ABSTRACT

The Evaluation of a Subsurface-Flow Constructed Wetland for On-site Wastewater Treatment under the NSF/ANSI Standard 40 Protocol Design Loading

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A subsurface-flow constructed wetland was studied using the National Sanitation Foundation/ American National Standards Institute Standard 40 protocol for Class I on-site wastewater treatment systems at the Baylor Wastewater Research Program (BWRP) site within the Waco Metropolitan Area Regional Sewerage System (WMARSS) treatment plant, Waco, Texas. Raw wastewater from the WMARSS plant was pumped into a two-chambered 1,500 gallon septic tank and flowed by gravity into the 375 ft^3 treatment wetland. Both septic tank and wetland effluent samples were analyzed for carbonaceous 5-day biochemical oxygen demand, total suspended solids, and nutrients. In addition, pH values were collected, as well as rainfall and temperature data. The study produced a TSS wetland effluent average of 11 mg/l (96 percent reduction) and CBOD wetland effluent average of 40 mg/l (84 percent reduction). Total nitrogen wetland effluent averaged 30 mg/l (19 percent reduction) and total phosphorus wetland effluent averaged 4.0 mg/l (31 percent reduction).

The Evaluation of a Subsurface-Flow Constructed Wetland for On-site Wastewater Treatment under the NSF/ANSI Standard 40 Protocol Design Loading

by

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A Thesis

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ABBREVIATIONS

ANOVA	Analysis of Variance
ANSI	American National Standards Institute
BOD	Biochemical Oxygen Demand
BWRP	Baylor Wastewater Research Program
CBOD	Carbonaceous Biochemical Oxygen Demand
CD	Compact Disc
Cm	Centimeters
Cm/day	Centimeters per day
CRASR	Center for Reservoir and Aquatic Research Systems
EPA	Environmental Protection Agency
Ft	Feet
Ft^3	Cubic feet
FWS	Free Water-Surface
G	Grams
M	Meters
Mg/l	Milligrams per liter
Mm	Millimeters
Ml	Milliliters
N	Nitrogen
NO_2	Nitrite

NO_3	Nitrate
NH_3	Ammonia
NH_4	Ammonium
NSF	National Sanitation Foundation- International
OSSF	On-Site Sewerage Facilities
SAS	SAS Institute Inc.
SD	Standard Deviation
SSF	Subsurface-Flow
TAES	Texas A&M Extension Services
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOWTRC	Texas On-Site Wastewater Treatment Research Council
TP	Total Phosphorus
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
WMARSS	Waco Metropolitan Area Regional Sewerage System
YSI	YSI Inc., Yellow Springs, Ohio

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Lastly I would like to thank my friends and family. When I thought that I had had enough and no longer wanted to continue there was the encouragement of a family member or humor of a friend to keep me calm. I thank my mom and younger brother for their support and encouragement during the difficult moments. I also acknowledge that nothing would have been possible without divine guidance.

CHAPTER ONE

Introduction

Proper wastewater treatment before dispersal into the environment prevents deterioration of our water resources and aquatic life. Wastewater treatment can be achieved through a variety of methods. The majority of rural residents use on-site sewerage facilities (OSSF) for wastewater treatment. The traditional on-site sewerage facility consists of a septic tank and soil absorption field. The septic tank allows for settling of suspended solids and some digestion of organic matter. Septic tank effluent is discharged through a perforated pipe to a soil absorption field where biological processes in the soil further treat the effluent.

There is a high demand for on-site sewerage facilities. In the United States OSSF serve nearly 22 million households (National Ground Water Association 2005). An advantage of OSSF is their cost effectiveness. Individual houses and small communities can avoid large investments and operating expenses required of a larger-scale municipal treatment system. Another advantage is minimal impact on the environment. The high point-source loading of pollutants into receiving waters from centralized plants can impact aquatic life (U.S. EPA Onsite Wastewater Treatment Systems Manual 2002), while the dispersed wastewater volumes of OSSF avoid the problem of high point-source loading.

Problems arise when OSSF are used in locations where soil absorption fields are not suitable. These unsuitable sites include areas of high flooding potential, steep slopes, thin topsoil, high groundwater tables or clay soils (Perkins 1989). Because the quality of the effluent into soil absorption fields is not monitored, contamination to nearby waterways may be possible. The repercussions include public health risks, degradation of surface water and groundwater, and a negative public perception of OSSF. Approximately one third of land in the United States is suited traditional soil absorption fields (U.S. EPA Onsite Wastewater Treatment Systems Manual 2002).

Concerns about traditional septic tank and soil absorption field appropriateness at certain sites have resulted in the search for OSSF alternatives. Among the more popular alternatives is the use of subsurface-flow constructed wetlands in place of the soil absorption field. In a subsurface-flow constructed wetland the media provides wastewater treatment and water is not directly exposed to the atmosphere, rather maintained below the media (U.S. EPA Constructed Wetlands Treatment of Municipal Wastewaters Manual 2000).

In a septic tank and subsurface-flow wetland treatment system, the septic tank receives wastewater directly from the household where solids settle toward the bottom and separate from liquid wastes. The liquid wastes flow into the subsurface-flow constructed wetland for secondary treatment. Treatment processes include sedimentation, filtration, precipitation, sorption, and microbial decomposition (Wynn and Liehr 2001). As wastewater flows through porous media (gravel is most commonly used) in a subsurface-flow wetland, it is slowed down and solids are allowed to settle out (U.S. EPA Constructed Treatment Wetlands 2004). Microbial bacteria attached to the media and plant roots are critical for decomposition of organic matter.

Although subsurface-flow (SSF) constructed wetlands are similar in function to natural wetlands, there are key differences. Natural wetlands are usually free water-surface (FWS) wetlands where water is visible at the surface. In subsurface-flow wetlands water is not exposed at the surface, but maintained within the media. Secondly, water flow in a subsurface-flow wetland is more consistent than in natural wetlands and volume is controlled by household use. In natural wetlands there is more fluctuation in response to rainfall because precipitation is less consistent and less predictable. A third distinction is the role wetlands serve for fauna. Natural wetlands support a diverse fauna, but in a subsurface-flow wetland fauna are limited because water is not exposed to the surface. Avoiding wastewater exposure at the surface contributes to the lack of odor problems and decreases health risks from exposure to untreated wastewater. The final difference is the efficiency of treatment per square meter. Subsurface-flow wetlands provide greater surface area for microbial bacteria in the media, which allows greater treatment efficiency per square meter of wetland (Moshiri 1993).

In vegetated wetlands, plants are some of the most visible features and are a critical component in defining jurisdictional wetlands. In subsurface-flow treatment wetlands the role of plants has been disputed. Some authors (Vymazal 2002) think the plants contribute very little and the media (gravel) performs the physical treatment, while the biofilm on the media is responsible for most of the biological treatment. However, plants may contribute several ways in subsurface-flow treatment wetlands. Plants provide aesthetics with greenery and sometimes flowers. The plants also transpire water and therefore increase residence time in the wetland which usually translates to better treatment (Griffin, Bhattarai, and Xiang 1999; Solano, Soriano, and Ciria 2004). Finally, plants contribute directly to treatment by adding oxygen through their roots (Moshiri 1993; Wynn and Liehr 2001). This last contribution is necessary for plant survival, because of the anoxic conditions that occur in subsurface-flow wetlands (U.S. EPA Subsurface Flow Constructed Wetlands for WasteWater Treatment: A Technology Assessment 1993).

In subsurface-flow wetlands nutrient uptake has been reported as negligible (Moshiri 1993). Nitrogen reduction/uptake, particularly ammonia, is limited. Nitrification, the conversion of ammonia to nitrate, requires oxygen. A subsurface-flow wetland is anaerobic, receiving minimal oxygen input from plants. Peter Hiley (1995) explains:

> The bacteria which oxidize ammonia do not compete well with BOD oxidizing bacteria in conventional treatment, requiring more time, space and oxygen to develop competent populations. It takes 4.3 g of oxygen to change 1 g of ammonia into nitrate, compared to about 1 g to oxidize 1 g of BOD. Therefore a normal domestic sewage with 40 mg/l ammonia and 150 mg/l BOD would need twice the land area to provide sufficient oxygen to treat both substances.

Studies on subsurface-flow constructed wetlands have verified them as reliable, low-cost, low-energy processes requiring minimal operational attention (U.S. EPA Subsurface Flow Constructed Wetlands for WasteWater Treatment: A Technology Assessment 1993). Physical, chemical, and biochemical reactions contribute in wastewater treatment to provide a high quality effluent for in-ground disposal. Studies on constructed wetlands for wastewater treatment show them to be effective for removal of BOD and TSS (U.S. EPA Wastewater Technology Fact Sheet 2000). The EPA's Subsurface Flow Constructed Wetlands for Wastewater Treatment: A Technology Assessment (1993) was based on fourteen systems thought to be representative of systems in operation in the United States and results showed effluent levels below 20 mg/l for BOD and TSS. Table 1 shows the performance of the 14 systems with averages and ranges for the parameters tested.

Table 1. Summary of performance for 14 SSF wetland systems*

Constituent	Mean Influent (mg/l)	Mean Effluent (mg/l)
BOD_5	28** (5-51)***	8** (1-15)***
TSS	60 (23-118)	10 (3-23)
TKN as N	15 (5-22)	9 (2-18)
NH_3/NH_4 as N	5 (1-10)	5 (2-10)
NO_3 as N	9 (1-18)	3 (0.1-13)
TN	20 (9-48)	9 (7-12)
TP	4 (2-6)	2 (0.2-3)

* Mean detention time 3 d (range 1 to 5 d). ** Mean value. *** Range of values.
Source: U.S. EPA Wastewater Technology Fact Sheet 2000.

Another EPA publication, *Constructed Wetlands Treatment of Municipal Wastewaters Manual 2000,* provides results of four studies of varied size, location, and hydraulic loading. Performance history for the Mesquite Nevada, June 1992-May 1993, study shows 55% and 77% reduction for BOD and TSS respectively, as well as average effluent values of 16 mg/l TKN and 6.2 mg/l Total Phosphorus. The report includes monthly effluent characteristics in relation to temperature (Table 2). Studies have shown temperature to be a factor in removal of BOD and various forms of nitrogen (U.S. EPA Wastewater Technology Fact Sheet 2000).

Table 2. Monthly effluent characteristics in response to temperature

Month	Temp. °C	BOD mg/l	TSS mg/l	NH_4-N mg/l	TKN mg/l	TP mg/l
1992						
Jun	21.6	32	6	3.3	6.7	5.0
Jul	26.7	24	6	4.3	6.4	5.3
Aug	27.1	26	6	4.5	7.6	4.8
Sep	23.6	22	5	4.1	6.8	5.5
Oct	19.1	37	5	3.3	5.6	6.1
Nov	13.5	32	22	5.3	8.6	5.8
Dec	7.5	27	16	15.7	22.3	4.7
1993						
Jan	8.1	24	14	19.8	29.7	6.1
Feb	12.7	24	18	21.9	29.9	8.0
Mar	13.9	23	16	22.1	29.9	9.2
Apr	16.2	49	17	12.4	23.6	7.1
May	20.3	27	21	6.0	9.5	7.0

Source: U.S. EPA Constructed Wetlands Treatment of Municipal Wastewaters Manual 2000.

Despite studies that show evidence of subsurface-flow constructed wetlands' ability to provide a high quality effluent, the question as to how subsurface-flow wetlands perform when the same standards applied to other on-site wastewater advanced treatment systems, such as aerobic units, remains. In addition, previous studies have not tested subsurface-flow treatment wetlands under typical on-site use conditions.

In this study a subsurface-flow constructed wetland was evaluated using the NSF/ANSI Standard 40 protocol for on-site wastewater aerobic treatment units. Figure 1 represents the subsurface-flow wetland design used in this study. More detailed information on the design and construction of the wetland can be found in Appendix A.

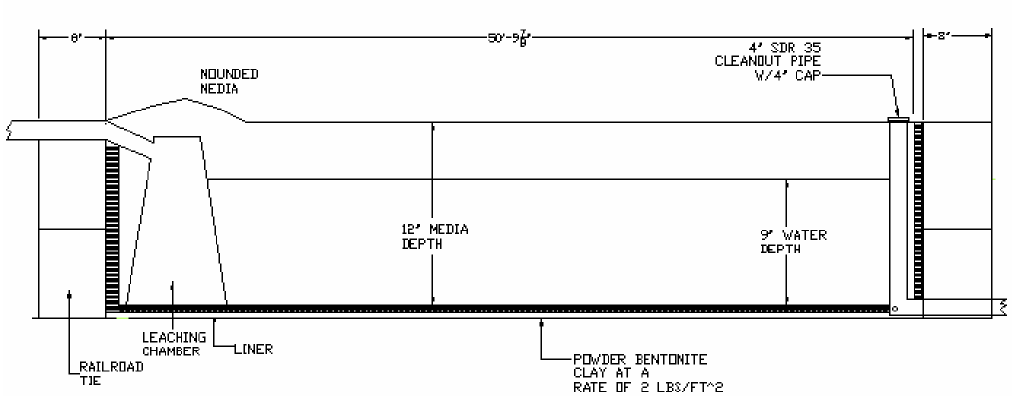

Fig. 1. Design of subsurface-flow wetland. The width of 10 feet is not shown. *Source*: Texas Cooperative Extension 2005.

By applying the NSF/ANSI Standard 40 protocol, the subsurface-flow wetland can be evaluated under a rigorous test schedule and compared directly to on-site aerobic treatment units evaluated with the same protocol. NSF International is the leading agency in testing and permitting on-site wastewater treatment systems. NSF/ANSI Standard 40, relating to residential wastewater treatment systems, simulates typical household usage and requires six months of performance testing with specific dosing amounts and schedules, incorporating stress tests to simulate wash day, working parent, power outage, and vacation conditions. This study provides results on the effectiveness of a constructed subsurface-flow wetland for wastewater treatment during the first 16 weeks of design loading under these rigorous test conditions.

The objective is to study a subsurface-flow constructed wetland under the NSF/ANSI Standard 40 Class I on-site wastewater treatment system protocol for design loading. Three specific objectives of the study are to:

a) Evaluate treatment effectiveness under NSF/ANSI Standard 40 protocol

b) Compare treatment effectiveness between septic tank and wetland effluents

c) Evaluate appropriateness of NSF/ANSI Standard 40 for constructed wetlands.

Hypotheses

1) The subsurface-flow constructed wetland will produce an effluent that meets or exceeds NSF/ANSI Standard 40 criteria. NSF/ANSI Standard 40 protocol specific requirements for effluent are:

    7-day average TSS shall not exceed 45 mg/l

    30-day average TSS shall not exceed 30 mg/l

    7-day average CBOD shall not exceed 40 mg/l

    30-day average CBOD shall not exceed 25 mg/l

2) The subsurface-flow constructed wetland will significantly reduce total suspended solids (TSS), carbonaceous 5-day biological oxygen demand ($CBOD_5$), total nitrogen, and total phosphorus. Reduction calculations were made between raw wastewater values and septic effluent values for TSS and BOD. Septic tank and wetland system reduction was calculated by comparing raw wastewater values to septic tank effluent values and wetland effluent values for TSS and CBOD (raw wastewater values measured in BOD and wetland effluent values in CBOD).

