PHOSPHORUS REMOVAL IN LAKE OKEECHOBEE TRIBUTARIES USING CDS AND BAFFLE BOX UNITS

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ABSTRACT: Phosphorus inputs from tributaries are thought to be primary sources of phosphorus loadings to Lake Okeechobee. From 2000-2004, a demonstration project was conducted in Lettuce Creek, a tributary on the northeast side of Lake Okeechobee, to evaluate the phosphorus reduction benefits of Continuous Deflective Separation (CDS) and a traditional baffle box or Tributary Sediment Trap (TST). The units were constructed side-by-side, adjacent to Lettuce Creek, with a single intake pipe feeding each unit. Efficiency testing for the CDS and TST units was conducted at inflow rates of 1, 5, and 11 cfs. No significant removal of phosphorus species or TSS was observed in the CDS or TST units during operation at 1, 5, or 11 cfs. On an average basis, the CDS unit exhibited a mean TSS removal of 0.76 mg/l and a mean total phosphorus removal of 1.1 μg/l. On an average basis, the TST unit removed 0.57 mg/l of TSS and 0.79 μg/l of total phosphorus. The low observed removal efficiencies for these units are thought to be related to small particle sizes and a high dissolved phosphorus fraction. CDS and TST units appear to be better suited to an urban environment where particle sizes may be larger.

KEY TERMS: Lake Okeechobee, Phosphorus Removal, Nonpoint Source Pollution, Nutrients, Sediment, Watershed Management

INTRODUCTION

Lake Okeechobee is a critical water source for south Florida. The lake serves multiple purposes for the region, including drinking water supply; flood control; agricultural water supply; habitat for fish, birds, and other wildlife; urban and industrial water supply; and water supply for the Everglades. Over the past three decades, eutrophication of the lake has accelerated, largely due to excessive nonpoint source loadings from tributary basins north of the lake.

In 1987, the Florida Legislature delegated the South Florida Water Management District (SFWMD) to "design and implement a program to protect the water quality of Lake Okeechobee" (S. 373.4595, Florida Statutes) as part of the Surface Water Improvement and Management (SWIM) Act. The SWIM Act requires that the program be designed to lower phosphorus loading to the lake by a specific amount. Since the implementation of the SWIM Plan, phosphorus loading to the lake has been significantly reduced through multiple phosphorus management programs. However, the overall pollution load reduction goal has not yet been achieved. The SWIM plan update of 1993 identified tributary sediment as a potential source of phosphorus to the lake that should be controlled.

A study was conducted in 1997 to determine the phosphorus content and transport potential of sediment from various tributaries in the north Lake Okeechobee watershed that convey stormwater runoff to the lake and to analyze feasible management alternatives for source removal and control. The study concluded that sediment removal will reduce phosphorus loads to Lake Okeechobee (Mock, Roos, & Assoc., 1997). The total phosphorus reduction achieved by sediment removal will be limited by the fraction of particulate phosphorus in the tributary bed load, estimated to be approximately 25%. It was estimated that between 5-25% of the particulate phosphorus entering the lake could be attenuated by direct sediment removal. The information from the study led to the development of the project addressed in this paper which is designed to demonstrate the phosphorus reduction benefits which can be realized by tributary sediment removal.

In 2000, the SFWMD selected two sediment removal technologies, Continuous Deflective Separation (CDS) and a traditional Baffle Box or Tributary Sediment Trap (TST), to be evaluated by this project. According to available literature (Boman et al., 2000), these technologies: (1) are effective in reducing particulate phosphorus loading; (2) can be applied in open channel flow conditions and have a high treatment capacity; (3) are on the lower end of cost for treatment facilities; and (4) can be easily maintained.

The CDS unit is a patented technology designed for the removal of gross pollutants. It was developed in Australia by CDS Technologies, Ltd. and is manufactured in the United States by CDS Technologies, Inc. Inflow enters into the center chamber of the CDS unit, initiating a vortex action, and passes through a screen to an outer chamber prior to discharging downstream. Gross pollutants are trapped in a sump area located below the separation screen. The baffle box or TST achieves sediment removal using sedimentation. Water velocities are suddenly slowed by an increase in cross-sectional area and/or one or more internal baffles, allowing sediment to settle in the bottom of the trap.

SITE DESCRIPTION

Routine water quality monitoring, conducted by SFWMD, suggested that Lettuce Creek, which drains a large agricultural area northeast of Lake Okeechobee, may be a significant source of sediment and particulate loading to the lake, particularly under high flow conditions. As a result, Lettuce Creek was selected as a logical location for evaluation of the two sediment removal technologies. The site was selected according to the following criteria: (1) continuous flow conditions throughout much of the year; (2) no upstream water control structures; (3) relatively high sediment phosphorus content and particulate phosphorus concentrations; (4) erosive soil in upstream portions of the watershed; (5) relatively high sediment transport rate; (6) diversified land uses in the watershed; (7) a long period of historical record; and (8) high average water column phosphorus concentrations. A general site location map for Lettuce Creek and other significant Lake Okeechobee tributaries is given in Figure 1.

Historically, Lettuce Creek discharged directly into Lake Okeechobee through a forested wetland system. However construction of the L-63S Canal intercepted the Lettuce Creek tributary, which now discharges into the L-63S Canal. Flow in the L-63S Canal travels in a northwest direction, discharging into Nubbin Slough, and ultimately Lake Okeechobee. Discharges from Lettuce Creek into the L-63S Canal are regulated by nine separate riser structures constructed out of 72-inch CMPs. In general, water levels within Lettuce Creek are maintained at approximately 2-3 ft higher than water surface elevations in the L-63S Canal. Water flow rates in Lettuce Creek are highly variable, depending primarily upon antecedent rainfall conditions. During periods of low rainfall, flow rates through Lettuce Creek decrease, with water surface elevations falling below the riser boards in the outfall structure during extended dry periods. However, during periods of extended or heavy rainfall conditions, flow rates in Lettuce Creek increase substantially, exceeding 500 cfs for short periods during rainy conditions.

