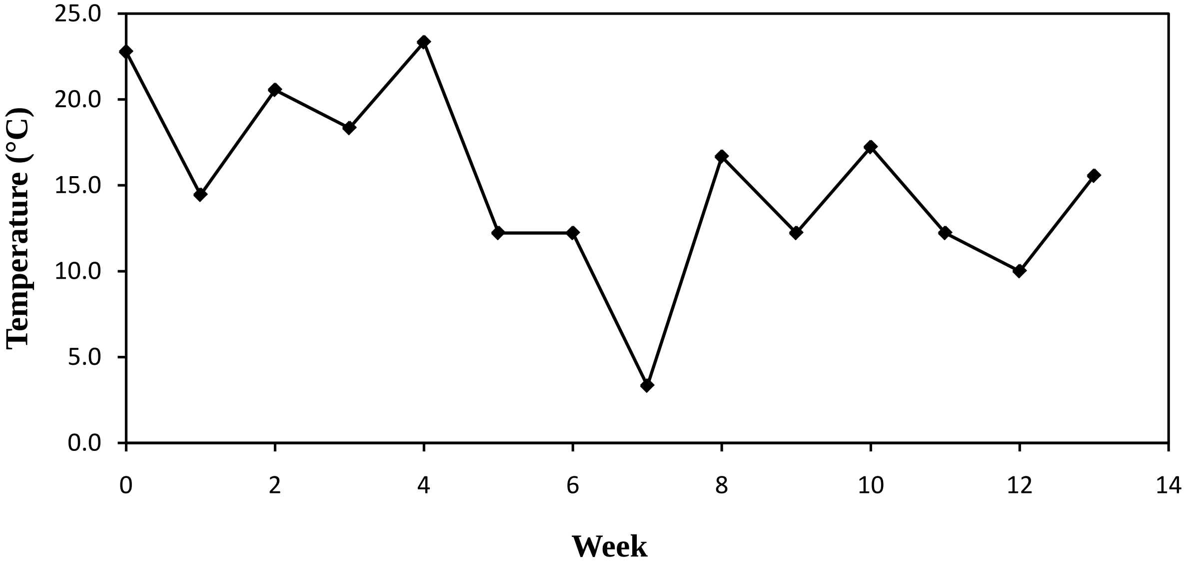


Figure 17: Variation of Ambient Temperature during 2nd Phase

(a) **(b)**

Figure 18: (a) Microcosms at the End of 2nd Phase (b) Canna and Juncus at Freezing Temperature

One-way ANOVA shows that sorption media has significant effect on the plant biomass (for Canna: p= 0.008; for Juncus: p=0.001). For stem heights nutrient concentration did not show significant effect most of the time (Table 5), but for root length nutrient effect is salient most of the time (Table 6). Although the one-way ANOVA study confirms the credibility of this 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 5 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 6 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

4.2 Mesocosm Study

According to The National Stormwater Quality Database (NSQD) (Pitt et al., 2004), stormwater runoff contains 3 mg•L^{-1} Total Nitrogen and less than 1 mg•L^{-1} Total Phosphorus on an average. Due to different bottom mud compaction and corresponding change in water volume it was difficult to maintain constant initial nutrient loading in our experiment. Therefore, small amount of deviation from the usual stormwater quality was observed in the initial nutrient concentrations. Both influent and effluent concentrations of various parameters are shown in Table 7 which indicates the efficacy of the FTW system. Although control case (Case-1) is supposed to show 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 are satisfactorily low. Actually, the absence of plants in the control case allowed them to grow and cover the whole surface resulting in significant amount of nutrient removal.

Duckweeds require a lot of nutrients to grow, so typically they are found in nutrient-rich environments. A surface layer of duckweeds will prevent sunlight from reaching the deeper parts of the water column. This means that underwater plants and algae can no longer photosynthesize and produce oxygen which can greatly stress or even kill fishes.

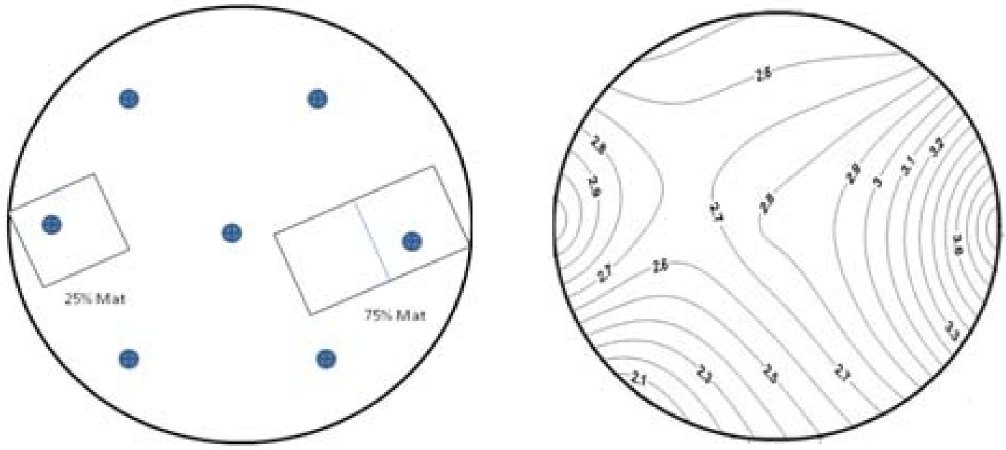
Table 7 GroupWise effluent concentration after 30 days of floating wetland treatment (Cycle-1)

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

4.2.1 Nutrients Aggregation toward Rhizospheric Zone

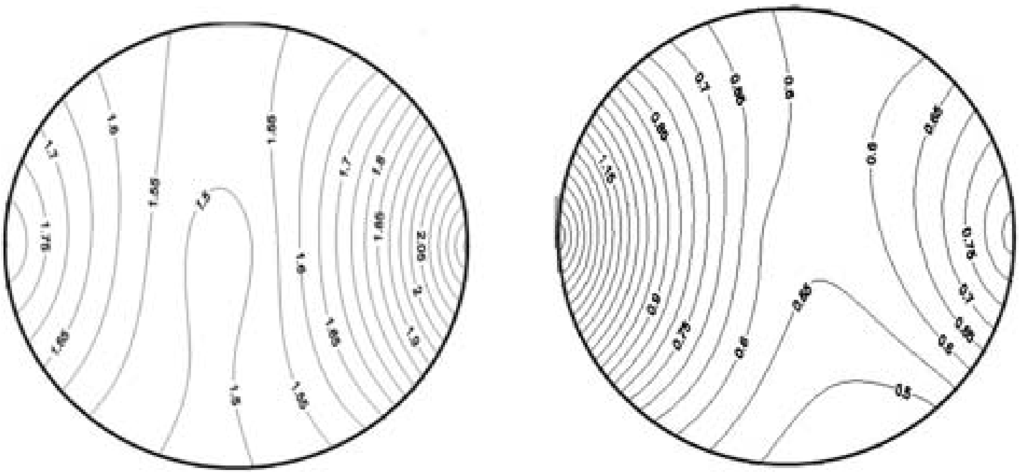
Sasser et al. (1991) reported that nitrogen and phosphorus concentrations within the floating marsh system were consistently higher than adjacent lake and sediment-rooted swamp water. This may be related to the fact that the plant root mats have a much greater potential for interaction with the water column. There is a high likelihood that any dissolved elements liberated from decomposing root or peat material suspended in the floating mat will return to the underlying water column. The dissolved nutrients that are enriched in the free-water under the floating mat are drawn upward by the transpiration stream, and root absorption and microbial activity decrease their concentrations in the upper levels of the marsh substrate. For observation of nutrient aggregation Case-8 was selected which has 90 cm water depth, no littoral zone and 10% coverage of floating mat.