Setting

The study was conducted at the Baylor Wastewater Research Program site, within the confines of the Waco Metropolitan Area Regional Sewerage System (WMARSS) plant; immediately adjacent to the NSF International-Waco certification site. WMARSS is approximately five miles south of downtown Waco, adjacent to the Brazos River. Waco is in McLennan County, midway between the cities of Dallas and Austin on Interstate-35 and generally in the middle of the state of Texas. Central Texas temperatures range from 1.1°C to 36.1°C, with an average of 19.6°C. Average rainfall is 32 inches per year (City of Waco 2006). The study began on February 6 and ended May 31.

CHAPTER TWO

Materials and Methods

System Components

The combination of a 1,500 gallon two-chambered septic tank and subsurface-flow constructed wetland was designed to treat 500 gallons of wastewater per day, the approximate use of a three bedroom four person household. Raw wastewater was pumped from the WMARSS plant to the NSF facility. From the NSF International site raw wastewater was pumped to the BWRP dosing shed. Raw wastewater was then pumped into a calibrated five gallon bucket that discharged one dose (five gallons) into the septic tank. As raw wastewater entered the septic tank it displaced fluid in the septic tank that then flowed into the wetland. An effluent filter was installed in the septic tank to reduce solids and minimize potential clogging in the wetland media. Because there was no gradient in the wetland, water flowed as a result of displacement when dosing occurred. Hydraulic residence time in the septic tank was three days (500 gallons per day and 1500 gallon capacity), but varied according to precipitation and evapotranspiration rates in the wetland. When there was no evapotranspiration the residence time in the wetland was approximately two days since the wetland holds approximately 1,000 gallons. Calculation on wetland capacity can be found in Appendix B. The wetland effluent flowed by gravity into a buried storage tank with a capacity of 3,000 gallons before it was eventually returned to the WMARSS treatment plant.

Construction

As designed by Dr. Bruce Lesikar of Texas Cooperative Extension, wetland dimensions were 50 feet long x 10 feet wide x 1 foot deep, with no gradient. A 45 mil rubber pond liner and bentonite clay pellets underneath the liner were installed to prevent water loss to soil filtration. The wetland was filled with "Grade 3 concrete rock" media (Appendix B). The media was composed of siliceous and carbonate gravel, ¾ to 1½ inches in diameter, with an average porosity of 37.3 percent.

Vegetation

Plants used in this study included cattail (T*ypha latifolia*), bulrush (*Scirpus cubensis*), pickerel weed (*Pontederia* cordata) and iris (*Iris pseudacorus*). Plants were selected based on size, suitability, availability, and seasonal growth pattern. A total of 141 plants with an average density of one plant per 3 ft^2 (first five feet of wetland adjacent to septic tank were unvegetated because an infiltrator panel was located in this area to disperse the wastewater more evenly) were planted in a grid pattern. The specific plant locations in the wetland were selected for aesthetic reasons and to minimize any short-circuiting or preferred flow path. Plant growth was monitored with plant assessments performed periodically (Appendix C).

System Dosing

Wastewater dosing was in accordance to NSF/ANSI Standard 40 protocol (Table 3). Wastewater dosing to the wetland was accomplished through a digital timer that activated a dosing pump to fill a calibrated five-gallon bucket after which a valve was activated to drain the bucket into the 1,500-gallon septic tank. Then the valve closed as the timer activated the pump again until the proper number of doses was delivered. The NSF/ANSI Standard 40 dosing schedule is shown in Table 3.

Table 3. NSF/ANSI Standard 40 design loading specifications

Time Frame	Percent of daily hydraulic capacity
6:00 a.m. – 9:00 a.m.	35% (175 gallons)
11:00 a.m. – 2:00 p.m.	25% (125 gallons)
5:00 p.m. – 8:00 p.m.	40% (200 gallons)
	Total = 500 gallons

Source: NSF International 2005.

Using this schedule there were 100 doses a day (five gallons per dose) totaling 500 gallons a day. To monitor dosing volume a float counter and hour meter were installed to verify whether the system received the correct number of full doses (35 + 25 + 40 = 100/ day). The hour meter recorded the hours (and hundredths of hours) of electrical power to the dosing pump (Appendix D). A meter on the return tank recorded the number of gallons that flowed through the wetland each day.

Sample Collection

NSF/ANSI Standard 40 protocol requires samples be flow-proportional, 24-hour composites. This was accomplished by using timers and peristaltic pumps to extract volumetrically calibrated samples during each dosing cycle. The composite samples, septic tank effluent and wetland effluent were collected in refrigerated containers retrieved each day and analyzed within 48 hours. All programs for the septic tank effluent sampling pump had at least a five-minute delay to allow fresh sample to reach the area near the sample extraction pump. The minimum delay on the wetland timer was ten minutes after dosing started which was adequate since flow as observed to increase within two to three minutes at the sump (wetland effluent) after dosing started (Appendix E).

Analytical Procedures

Standard 40 Protocol requires effluent samples be analyzed for total suspended solids (TSS), carbonaceous 5-day biochemical oxygen demand ($CBOD_5$), and pH. Raw influent values are required to be analyzed for TSS and biochemical oxygen demand (BOD). Samples were also analyzed for total nitrogen and total phosphorus. All data values are available on attached data compact disc.

Total Suspended Solids (TSS), Carbonaceous 5-day Biochemical Oxygen Demand ($CBOD_5$), and Biochemical Oxygen Demand (BOD)

Septic tank effluent and wetland effluent composite samples were collected and analyzed five days a week, Monday through Friday. Septic tank effluent and wetland effluent samples were sent to an outside lab, AquaTech, for TSS and CBOD analysis. Septic tank effluent samples were also sent to the WMARSS lab for TSS and BOD analysis.

pH and Temperature

A YSI® 650MDS display and 600QS sonde at both septic tank effluent and wetland effluent points measured pH and temperature every hour and these hourly measurements were averaged for the daily 24-hour composites.

Total Nitrogen and Total Phosphorus

Samples were analyzed twice a week by lab technicians at the Baylor University Center for Reservoir and Aquatic Systems Research (CRASR). Analysis was performed with a Lachat QuickChem 8500 Flow Injection Analyzer.

Data Management

Temperature and pH values recorded every hour were used to obtain a daily average. For a weekly average, the daily averages from Sunday to Friday were used. When comparing wetland effluent values for TSS and CBOD to NSF/ANSI Standard 40 requirements a 7-day average had to include a minimum of three data days within a calendar week. A 30-day average required a minimum of 15 data days within a calendar month.

To calculate percent removal for TSS and CBOD septic tank effluent samples were paired with wetland effluent samples discharged two days later. Therefore, there were three paired data points per week; Monday septic tank effluent compared to Wednesday wetland effluent, Tuesday septic tank effluent compared to Thursday wetland effluent, and Wednesday septic tank effluent compared to Friday wetland effluent. The difference in mg/l was then divided by septic tank effluent concentrations in mg/l to obtain percent removal. For total nitrogen and total phosphorus a monthly percent removal was calculated because there were only two samples per week for TN and TP. Rainfall events greater than 0.1 inches (34 gallons) were plotted against CBOD, TSS and TN (Appendix F).

Several difficulties arose relating to either insufficient or excess gallons to the system. NSF/ANSI Standard 40 protocol specifies system dosing at 500 $\pm$ 50 gallons, providing a range from 450 to 550 gallons. Too little or too much flow is unacceptable under NSF/ANSI Standard 40. To monitor data, all days with >90 doses (minimum of 450 gallons) from counter data were counted as “good” data days. The same concept was applied for return gallons. If the flow meter on the return tank showed the system had treated more than 550 gallons that day, then it was considered a "bad" data day. Instances when "bad" data days were encountered included rainfall events that produced greater flow and pump or line clogging that resulted in too little flow. Rather than throw these days out, the days were included in the study and notes were made of the particular problem encountered that sample day.

Statistical Analyses

One-way analysis of variance (ANOVA) was performed with SAS Software on TSS and CBOD raw wastewater, septic tank effluent and wetland effluent values, with probability $\alpha = 0.05$. First, all TSS and CBOD raw wastewater, septic tank effluent and wetland effluent values from February 6 to May 31 were analyzed. Next, raw wastewater, septic tank effluent and wetland effluent values were analyzed by month (February, March, April and May) for TSS and CBOD. When assumptions of normally distributed data and equality of variances were not satisfied, data transformation to satisfy the assumptions was performed. If the assumptions were not satisfied after data transformation, a non-parametric test was run. A non-parametric test was run for all TSS raw wastewater, septic tank effluent and wetland effluent values. Log (X) transformation was required for TSS values for the months of March and April. All CBOD raw wastewater, septic tank effluent and wetland effluent values were transformed by taking the square root of data values. A non-parametric test was run for CBOD values for the months of February and April. Log (X) transformation was required for CBOD values for the months of March and May.

Total nitrogen (TN) and total phosphorus (TP) values were collected on septic tank effluent and wetland effluent samples. Therefore, ANOVA could not be performed.

Instead, a pooled t-test was run to determine significant differences between septic tank effluent and wetland effluent values for TN and TP (probability $\alpha = 0.05$). Next, pooled t-tests were run for septic tank effluent and wetland effluent samples for TN and TP for the months of February, March, April and May.

CHAPTER THREE

Results and Discussion

NSF/ANSI Standard 40 requirements are based on weekly and monthly averages of at least three (3) data days per week and 15 data days per month (NSF International 2005). Therefore, the results in this section are reported and analyzed as weekly and monthly averages for this hypothesis. The nutrients, nitrogen and phosphorus, are not considered in NSF/ANSI Standard 40 but were monitored in this study to allow for more insight of the role of subsurface-flow constructed wetlands. Total nitrogen and total phosphorus were sampled only twice a week therefore weekly averages are not appropriate. However, monthly averages were included and the complete data set for nutrients can be found in Appendix H. This study routinely sampled five days per week and therefore had a more robust data set than the minimum NSF/ANSI Standard 40 requirements.

Hypothesis #1: The Subsurface-Flow Constructed Wetland Will Produce An Effluent That Meets Or Exceeds NSF/ANSI Standard 40 Criteria

Weekly averages for wetland effluent values for all parameters are shown in Table 4. The pH weekly average values range from 6.5 to 7.0 pH units are within the NSF/ANSI Standard 40 required range of 6.0 to 9.0 pH units, but on the lower end of this range. The TSS weekly average values range from 5.0 mg/l to 22.4 mg/l and all of these values meet the NSF/ANSI Standard 40 requirement of less than 45 mg/l (Figure 2).

Table 4. Wetland effluent weekly averages

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TSS (mg/l)	19	15	22	11	12	16	11	8.6	5.0	6.4	6.4	7.6	11	6.7	5.4	6.0
CBOD (mg/l)	61	67	70	79	72	77	41	43	19	33	16	18	14	11	8.0	6.8
pH	7.0	7.0	7.0	6.9	6.9	6.8	6.9	7.0	6.9	6.8	6.8	6.7	6.6	6.5	6.5	6.5
Temp. (°C)	17	15	14	18	20	21	19	20	23	22	26	23	25	26	24	28

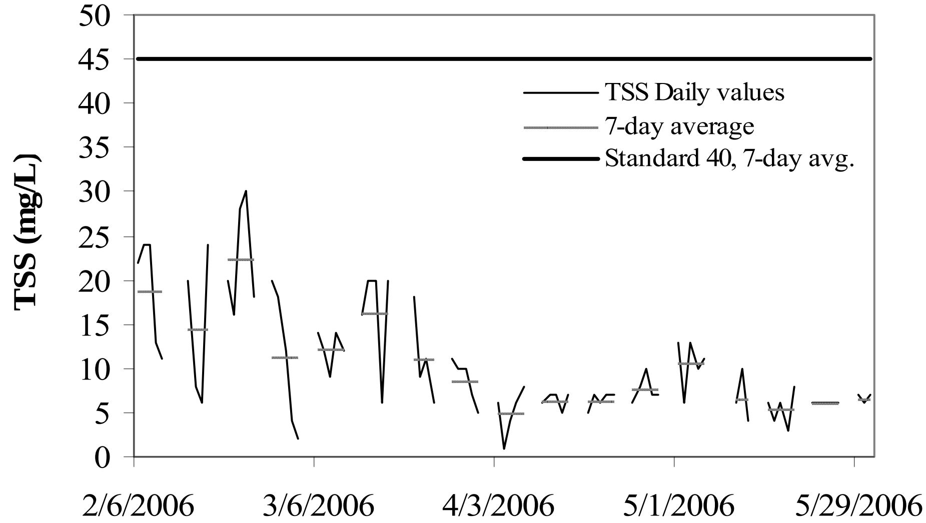

Fig. 2. The TSS daily values and 7-day averages compared to the NSF/ANSI Standard 40 required limit of 45 mg/l for a 7-day average.

The CBOD weekly average values range from 6.8 mg/l to 79 mg/l. The first eight weeks do not meet the NSF/ANSI Standard 40, 7-day average requirement of CBOD less than 40 mg/l, but the last eight weeks are well below the 40 mg/l standard and meet the requirements (Figure 3).

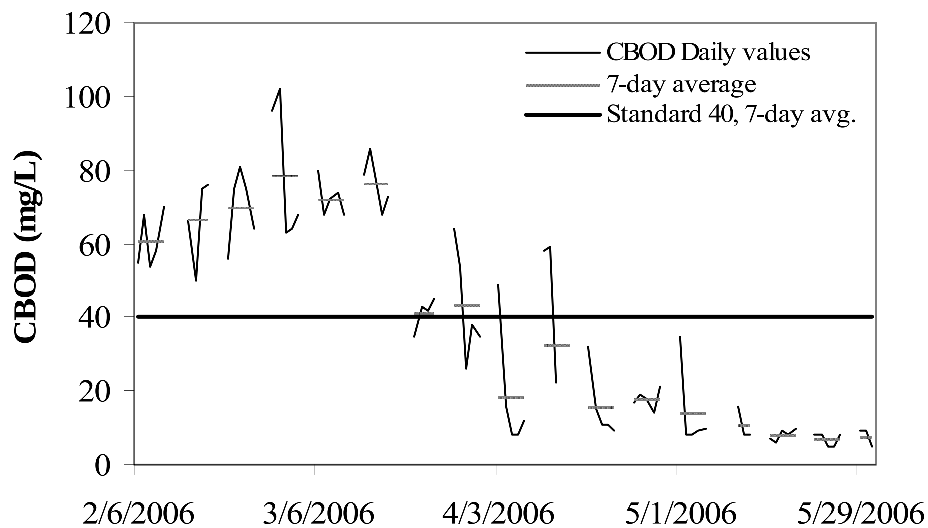

Fig. 3. The CBOD daily values and 7-day averages compared to the NSF/ANSI Standard 40 required limit of 40 mg/l for a 7-day average.