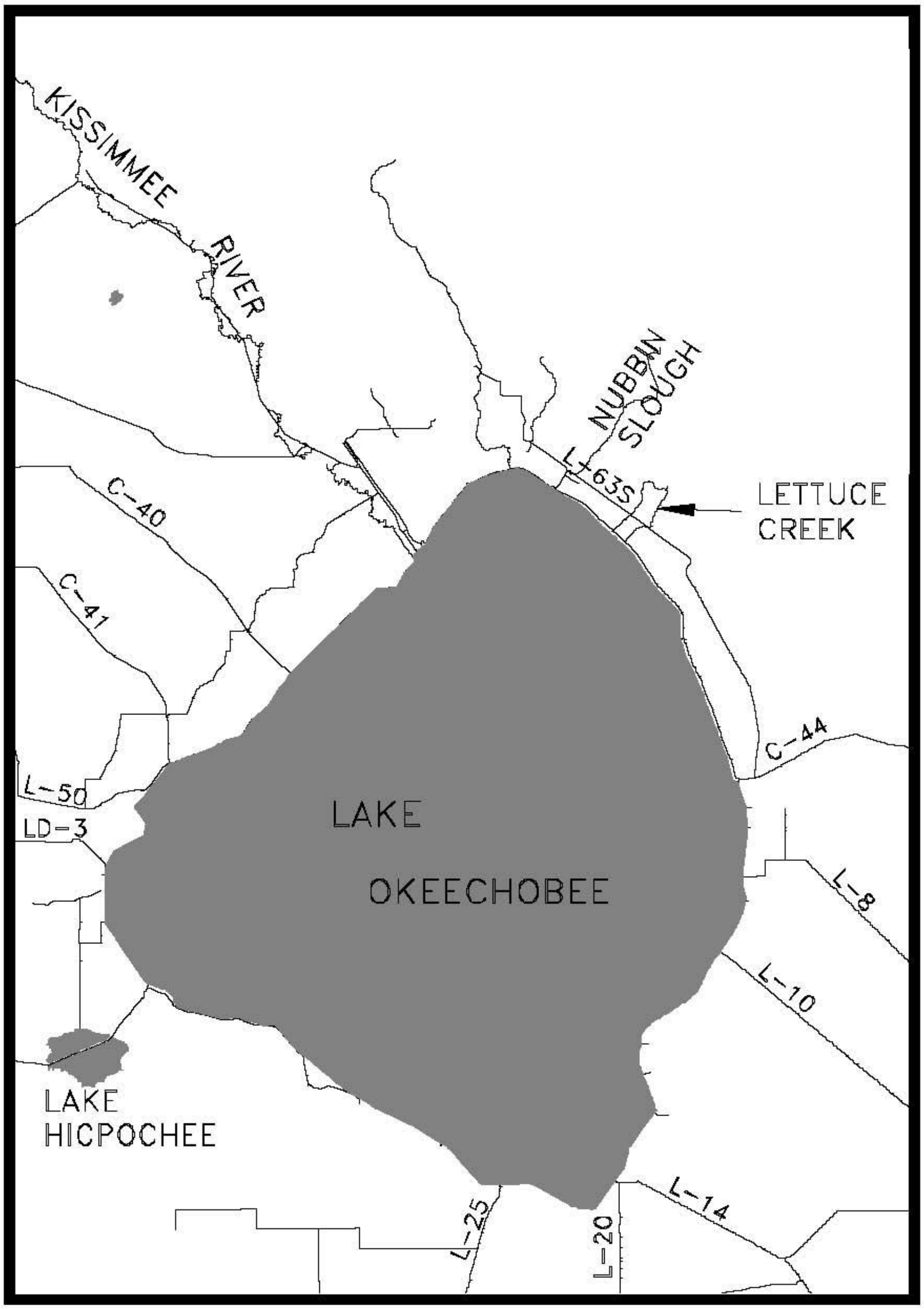

Figure 1. Location of Lettuce Creek and Other Significant Lake Okeechobee Tributaries.

DETAILS OF THE CDS AND TST UNITS

A plan view of the CDS and TST system design is given in Figure 2. Water flowing through Lettuce Creek is diverted into the CDS and TST units through 45 linear ft of 36-inch corrugated metal pipe (CMP). A 6-ft diameter CMP inflow manhole was constructed at the downstream end of the 36-inch CMP to divert flow into the CDS unit and the TST. A 4-ft x 5-ft sluice gate with handwheel was installed in the 6-ft diameter CMP manhole to isolate the systems from Lettuce Creek for cleaning and maintenance. The inflow manhole was connected to the CDS and TST units using 30-inch CMP so that the maximum pipe entrance velocity, at the maximum design inflow of 11 cfs, will be 2.1 ft/sec.

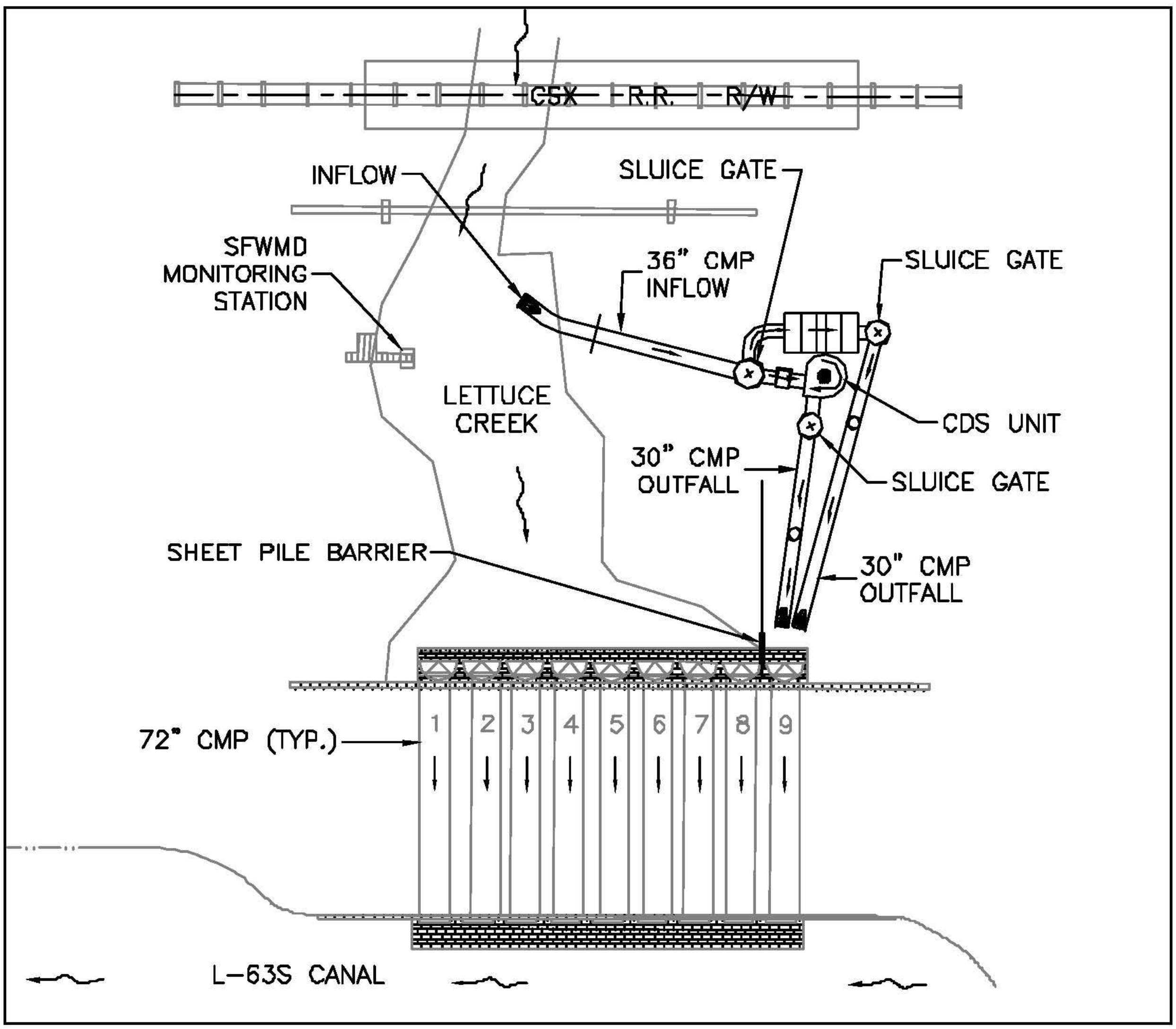

Figure 2. Plan View of the CDS and TST Unit Installation.

Physical characteristics of the CDS and TST units are summarized in Table 1. The TST unit is 8-ft wide, 15-ft long, and 10-ft deep, and constructed of welded steel. The steel TST unit has two movable internal baffles so that the unit can be divided into three equal chambers. The bottom of the sediment trap is 3-ft below the inflow pipe invert and the baffles extend 6 ft from the bottom of the trap. At the maximum design flow rate of 11 cfs, the water depth in the sediment trap is approximately 8 ft, with a cross-sectional area of 64 ft^2 and an average velocity of 0.17 ft/sec.

TABLE 1

PHYSICAL CHARACTERISTICS OF THE INSTALLED CDS AND TST UNITS

PARAMETER	CDS UNIT	TST UNIT
Model	PSW56_53	--
Materials	Concrete	Welded Steel
Dimensions	9.5 ft diameter 18.5 ft deep	8 ft wide 15 ft long 10 ft deep
Design Flow Rate	11 cfs	11 cfs
Removal Features	1. Vortex action 2. 2400 μm screen	1. Two internal baffles

The CDS unit is a pre-cast concrete structure, Model PSW56_53, which contains a 2400-micron stainless steel screen for separation of gross pollutants and large solids. This unit has an inside diameter of approximately 8 ft, an outside diameter of 9 ft-6 in, and an overall depth, from the finished grade to the bottom of the sump, of approximately 18 ft-6 in. The bottom sump area has a diameter of 8 ft and a depth of 3 ft-6 in, with a total volume of 176 ft^3.