To observe this phenomenon, floating mats were split (75% and 25%) and anchored in two opposite edges of the diameter. Samples were collected from both directly beneath the floating mats and far from the root zone. At the beginning of the study nutrient concentration was homogenous all over the surface area irrespective of the vicinity of the root zone. After 30 days, again samples were collected in the same manner and tested in the laboratory. Observed values were plotted (Figure 19) in the contouring software Surfer 8.0 and it is seen that nutrient concentration was much higher near the root zone and in all the cases (except Total Nitrogen) density is higher near the larger floating mat.



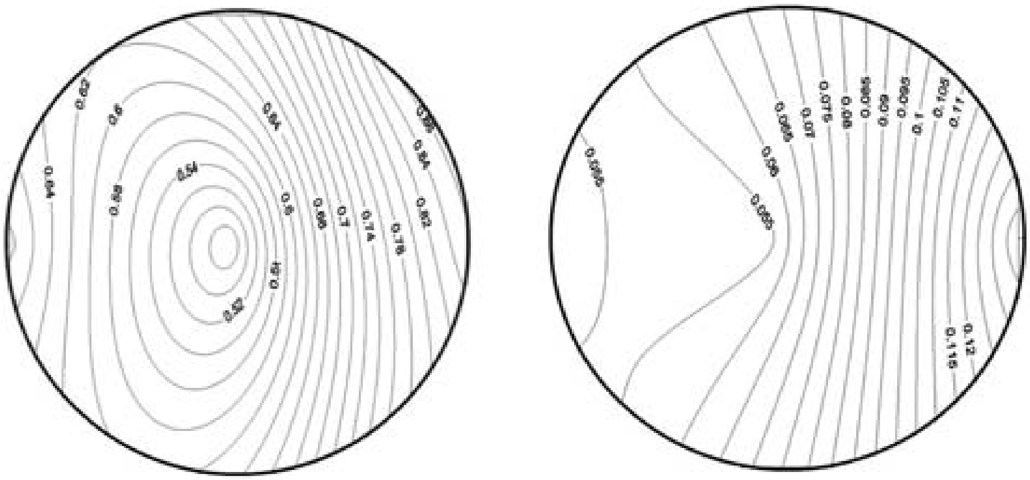
● Sampling Points

Total Phosphorus (mg/L)



Orthophosphate (mg/L)

Total Nitrogen (mg/L)



Nitrate (mg/L)

Ammonia (mg/L)

Figure 19: Contour Diagram of Nutrient Concentrations

4.2.2 Effect of Water Depths

Several mesocosms were set up with varying depth of water column under the floating mat. One-way ANOVA test was performed by Minitab software to check if there is 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 depth, 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) indicate that the distinction of water column depth is not statistically significant across the relevant mesocosms.

4.2.3 Effect of % Area Coverage

Excluding control case, nutrient removal efficiency was not significantly different (Figure 20 & 21) between mesocosms with 5% and 10% floating macrophyte coverage. It can be inferred that, even without the presence of littoral zone 5% coverage is enough for significant amount (53.82% TP, 48.06% OP, 31.84% TN and 48.21% Nitrate) of nutrient removal in just 15 days. Moreover, in actual pond it might not be feasible to go over 5% floating mat coverage for the requirement of large surface area which will also inhibit sunlight to reach the bottom of the pond.

Although algae are big nutrient consumers in the aquatic ecosystem, they cannot grow much competing with floating plants. With the increase of percent area coverage of floating macrophytes, a decrease in Chl-a value was observed (Figure 21), which is an indicator of decreased algae. Without littoral zone, however, this relationship is not salient.

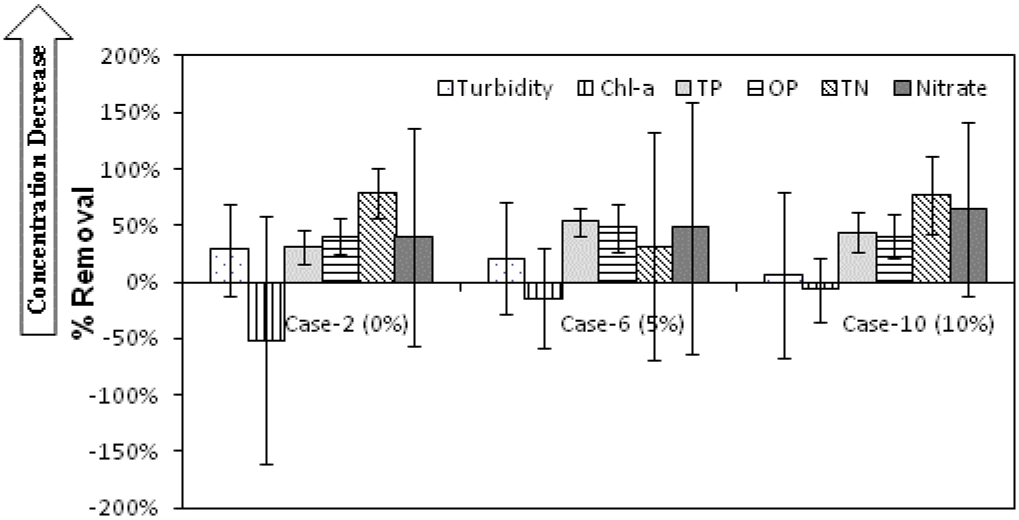


Figure 20: Effect of % Area Coverage with Littoral Zone (15 Days Removal Efficiency)