Monthly averages for wetland effluent values are shown in Table 5. The TSS monthly averages range from 6.4 mg/l to 19 mg/l and all of these values meet the Standard 40 requirement of less than 30 mg/l (Figure 4). The CBOD monthly averages range from 9.5 mg/l to 70 mg/l. The first two months (February and March) do not meet the NSF/ANSI Standard 40, 30-day average requirement of CBOD less than 25 mg/l, but the last two months (April and May) meet the requirements (Figure 5). Figure 5 shows the high variability of samples in February and March when the system did not meet the NSF/ANSI Standard 40 requirements. In April the system did meet the NSF/ANSI Standard 40 requirements, but still had high variation within samples. In May the values were more consistent and well below the NSF/ANSI Standard 40 requirements.

Table 5. Wetland effluent monthly averages

	Feb.	Mar.	Apr.	May
TSS (mg/l)	19	11	6.4	7.1
CBOD (mg/l)	70	60	21	9.5
pH	7.0	6.9	6.8	6.5
Temp. (°C)	15.3	20.0	23.4	25.9
TN (mg/l)	26.4	29.5	34.5	27.3
TP (mg/l)	3.20	4.68	4.57	3.54

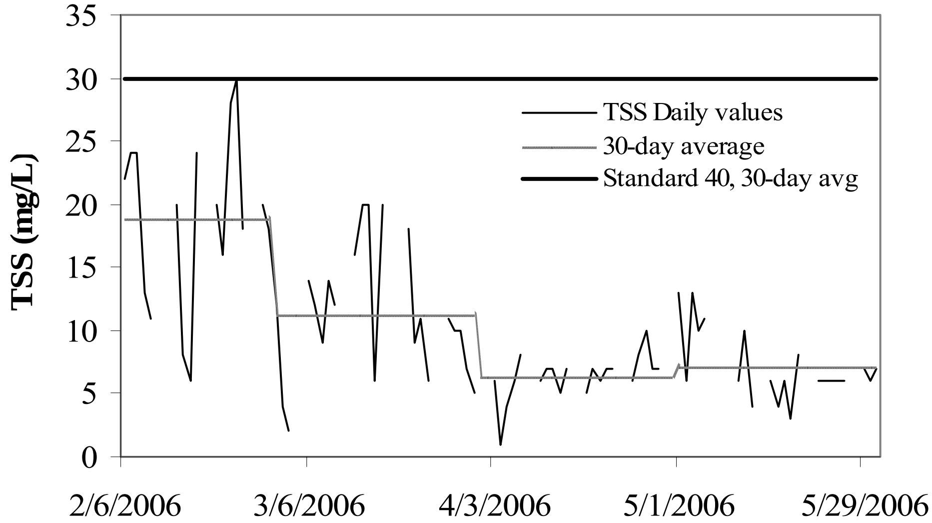

Fig. 4. The TSS daily values and 30-day averages compared to the NSF/ANSI Standard 40 required limit of 30 mg/l for a 30-day average.

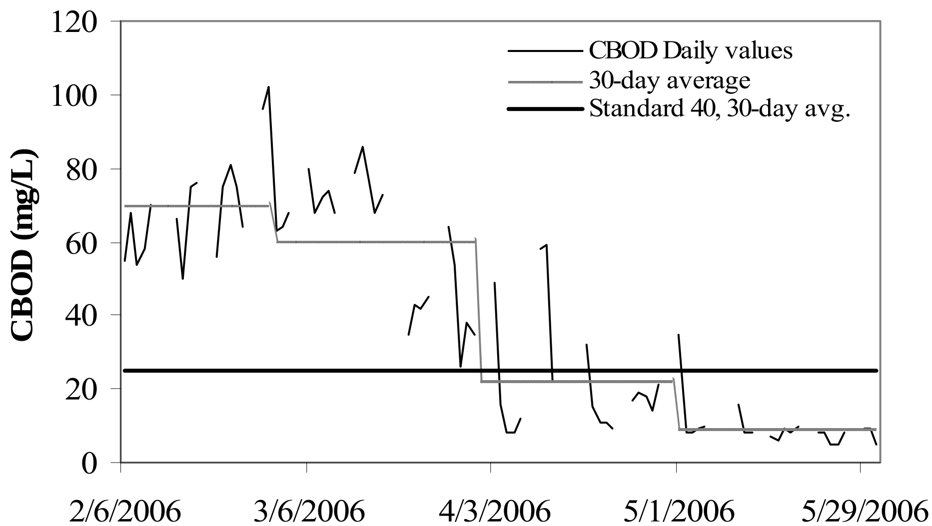

Fig. 5. The CBOD daily values and 30-day averages compared to the NSF/ANSI Standard 40 required limit of 25 mg/l for a 30-day average.

The monthly averages for TN and TP did not show much change over time and ranged from 26.4 mg/l to 34.5 mg/l and 3.20 mg/l to 4.68 mg/l respectively (Table 5). Although there are no limits for TN and TP in the current version of NSF/ANSI Standard

40, the monthly averages for the design loading phase of this study may be used for future comparisons, discussion, and design criteria.

Under NSF/ANSI Standard 40 design loading conditions the wetland showed excellent and immediate treatment for TSS. The immediate reduction in TSS can be attributed to physical settling as well as biological decomposition in the reduction (Wynn and Liehr 2001; Solano, Soriano and Ciria 2004). The improvement in effluent quality exhibited in figures 4 and 5 are probably the result of several factors: temperature, plant development, biofilm development, and septic tank development. When dosing to the wetland began in January the temperatures were close to 15°C (Table 4), the plants were only roots, the media was clean, washed gravel with no biofilm development and the septic tank was new. The maturation of the wetland included plant growth, biofilm development and septic tank maturation (growth of bacterial communities) which are all positively related to increasing temperature (Griffin, Bhattarai and Xiang 1999; Kaseva 2004; Wynn and Liehr 2001; U.S. EPA Manual: Constructed Wetlands Treatment of Municipal Wastewaters 2000). Another reason for the delay in the system effectiveness may have been rainfall in the early stages because near the onset of the study, precipitation events may have diluted the fluid in the wetland and delayed the biofilm development which is critical for CBOD reduction. Another consideration for the delay in biofilm development is a system overload that occurred toward the end of February due to a leaky valve which added gallons to the daily dosing (Appendix G). It is unclear how much startup time may be required for the system to reach optimal performance under different conditions. This study required 6-8 weeks to meet the NSF/ANSI

Standard 40 requirements with a brand new system, wastewater overloading and seasonally cool temperatures (Table 4).

Hypothesis #2: Significant Reduction

Treatment system performance was assessed by calculating percent reduction and significant differences among raw wastewater, septic tank effluent and wetland effluent. The percent reduction for the entire treatment system was calculated by the difference between the raw wastewater values and the wetland effluent values. The percent reduction for the wetland system was calculated by the difference between the septic tank effluent values and the wetland effluent values.

Tables 6 and 7 show TSS and CBOD values by month for raw wastewater, septic tank effluent and wetland effluent. Tables 6 and 7 also show significant differences ($\alpha = 0.05$) by month between raw wastewater, septic tank effluent and wetland effluent for TSS and CBOD. Table 6 shows that raw wastewater TSS monthly averages were fairly consistent, ranging from 272 mg/l to 354 mg/l. Septic tank effluent TSS monthly averages decreased each month to a low value of 29 mg/l. Wetland effluent TSS monthly averages decreased each month before leveling off in April (6.4 mg/l) and May (7.1 mg/l). Wetland TSS percent reduction increased by month from 51 percent in February to 78 percent in April and 76 percent in May. Treatment system TSS percent reduction was effective immediately, with a 93 percent reduction in February and a peak of 98 percent reduction in April. There was significant difference for TSS among all three sources: raw wastewater, septic tank effluent and wetland effluent for the months of March and April. For the months of February and May there was statistical difference between raw wastewater and septic tank effluent, and between raw wastewater and wetland effluent values. However, there was no significant difference between septic tank effluent and wetland effluent. As the septic tank effluent improves there will be less difference between septic tank effluent and wetland effluent values. Although there was no significant difference between septic tank effluent and wetland effluent for the month of May, the wetland had 76 percent reduction.

Table 6. Wetland and treatment system monthly percent reduction and significant difference for TSS

	Raw Wastewater (mg/l; ±SD)	Septic Effluent (mg/l; ±SD)	Wetland Effluent (mg/l; ±SD)	Wetland % Reduction	System % Reduction
February	278 ± 109[a]	39 ± 13[b]	19 ± 6.8[b]	51	93
March	309 ±163[a]	29 ± 11[b]	11 ± 5.2[c]	62	96
April	354 ± 171[a]	29 ± 8.7[b]	6.4 ± 1.8[c]	78	98
May	272 ± 151[a]	29 ± 6.5[b]	7.1 ± 2.7[b]	76	97

Note: Values in columns with different letters indicate significant differences (probability $\alpha = 0.05$).

Table 7. Wetland and treatment system monthly percent reduction and significant difference for CBOD

	Raw Wastewater (mg/l; ±SD)	Septic Effluent (mg/l; ±SD)	Wetland Effluent (mg/l; ±SD)	Wetland % Reduction	System % Reduction
February	275 ± 62[a]	127 ± 10[b]	70 ± 15[c]	45	72
March	249 ± 67[a]	128 ± 30[b]	60 ± 17[c]	53	76
April	289 ± 96[a]	106 ± 33[b]	21 ± 16[c]	80	93
May	233 ± 67[a]	46 ± 16[b]	9.5 ± 6.3[c]	79	96

Note: Values in columns with different letters indicate significant differences (probability $\alpha = 0.05$).

Table 7 shows raw wastewater CBOD monthly averages were fairly consistent over the study period, with monthly averages between 233 mg/l and 289 mg/l. Septic tank effluent CBOD monthly averages decreased steadily between February and April, and drastically between April (106 mg/l) and May (46 mg/l). Wetland effluent CBOD monthly averages decreased each month to 9.5 mg/l in May. Wetland CBOD percent reduction increased in February and March but leveled off in April and May. Treatment system CBOD percent reduction increased each month, peaking in May at 96 percent. Table 7 shows a statistically significant difference for CBOD among all three sources: raw wastewater, septic tank effluent and wetland effluent for every month during the study. Therefore, although the wetland percent reduction (45% and 53%) and treatment system percent reduction (72% and 76%) in February and March did not compare to those of April and May, there was a statistically significant difference among the systems.

All TSS and CBOD values collected from February 6 to May 31 were plotted by source in figures 6 and 7. The box plots show the minimum and maximum values, the median and mean, and the interquartile range. Raw wastewater TSS values ranged from 89 mg/l to 884 mg/l, with a mean of 310 mg/l (Figure 6). Septic tank effluent TSS values ranged from 12 mg/l to 60 mg/l, with a mean of 31 mg/l (Figure 6). Wetland effluent TSS values ranged from 1 mg/l to 30 mg/l, with a mean of 10.5 mg/l (Figure 6).

Raw wastewater CBOD values ranged from 106 mg/l to 590 mg/l, with a mean of 261.6 mg/l (Figure 7). Septic tank effluent CBOD values ranged from 21 mg/l to 215 mg/l, with a mean of 108.5 mg/l (Figure 7). Wetland effluent CBOD values ranged from 2 mg/l to 102 mg/l, with a mean of 38.8 mg/l (Figure 7).

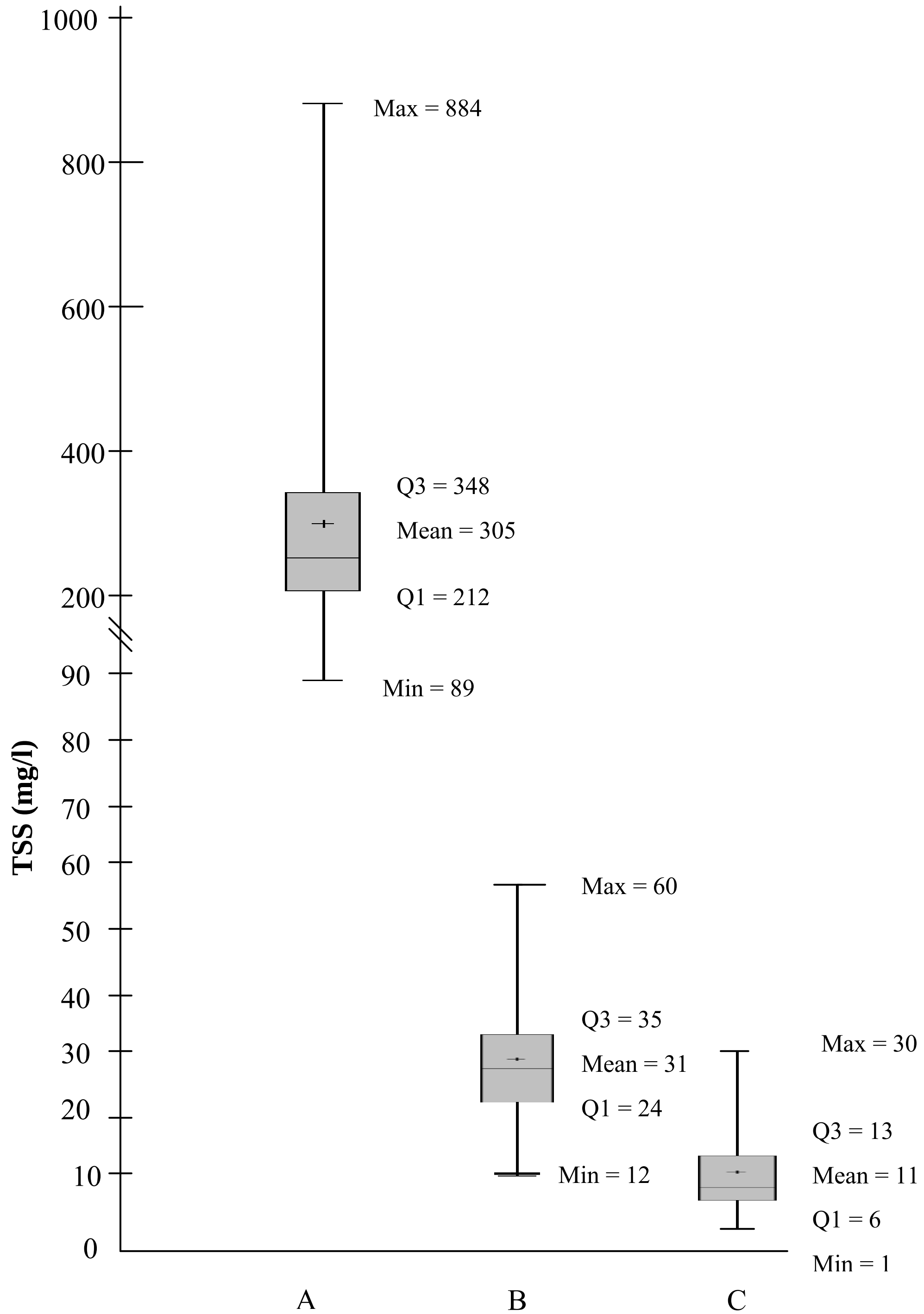

Fig. 6. TSS daily values for raw wastewater (A), septic tank effluent (B) and wetland effluent (C). Mean values are shown and denoted by "+". Median values are not shown but denoted by line across box plots.