Approximate construction costs for the CDS and TST units are given in Table 2. The basic structure cost is approximately 50% of the installed costs for both the CDS and TST units. In addition to the units themselves, additional structures, piping, gates, and valves were required for regulation of flow to the units and to provide access for performance monitoring. The total installed cost is approximately $116,684 for the CDS unit and $71,216 for the TST unit.

TABLE 2

APPROXIMATE CONSTRUCTION COSTS FOR THE CDS AND TST UNITS

ITEM	COST ($)	
	CDS UNIT	TST UNIT
Structure (Installed)	67,310	38,300
Miscellaneous Structures/Labor, etc.	49,374	32,916
TOTALS:	**$ 116,684**	**$ 71, 216**

METHODOLOGY

Field Monitoring

A network of monitoring equipment was installed at the Lettuce Creek site to provide estimates of the hydraulic characteristics of discharges through Lettuce Creek and perform inflow and outflow monitoring for the CDS and TST units to assist in characterizing the performance efficiency of each unit. A pressure transducer shaft encoder, KPSI Model 760, was installed in Lettuce Creek upstream of the riser structures to provide a continuous record of surface elevations in Lettuce Creek. Relationships between Lettuce Creek water surface elevation and flow rate were developed based upon measured surface water elevations and field flow measurements of Lettuce Creek discharge conducted by field personnel. The developed relationships were used to estimate flow discharge to Lettuce Creek throughout the monitoring program.

Three Sigma Model 900-MAX all-weather refrigerated samplers were installed at the site inside climate-controlled sheds. One of the samplers was used to monitor the characteristics of inputs into the inflow manhole, while the remaining two samplers were used to monitor the outfall from the TST and CDS units. Area velocity (AV) flow meters were installed in the discharge pipes from the TST and CDS units to provide estimates of flow rates through each of the two units during periods of experimentation.

Field monitoring was conducted from November 2002 to November 2003. Testing was performed simultaneously in each unit, using the same inflow water source, at approximately 10%, 50%, and 100% of the design unit flow. Based on a design capacity of 11 cfs for each unit, the tested flows were 1, 5, and 11 cfs. A summary of monitoring history at the Lettuce Creek site is given in Table 3.

TABLE 3

MONITORING HISTORY

DATE	ACTIVITY
October 31, 2002	Monitoring installed
November 1, 2002-June 26, 2003	Field testing at 1 cfs
June 27-August 27, 2003	Field testing at 5 cfs
August 27-October 17, 2003	Field testing at 11 cfs

Particle Characterization

Characterization studies were performed on two separate occasions to evaluate the physical and chemical characteristics of particles entrained in the water column of Lettuce Creek. The first collection event was performed on August 17, 2001. During this event, approximately 225 gallons of Lettuce Creek water was collected upstream of the discharge riser structures, approximately 2 ft below the water surface. The discharge through Lettuce Creek at the time of this collection event was measured to be approximately 26 cfs, reflecting relatively low flow conditions within the creek. The second monitoring event was conducted on September 18, 2001 after flow conditions in Lettuce Creek had increased to approximately 163 cfs.

Suspended sediment particles were separated from the Lettuce Creek water samples using a series of nylon net filters manufactured by Millipore. A sequential series of filtrations was performed using the net filters with pore sizes of 180, 140, 100, 80, 60, 41, 30, 20, and 11 μm. A 32-liter water sample, sub-sample from the initial 225-gallon sample, was used for the separation. The filters were segregated by pore size and placed in 250-ml polycarbonate bottles. Deionized water (50 ml) was added to each bottle and shaken for fifteen minutes on a shaker table to resuspend the sediment particles from the filters. The resuspended particulate solution was then analyzed for total suspended solids, volatile suspended solids, and total phosphorus.

Settling rates for the particle fractions were estimated using Stokes Law:

$$v_s = \frac{9.8\,(\rho_{part} - \rho_{H_2O})\,D_p^2}{(18\ \mu)\,1000}$$

where:

ρ_{part}	=	particle density
ρ_{H2O}	=	density of water (at 20 ^{o}C, 0.9982 g/cm^3)
D_p	=	particle diameter
μ	=	dynamic viscosity of water (at 20 ^{o}C, 1003 N-S/m^2)

Particle diameter is estimated as the midpoint of the range of particle sizes represented by each sequential particle separation. A composite particle density was calculated from the volatile suspended solids (VSS) and non-volatile suspended solids (NVSS) fractions by assuming a density of 1.05 g/cm^3 for the VSS fraction and 2.50 g/cm^3 for the NVSS fraction.

Sediment Monitoring

Collection and analysis of sediment samples from Lettuce Creek was performed on multiple occasions to identify the characteristics of sediment particles and quantify changes in sediment characteristics within Lettuce Creek before and after periods of high flow conditions. Sediment samples were collected at three separate locations in Lettuce Creek, approximately 150 ft (Site 1), 450 ft (Site 2), and 700 ft (Site 3) upstream of the project area. Approximate locations of the sediment collection sites in Lettuce Creek are indicated on Figure 3.

Composite sediment samples were generated at each monitoring site by collecting multiple samples along transects perpendicular to the flow in Lettuce Creek. Sediment sub-samples were collected along each transect at distances of 25%, 50%, and 75% of the creek width at each site. Sub-samples collected from each of the three transect sites were combined together to form a single composite sediment sample at each site. Separate composite samples were formed from the 0-1 inch depth and 1-6 inch depth at each site. Sediment samples were collected using a stainless steel split-spoon type core device which was penetrated into the sediments to a depth of approximately 1-2 ft. The core sampler was retrieved and opened to obtain access to the collected core sample. Following collection, the composite sediment samples were returned on ice to the laboratory for physical and chemical analyses.