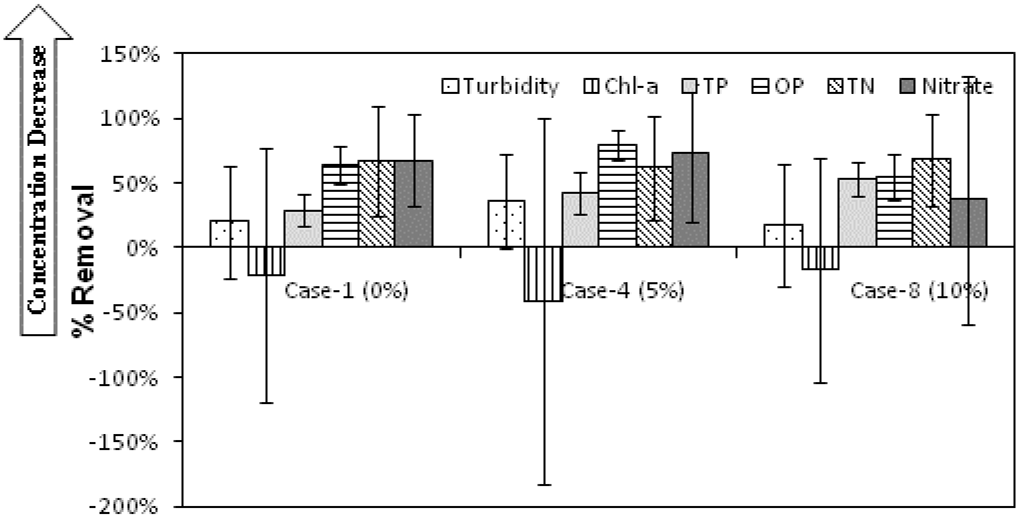


Figure 21: Effect of % Area Coverage without Littoral Zone (15 Days Removal Efficiency)

4.2.4 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). Comparing Case-3 and Case-5, we see the effect of littoral zone is prominent on Chl-a and turbidity (Figure 22) - both of them decreased significantly due to the presence of littoral zone. However, nutrient removal efficiency is almost the same in both cases. Comparison of other specific cases also show the effect of littoral zone, but for aforementioned reason, it is not possible to decide the value of littoral zones in terms of nutrient removal efficiency in these experiments.

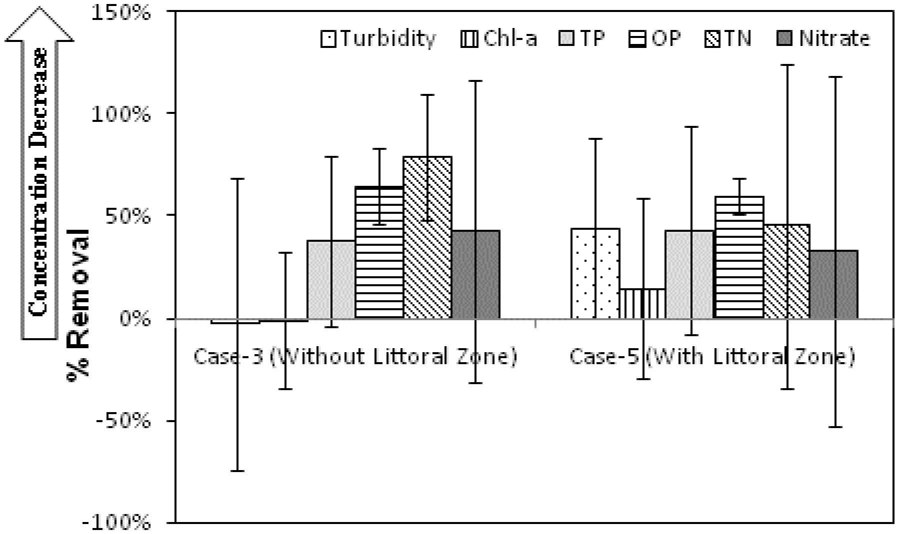


Figure 22: Effect of Littoral Zone on Removal Efficiencies (15 Days Removal Efficiency)

4.2.5 Effect of Sorption Media

Total Phosphorus and Orthophosphate removal was much better (Table 8) in the mesocosm with sorption media especially in Cycle-2 and Cycle-3. Nitrate removal efficiency was almost same. However, Total Nitrogen removal was better in the mesocosm without any media. Phosphorus might be removed by both adsorption and absorption. Moreover, a biofilm formation is possible on the surface of the sorption media particles to allow microbes to assimilate nitrogen species although nitrogen cannot be removed by sorption directly.

Table 8 Effect of sorption media on effluent water quality

Cycle*	**Sorption Media**	**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 ($mg.L^{-1}$)
Cycle-1	With Media	2.313	0.742	2.001	0.462	3.447	1.348	0.916	0.065
	Without Media	2.807	0.398	2.253	0.210	4.253	0.816	1.030	0.057
Cycle-2	With Media	1.668	0.264	0.767	0.137	1.969	0.000	0.661	0.133
	Without Media	1.841	0.664	0.844	0.214	1.244	0.000	0.840	0.010
Cycle-3	With Media	3.538	0.883	1.948	0.385	0.744	0.512	0.231	0.114
	Without Media	3.816	1.832	2.329	1.190	1.384	0.000	0.307	0.086

*** 30 days monthly cycle**

4.2.6 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 are expressed (Figure 23) as the percentage of their dry weights. It is seen that, roots and shoots have taken almost equal amount of nutrient. Nitrogen uptake was much higher than that of Phosphorus which is 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 nutrient as the representative sample, daily nutrient uptake per unit area of floating mat has been calculated for each mesocosm. On an average nitrogen uptake rate was 36.39 $mg/m^2/day$ and phosphorus uptake rate was 1.48 $mg/m^2/day$ for the FWT systems.

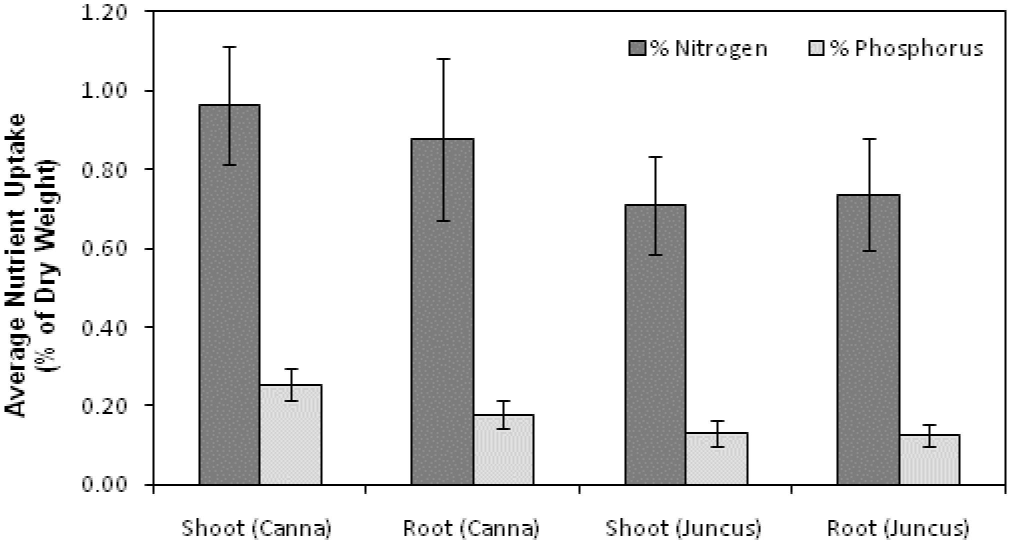


Figure 23: Average Tissue Nutrient Concentrations (% of Dry Weight)