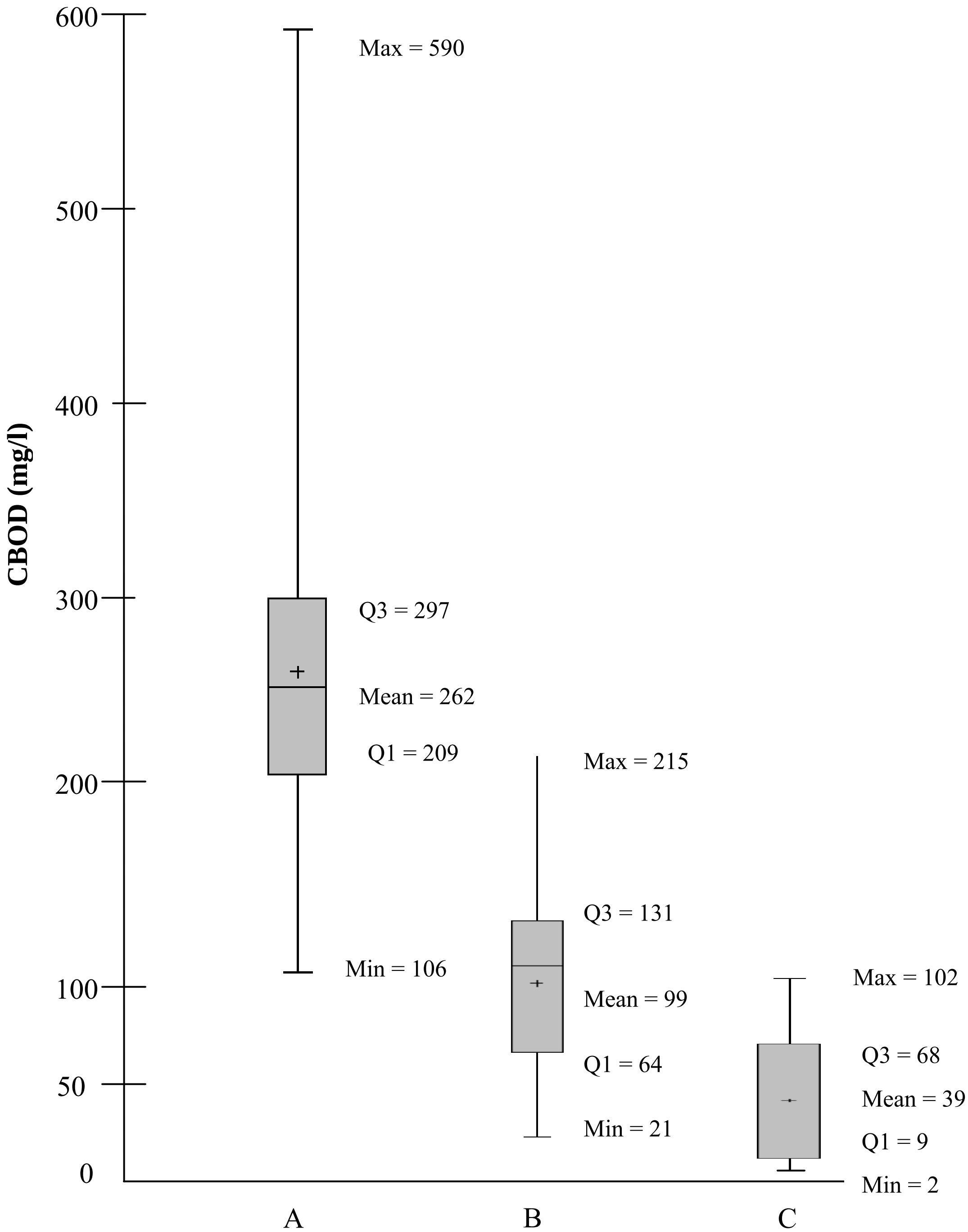

Fig. 7. CBOD daily values for raw wastewater (A), septic tank effluent (B), and wetland effluent (C). Mean values are shown and denoted by "+". Median values are not shown but denoted by line across box plots.

Another way to look at wetland percent reduction other than comparing monthly averages was to compile paired data days. This was accomplished by using the hydraulic residence time (two days) of the wetland and pairing the two samples (septic effluent and wetland effluent) that essentially represent the same wastewater. Because samples were collected five days a week, approximately three paired data days occurred each week. The percent reduction for TSS and CBOD in paired data days from February 6 to May 31 are shown in Figures 12 and 13. Figure 12 shows that TSS percent reduction was immediate and varied from 60 percent to 85 percent. These results are slightly better than the monthly average comparison for TSS which ranged from 52 percent to 78 percent (Table 6). The one data point where there was zero percent reduction was when the septic tank effluent and wetland effluent TSS values were the same. The wetland percent reduction in TSS appears to increase and become more consistent over time (Figure 8).

Figure 13 shows CBOD percent reduction for the wetland for paired data days increased steadily and leveled off near the middle of the study (April). The CBOD percent reduction for the wetland in paired data days also exceed the range seen in monthly averages (Figure 9). The wetland percent reduction in CBOD for paired data days ranged from <40 percent to almost 100 percent and exceed 80 percent on numerous occasion.

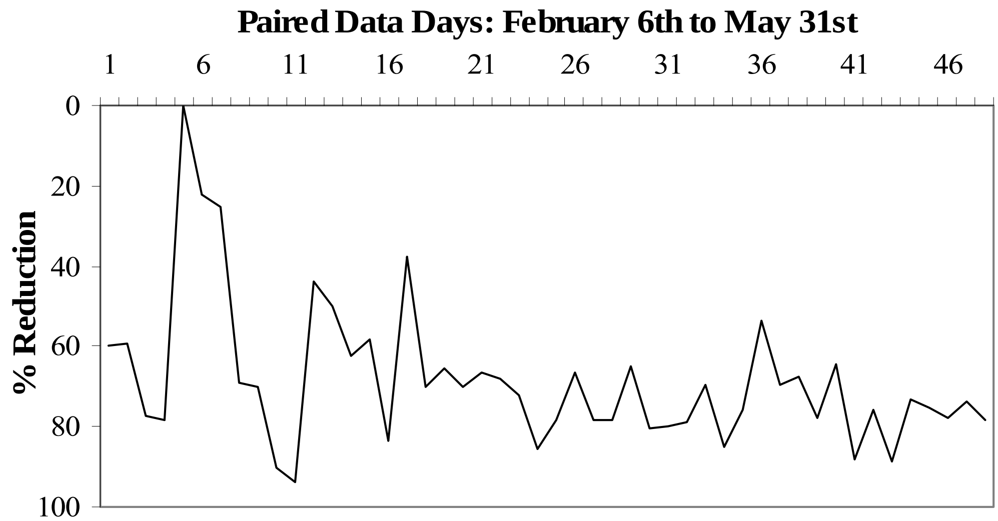

Fig. 8. TSS percent reduction from septic effluent samples paired with wetland effluent samples two days later.

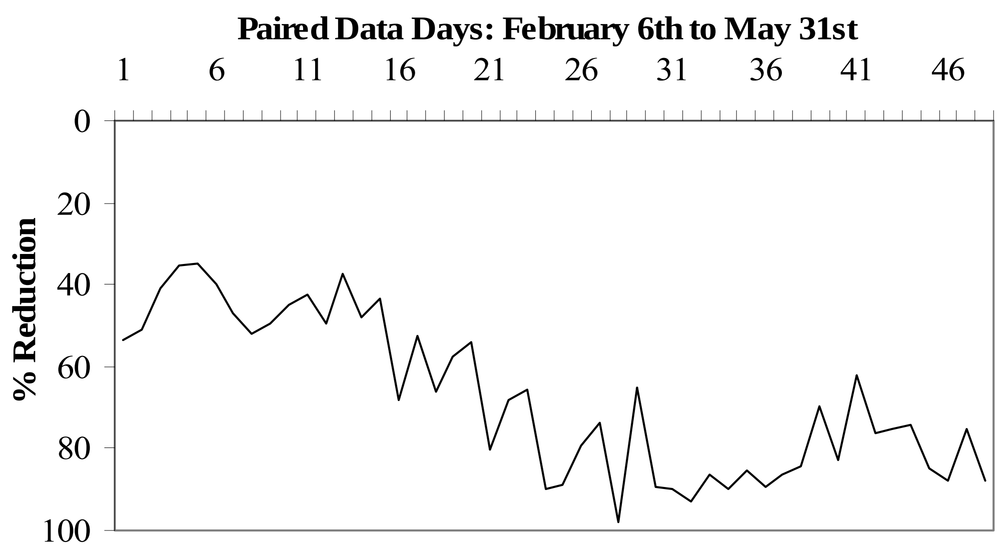

Fig. 9. CBOD percent reduction from septic effluent samples paired with wetland effluent samples two days later.

Total nitrogen (TN) and total phosphorus (TP) were collected twice a week and on several occasions only one sample per week was collected. Table 5 shows monthly averages from February to May. Total nitrogen wetland effluent monthly averages range from 26.4 mg/l to 34.5 mg/l. There was no apparent trend in monthly averages for TN in the wetland effluent. Tables 8 and 9 show the wetland percent reduction by month for TN and TP. Wetland percent reduction for TN was lowest in March (5.6 percent) and highest in May (27 percent). Although the wetland monthly average percent reduction values do not seem high, there was a statistical difference between septic tank effluent and wetland effluent averages in TN for the months of February and May. There was no statistical difference for TN between septic tank effluent and wetland effluent for the months with the lowest percent reduction, March and April. The percent reduction in February may be due to plant uptake at the beginning of the study. The decrease in percent reduction may be explained by plants reaching their saturation point and no longer able to take up nutrients.

Total phosphorus wetland effluent monthly averages range from 3.2 mg/l to 4.7 mg/l (Table 9). There as no apparent trend in monthly averages. Wetland percent reduction was lowest in April (19 percent) and highest in February (47 percent). There was a statistical difference in TP among septic tank effluent and wetland effluent each month, from February to May. The highest percent reduction in February may be due to possible adsorption onto the media (gravel).

Table 8. Wetland monthly percent reduction for Total Nitrogen

	Septic Effluent (mg/l; $\pm$SD)	Wetland Effluent (mg/l; $\pm$SD)	Δ mg/l	% Reduction
February	35 ± 3.1^{b}	26 ± 5.5^{c}	8.1	24
March	35 ± 6.6^{b}	33 ± 4.7^{b}	2.0	5.6
April	43 ± 14^{b}	35 ± 5.5^{b}	8.5	20
May	37 ± 5.4^{b}	27 ± 8.7^{c}	10.2	27

Note: Values in columns with different letters indicate significant differences (probability $\alpha = 0.05$). Letters ‘b’ and ‘c’ used to be consistent with tables 6 and 7.

Table 9. Wetland monthly percent reduction for Total Phosphorus

	Septic Effluent (mg/l; $\pm$SD)	Wetland Effluent (mg/l; $\pm$SD)	Δ mg/l	% Reduction
February	6.0 ± 0.8^b	3.2 ± 1.4^c	2.8	47
March	6.4 ± 0.9^b	4.7 ± 0.3^c	1.7	26
April	5.7 ± 0.5^b	4.6 ± 0.4^c	1.1	19
May	5.1 ± 0.5^b	3.5 ± 0.7^c	1.6	31

Note: Values in columns with different letters indicate significant differences (probability $\alpha = 0.05$). Letters 'b' and 'c' used to be consistent with tables 6 and 7.

Precipitation

There were several significant rainfall events during the study. The majority of these rainfall events occurred during weekends when no samples were collected during the event or immediately after the event. Under NSF/ANSI Standard 40 protocol, flow should not vary by more than 10 percent either way and during rainfall events this guideline was exceeded. Although NSF/ANSI Standard 40 uses a monthly average to assess appropriate flow, rainfall may or may not have a significant impact. Rainfall events, in gallons of rain calculated from inches of rain falling on the wetland, and daily TSS, CBOD and TN concentration values were plotted to see if the precipitation appeared to have any large effects but none were noted (Figures 10-12). Rainfall events may disrupt the system by adding excess gallons and possibly reducing residence time, but they may also dilute the effluent thereby offsetting any major impact. Appendix F shows the days when flow was outside the NSF/ANSI Standard 40 range.

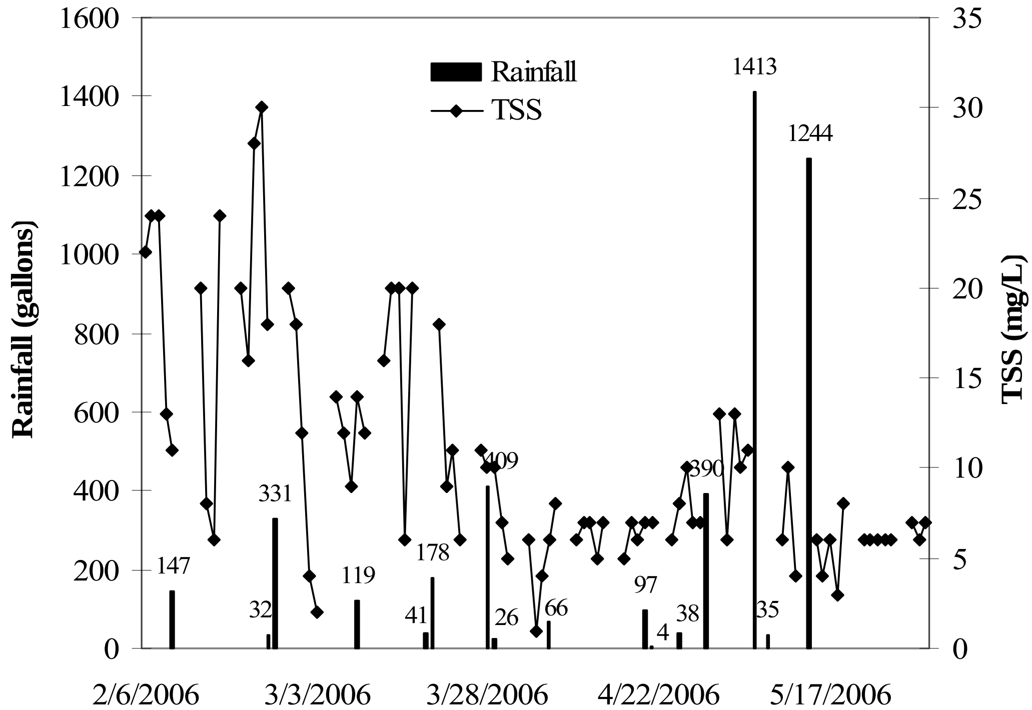

Fig. 10. The TSS concentration values plotted with rainfall events in gallons of rain falling on the wetland from February 6 to May 31.