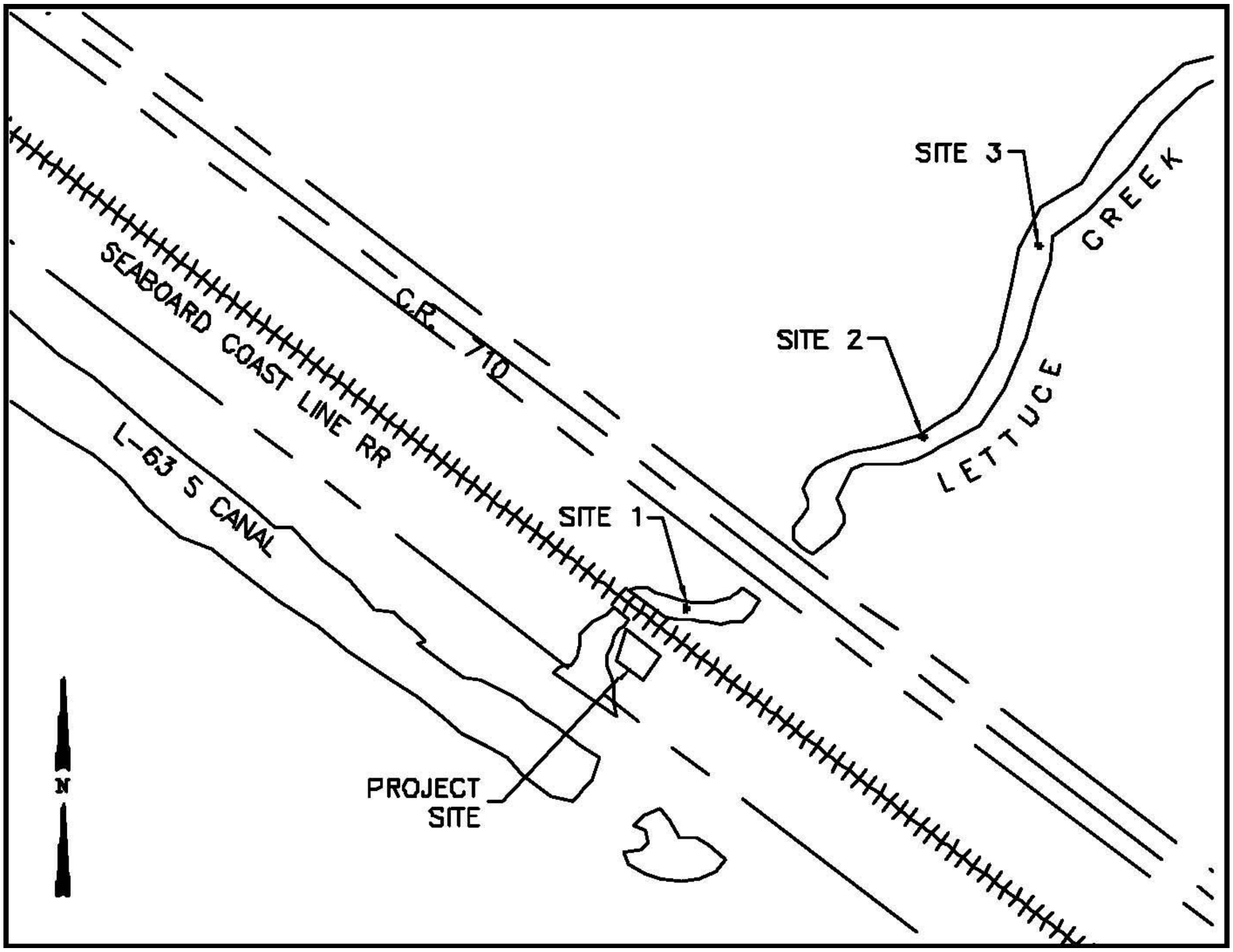

Figure 3. Sediment Core Collection Sites in Lettuce Creek.

Removal of Accumulated Sediments

Accumulated sediments were removed from the TST and CDS units on a periodic basis. Sediment removal was performed on the TST unit on June 13 and August 19-21, 2003. Sediment removal from the CDS unit was performed on three separate occasions, including June 13, August 19-21, and September 9, 2003. During each cleaning operation, the quantity of sediments removed from both the TST and CDS units was quantified, and a representative sample was returned to the laboratory for further evaluation.

Sediment removal in both the TST and CDS units was conducted manually. During a typical clean-out operation, the inflow and outflow to the TST and CDS units would be closed using the inflow and outflow sluice gates. The water within each unit was pumped down to leave approximately 6-12 inches. A field technician then entered the unit and collected the accumulated sediments using a broad flat shovel. The accumulated sediments were placed into a plastic 5-gallon bucket which was lifted to the surface by rope. The collected sediments from each unit were placed into separate 150-gallon polyethylene containers for quantification of the volume of material collected and collection of a well-mixed sub-sample for subsequent laboratory analyses.

TABLE 4

SUMMARY OF LABORATORY METHODS AND DETECTION LIMITS

PARAMETER	METHOD OF ANALYSIS	METHOD DETECTION LIMIT (MDL)
A. Water Samples Orthophosphorus	EPA-83[1], Sec. 365.1	0.001 mg/l
Total P	Alk. Persulfate[2]/EPA-83, Sec. 365.1	0.001 mg/l
TSS	EPA-83, Sec. 160.2	0.7 mg/l
VSS	EPA-83, Sec. 160.4	1 mg/l
B. Sediment Samples Moisture Content	EPA/CE-81-1[3]; pp. 3-54 and 3-58	0.1%
Organic Content	EPA/CE-81-1; pp. 3-59 and 3-60	0.1%
Total P	EPA-83, Sec. 365.4	0.005 mg/kg

1. Methods for Chemical Analysis of Water and Wastes, EPA 600/4-79-020, Revised March 1983
2. Alkaline Persulfate Digestion: FDEP-approved alternate method for digestion of Total P
3. Procedures for Handling and Chemical Analysis of Sediments and Water Samples, EPA/Corps of Engineers, EPA/CE-81-1, 1981

Laboratory Analyses

Laboratory analyses were performed on each of the collected inflow and outflow samples used to evaluate the performance efficiency of the CDS and TST units. Laboratory analyses were also performed on sediment samples collected from Lettuce Creek as well as accumulated sediments within the CDS and TST units. A summary of laboratory methods and detection limits for water and sediment sample analyses is given in Table 4.

RESULTS

Discharge Characteristics

A plot of discharges through Lettuce Creek from November 1, 2002-December 1, 2003 is given in Figure 4. Discharge rates in Lettuce Creek were highly variable during the monitoring period, with discharge regulated primarily by rain events within the watershed. The vast majority of flow rates observed in Lettuce Creek during this monitoring program were approximately 10 cfs or less. However, short-term increases in discharge rates to approximately 100 cfs were observed on two separate occasions, and approximately 475 cfs on one occasion.

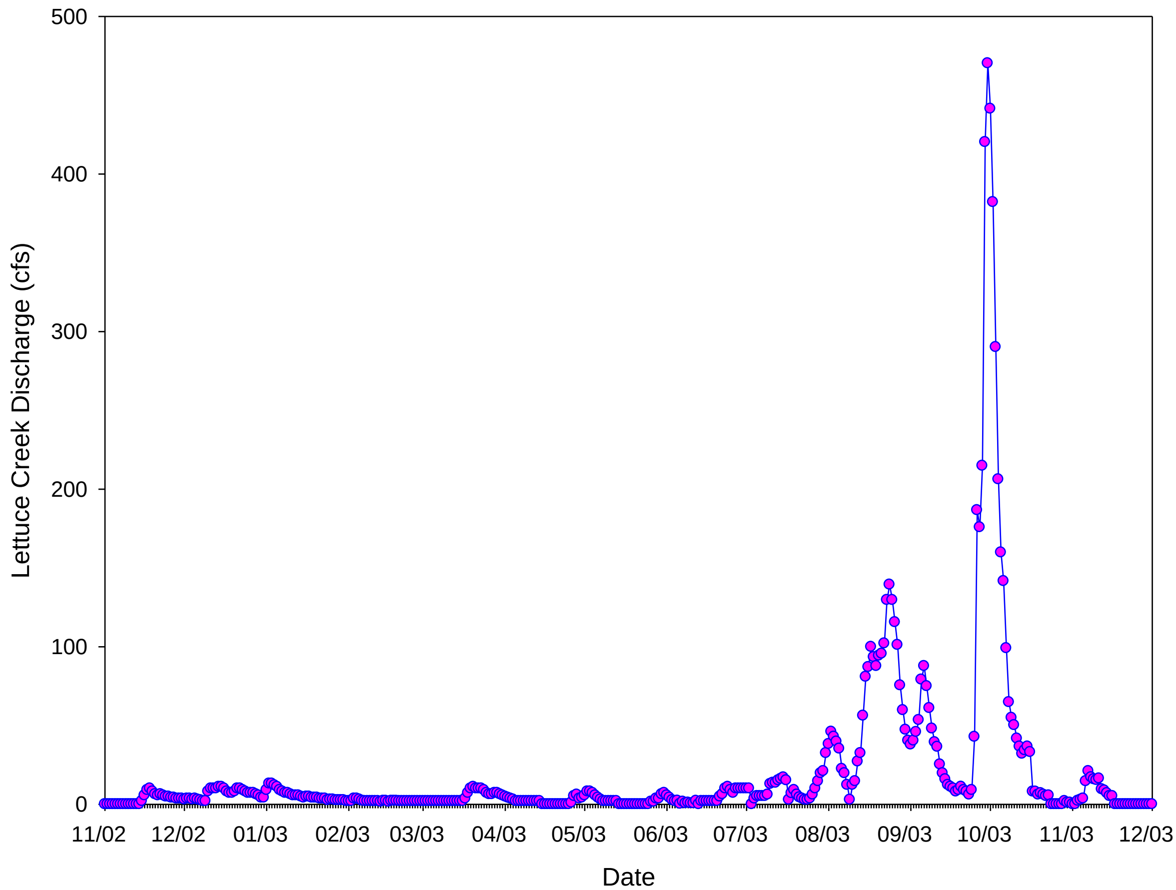

Figure 4. Lettuce Creek Discharge (11/1/02 – 12/1/03)

Water Quality Characteristics

A summary of the composition of phosphorus species in Lettuce Creek water is given in Table 5. Water flowing through Lettuce Creek exhibited a high degree of variability in measured concentrations of dissolved organic phosphorus, particulate phosphorus, total phosphorus, and TSS. Measured concentrations of organic phosphorus, particulate phosphorus, and total phosphorus cover several orders of magnitude between the minimum and maximum values. On an average basis, approximately 17% of the total phosphorus measured in Lettuce Creek is comprised of dissolved species (orthophosphorus + dissolved organic phosphorus), with 23% contributed by particulate phosphorus.