4.2.7 Efficacy of FTWs Based on Macrophyte- Epiphyte-Phytoplankton Competition

Fertilizer was dosed on a monthly basis for the nutritive importance of the macrophytes. As the time went, various weeds and algae started to grow. Most visible one was duckweed (*Lemna minor*). Duckweeds are free-floating plants that can totally cover the surface of a pond. These plants require a lot of nutrients (nitrogen and phosphorus) to grow, so typically they are found in nutrient-rich environments. Table 9 shows almost all the ecological findings in a sequential manner. After 3 months, control case (Case-1) became infested (100%) with duckweeds for the absence of macrophytes. Some other mesocosms also had partial duckweed coverage. Although they had floating macrophytes or 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; it was covered 100% by filamentous blue green algae (Cyanophyceae). This algae was tested in the laboratory and identified that majority of samples had Oscillatoria. There were also other two species named Microcystis and Ankistrodemus. After 7 months, there were not only duckweeds and algae, but also significant amount of other plant species near the floating plant roots. In control cases, there were no floating plants. For this reason other plants could not grow.

From above observation on temporal ecological changes, it is evident that FTWs can suppress algae and duckweed growth significantly especially if compared with control cases. Other weeds (Alligator weed, Dogfennel, False hop sedge, Bladderwort, Goosefoot etc.) found after 7 months, might be beneficiary for the system as they grew on the floating mats along with Canna and Juncus; and it is possible for them to take up nutrients. At this stage, few mesocosms showed 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. Rather, a nutrient source that significantly influenced epiphyte P metabolism throughout the growing season. Bottom sediments might also be the possible contributor for providing this extra nutrient as they were getting old.

Table 9 GroupWise proportion of epiphytes and phytoplankton

				After 3 Months (Sep-Oct-Nov)	After 5 Months (Dec-Jan)		After 7 Months (Feb-Mar)		
Scenario	Macrophyte Area Coverage	Littoral Zone	Water Depth (cm)	Epiphyte	Epiphyte	Phytoplankton	Epiphyte		Phytoplankton
				Duckweed	Duckweed	Algae	Duckweed	Other#	Algae
Case-1*	0%	No	90	100%	0%	100%	40%	-	20%
Case-2*	0%	Yes	90	1%	0%	100%	20%	-	35%
Case-3	5%	No	56	25%	15%	2%	0%	Type-3	15%
Case-4	5%	No	90	2%	2%	0%	80%	Type-1, 2, 3	50%
Case-5	5%	Yes	56	60%	5%	0%	10%	Type-4	5%
Case-6	5%	Yes	90	1%	0%	10%	20%	Type-1, 2	18%
Case-7a	10%	No	56	0%	10%	0%	0%	Type-1, 2, 5	75%
Case-7b	10%	No	56	0%	25%	0%	1%	-	3%
Case-8	10%	No	90	30%	5%	5%	90%	Type-1	10%
Case-9	10%	Yes	56	8%	0%	10%	3%	Type-1, 2	50%
Case-10	10%	Yes	90	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 are shown in Table 10. For comparison purpose nutrient consumption is shown instead of effluent concentration. Increased nutrient removal efficiencies were observed over the period of time while epiphytes and phytoplankton were growing. In control case, first 3 months of observation showed nutrient removal by only duckweeds as there were no macrophytes. Results after 5 months indicate the nutrient removal by only algae as no duckweeds were present at that time and after 7 months nutrient removal from the water column was lowest (20.42% TP and 74.74% TN). During this time both duckweeds and algae were present in much lesser proportion and some of them died resulting in less nutrient consumption. This observation on control case shows the demand of duckweeds and algae for nutrients which should have significant impact on other mesocosms with floating and emergent macrophytes.

Comparing nutrient consumption data between Case-1 and Case-2 (Table-10), we can see that they are more in Case-2 which should be due to the presence of littoral zone. In other cases, most of the time nutrient removal efficiencies and consumptions increased due to the presence of the epiphytes and phytoplankton.

Table 10 Nutrient removal efficiencies in association with ecological changes

Scenario	After 3 Months (Sep-Oct-Nov)		After 5 Months (Dec-Jan)		After 7 Months (Feb-Mar)	
	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}

4.2.8 Acclimation of FTWs in Aquatic Environment

Temperature and pH did not change that significantly during three months of observation (Figure 24). In Case-4 Chlorophyll-a (Chl-a hereafter) was observed higher (6.88 µg.L^{-1}) than the others. Some sort of contamination might have occurred in this mesocosm. A decrease in turbidity (Table 11) with increasing use in FTWs was also observed. For example, without any FTWs, control case (Case-1) showed highest turbidity (26.69 NTU), Case-2 was more transparent (18.56 NTU) for the presence of littoral zone and Case-10 was the most transparent one which had both littoral zone and 10% floating mat coverage. This is reasonable as both sediment rooted and floating plants reduce the amount of sediments that accumulates within the system by retaining biosolids within the root mass.