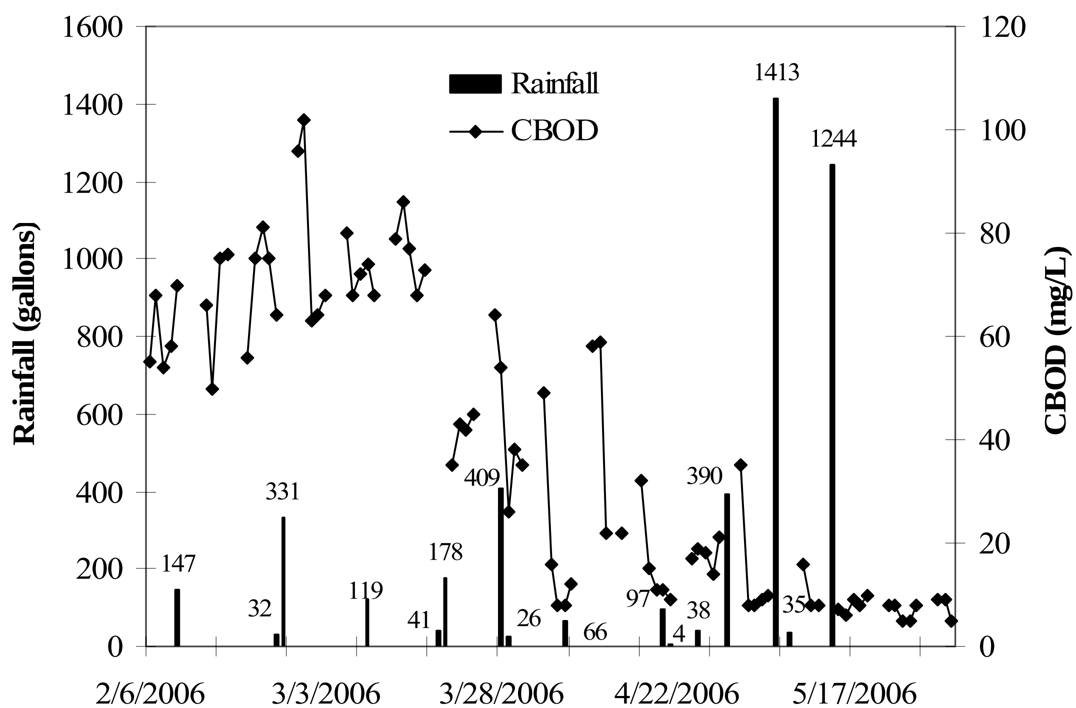

Fig. 11. The CBOD concentration values plotted with rainfall events in gallons of rain falling on the wetland from February 6 to May 31.

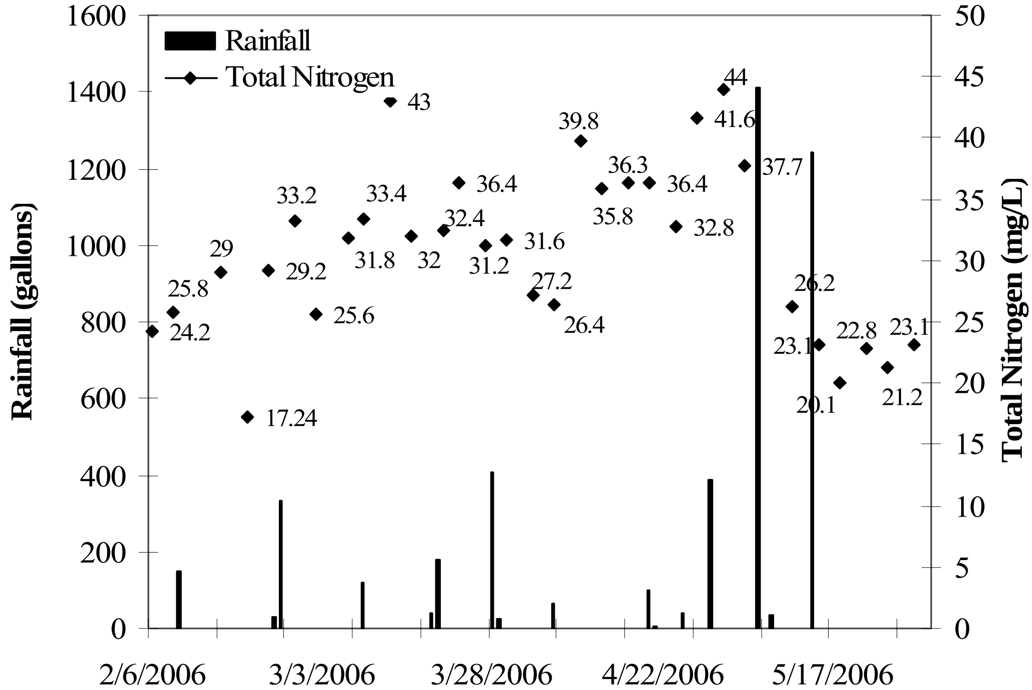

Fig. 12. Rainfall events in gallons falling on wetland and TN concentration in mg/l from February 6 to May 31.

Vegetation

The vegetation was transplanted in January and the original plants were basically roots without stems. Because the effluent quality improved over time and the plants grew larger during the same time, plant growth was measured. Plant growth rates were calculated by measuring the height of tallest stem and number of stems at different times and then calculating the growth per day (Table 10). Cattail had the greatest growth in height of tallest stem per day, and along with pickerel weed, the highest growth in total number of stems per day. Figure 13 shows the height of tallest stem per day growth rates for each plant species. Cattail growth in height of tallest stem per day exceeds that of other plant species (>1 cm per day). Bulrush is second in height of tallest stem per day growth rate (0.86 cm per day), while pickerel weed and iris have similar growth rates of

0.50 cm per day (Table 10). Figure 14 shows growth rates in total number of stems per day. Again, cattail growth in total number of stems per day (0.64 stems per day) exceeds that of other plant species. Pickerel weed (0.55 stems per day) is second followed by iris (0.30 stems per day) and bulrush (0.16 stems per day). Because there were so few cattail and iris plants, they were not used in the derived growth statistic of height times (X) number of stems. Pickerel weed and bulrush tallest stem averages were multiplied by number of stems averages (Figure 15) and used to monitor growth rates.

Table 10. Average growth rates by species: January 21 to June 7

Plant	Height of tallest stem (cm) per day	Total Number of Stems per day
Pickerel weed	0.50	0.55
Iris	0.50	0.30
Bulrush	0.86	0.16
Cattail	1.51	0.64

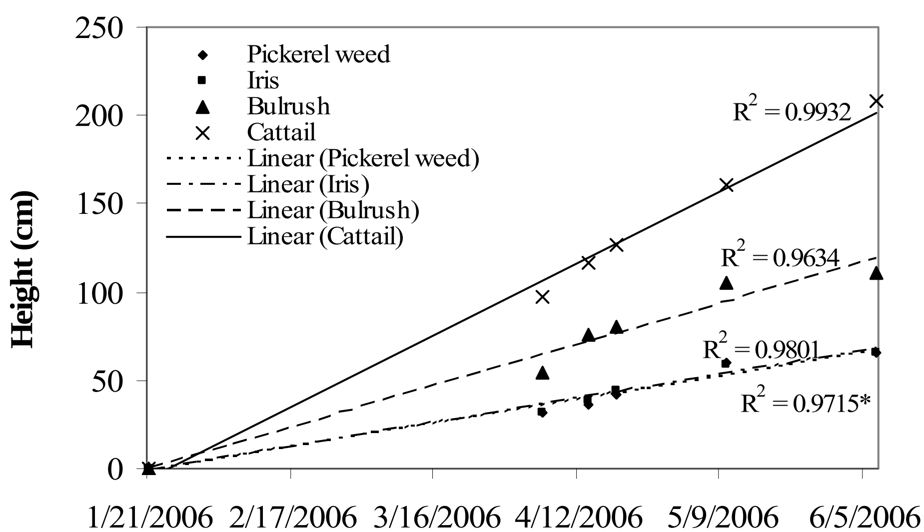

Fig. 13. Growth of tallest stem by plant species from January 21 to June 7.
*Pickerel weed.

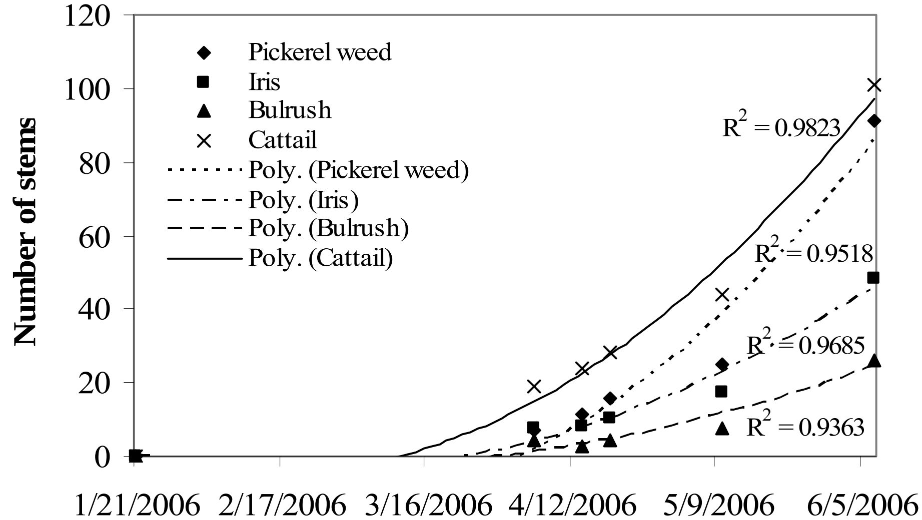

Fig. 14. Growth in number of stems by plant species from January 21 to June 7.

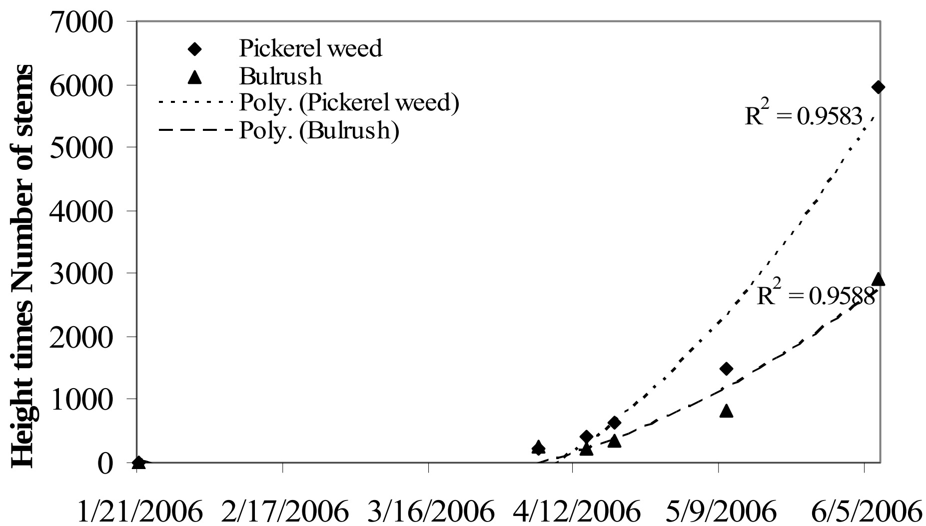

Fig. 15. Height times number of stems growth for Bulrush and Pickerel weed from January 21 to June 7.

Height of tallest stem growth rates in April (April 5 to May 10) and May (May 10 to June 7) were compared (Table 11). Cattail had the highest growth in both April and May. Cattail was also the only plant species with an increase in height of tallest stem growth rate both months; pickerel weed, iris, and bulrush growth rates actually decreased.

Table 11. Height of tallest stem growth rates (cm/day) by plant species for April and May

Plant	April	May
Pickerel weed	0.82	0.21
Iris	0.77	0.24
Bulrush	1.39	0.20
Cattail	1.77	1.71

Growth in number of stems by month is shown in Table 12. Cattail had the highest growth rate of total number of stems in April (0.73 stems per day) and second highest (2.04 stems per day) in May. Pickerel weed had the highest total number of stems growth rate in May (2.36 stems per day), as well as the greatest increase between April and May growth rates (4.75 fold). The growth rate in total number of stems for all four plant species increased between April and May.

Table 12. Total number of stems growth rates (# stems/day) by plant species for April and May

Plant	April	May
Pickerel weed	0.50	2.36
Iris	0.31	1.07
Bulrush	0.12	0.64
Cattail	0.73	2.04

Comparisons of plant growth within the wetland were conducted between wetland thirds with pickerel weed data because there were more pickerel weeds than any other plant species. If the wetland is divided into thirds, the first third is nearest the inflow and the last third is adjacent to the effluent discharge. Visible differences were observed between pickerel weeds in the first wetland third compared to those in the last wetland third (Appendix C). Figure 16 shows the average growth for height of tallest stem for pickerel weed from April 5 to June 7 by wetland third. Figure 17 shows total number of stems growth by wetland third. The last wetland third maintains the highest growth rate throughout the whole study.

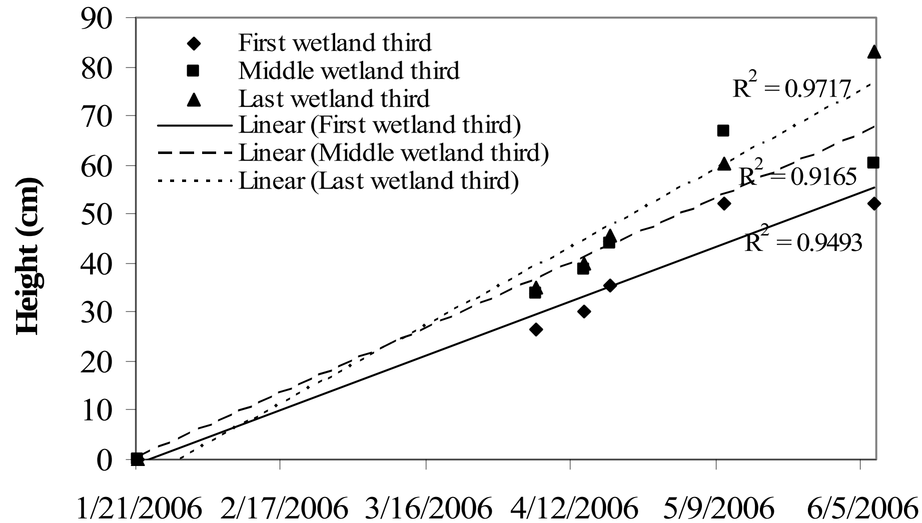

Fig. 16. Pickerel weed tallest stem growth by wetland third from January 21 to June 7.