TABLE 5

COMPOSITION OF PHOSPHORUS SPECIES IN LETTUCE CREEK WATER FROM 11/02-11/03

PARAMETER	UNITS	RANGE OF VALUE	MEAN VALUE	PERCENT OF TOTAL (%)
Ortho-P	µg/l	214-1345	545	61
Diss. Org. P	µg/l	7-1039	140	16
Part. P	µg/l	22-3845	213	23
Total P	µg/l	345-5575	898	100
TSS	mg/l	2.5-61.0	12.7	--

Particulate Characteristics

The characteristics of particulate matter in Lettuce Creek water were evaluated under both low flow (26 cfs) and high flow (163 cfs) conditions. Characteristics of particles collected in Lettuce Creek are summarized in Table 6. Approximately one-third to one-half of the particulate matter discharging through Lettuce Creek under both low and high flow conditions is comprised of particles less than 11 microns (µm) in size. These particles are comprised primarily of organic matter with elevated concentrations of total phosphorus and extremely slow settling velocities (~10^{-6} m/s). Much of the remaining particulate matter discharging through Lettuce Creek, particularly under high flow conditions, appears to be comprised of fine sand, characterized by particle sizes in the 100-140 µm range, with a low organic content and low phosphorus concentration. Under low flow conditions, 60-90% of the particulate material is comprised of organic matter. The fraction of inorganic matter appears to increase substantially under high flow conditions.

Estimates of the instantaneous total particulate phosphorus load, in terms of mg phosphorus per second, were calculated for each measured particle size fraction by multiplying the total particulate phosphorus concentration measured for particles in each size range times the measured discharge rate in Lettuce Creek on each of the two monitoring dates. A bar graph of the instantaneous total particulate phosphorus load by particle size is provided in Figure 5.

During low flow conditions, the total particulate phosphorus load appears to be relatively evenly distributed throughout each of the measured particle sizes, with a slight skew to higher particulate phosphorus loadings at lower particle sizes. However, under high flow conditions, the vast majority of the instantaneous total particulate phosphorus load is comprised of particles < 11 µm in size. It appears that these particles have become mobilized from the sediments or other sources and entrained within the creek flow. Particles in this size range have estimated settling velocities of approximately 10^{-6} m/s, suggesting extremely slow settling for these particles. Particles in this size range can only be effectively settled by extended periods of sedimentation under quiescent conditions.

TABLE 6

CHARACTERISTICS OF PARTICLES IN LETTUCE CREEK WATER

DATE/ FLOW	PARTICLE SIZE (µm)	SOLIDS CONCENTRATION (mg/l)			ORGANIC CONTENT (%)	PARTICLE DENSITY (g/cm^3)	PHOSPHORUS CONCENTRATION (µg/g)	SETTLING VELOCITY (m/s)
		VSS	NVSS	TSS				
8/17/01 Flow = 26 cfs	> 100	0.39	0.22	0.61	63.6	1.55	5180	1.2×10^{-2}
	80-100	0.24	0.09	0.34	72.3	1.42	7016	1.8×10^{-3}
	41-80	0.65	0.26	0.91	71.7	1.42	6057	8.3×10^{-4}
	20-41	0.52	0.20	0.72	72.1	1.42	9605	2.1×10^{-4}
	11-20	0.32	0.10	0.41	76.9	1.35	8629	4.2×10^{-5}
	< 11	2.27	0.28	2.55	88.9	1.17	8050	2.3×10^{-6}
	TOTALS:	**4.39**	**1.15**	**5.54**	**--**	**--**	**--**	**--**
9/18/01 Flow = 163 cfs	> 180	0.20	0.04	0.24	85.0	1.03	370	7.8×10^{-4}
	140-180	0.21	0.40	0.61	34.7	1.98	743	1.4×10^{-2}
	100-140	0.25	4.99	5.25	4.8	2.43	195	1.1×10^{-2}
	80-100	0.11	0.65	0.76	14.7	2.28	1516	5.6×10^{-3}
	60-80	0.17	0.21	0.38	43.5	1.85	2229	2.3×10^{-3}
	41-60	0.25	0.35	0.60	41.4	1.88	2937	1.2×10^{-3}
	30-41	0.20	0.24	0.44	44.9	1.83	3992	5.5×10^{-4}
	20-30	0.22	0.24	0.45	48.2	1.78	4824	2.6×10^{-4}
	11-20	0.41	0.38	0.79	51.7	1.73	7078	8.9×10^{-5}
	< 11	3.70	1.58	5.28	70.0	1.45	7696	6.1×10^{-6}
	TOTALS:	**5.71**	**9.09**	**14.80**	**--**	**--**	**--**	**--**

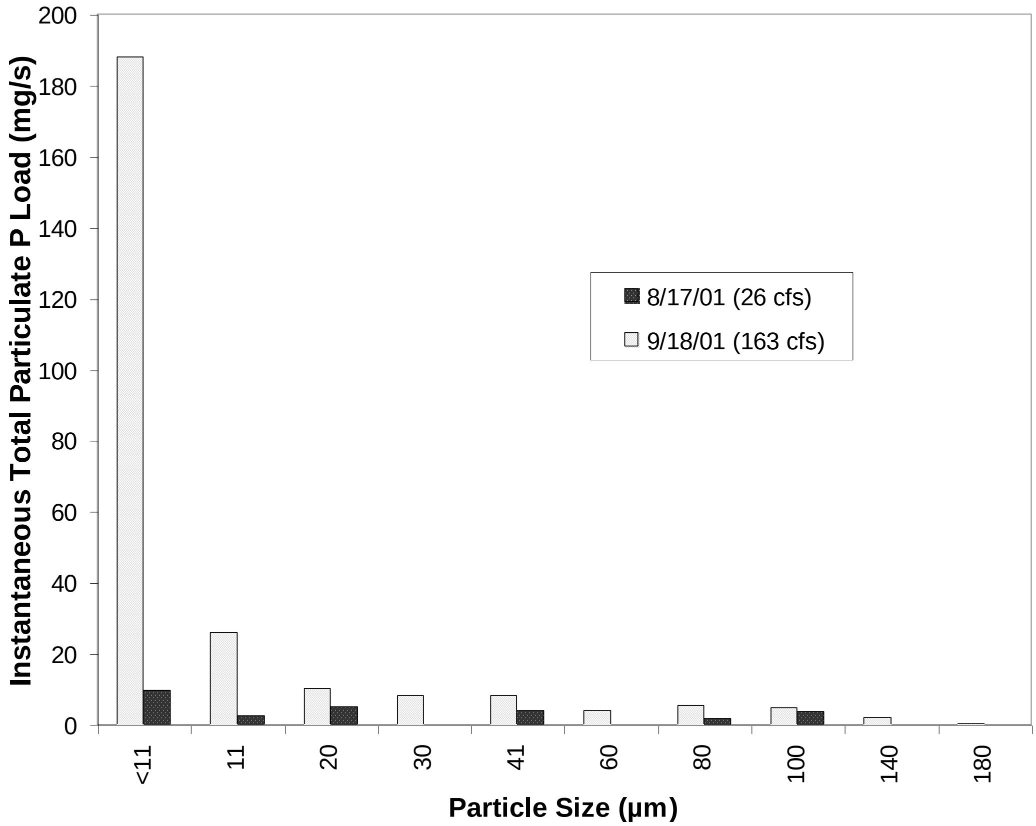

Figure 5. Instantaneous Total Particulate Phosphorus Load by Particle Size.