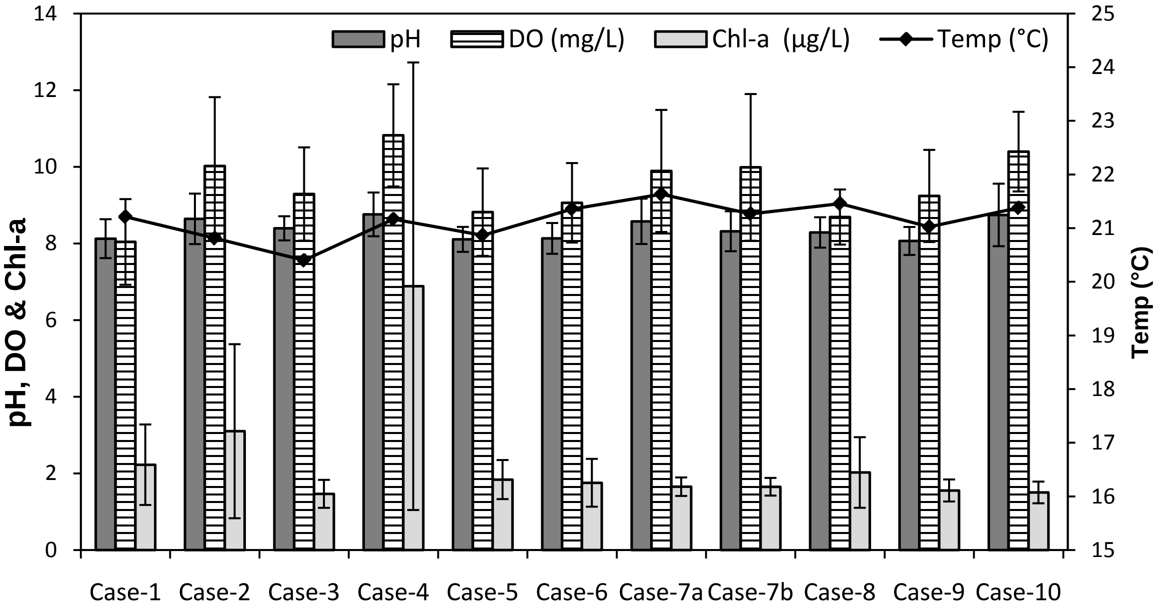


Figure 24: Variation of pH, DO, Chl-a and Temperature

Table 11 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

During photosynthesis, plants release oxygen into the water. During respiration, plants remove oxygen from the water. Bacteria and fungi use oxygen as they decompose dead organic matter in the stream. These types of organisms (plant, bacteria, fungi etc.) affect the DO concentration in a water body. If many plants are present, the water can be supersaturated with DO during the day, as photosynthesis occurs. Concentrations of oxygen can decrease significantly during the night, due to respiration. DO concentrations are usually highest in the late afternoon, because photosynthesis has been occurring all day. In our mesocosms, same phenomena were observed (Figure 25). During noon, sometimes it was oversaturated. Dissolved oxygen was lowest (8.04 mg•L^{-1}) in the control case which is due to the lack of FTWs. However, on an average, DO was 9.48 mg•L^{-1} in all the mesocosms which is needed for aquatic health.

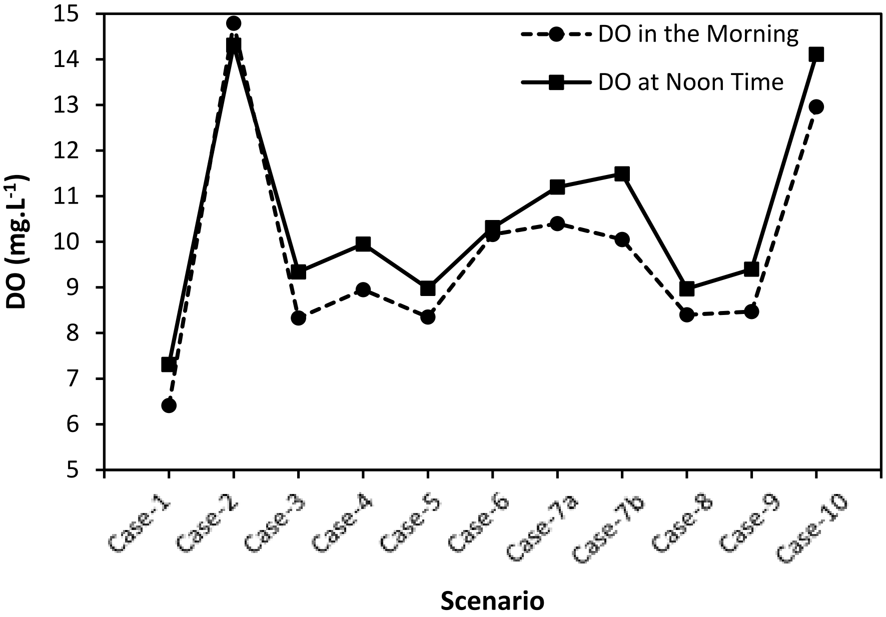


Figure 25: Day to Night Variation of Dissolved Oxygen

Duckweed and algae can 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, thick growths of these plants can prevent sunlight from reaching the deeper parts of the water body. Thus reducing the ability of sub-surface plants to photosynthesize and produce oxygen, which in turn may reduce the levels of dissolved oxygen below the acceptable levels required for a healthy fish population. Figure 26 shows decrease in DO in two months when duckweeds, algae and other weeds grew from month 5 to moth 7 (Shown in Table 9). The left axis shows 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 is sometimes more than 100%. Right axis shows 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 couple of exceptions, DO change was prominent with the amount of duckweeds and algae.