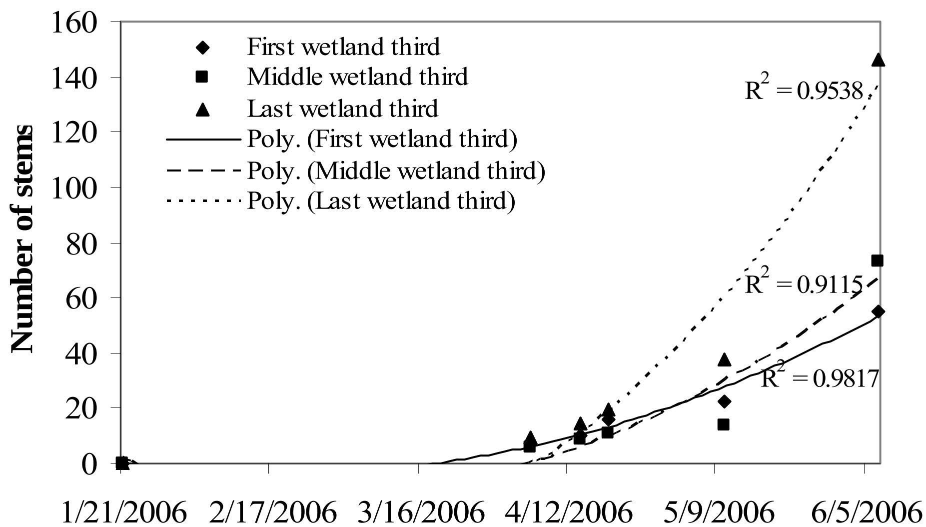

Fig. 17. Pickerel weed cumulative number of stems growth by wetland third from January 21 to June 7.

Plant growth data (Table 10) show that cattail species had the highest growth rates. Both pickerel weed and iris seem to have neared optimal height, evident from their decreased growth rate in tallest stem data (Table 11). Despite decreased growth in tallest stem, both pickerel weed and iris have continued to grow in relation to number of stems. In fact, number of stems growth rate for the pickerel weed and iris plants has increased 4.75 and 3.8 fold respectively (Table 12).

Observation revealed a noticeable difference in size of pickerel weed at the beginning and end of the wetland (Appendix C). It is possible that the effects on plant growth may be related to factors such as wastewater strength, NH_3 toxicity and lack of oxygen to the roots.

Plants provided aesthetics with greenery and even flowers (pickerel weed and iris) in this study. Other contributions of plants are

Comparisons to Previous Studies

When compared with previous studies (Table 1) the wetland performance in this study is superior in TSS effluent levels, but not with regard to CBOD. The influent to our wetland system (septic tank effluent) had a higher BOD and a lower TSS mean value than the means in the EPA study (Tables 1, 6 and 7). In this study the residence time in the wetland averaged two (2) days compared to on average three (3) days in the EPA study. In general, longer residence time equates to better treatment (Griffin, Bhattarai and Xiang 1999; Solano, Soriano and Ciria 2004). When compared to the EPA study the wetland in this study discharged higher mean effluent levels for both total nitrogen and total phosphorus.

The EPA Wastewater Technology Fact Sheet (2000) mentions BOD removal is temperature dependent. This study has shown a steady improvement in CBOD removal (Table 5). Part of the decrease in CBOD is attributed to biofilm development and maturation of the septic tank, but this study also began in January. As temperature increased, residence time also increased due to higher evapotranspiration rates, and treatment system performance improved.

For this study the overall system percent reduction, calculated by averaging the averages of each month, for TSS and CBOD, is 96 percent and 84 percent, respectively. In comparison to the EPA studies from Table 1 the wetland treatment system in this study exceeded their performance of 71 percent and 83 percent for TSS and BOD, respectively.

A study by Neralla et al. (2000) looked at eight subsurface-flow constructed wetlands for household use throughout the state of Texas. The average flow ranged from 150 gallons per day to 300 gallons per day; influent wastewater ranged from 26 mg/l to 114 mg/l TSS and 64 mg/l to 177 mg/l BOD. This study averaged 500 gallons per day. Table 13 shows the summary of the results in percent reduction for Neralla et al., in comparisons to results from this study. TSS percent reduction for this study was tied with another site for highest percent reduction. BOD percent reduction was in the middle range at 84 percent reduction. One thing to consider is that results from Neralla et al. were after two to four years of the study while the system in this study only operated for four months and was still developing or maturing for the first two months. If one uses the percent reduction of this study for TSS and BOD/CBOD in May (97 percent and 96 percent respectively), then this study (Tables 6 and 7) has higher percent reduction than any of the previous studies (Tables 1 and 13).

Table 13. Comparison of TSS and CBOD percent reduction of wetland in this study to previous studies

Location	TSS % reduction	BOD % Reduction
College station	73	89
Bryan	73	90
D'Hanis	87	88
Stephenville	70	84
Houston	61	80
Tomball	59	86
Dublin	91	83
Weslaco	96	79
Waco*	96	84**

*This study. **BOD/CBOD values. *Source*: Neralla et al. 2000.

Comparisons also can be made using hydraulic loading rates (cm/day). The hydraulic loading rate for this study was 4.07 cm/day. The loading rate falls within the range of loading rates of other subsurface-flow wetlands in North America (Mitsch and Gosselink 2000). Total nitrogen (557 g m^{-2} yr^{-1}) and total phosphorus (86 g m^{-2} yr^{-1}) loading rates for this study were also calculated. Respective percent removal was plotted versus respective loading rate and compared to other studies (Figure 18). This study was in the higher end of nutrient loading, both nitrogen and phosphorus, and lower end of nutrient removal compared to the systems reported in Mitsch and Gosselink. In this study nutrient uptake by plants can account for all of our TN and TP removal. Using nutrient tissue content values of 4 percent for nitrogen and 0.4 percent for phosphorus of dry weight (Gerloff and Krombholz 1966) calculations showed that TN and TP removal in this study can all be attributed by plant uptake.

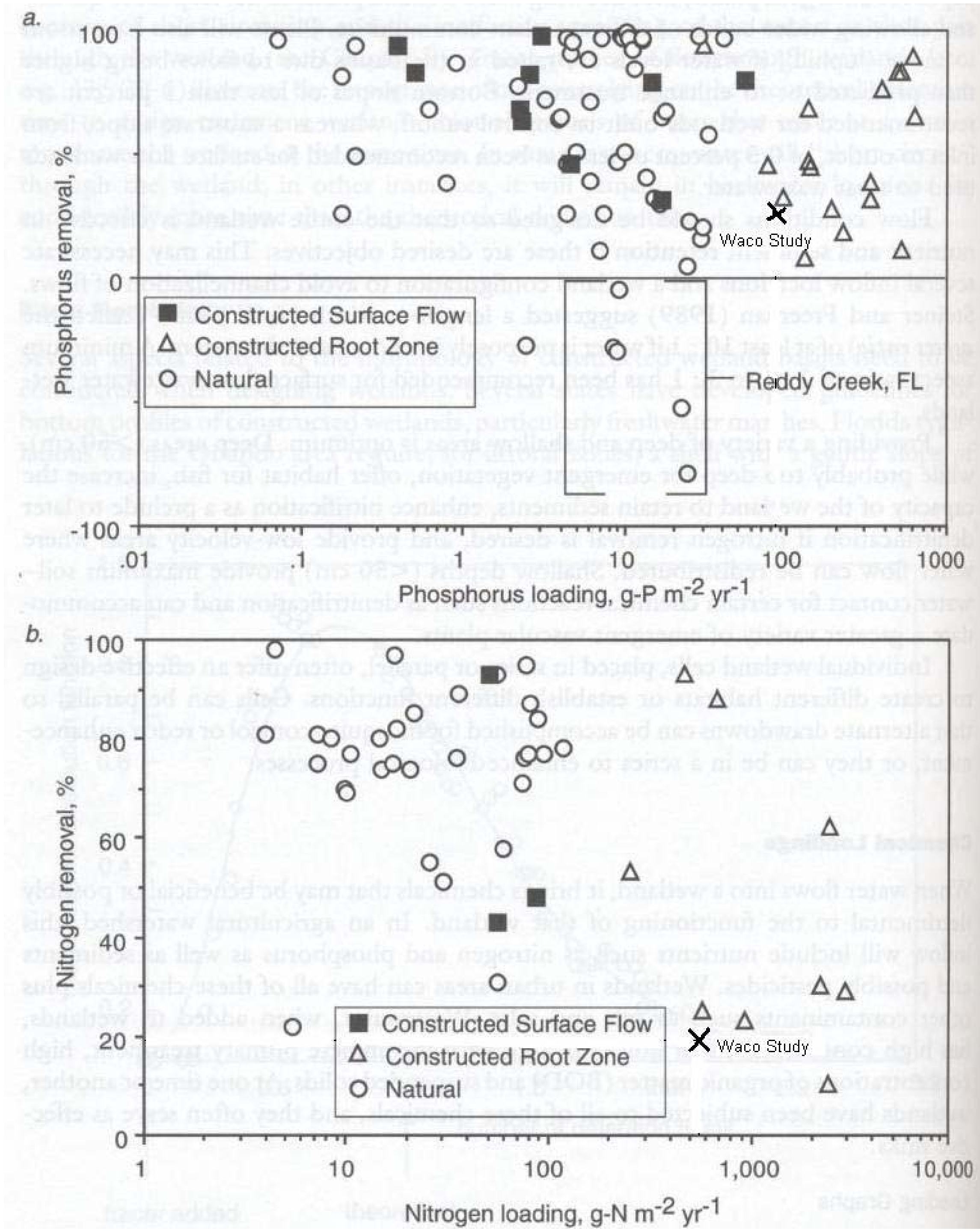

Fig. 18. Nutrient removal versus nutrient loading of our study with comparisons to previous studies. *Source*: Mitsch and Gosselink 2000.

CHAPTER FOUR

Conclusions

The importance of this study is that it has tested a subsurface-flow wetland under the same general conditions as other onsite advanced wastewater treatment systems. The study also addressed the appropriateness of the NSF/ANSI Standard 40 test for subsurface-flow constructed wetlands.

The frequency of sampling and number of parameters tested enabled a comprehensive study that provided more insight on subsurface-flow constructed wetlands for wastewater treatment. The conclusions from this study are listed below.

1) The raw influent for this study was toward the higher end of the NSF/ANSI Standard 40 requirements, ranging from 89 to 884 mg/l and averaging 305 mg/l for TSS, while ranging from 106 to 590 mg/l and averaging 260 mg/l for BOD. Raw influent acceptable for NSF/ANSI Standard 40 must have a mean between 100 mg/l and 350 mg/l for TSS and 100 mg/l and 300 mg/l for BOD.
2) The wetland effluent met the pH requirements for NSF/ANSI Standard 40 and ranged from 6.5 to 7.0 pH units during the study.
3) The wetland effluent met the NSF/ANSI Standard 40 requirements for both the 7-day and 30-day average for TSS.
4) The wetland effluent did not meet the NSF/ANSI Standard 40 requirements for 7-day or 30-day average for CBOD during February and March.

5) The wetland effluent met the NSF/ANSI Standard 40 requirements for 7-day and 30-day average for CBOD during April and May.
6) The wetland significantly reduced TSS, CBOD, TN and TP. However, the reduction in TN and TP was not comparable to the TSS or CBOD and may not meet desired values.
7) NSF/ANSI Standard 40 does not account for weather and seasonality. This study indicated modifications may be necessary to account for variations due to precipitation, evaporation, plant growth and temperature when applied to subsurface-flow treatment wetlands.
8) Although it took about two months to mature, the wetland was effective in TSS and CBOD reduction under the rigors of NSF/ANSI Standard 40 protocol during design loading.

APPENDICES

APPENDIX A

Construction

Construction began on December 7, 2005. Railroad ties were pre drilled with a ¼-inch drill bit and secured with two-foot long pieces of rebar. The first layer of railroad ties was secured into the ground with rebar. The second layer was staggered, secured with rebar to the first layer, and placed so that the top of the railroad tie to the ground was 12 inches high (Figure A1). Inclement weather prevented completion on the first day. Figure A2 shows the 1,500 gallon two-chambered septic tank and shape the wetland had taken after the railroad ties were set.

Fig. A.1. Railroad ties being set in place with rebar to form wetland skeleton structure.

Fig. A.2. Septic tank (1,500 gallon, two-chambered) and wetland on December 7, 2005.

On December 8, 2005 Brian Scheffe and Pablo Davila installed the dosing bucket, rotating actuated valve, overflow pipe and other necessary connections needed to dose the wetland. The dosing bucket was placed in an elevated position to the septic tank for wastewater to gravity flow (1/8 inch drop per foot distance). A ¾-inch conduit pipe is where the wastewater enters the dosing bucket (Figure A3). As the dosing bucket fills with wastewater the rotating actuated valve is in the "closed valve" position, allowing the bucket to fill without wastewater entering the septic tank. An overflow pipe is positioned in the dosing bucket to a level calibrated to five gallons. When the wastewater rises above the overflow pipe (five gallons) it drains into the site return tank (Figure A3). When dosing stops the rotating actuated valve is then activated and turns to the "open valve" position. This allows for the one dose of five gallons to enter the system.

Fig. A.3. Dosing bucket to wetland system. Left) Empty bucket showing overflow pipe (middle) and incoming (lower left). Right) Full five-gallon dose and float counter near top.

Fig. A.4. Valve which opens and closes to dose wastewater into the septic tank and system.

On December 15, 2005 the crew from Texas A&M University returned to work on the wetland. The ground within the railroad ties was covered with a bentonite clay layer. A 10-foot long board was used to smooth out the thin bentonite layer (Figure A5). The 45-mil rubber liner liner was rolled out adjacent to the wetland and cut 54 feet 6 inches long. The liner was then raised and set over the wetland. The liner was set in place by nailing one-by-four boards 10 feet long onto the top inside of the railroad ties (Figure A6). The bottom of the boards were placed just above the fluid level inside the wetland. An infiltrator chamber was placed at the front end of the wetland. The purpose of the chamber is to evenly distribute incoming wastewater into the wetland (Figure A7). At the back end of the wetland a four-inch sewer pipe with sleeves was secured with a glue gun and reinforced with black silicon. A perforated four-inch sewer line was placed across the wetland that connected the cleanout and outlet port (Figure A8). Three sampling ports (12.5 ft, 25 ft, and 37.5 ft from the front end of the wetland) and 10 piezometers were placed in the wetland. Once all of the tubing was in place the wetland was filled with gravel. The gravel was added using a backhoe and then distributed evenly with shovels. The sampling ports and piezometers were held in place as the gravel was added. Figure A9 shows the wetland at the end of the day on December 15, 2005.