Performance Efficiencies of the CDS and TST Units

A comparison of phosphorus concentrations in inflow and outflow from the CDS and TST units is given in Figure 6 for system operation at 1, 5, and 11 cfs. Inflow and outflow phosphorus concentrations for both the CDS and TST units appear to be virtually identical for all measured species.

The water volume contained within the CDS unit is approximately 373 ft^3 which equates to mean detention times of 6.2, 1.2, and 0.6 minutes at flow rates of 1, 5, and 11 cfs, respectively. The water volume contained within the TST unit is approximately 560 ft^3 which equates to mean detention times of 9.3, 1.9, and 0.9 minutes at flow rates of 1, 5, and 11 cfs, respectively. The majority of phosphorus-laden particles in Lettuce Creek are <11 microns in diameter and have settling velocities in the order of 10^{-5} to 10^{-6} m/s. Settling of these particles in a 6-ft deep water column would require approximately 21 days under totally quiescent conditions.

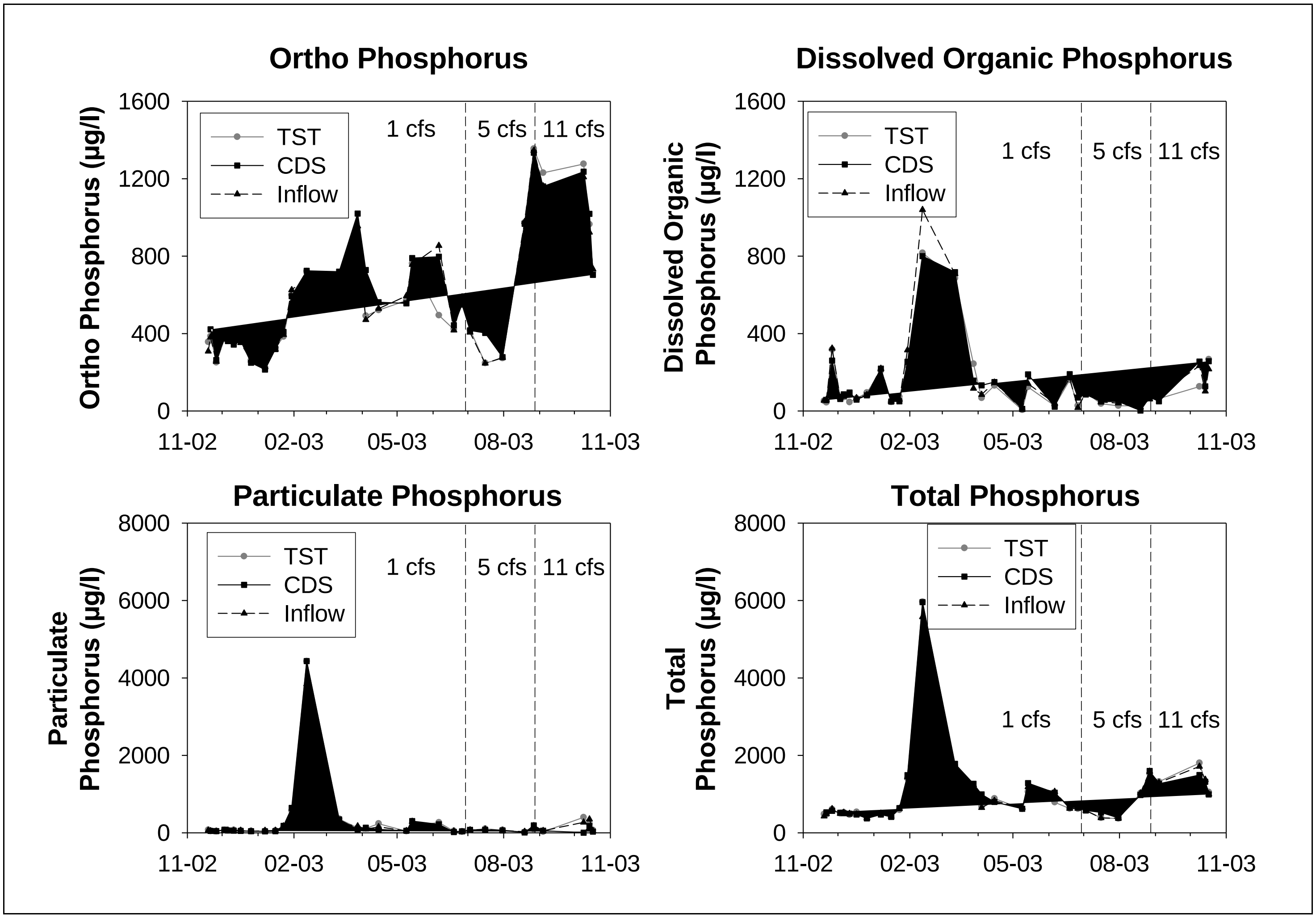

Figure 6. Concentrations of Phosphorus Species in Inflow and Outflow of the CDS and TST Units.

A factor which significantly complicated both the operation and performance evaluation of the units is the accumulation of fish which entered through the inflow pipe connected to Lettuce Creek. Large accumulations of fish, primarily catfish, were observed in both the CDS and TST units throughout the monitoring program, numbering in excess of 100 in each of the two units on many occasions. Numerous efforts were undertaken to both remove these fish and prevent them from entering the units. However, these efforts were largely unsuccessful. Accumulation of fish was a particular problem in the CDS unit since the fish had no avenue of escaping the unit once they entered the center sump area. Impacts from fish wastes, from both living and dead organisms, are apparent throughout the monitoring data. However, since this project is designed to demonstrate the feasibility of using solids removal units in tributaries, accumulation of fish within the units is thought to represent a likely operating condition which would also occur at other locations.

Mass inputs and outputs from the CDS and TST units were calculated for each of the test flows (1, 5, and 11 cfs) evaluated. A graphical comparison of mass removal efficiencies for phosphorus species at flow rates of 1, 5, and 11 cfs in the CDS and TST units is given in Figure 7. For orthophosphorus, the CDS unit exhibited negative mass removal efficiencies ranging from approximately -1% to -4% at each of the three evaluated flow rates. The TST unit exhibited a positive mass removal of approximately 5% for orthophosphorus at a flow rate of 1 cfs, with negative removals observed at higher flow rates.

No significant removal of any measured parameter was observed within the CDS unit during operation at 5 cfs. At this flow rate, the mass of phosphorus increased by 3%. However, at a flow rate of 11 cfs, approximately 55% of the particulate phosphorus and 5% of the total phosphorus was retained within the unit. The operation of the CDS unit appears to be best at the highest flow rate. These findings may be related to operational characteristics within the CDS unit which were visually observed during this project. At low flow rates, the vortex activity, responsible for the removal of suspended solids, was not observed within the CDS unit. However, at more elevated flow rates, the vortex activity was clearly evident. This may partially explain the enhanced removal efficiency at higher flow rates in the CDS unit.