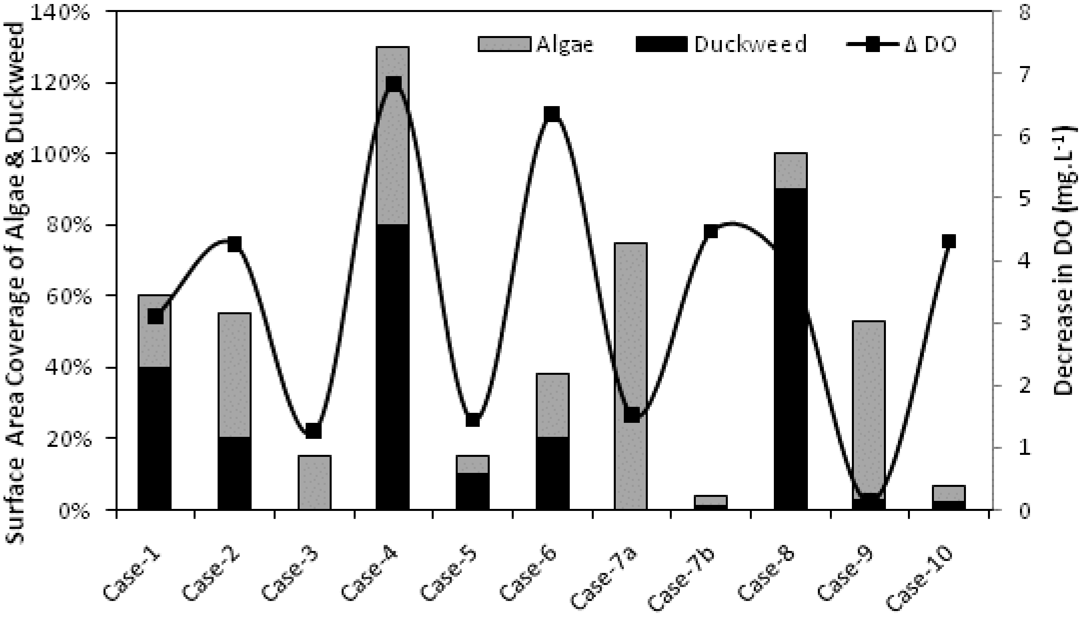


Figure 26: Effects of Epiphyte and Phytoplankton on Dissolved Oxygen Level

CHAPTER 5: CONCLUSION

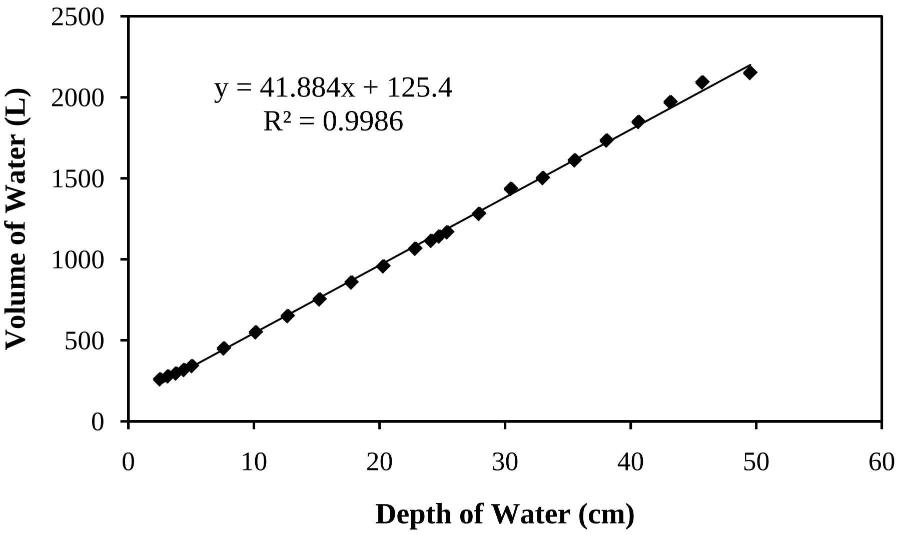
From this research, a better understanding of FTWs, plant selection and holding media has been achieved. It is clear that implementing floating macrophyte mats (FTWs) on existing stormwater wet detention pond systems should to be an effective way of increasing nutrient treatment performances without any structural changes to a pond.

From microcosm study, it can be inferred that although roots successfully penetrated the geotextile filter, their growth might be slightly inhibited lengthwise. However, significant increase in plant biomass was observed when a mixture of 80% Expanded Clay and 20% Tire Crumb was used. It can be calculated that for Canna, a minimum of 1.71 $mg \cdot L^{-1}$ TN and 0.409 $mg \cdot L^{-1}$ TP is required to maintain life for at least 4 weeks. During this time the system can remove 88.4% TN and 80.68% TP (Calculated from Figure 14c). For Juncus, the duration is 6 weeks with same amount of dosing. Although this high nutrient requirement (or consumption) shows efficacy of the FTW system, the microcosm study was actually performed without any sediment or littoral zone inclusion. In an actual pond, less amount of nutrient concentration should be able to keep the plants alive with other contributions. Temperature is clearly one environmental factor which can constrain growth of the macrophytes. As Canna has a poor tolerance for lower temperature they might release a large percentage of nutrients at senescence. Regular harvesting is recommended and mixed planting will be advantageous to keep the system operative during winter season.

From mesocosm study, we can conclude that, varying water depth is not a concern in terms of treatment efficiency of nutrient removal in FTWs, which might be affected by fluctuations in seasonal water levels. For this reason, it is envisioned that even during excessive rainfall, the FTW systems will be still working although the sediment rooted plants might be inactive. Within the feasible limit of floating mat coverage, from 5% to 10% increase did not significantly increase system efficiency. Rather it is clear that only with 5% coverage of the floating mat it is possible to achieve 53% TP, 79% OP, 61% TN, 73% Nitrate and almost 100% Ammonia removal within 15 days time span when the initial concentration is approximately 1 $mg \bullet L^{-1}$ Phosphate and 3 $mg \bullet L^{-1}$ Nitrate. More area coverage will not be suitable from engineering perspective and might inhibit the sunlight to reach the bottom of the actual pond. Existence of littoral zone increased transparency of water column by reducing turbidity and Chl-a. However, in our experiment, it was not clearly understood whether they helped removing pollutants or acted as a source or simply played the role of the neutral site for attachment. This led us toward the long-standing controversy in aquatic ecology. Total Phosphorus and Orthophosphate removed better in the mesocosm with sorption media, whereas, Nitrate removal was almost the same and Total Nitrogen removal was not significant with the addition of sorption media. From spatial sampling and contour diagram a higher concentration of nutrients was observed near the rhizospheric zone and it is recommended that, the deployment of the FTWs should not be in the vicinity of the outlet of the pond because the assimilated nutrients around the root zone might break loose and contaminate the discharged water through the outlet. Considering ecological point of view, FTWs can suppress algae and duckweed growth significantly which may harm the fish population and create aesthetic issues in stormwater management wet detention ponds. Ease of harvesting is another advantage of this FTW system which is important because the full vegetation cycle involves return of most nutrients from senescing and decomposing. This grouped mesocosm study clearly showed the probable evolution of unwanted plant species which should enrich knowledge among the practitioners of FTWs.

The perils of conclusions based on short-term uptake measurements in wetland and aquatic systems are very well known. As budget constraints did not allow us to replicate the mesocosm, identical cycles were performed to ensure that aforementioned removal efficiencies are consistent. Finally, this study also shows that even in the mesocosm study of FTWs, it is important to include littoral zone and bottom sediment as they may regulate the metabolism of the entire ecosystem in the pond. Nevertheless, additional studies are needed with typical wetland hydrologic characteristics with different types of vegetation or floating mat to better understand the effects and overall epiphyte, phytoplankton and macrophyte ecology in order to elucidate the internal nutrient dynamics.