Fig. A.5. Benonite provides smooth surface and acts as a sealant for potential leaks.

Fig. A.6. Forty five mil rubber liner stretched over wetland footprint. Donated by Firestone Building Products Company.

Fig. A.7. Front end of wetland. Infiltrator chamber helps equally distribute wastewater.

Fig. A.8. Back end of wetland. Perforated four-inch collection pipe across wetland.

Fig. A.9. Wetland filled with “Grade 3 concrete rock,” December 15, 2005.

Wetland effluent overflow from the wetland sump flows into a 3,000 gallon storage tank. From the storage tank wetland effluent is pumped to a 500 gallon tank that pumps, on demand, all water used at the BWRP site back to the adjacent NSF site and then to the WMARSS treatment plant. A flow meter records the gallons pumped out of the 3,000 gallon return tank and flow is recorded each day (Figure A10). The 3,000 gallon storage is pumped down by a timer with a float switch at 10:00 p.m. every day. The 3,000 storage tank’s size allows the site to store discharge from large rainfall events. A three-inch rain would add approximately 900-gallons to the wetland. The 3,000 gallon storage tank can store a six-inch rain and a catastrophic draining of the wetland in a 24-hour period.

Fig. A.10. Flow meter to measure gallons leaving the wetland system each day.

APPENDIX B

Media

Media used in this study was selected for several reasons. First, it was important for the media to be practical and therefore generally available at a reasonable cost. It was also important that the media characteristics be repeatable and within some degree of accuracy and precision. “Grade 3 concrete rock” (Figure B1) has standards that are measurable and repeatable and is readily available at distribution centers. “Grade 3 concrete rock” contains washed gravel between ¾ to 1½ inches in diameter (Table B2). In this study the gravel truck drove under the wash once before leaving the quarry to reduce fines as much as possible. The gravel used in this study contains both siliceous and carbonate particles and was mined from the lower terraces of the Brazos River several miles south of Waco, Texas.

Fig. B.1. “Grade 3 concrete rock” media used in the wetland.

Porosity

The porosity of the gravel media used in the wetland was determined by filling a 2000-ml graduated cylinder with approximately 1200 ml of the dry gravel used in the wetland and then shaking the gravel to settle or pack the gravel as densely a practical. Water was added to the graduated cylinder until the water level in the pores reached the 1000-ml mark. This water was then drained into a container and measured using a 100-ml graduated cylinder. This smaller size of graduated cylinder allowed the measurements to be more accurate than using a larger container. The volume of water was then divided by 1000-ml and multiplied by 100 to represent the porosity as a percent. Three different random samples of the gravel media (A, B, and C) collected from the media pile when the gravel was placed in the wetland were used in these calculations and the porosity calculation was repeated three times with each sample. The overall average of the nine calculations was 37.3 percent and this value was used as the representative porosity (Table B1). This porosity value of 37.3 percent is probably greater than the actual value because the packing in the graduated cylinder is probably less dense than in the wetland.

Particle Analysis

A sieve analysis of the gravel used in the wetland was conducted by the Texas Cooperative Extension Service. The sieve analysis showed the gravel was very clean with almost no fines and the three samples randomly selected for analysis were very consistent (Figure B2 and Table B2).

Table B.1. Lab porosity values for gravel media in the subsurface-flow wetland

Sample		ml	%
A	trial #1	367	36.7
	trial #2	373	37.3
	trial #3	369	36.9
	Average	370	37.0
B	trial #1	374	37.4
	trial #2	369	36.9
	trial #3	373	37.3
	Average	372	37.2
C	trial #1	375	37.5
	trial #2	381	38.1
	trial #3	377	37.7
	Average	378	37.8
Overall	High	381	38.1
	Mean	373	37.3
	Low	367	36.7

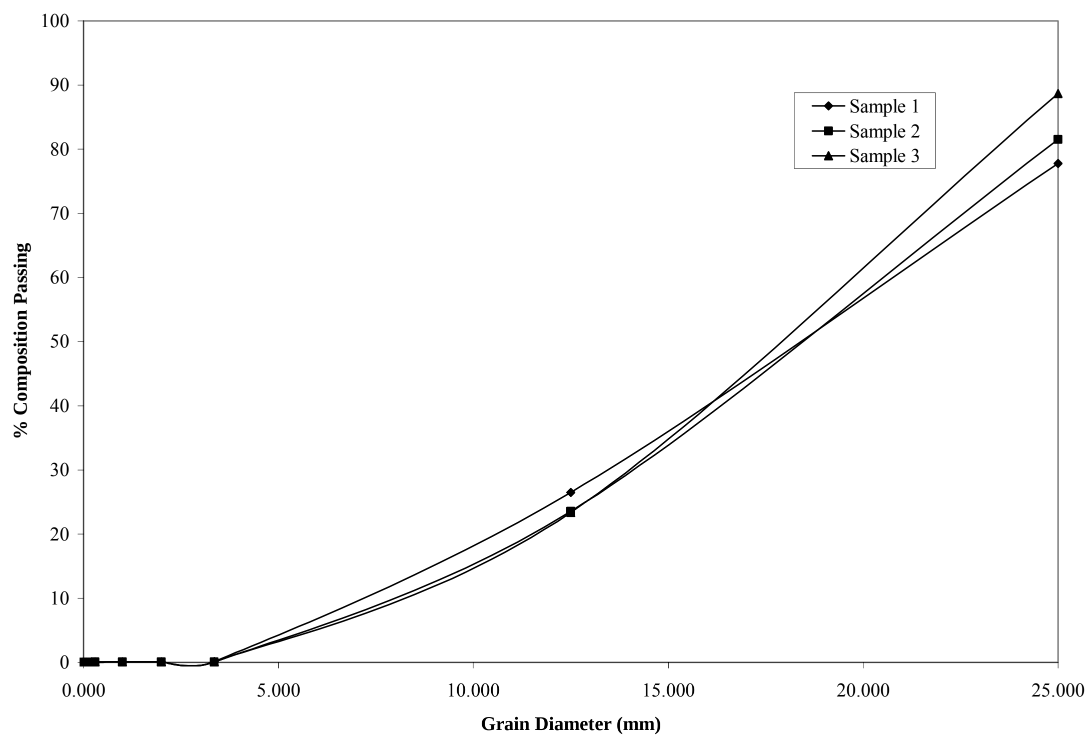

Fig. B.2. Grain size gradation curves by sieve analysis for Sample 1, 2 and 3. *Source*: Texas Cooperative Extension 2005.

Table B.2. Sieve analysis results performed by Texas Cooperative Extension

	Sieves Number	Opening Size (mm)	Sieves Weight (g)	Sample Weight (g)	Sample Retained (g)	Percent Retained	Percent Passing
Test 1		25.000	494.1	605.1	111.0	22.21	77.79
		12.500	496.7	752.9	256.2	51.27	26.52
	6	3.360	503.9	635.9	132.0	26.42	0.10
	10	2.000	423.2	423.3	0.1	0.02	0.08
	18	1.000	442.1	442.3	0.2	0.04	0.04
Sample Weight (g) 499.7	50	0.300	330.9	331.0	0.1	0.02	0.02
	70	0.212	320.1	320.1	0.0	0.00	0.02
	200	0.075	303.5	303.5	0.0	0.00	0.02
	Plate	0.000	362.4	362.5	0.1	0.02	0.00
				Total (g): 499.7			
Test 2	Sieves Number	Opening Size (mm)	Sieves Weight (g)	Sample Weight (g)	Sample Retained (g)	Percent Retained	Percent Passing
		25.000	494.1	586.5	92.4	18.49	81.53
		12.500	496.7	786.7	290.0	58.03	23.57
	6	3.360	503.9	621.6	117.7	23.55	0.04
	10	2.000	423.2	423.2	0.0	0.00	0.04
	18	1.000	442.1	442.1	0.0	0.00	0.04
Sample Weight (g) 500.3	50	0.300	330.9	330.9	0.0	0.00	0.04
	70	0.212	320.1	320.2	0.1	0.02	0.02
	200	0.075	303.5	303.5	0.0	0.00	0.02
	Plate	0.000	362.4	362.5	0.1	0.02	0.00
				Total (g): 500.3			
Test 3	Sieves Number	Opening Size (mm)	Sieves Weight (g)	Sample Weight (g)	Sample Retained (g)	Percent Retained	Percent Passing
		25.000	494.1	550.6	56.5	11.31	88.70
		12.500	496.7	823.2	326.5	65.34	23.37
	6	3.360	503.9	620.4	116.5	23.31	0.06
	10	2.000	423.2	423.3	0.1	0.02	0.04
	18	1.000	442.1	442.1	0.0	0.00	0.04
Sample Weight (g) 499.8	50	0.300	330.9	330.9	0.0	0.00	0.04
	70	0.212	320.1	320.1	0.0	0.00	0.04
	200	0.075	303.5	303.6	0.1	0.02	0.02
	Plate	0.000	362.4	362.5	0.1	0.02	0.00
				Total (g): 499.8			

APPENDIX C

Vegetation

Under the consultation of Dr. Robert Doyle, wetland ecologist, and supervision of Dr. Joe C. Yelderman Jr., plants were transplanted to the treatment wetland (filled with make-up water). The majority of the plants originated from the Lake Waco Wetlands, but irises were transplanted from Bryan-College Station area. Plants were removed from the Lake Waco Wetlands with roots intact and placed into buckets with water. Plants were taken to BWRP site immediately. Plant roots were washed and rinsed to eliminate solids from entering the subsurface-flow treatment wetland. An inverted traffic cone with the top cut out was used to displace gravel and hold an opening where the plant was placed. Roots were located below water level and the above ground biomass was trimmed to a few inches above the surface.

Plants used in this study were cattail (*Typha latifolia*), bulrush (*Scirpus cubensis*), pickerel weed (*Pontederia cordata*) and iris (*Iris pseudacorus*). Plants were selected based on size, suitability, availability, and seasonal growth pattern. The selection provides a mixture of larger plants, bulrush and cattail, with smaller, flowering plants, pickerel weed and iris. A density of one plant per 3 ft^2 was used, for a total of 141 total plants. The first five feet of the wetland were left unvegetated near the infiltrator chamber to allow unimpeded flow in this area (Figure C1).

Plant layout was designed with aesthetics in mind as smaller flowering plants were placed along the edges (pickerel weed and iris) and larger plants in the center of the wetland. The layout was altered by plant deaths and inexplicable emergence of one volunteer elephant ear (*Opuntia tuna*).

	No Plants		**No Plants**	
P	P	P	P	P
P +	P +	P	P +	P +
P	P	P	P	P
I	P	I	P	I
P	P	P	P	P
P +	P +	o	P +	P +
P	P	EE	P	P
B	B	B	B	B
B	B	C	B	B
B	B	C	B	B
B	B	C	B	B
B	X	B	B	B
P	I	P	I	P
P	I	O	I	P
P	I	P	I	P
P	B	B	B	P
P	B	C	X	P
B	B	C	B	X
P	B	X	B	B
P	B	B	B	P
P	P	I	P	P
P	P	o	P	P
P	P	I	P	P
B	B	X	B	B
I	B	B	B	I
I	B	C	B	I
I	B	C	B	I
B	B	C	B	B
P	P	O	P	P
P	P	I	P	P co

Fig. C.1. Plant layout as of June 7, 2006. P= 65 pickerel weed (*Pontederia cordata*); I= 18 iris (*Iris pseudacorus*); B= 49 bulrush (*Scirpus cubensis*); C= 8 cattail (*Typha latifolia*); EE= 1 elephant ear (*Opuntia tuna)*; O= sampling port; CO= cleanout port; and (+) = piezometer

Fig. C.2. Plants used in this study. Iris (top left), cattail (top right), pickerel weed (bottom left) and bulrush (bottom right).

Plant growth was monitored periodically by randomly selecting three plants of each species for each third of the wetland length. A total of 12 plants per wetland third were measured representing an average performance for each plant species by wetland third. There were four bulrush plants measured in the first wetland third and four pickerel weed measured in the last wetland third. Also, one of the cattails in the middle wetland third died sometime between May 10 and June 7 plant assessments. Plant growth was monitored by recording tallest stem height (cm) and number of stems per plant. A total of five plant assessments were performed between April 5 and June 7 (Table C1). Growth was monitored by tallest stem height per plant and number of stems per plant. An average of plant growth was computed by plant species.

Table C.1. Plant assessments from April 5 to June 7

A. April 5, Reporter: Reddy Adapala

Plant #	Height	Number of Stems
P 1.1	32	6
P 1.2	19	4
P 1.3	29	11
I 1.1	34	6
I 1.2	9	3
I 1.3	33	12
B 1.1	73	4
B 1.2	72	5
B 1.3	68	3
B 1.4	62	3
C 1.1	108	27
C 1.2	96	29
C 1.3	106	17
P 2.1	33	5
P 2.2	35	6
P 2.3	33	6
I 2.1	50	13
I 2.2	26	5
I 2.3	27	8
B 2.1	8	5
B 2.2	58	8
B 2.3	58	2
C 2.1	114	19
C 2.2	64	6
C 2.3	26	7
I 3.1	39	6
I 3.2	26	5
I 3.3	46	9
B 3.1	53	6
B 3.2	76	4
B 3.3	32	3
C 3.1	112	26
C 3.2	96	16
C 3.3	94	18
P 3.1	32	9
P 3.2	35	10
P 3.3	30	10
P 3.4	43	8

B. April 14, Reporter: Reddy Adapala

Plant #	Height	Number of Stems
P 1.1	38	8
P 1.2	23	7
P 1.3	30	16
I 1.1	44	10
I 1.2	11	1
I 1.3	43	12
B 1.1	82	3
B 1.2	66	1
B 1.3	72	2
B 1.4	84	4
C 1.1	130	32
C 1.2	114	38
C 1.3	120	22
P 2.1	42	7
P 2.2	40	10
P 2.3	34	10
I 2.1	56	13
I 2.2	33	4
I 2.3	34	9
B 2.1	98	3
B 2.2	73	2
B 2.3	62	4
C 2.1	136	28
C 2.2	86	9
C 2.3	32	6
I 3.1	45	7
I 3.2	28	5
I 3.3	56	11
B 3.1	84	3
B 3.2	82	2
B 3.3	54	4
C 3.1	132	29
C 3.2	106	18
C 3.3	110	21
P 3.1	42	17
P 3.2	40	14
P 3.3	35	15
P 3.4	43	12