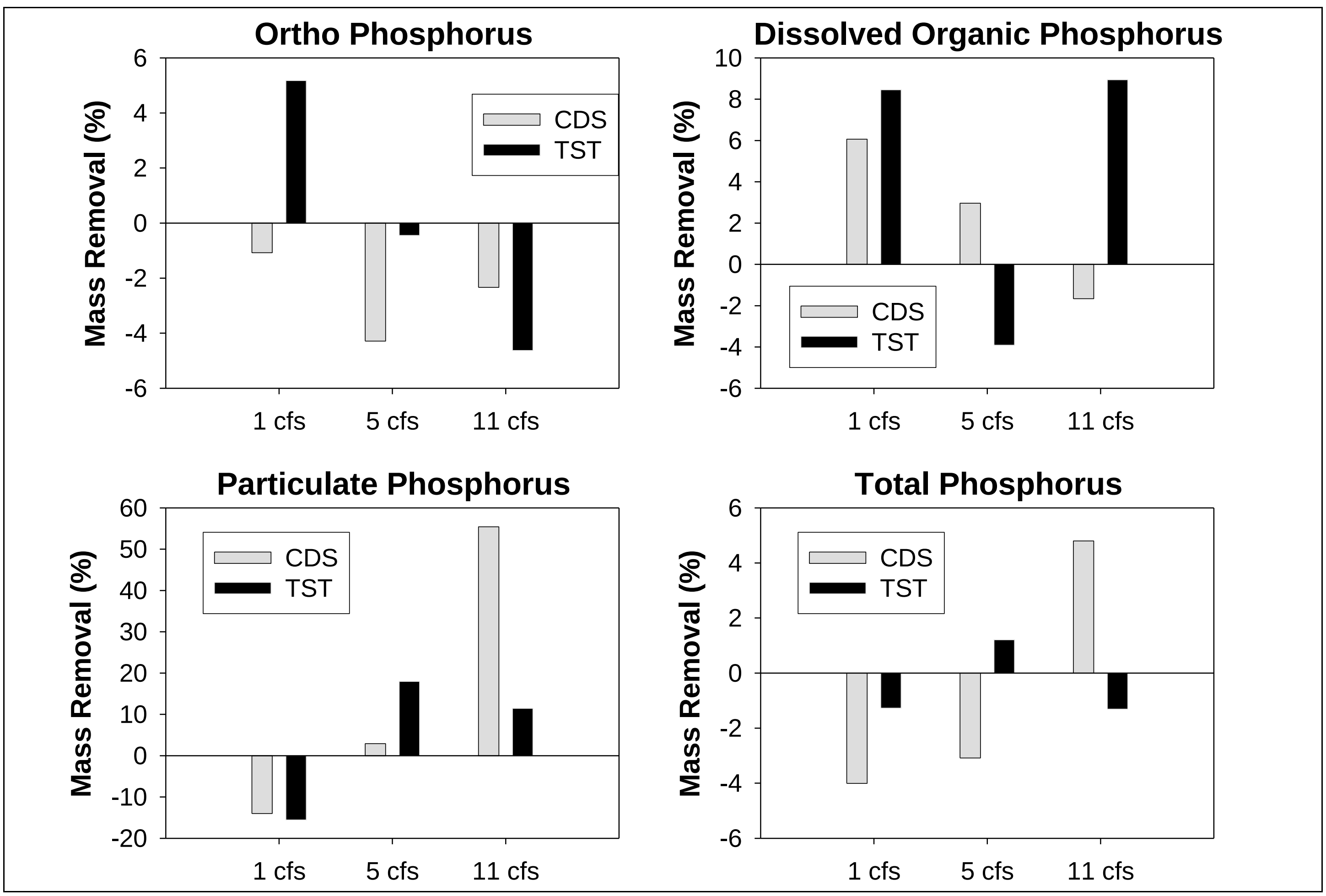

Figure 7. Comparative Mass Removal Efficiencies for Phosphorus Species in the CDS and TST Units.

Virtually no significant mass removal was observed within the TST unit during operation at either 5 or 11 cfs. At a flow rate of 5 cfs, approximately 1% of the total phosphorus mass was removed. At a flow rate of 11 cfs, a net export of 1% was observed for total phosphorus. However, none of the observed total phosphorus mass removals, for either the CDS or TST unit, are statistically significant, indicating that neither of the two units exhibited a statistically significant phosphorus removal.

Characteristics of Collected Particulate Matter

Characteristics of sediment material removed from the CDS and TST units are illustrated on Figure 8. The vast majority of particles collected within the CDS unit are in the 100-425 μm range, with relatively few particles above and below this range. The majority of particles collected from the TST unit are within the 100-425 μm range. Particles within the 100-425 μm range are characterized by relatively low organic contents and low concentrations of total phosphorus. Substantially higher concentrations of nutrients are present in particles larger and smaller than the optimum range. Particles larger than the optimum range reflect primarily vegetation and detritus which enters the unit. It appears that the units are approximately equal in terms of collecting particles less than 100 μm in size and greater than 850 μm in size. However, between these ranges, the CDS unit appears to collect a wider range of particles, while the TST unit collects a smaller range of particle sizes.

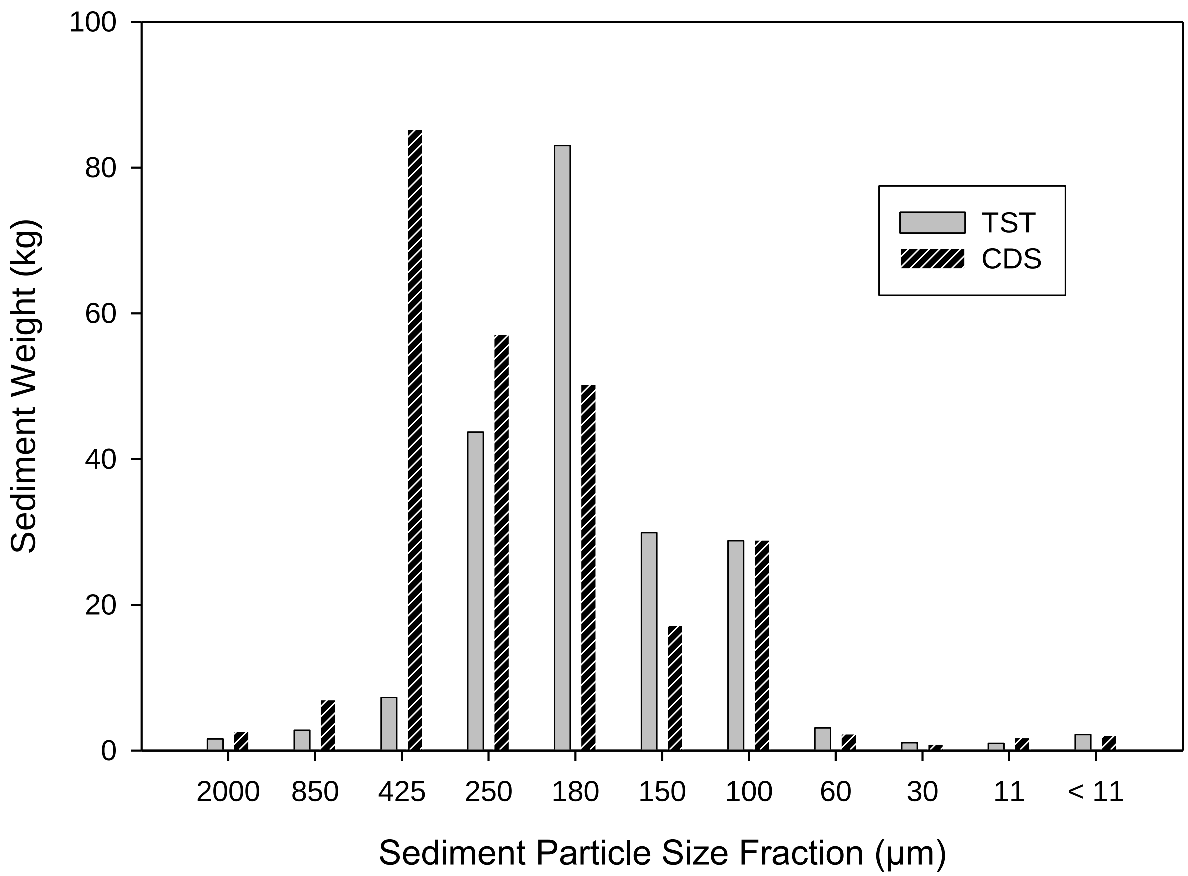

Figure 8. Particle Size Distribution of Suspended Solids Removed from the CDS and TST Units.