APPENDIX A: TANK CALIBRATION FOR CALCULATION OF WATER VOLUME IN THE MICROCOSM


y = 41.884x + 125.4
R² = 0.9986
Volume of Water (L)
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
Depth of Water (cm)

APPENDIX B: AVERAGE STEM HEIGHTS (PHASE-1 OF THE MICROCOSM STUDY)

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 LENGTHS (PHASE-1 OF THE MICROCOSM STUDY)

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 HEIGHTS (PHASE-2 OF THE MICROCOSM STUDY)

Microcosm-1

		Canna (cm)		Juncus (cm)
Week	Without Media (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
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 (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
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 (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
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 LENGTHS (PHASE-2 OF THE MICROCOSM STUDY)

Microcosm-1

		Canna (cm)		Juncus (cm)
Week	Without Media (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
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 (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
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 (Canna)	With Media (Canna)	Without Media (Juncus)	With Media (Juncus)
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 OF THE MICROCOSM STUDY)

	Microcosm 1		Microcosm 2		Microcosm 3	
Week	TN (mg.L^{-1})	TP (mg.L^{-1})	TN (mg.L^{-1})	TP (mg.L^{-1})	TN (mg.L^{-1})	TP (mg.L^{-1})
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 OF THE MICROCOSM STUDY)

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

APPENDIX H: VARIATION OF pH VALUES IN THE MESOCOSMS

Days	**0**	**30**	**64**	**78**	**93**	**109**	**126**	**144**	**164**	**179**	**209**
Scenario											
Case-1	8.76	8.99	7.64	7.83	7.66	7.58	8.40	8.12	8.14	8.12	8.19
Case-2	8.77	8.28	8.21	8.95	8.14	7.87	8.25	9.71	9.59	8.64	8.73
Case-3	8.75	7.99	8.08	8.19	8.29	8.17	8.73	8.80	8.55	8.39	8.50
Case-4	9.20	9.51	8.36	9.60	8.59	7.93	8.26	8.63	8.74	8.76	7.94
Case-5	8.28	7.99	7.86	7.86	7.88	7.82	8.09	8.80	8.37	8.11	8.63
Case-6	8.45	8.54	7.77	8.35	7.78	7.63	7.84	8.75	8.07	8.13	7.99
Case-7a	9.09	8.71	7.94	8.37	8.52	7.92	7.93	9.30	9.41	8.58	9.02
Case-7b	8.18	8.18	7.55	8.19	8.34	7.83	9.34	8.79	8.46	8.32	8.20
Case-8	9.08	8.00	7.76	8.25	8.32	7.94	8.64	8.40	8.19	8.29	8.04
Case-9	8.25	7.81	7.73	7.94	7.91	7.69	8.73	8.54	7.98	8.06	8.67
Case-10	8.23	8.27	8.08	9.09	8.44	7.86	8.63	10.02	10.07	8.74	8.57

APPENDIX I: VARIATION OF TEMPERATURE IN THE MESOCOSMS

Days	**0**	**30**	**64**	**78**	**93**	**109**	**126**	**144**	**164**	**209**
Scenario										
Case-1	31.2	29.0	25.5	22.7	12.0	16.5	16.9	17.4	19.7	27.6
Case-2	31.3	28.3	23.1	23.3	12.2	18.7	15.0	16.2	19.2	25.0
Case-3	31.0	24.4	22.3	24.0	11.5	18.5	15.0	16.7	20.2	26.5
Case-4	31.3	28.7	22.3	25.0	13.0	19.0	16.1	16.3	18.8	26.5
Case-5	31.1	28.5	23.4	23.5	11.1	18.0	16.5	16.3	19.4	28.7
Case-6	31.4	29.4	23.5	24.4	12.2	19.0	14.8	17.5	20.0	20.2
Case-7a	31.3	29.0	23.5	24.5	12.7	19.5	16.5	17.5	20.2	28.1
Case-7b	31.5	28.2	24.2	24.2	12.3	18.7	14.7	17.0	20.6	28.1
Case-8	31.6	28.2	24.4	25.2	13.9	18.9	14.6	17.1	19.2	24.8
Case-9	31.8	29.5	22.4	23.9	11.6	17.6	16.0	16.8	19.6	28.3
Case-10	31.6	29.3	23.3	24.0	12.2	19.5	15.4	17.4	19.7	26.8

APPENDIX J: VARIATION OF TURBIDITY IN THE MESOCOSMS

Days	**0**	**30**	**64**	**78**	**93**	**109**	**126**	**144**	**164**
Scenario									
Case-1	10.22	21.10	51.50	57.80	34.70	36.65	9.72	11.60	6.93
Case-2	4.96	7.97	21.40	22.40	18.70	70.15	8.91	7.48	5.06
Case-3	3.79	13.15	11.20	7.00	8.87	7.53	14.30	4.26	5.34
Case-4	3.83	3.17	20.10	19.00	17.90	95.20	22.10	9.85	10.10
Case-5	4.23	14.70	39.00	33.30	25.65	70.20	3.51	17.20	9.06
Case-6	5.93	4.02	6.30	9.10	7.65	31.70	19.50	4.76	2.37
Case-7a	4.21	20.30	23.30	16.80	16.40	48.15	9.38	9.01	5.93
Case-7b	11.77	4.62	48.60	52.20	6.00	13.05	3.30	2.41	5.78
Case-8	5.74	3.48	11.20	12.70	11.10	32.40	4.32	4.99	2.70
Case-9	3.28	7.62	14.00	8.90	5.14	6.41	15.00	2.79	3.95
Case-10	5.73	2.31	3.60	3.20	2.98	35.75	2.60	4.83	5.99

APPENDIX K: VARIATION OF CHL-a VALUES IN THE MESOCOSMS

Days	**64**	**78**	**93**	**109**	**126**	**144**	**164**	**209**
Scenario								
Case-1	1.71	4.53	2.20	2.08	2.01	1.50	1.56	1.28
Case-2	1.88	5.77	6.84	2.05	2.73	1.26	1.18	1.13
Case-3	1.49	1.70	1.96	1.39	1.71	0.88	1.14	0.82
Case-4	7.31	19.19	2.29	7.19	1.81	4.79	5.60	1.61
Case-5	1.87	2.66	1.60	2.40	1.29	1.54	1.50	0.89
Case-6	1.28	2.01	2.88	1.96	1.85	1.15	1.16	0.93
Case-7a	1.65	1.91	1.78	1.93	1.44	1.28	1.58	1.32
Case-7b	1.92	1.98	1.54	1.68	1.59	1.32	1.53	1.23
Case-8	1.84	3.96	1.58	2.26	1.08	1.78	1.67	1.46
Case-9	1.44	1.90	1.90	1.30	1.70	1.17	1.46	1.04
Case-10	1.26	1.48	2.00	1.57	1.64	1.12	1.45	0.92

LIST OF REFERENCES

Adams, EB (1992) Wetlands: Nature's Water Purifiers. Cooperative Extension, Washington State University

Baldwin AH, Simpson TW, Weammert SE (2009) Urban Wet Ponds and Wetlands Best Management Practice. Final Report December

Belmont MA, Metcalfe CD (2003) Feasibility of using ornamental plants (Zantedeschia aethiopica) in subsurface flow treatment wetlands to remove nitrogen, chemical oxygen demand and nonylphenol ethoxylate surfactants a laboratory-scale study. Ecol Eng 21:233-247

Benton TG, Solan M, Travis JMJ, Sait SM (2007) Microcosm experiments can inform global ecological problems. Trends Ecol Evol 22:516-521

Beutel MW (2006) Inhibition of ammonia release from anoxic profundal sediments in lakes using hypolimnetic oxygenation. Ecol Eng 28:271-279