C. April 19, Reporter: Reddy Adapala

Plant #	Height	Number of Stems
P 1.1	46	15
P 1.2	28	10
P 1.3	32	23
I 1.1	46	15
I 1.2	6	2
I 1.3	48	11
B 1.1	80	6
B 1.2	66	2
B 1.3	70	3
B 1.4	88	6
C 1.1	134	37
C 1.2	124	41
C 1.3	122	28
P 2.1	46	9
P 2.2	44	14
P 2.3	42	10
I 2.1	66	17
I 2.2	38	5
I 2.3	38	9
B 2.1	100	3
B 2.2	76	3
B 2.3	60	5
C 2.1	150	32
C 2.2	98	11
C 2.3	34	6
I 3.1	56	8
I 3.2	34	5
I 3.3	60	20
B 3.1	106	7
B 3.2	84	3
B 3.3	66	4
C 3.1	150	35
C 3.2	120	20
C 3.3	120	28
P 3.1	48	24
P 3.2	44	19
P 3.3	44	20
P 3.4	46	16

D. May 10, Reporter: Reddy Adapala

Plant #	Height	Number of Stems
P 1.1	56	21
P 1.2	40	14
P 1.3	60	33
I 1.1	70	23
I 1.2	20	6
I 1.3	75	16
B 1.1	90	5
B 1.2	100	7
B 1.3	105	7
B 1.4	110	9
C 1.1	180	56
C 1.2	170	52
C 1.3	160	42
P 2.1	75	12
P 2.2	65	18
P 2.3	60	12
I 2.1	85	32
I 2.2	56	8
I 2.3	45	12
B 2.1	120	7
B 2.2	90	6
B 2.3	75	11
C 2.1	180	56
C 2.2	109	14
C 2.3	60	11
I 3.1	64	15
I 3.2	48	18
I 3.3	70	28
B 3.1	106	11
B 3.2	75	7
B 3.3	180	6
C 3.1	170	56
C 3.2	160	42
C 3.3	170	43
P 3.1	64	40
P 3.2	59	32
P 3.3	60	45
P 3.4	58	34

E. June 7, Reporter: Pablo Davila

Plant #	Height	Number of Stems
P 1.1	48	65
P 1.2	55	29
P 1.3	53	71
I 1.1	69	38
I 1.2	41	8
I 1.3	70	48
B 1.1	112	43
B 1.2	87	10
B 1.3	90	13
B 1.4	110	53
C 1.1	225	105
C 1.2	207	140
C 1.3	200	82
P 2.1	61	75
P 2.2	54	75
P 2.3	66	69
I 2.1	73	96
I 2.2	55	25
I 2.3	62	18
B 2.1	102	35
B 2.2	87	23
B 2.3	103	43
C 2.1	209	143
C 2.2	194	51
C 2.3	Dead	dead
I 3.1	88	68
I 3.2	69	45
I 3.3	65	89
B 3.1	155	12
B 3.2	135	6
B 3.3	118	27
C 3.1	218	120
C 3.2	216	66
C 3.3	203	105
P 3.1	81	170
P 3.2	81	140
P 3.3	85	164
P 3.4	86	111

APPENDIX D

Hour Meter and Float Counter

The mass balance of fluids is important in this study. Therefore, an hour meter and a float counter were installed to record the time the dosing pump was on and the number of full doses received, respectively. These two items provide two separate ways to check on the dosing volume and help troubleshoot any problem experience with the wastewater dosing.

The hour meter records the hours that the dosing pump receives power. The meter reading is in hours and hundredths of hours (not in hours and minutes). The pump should be on for two minutes for each does as the dosing bucket fills. However, the first dose in each cycle pumps for three minutes. There are 100 doses per day; 35 from 6:00 a.m. to 9:00 a.m., 25 from 11:00 a.m. to 2:00 p.m., and 40 from 5:00 p.m. to 8:00 p.m. Therefore there are 100 doses x two (2) minutes plus three (3) extra minutes, or 203 minutes when the pump should be on each day. When 203 minutes is divided by 60 minutes per hour it is equal to 3.38 hours +/- .01 hour if the pump is receiving power correctly. The morning dose should receive power for 71 minutes or 1.183 hours, the noon dose should receive power for 51 minutes or .85 hours and the evening dose should receive power for 81 minutes or 1.35 hrs. There should be a change of 23.68 hours per week and 101.5 hrs per month (30 days). The hour meter is read every day to see if the pump received the correct amount of power. On Monday the hour meter should change by 10.15 hours from dosing over the weekend (three days). The pump should be pumping when the power is on but if it is clogged we may not be getting wastewater. Therefore, there is also a float counter in the dosing bucket to count each time the bucket fills and empties (one dose).

A float counter is located near the fill line of the bucket and records a click each time the bucket fills. At 100 doses per day there should be 100 counts each day. Like the hour meter, the float counter can also be read with respect to the morning, noon and evening dosing schedule. If there are fewer than the required doses the site managers are alerted to a problem. The actual number of doses can be multiplied by five gallons per dose to calculate the actual gallons received for any given day or dosing period. The combination of an hour meter and float counter allow the site managers to monitor the dosing and help ensure proper dosing.

Fig. D.1. Breaker box, timers, hour meter, and float counter. The two small boxes adjacent to large breaker box are the hour meter (bottom) and counter (top).

APPENDIX E

Sample Collection

Samples were collected with peristaltic pumps that extracted the samples and pumped the fluid into bottles within mini-refrigerators immediately adjacent to the site. The pumps were activated with timers programmed to the desired schedule (Tables E1 and E2).

The sampling is required to be flow proportional: 35 percent in the morning, 25 percent at noon and 40 percent in the evening. Samplers sample for 175 minutes when the dose is 175 gallons in the morning (35%), 125 minutes at noon when the dose is 125 gallons (25%) and 200 minutes in the evening when the dose is 200 gallons (40%). Therefore, no matter what the sample size or pumping rate of the peristaltic pump, proportionality will still be appropriate. The minimum delay on the wetland timer is 10 minutes after dosing starts which is adequate since flow is observed to increase within two to three minutes at the pump (wetland effluent) after dosing starts.

All programs have at least a five-minute delay to allow fresh sample to reach the area near the pump. The noon dose has almost an hour delay. This is when the dosing schedule has 10 minute instead of five minute intervals so we avoid any dilution but still get 25 percent of sample during the 25 percent dose.

The "programmed time" in Tables E1 and E2 is different from the real time because a sample day was from noon to 9:00 a.m. the following day. This allowed for samples to be collected in the morning and avoided sample collection on weekends.

Sample days still consisted of the three dosing schedules, but in a different order: noon (25%), evening (40%) and morning (35%). Therefore, a sample week began on Sunday at noon and ended Friday at 9:10 a.m.

Table E.1. Peristaltic pump schedule set to collect 24-hour, flow proportional septic effluent samples

	On/Off	Programmed time	Real time
Program	On	2:00 a.m.	12:00 p.m.
#1	Off	4:05 a.m.	2:05 p.m.
Program	On	7:10 a.m.	5:10 p.m.
#2	Off	10:30 a.m.	8:30 p.m.
Program	On	8:05 p.m.	6:05 a.m.
#3	Off	11:00 p.m.	9:00 a.m.

Table E.2. Peristaltic pump schedule set to collect 24-hour, flow proportional wetland effluent samples

	On/Off	Programmed time	Real time
Program	On	2:00 a.m.	12:00 p.m.
#1	Off	4:05 a.m.	2:05 p.m.
Program	On	7:10 a.m.	5:10 p.m.
#2	Off	10:30 a.m.	8:30 p.m.
Program	On	8:15 p.m.	6:15 a.m.
#3	Off	11:10 p.m.	9:10 a.m.

Fig. E.1. Septic tank effluent sampling unit. Peristaltic tubing covered with insulation collects sample from the pipe dispensing septic effluent. The sample is pumped to a bottle inside a refrigerator inside the box shown in Figure E2.

Fig. E.2. Inside septic tank effluent sampling unit. Left) Sample is collected by peristaltic pump and collected in sample bottle inside refrigerator. Right) Peristaltic pump within septic tank effluent sampling timer unit programmed to collect 24-hour flow-proportional sample.

Fig. E.3. Wetland effluent sampling unit. Peristaltic tubing collecting sample from wetland sump (black container). The large gray box houses the refrigerator where the samples are stored during the 24-hour sampling period.

Fig. E.4. Wetland sump that controls water level in the wetland and where wetland effluent sample is collected by peristaltic tubing.

APPENDIX F

Precipitation

The subsurface-flow treatment wetland is exposed to the weather and although it is designed where no runoff can drain into the wetland, direct rainfall onto the wetland will infiltrate into the media and affect the volume and perhaps the concentration of the effluent. A tipping bucket recording rain gauge with data logger was installed on top of the site office building. The official weather stations for Waco is nearly 15 miles away and the local rainfall on the site was critical for accurate assessments.

Because there is a three-inch layer of dry gravel above the level of wastewater in the wetland, small amounts of rainfall will be adsorbed onto the gravel before reaching the saturated portion of the wetland. This moisture adsorbed onto the rocks above the saturated zone will evaporate back into the atmosphere (unless there is immediate subsequent rainfall).

In order to calculate the amount of rain that would be adsorbed onto the gravel at the wetland a 2000-ml graduated cylinder was filled with dry gravel and then saturated to the 2000 ml mark. The amount of water needed to saturate the gravel was measured and then the amount of water that could be poured out of the graduated cylinder was measured. The difference between the amount poured in and the amount poured out is the amount adsorbed onto the gravel. This was repeated three times. The average volume of water adsorbed onto the gravel was 72 ml (0.0189473 gallons or .0025327 ft^3).

The volume of the graduated cylinder was 0.5263157 gallons or 0.0703536 ft^3.

Therefore, 0.0189473 gallons of water is adsorbed for each 0.0703536 ft^3 of gravel.

To calculate the amount of water adsorbed for each ft^3:

$$\frac{0.0189473 \text{ gallons of water}}{0.0703536 \text{ ft}^3 \text{ of gravel}} = \frac{0.2693152 \text{ gallons}}{1 \text{ ft}^3 \text{ of gravel}}$$

There are 125 ft^3 of dry gravel on the top of the wetland (50 feet long X 10 feet wide X 0.25 feet height). This equates to:

$$= 0.2693152 \text{ gallon/ ft}^3 \text{ X } 125 \text{ ft}^3$$

$$= 33.66 \text{ gallons}$$

Therefore it takes approximately 34 gallons to "wet" the three inches (0.25 ft) of gravel on top of the wetland. The 33.66 gallons is equivalent to 4.5 ft^3. If you divide 4.5 ft^3 by 500 ft^2 the result is 0.009 ft or 0.108 inches which means it takes approximately 0.1 inches of rain to saturate the dry gravel before recharging the wetland. When calculating the amount of water added to the wetland from a precipitation event, 0.1 inches of rain or 34 gallons should be subtracted from the amount of rainfall.

Sample:

$$\frac{\text{X inches of rainfall}}{\text{12 inches per foot}} \text{ x } 500 \text{ ft}^2 \text{ of wetland area} - 4.5 \text{ ft}^3 = \text{XX ft}^3 \text{ of water added to wetland}$$

Any rainfall event less than 0.1 inches of rain will not contribute to the volume of fluid in the wetland. Errors could occur if the gravel is already wet from a previous rain fall event or as the plants mature and increase the interception area above the wetland media.

Table F.1. Rainfall events that contributed volume to the wetland

Date		Rainfall (1/100 inch)	Gallons to Wetland
February	10	58	147
	24	21	32
	25	117	331
March	9	49	119
	19	24	41
	20	68	178
	28	142	409
	29	19	26
April	6	32	66
	20	42	97
	21	12	4
	25	23	38
	29	136	390
May	6	464	1413
	8	22	35
	14	410	1244

Fig. F.1. Tipping bucket rain gauge used to collect data on precipitation events.

Fig. F.2. Tipping bucket located on top of office at BWRP. Location was chosen because there are no obstructions overlying the tipping bucket.

APPENDIX G

Data Days Outside of NSF/ANSI Standard 40 Range (450-550 gallons)

NSF/ANSI Standard 40 protocol calls for the 30-day average dosing volume to be within 500 gallons per day ± 50 gallons per day. Therefore, if system dosage, read from wetland return tank, falls between 450 gallons and 550 gallons, that particular data day is acceptable. Even though this ten percent range is based on a 30-day average any day with flow outside the 450-550 gallon range, may be considered a "bad data day" since it is outside the range specified by NSF/ANSI Standard 40. To identify days when the system received less than 450 gallons we looked at both the flow meter from the wetland return tank and the float counter data from the dosing bucket. The flow meter data may be affected by evapotranspiration so the float counter was considered critical. The system is expected to receive 100 doses at five gallons a dose. If the system receives less than 90 doses (450) gallons it falls outside the appropriate range. Instances when the system received less than 90 doses were due to line clogging or pump malfunction. Those individual days as well as the steps taken to address the problem are documented in Table G1.

System flow in excess of 550 gallons was identified by the flow meter from the return tank. The return tank is activated by a float valve that pumps down to the same level each day. When the flow meter indicated an excess of 550 gallons it was a result of extra gallons to the wetland. Instances when extra flow occurred to the wetland were a result of precipitation events and a leaky valve below the dosing bucket. Individual days when return tank flow read in excess of 550 gallons are listed below. All rainfall events that contributed additional volume to the wetland are also listed.

We did not eliminate data from days outside the range but used them for the overall evaluation and made notes of occurrences.

Table G.1. Data days with system flow outside 450-550 gallon range

Date		Return gallons	Rainfall gallons	Counter	Explanation
February	4-6	N/A	N/A	130 of 300	PVC line clogged; changed from 1 ¼" to 1 ½" line.
	11-13	N/A	N/A	149 of 300	Dosing pump clogged; cleaned out.
	16	N/A	N/A	50 of 100	One time event, did not persist.
	18-19	N/A	N/A	72 of 225	Dosing pump was clogged; cleaned out.
	22	592.4	0	N/A	Actuated valve was not closing completely allowing more than the calibrated 5 gallons to enter the system every dose. Problem corrected on March 8th by adjusting valve.
	23	567.5	0	N/A	
	24	585.6	0	N/A	
	25	608.3	0	N/A	
	26	970.0	331	N/A	
	27	566.6	0	N/A	
	28	570.9	0	N/A	
March	5	600.3	0	N/A	
	10	605.1	53.3	N/A	Rainfall
	15	N/A	N/A	89 of 100	No dosing to prevent overflow at NSF side.
	20	589.6	37.7	N/A	Rainfall
	21	570.1	178	N/A	Rainfall
	29	920.6	408.6	N/A	Rainfall
April	30	1307.6	389.9	N/A	Rainfall
May	6	1041.6	1412	N/A	Rainfall- not all pumped down on 6th, rest returned on 7th
	7	1110.5		N/A	
	15	1567.4	1244	N/A	Rainfall
	24	N/A	N/A	64 of 100	One time event; did not persist.

APPENDIX H

All Data

See accompanying Excel files for TSS, CBOD, nutrient, precipitation and YSI data.

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