A summary of mean removal characteristics for the CDS and TST units is given in Table 7. During an operational period of 207 days, with a total flow-through volume of 815.2 ac-ft, the CDS unit removed approximately 766.2 kg of dry solids from Lettuce Creek, containing approximately 0.14% total phosphorus by weight. Over the 207-day operation period, the CDS unit exhibited an average TSS removal of 0.76 mg/l and a mean total phosphorus removal of 1.1 μg/l. The TST unit was operated for a period of 193 days, with a total flow-through volume of 581.2 ac-ft, and removed 408.8 kg of dry solids which was 0.14% total phosphorus by weight. On an average basis, the TST unit removed 0.57 mg/l of TSS and 0.79 μg/l of total phosphorus.

TABLE 7

MEAN REMOVAL CHARACTERISTICS OF THE CDS AND TST UNITS

PARAMETER	CDS UNIT	TST UNIT
Total Flow Through Unit	815.2 ac-ft	581.2 ac-ft
TSS Removal		
1. Total Mass	766.2 kg (dry)	408.8 kg (dry)
2. Mean Concentration	0.76 mg/l	0.57 mg/l
Total P Removal		
1. Total Mass	1.106 kg	0.564 kg
2. Mean Concentration	1.1 μg/l	0.79 μg/l

Lettuce Creek Sediment Characteristics

Characteristics of sediment core samples collected in upstream portions of Lettuce Creek during July, August, and October 2003 are summarized in Table 8. Substantial reductions in measured total phosphorus concentrations were observed in the 0-1 inch layer at each of the three sites during the period from July-October 2003. During this period, sediment phosphorus concentrations at Site 1 decreased from 1732 μg/g to 127 μg/g, with a reduction from 292 μg/g to 146 μg/g at Site 2, and a reduction from 701 μg/g to 197 μg/g at Site 3. These decreases in sediment phosphorus concentrations in the 0-1 inch layer suggest mobilization and transport of surficial phosphorus within the sediments over this period. As seen in Figure 4, Lettuce Creek flow rates increased to approximately 50 cfs between the July 24 and July 31 monitoring events, with flow rates of approximately 150 cfs between the July 31 and August 27 monitoring dates, and flows in excess of 450 cfs between the August 27 and October 9 monitoring dates. It appears that these increased flows mobilized previously deposited sediment phosphorus over this period.

TABLE 8

CHARACTERISTICS OF SEDIMENT SAMPLES COLLECTED FROM THE 0-1 INCH LAYER IN UPSTREAM PORTIONS OF LETTUCE CREEK

SITE	DATE	MOISTURE CONTENT (%)	ORGANIC CONTENT (%)	TP (µg/g wet wt)
1	7/24/03	38.4	3.3	1732
	7/31/03	42.0	3.2	668
	8/27/03	24.2	1.0	366
	10/9/03	23.1	0.2	127
2	7/24/03	21.6	0.7	292
	7/31/03	26.2	0.3	222
	8/27/03	27.0	0.6	209
	10/9/03	39.7	1.2	146
3	7/24/03	31.0	1.7	702
	7/31/03	29.8	0.9	432
	8/27/03	43.6	3.0	267
	10/9/03	42.0	0.9	197

Economic Evaluation

Calculated present worth costs for the CDS and TST units are given in Table 9 based upon a 20-year life-cycle cost and an interest rate of 4% per year. Annual O&M costs are included for solids removal, disposal (assumed to be once/year), and mowing. The calculated 20-year present worth cost for the CDS unit is approximately $143,117, with a present worth cost of $96,086 for the TST unit.

TABLE 9

CALCULATED PRESENT WORTH COSTS FOR SOLIDS REMOVAL USING THE CDS AND TST UNITS (n = 20 year, i = 4%)

UNIT	CAPITAL COST ($)	ANNUAL O&M COST ($)	PRESENT WORTH ($)
CDS	116,684	1,945	143,117
TST	71,216	1,830	96,086

Estimated costs per mass removal for the CDS and TST units, based upon the 20-year present worth costs summarized in Table 9, are given in Table 10. Over a 20-year period, the CDS unit is estimated to remove approximately 27,021 kg of solids containing 39.0 kg of total phosphorus. Based upon the 20-year present worth cost of $143,117, the 20-year life-cycle cost for mass removal in the CDS unit is approximately $5.30/kg of solids and $3670/kg of total phosphorus.

Extrapolation of the measured mass removals for the TST unit indicates that over a 20-year period, the TST unit will remove approximately 15,462 kg of solids containing 21.3 kg of total phosphorus. Based upon the 20-year present worth cost of $96,086, this equates to a 20-year life-cycle cost of $6.21/kg of dry solids and $4511/kg of total phosphorus.

TABLE 10

ESTIMATED COST PER MASS REMOVAL FOR THE CDS AND TST UNITS (20-year period)

ITEM	CDS UNIT	TST UNIT
Estimated Removal Over 20-year Period	27,021 kg solids 39.0 kg TP	15,462 kg solids 21.3 kg TP
Cost per kg Removed[1]	$5.30/kg solids $3670/kg TP	$6.21/kg solids $4511/kg TP

1. Based on 20-year present worth costs

The cost/kg of TSS removed in the CDS and TST units ($5.30-6.21/kg) is similar to the cost of solids removal in other stormwater retrofit projects, typically $1-4/kg (ERD, 2004). However, the cost/kg of total phosphorus in the CDS and TST units ($3670-4511/kg) substantially exceeds phosphorus removal costs in other stormwater retrofit projects, typically $100-300/kg (ERD, 2004). It appears that the CDS and TST units are not economically attractive for removal of total phosphorus.

DISCUSSION

The inability of the CDS and TST units to capture particulate phosphorus appears to be related to the physical characteristics of sediment particles contained in water within Lettuce Creek. The majority of particles contained in Lettuce Creek water are approximately 100 microns or less in size. These particles also contain the vast majority of phosphorus associated with particulate matter. However, CDS and TST units are designed to provide effective removal for sediment particles of approximately 1000 microns or more. Therefore, the settling velocities of the particles present within Lettuce Creek are too slow to allow capture of the particles within the relatively short residence times provided by the two test units. The effectiveness of the units can only be improved by increasing the residence time within the systems by constructing substantially larger units, or by enhancing the settling velocity of the particles.

Based upon the extremely small size of the phosphorus-laden particles in Lettuce Creek, combined with the fact that only approximately 23% of the total phosphorus discharging through the tributary is particulate in nature, there appears to be no feasible modifications which could be made to either the CDS or TST units to substantially enhance removal of phosphorus within these units. Significant removal of extremely small diameter particles and dissolved phosphorus species can only be achieved using either chemical coagulation or a relatively long detention time in a pond or reservoir environment. Based on initial characterization studies performed on Lettuce Creek water samples, the vast majority of particulate phosphorus in Lettuce Creek is associated with particles less than 11 microns in size with an estimated settling velocity of approximately 10^{-6} meters/sec. Under perfectly quiescent conditions, settling of these particles in a water column 2 m deep would require approximately 23 days. As a result, any pond system designed to remove particulate phosphorus from tributary inflow would need to have a detention time of approximately 50 days, assuming a safety factor of 2 to account for turbulence within the pond.

The use of CDS and TST units for removal of particulate phosphorus in tributaries discharging to Lake Okeechobee does not appear to be a feasible nutrient reduction alternative. The use of CDS and TST technologies appears to be more suited to an urban environment where particle sizes would likely be larger. Although TSS removals may be enhanced in an urban environment, these units may still not be capable of removing a significant quantity of total nitrogen and total phosphorus from runoff flow.

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