Billore SK, Prashant, Sharma JK (2008) Restoration and conservation of stagnant water bodies by gravel-bed treatment wetlands and artificial floating reed beds in tropical India. The 12th World Lake Conference: 981-987

Breen PF (1990) A mass balance method for assessing the potential of artificial wetlands for wastewater treatment. Water Res 24:689-697

Carpenter SR (1999) Microcosm experiments have limited relevance for community and ecosystem ecology: reply. Ecology 80:1085-1088

Carpenter SR, Lodge DM (1986) Effects of submersed macrophytes on ecosystem processes. Aquat Bot 26: 341-370

Carr GM, Duthie HC, Taylor WD (1997) Models of aquatic plant productivity: a review of the factors that influence growth. Aquat Bot 59:195-215

Cedergreen N, Madsen TV (2003) Nitrate reductase activity in roots and shoots of aquatic macrophytes. Aquat Bot 76:203-212

Chang NB, Hossain F, Wanielista M (2010) Filter Media for Nutrient Removal in Natural Systems and Built Environments: I- Previous Trends and Perspectives. Environ Eng Sci 27:689-706

Chapin III FS, Vitousek PM, Van Cleve K (1986) The nature of nutrient limitation in plant communities. Am Nat 127:48-58

Cui L, Ouyang Y, Lou Q, Yang F, Chen Y, Zhu W, Luo S (2010) Removal of nutrients from wastewater with Canna indica L. under different vertical-flow constructed wetland conditions. Ecol Eng 36:1083-1088

DeBusk TA, Peterson JE, Ramesh Reddy K (1995) Use of aquatic and terrestrial plants for removing phosphorus from dairy wastewaters. Ecol Eng 5:371-390

Ewing K (1996). Tolerance of four wetland plant species to flooding and sediment deposition. Envir. Expt. Bot., 36, 131-146.

Figge DAH, Hetrick BAD, Wilson GWT (1995) Role of expanded clay and porous ceramic amendments on plant establishment in minespoils. Environmental Pollution 88:161-165

Fraser LH, Keddy P (1997) The role of experimental microcosms in ecological research. Trends Ecol Evol 12:478-481

Gabel B, Kozicki R, Lahl U, Podbielski A, Stachel B, Struss S (1982) Pollution of drinking water with nitrate. Chemosphere, 11:1147-1154

Gersberg, RM and Elkins, BV and Lyon, SR and Goldman, CR (1986) Role of aquatic plants in wastewater treatment by artificial wetlands. Water Research 20: 363-368

Govindarajan B (2008) Nitrogen dynamics in a constructed wetland receiving plant nursery runoff in southeastern United States. Dissertation, University of Florida

Greenway M, Polson C (2007) Macrophyte Establishment in Stormwater Wetlands: Coping with Flash Flooding and Fluctuating Water Levels in the Subtropics.

Hammer DA (1989) Constructed wetlands for wastewater treatment: Municipal, industrial, and agricultural. CRC Press, Boca Raton, Florida

Headley TR, Tanner CC, Council AR (2006) Application of floating wetlands for enhanced stormwater treatment: a review. NIWA Client Report, Auckland Regional Council, New Zealand

Hossain F, Chang NB, Wanielista M (2010) Modeling kinetics and isotherms of functionalized filter media for nutrient removal from stormwater dry ponds. Environ Prog Sustain Energy 29:319-333

Huang CP, Wang HW, Chiu PC (1998) Nitrate reduction by metallic iron. Water Res 32:2257-2264

Iamchaturapatra J, Yi SW, Rhee JS (2007) Nutrient removals by 21 aquatic plants for vertical free surface-flow (VFS) constructed wetland. Ecol Eng 29:287-293

Kadlec RH, Knight RL (1996) Treatment wetlands. CRC Press, Boca Raton, Florida

Kim-Shapiro DB, Gladwin MT, Patel RP, Hogg N (2005) The reaction between nitrite and hemoglobin: the role of nitrite in hemoglobin-mediated hypoxic vasodilation. J Inorg Biochem 99:237-246

Levin SA (1992) The problem of pattern and scale in ecology: the Robert H. MacArthur award lecture. Ecology 73:1943-1967

Mickle, A.M. and Wetzel, R.G. (1978a) Effectiveness of submersed angiosperm-epiphyte complexes on exchange of nutrients and organic carbon in littoral systems. I. Inorganic nutrients. Aquat. Bot. 4:303-316

Mickle, A.M. and Wetzel, R.G. (1978b) Effectiveness of submersed angiosperm-epiphyte complexes on exchange of nutrients and organic carbon in littoral systems. II. Dissolved organic carbon. Aquat. Bot. 4:317-329

Moshiri G (1993) Constructed wetlands for water quality improvement. Lewis Publishers, Boca Raton, Florida

Nahlik AM, Mitsch WJ (2006) Tropical treatment wetlands dominated by free-floating macrophytes for water quality improvement in Costa Rica. Ecol Eng 28:246-257

Pitt R, Maestre A, Morquecho R (2004) The National Stormwater Quality Database (NSQD, Version 1.1). 1st Annual Stormwater Management Research Symposium Proceedings: 13-51

Raun WR, Johnson GV (1995) Soil-plant buffering of inorganic nitrogen in continuous winter wheat. Agron J 87:827-833

Sasser CE, Gosselink JG, Shaffer GP (1991) Distribution of nitrogen and phosphorus in a Louisiana freshwater floating marsh. Aquat Bot 41: 317-331

Sawyer CN, McCarty PL, Parkin GF (2003) Chemistry for Environmental Engineering Science, McGraw-Hill, New York, USA, Fifth Edition

Servizi JA, Gordon RW (2005) Acute lethal toxicity of ammonia and suspended sediment mixtures to chinook salmon (Oncorhynchus tshawytscha). B Environ Contam Tox 44:650-656

Tarazona JV, Munoz MJ, Ortiz JA, Nunez MO, Camargo JA (2008) Fish mortality due to acute ammonia exposure. Aquac Res 18:167-172

Van der Valk AG, Davis CB, Baker JL, Beer CE (1979) Wetland Functions and Values, the State of Our Understanding. American Water Resources Association, Minneapolis, Minnesota. Pages: 457-467

Van Winkle SC, Pullman GS (2005) Achieving desired plant growth regulator levels in liquid plant tissue culture media that include activated carbon. Plant cell reports 24:201-208

Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380:48-65

White SA, Seda B, Cousins M, Klaine SJ, Whitwell T (2009) Nutrient remediation using vegetated floating mats. SNA Research Conference Vol. 54: 39-43

Xuan Z (2007) Nutrient and pathogen removal in a subsurface upflow wetland system using green sorption media. Dissertation, University of Central Florida