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Phragmites reed beds :: constructed wetlands for municipal wastewater treatment /

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PHRAGMITES REED BEDS: CONSTRUCTED WETLANDS FOR MUNICIPAL WASTEWATER TREATMENT

A Thesis Presented

by

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ABSTRACT

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Phragmites reed beds are an alternative technology wastewater treatment system that mimic the biogeochemical processes inherent in natural wetlands. Wetlands support many aerobic and anaerobic processes that help remove pollutants from the waste stream. The purpose of this project was to determine the effectiveness of a reed bed sludge treatment system (RBSTS) in southern New England after a six-year period of operation by examining the concentrations of selected metals in the reed bed sludge biomass and by determining the fate of solids and selected nutrients. The following parameters were assessed in both the reed bed influent and effluent: total suspended solids, biochemical oxygen demand, nitrate-nitrogen and total phosphorus. In addition the following metals were studied not only in the reed bed influent and effluent but also in the *Phragmites* plant tissue and the sludge core biomass: boron, cadmium, chromium, copper, iron, lead, manganese, molybdenum, nickel, and zinc. The removal efficiencies for sludge dewatering, total suspended solids and biochemical oxygen demand were all over 90%. Nitrate and total phosphorus removal rates were 90% and 80% respectively. Overall metals removal efficiency was 87%. Copper was the only metal in the sludge biomass

that exceeded the standards set by the Massachusetts Department of Environmental Protection for land disposal of sludge. The highest metal concentrations, for the most part, tended to be in the lower tier of the sludge profile. The exception was boron which was more concentrated in the middle tier of the sludge profile. The data and results presented in this paper support the notion that reed bed sludge treatment systems and the use of *Phragmites* reed beds provide an efficient and cost effective alternative for municipal sludge treatment.

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CHAPTER 1

REED BED SLUDGE TREATMENT SYSTEMS

Introduction

Constructed wetlands for wastewater treatment (CWWT's) are complex biological systems that mimic self cleansing processes inherent in natural wetlands. CWWT technology has been around for many years and has been shown to have a broad applicability as a wastewater treatment system (Watson et al., 1989). CWWT's are currently used worldwide for the control of pollution arising from mines, farms, urban runoff, industries, and municipal wastewater (Bastian and Hammer, 1993). At present, there is a resurgence of interest in constructed wetland systems because of the relative ease of operation and the reduced costs in manpower and energy. Considered to be on the cutting edge of environmental technology, constructed wetlands come in various shapes and sizes and are designed to site specific and wastewater specific needs. A reed bed is a type of a constructed wetland system known as a vegetated submerged bed.
The term "reed bed" as used in this paper is interchangeable with the term "constructed wetland." The common link in the various types of constructed wetlands is that they all use natural biological and ecological treatment processes.

One type of constructed wetland that has proven to be effective worldwide and is the focus of this research is the Reed Bed Sludge Treatment System (RBSTS). The RBSTS is a vegetated submerged bed that can be used to dewater sludge to the same extent as a conventional sand sludge drying bed. Unlike a conventional bed, the RBSTS is planted with wetland plants such as *Phragmites australis* Cav. (common reed).

The sludge drying or dewatering process using *Phragmites* has been used with success since the 1950's in Europe. Data show that due to drying and mineralization the liquid sludge volume is reduced by as much as 90%, with almost 100% total suspended solids removal from the RBSTS effluent (Seidel, 1976). The primary removal mechanism of suspended solids is physical filtration, with a removal rate of 92.6% (Yang et al., 1995). Over the eight to ten-year life-cycle of a RBSTS the initial sludge volume will be reduced significantly through biological, physical and chemical processes. Typical removal efficiency values for suspended solids are presented in Table 1.1. The final product is a well decomposed, stabilized compost suitable for land application (Krueger, 1991).

Sludge dewatering efficiency reported in 1992 from RBSTS's constructed in France showed an average liquid sludge volume reduction to 90% dried matter, with underdrain effluent quality showing 98.8% TSS removal (Lienard et al., 1995). Based on a three-year controlled experiment Lienard et al. (1995) reported that flow velocity in a sludge bed containing *Phragmites* occurred at twice the rate (6mm/hour) of a control sludge bed underlain by sand (3mm/hour). Brix (1994) attributed the difference in flow rate to macropore channelization created by the roots and rhizomes of *Phragmites* plants. Brix (1997) in experiments in the Netherlands and the United Kingdom reported that initial rates of hydraulic conductivity in RBSTS's tended to decrease over a three-year period from 10^{-3} (3.6mm/hour) to 10^{-6} m /sec (3.6mm/hour). Although RBSTS's have been in place for the past twenty-five years and have generally been found to be effective (Cooper and Green, 1995; Kim and Smith, 1997; Yang et al., 1995), details of the actual treatment process remain obscure and reports of their effectiveness differ.

Table 1.1 Total suspended solids removal efficiencies in *Phragmites* planted sludge beds as reported in the literature.

Author	Year	Volume reduction
		----- %-----
Cooper and Green	1995	46 - 91
Yang et al.	1995	84 - 92.6
Lienard et al.	1995	98.8
Lavigne	1996	96.9
Wood	1995	69

Many of these processes are often difficult to measure and are generally not included in routine monitoring schemes to evaluate treatment efficiency (Reddy and D'Angelo, 1997).

The project described in this report uses a data series that begins in the fall of 1992 and continues until the spring of 1999. The information was generated at the Shelburne/Buckland wastewater treatment plant (SBWWTP) located in Buckland, MA., to examine the effectiveness of a RBSTS in southern New England. The general hypothesis of this project was that RBSTS's serve not only as an effective sludge dewatering system, but that they also mimic biogeochemical processes found in natural wetland systems to such a degree as to produce underdrain effluent quality meeting National Point Discharge Environmental Standards (NPDES) for direct discharge into our waterways. This hypothesis is based on earlier work by Lavigne (1979) using *Phalaris arundinacea* L. (reed canary grass) to treat landfill leachate. Additionally, the project examines the fate of metals in the sludge biomass and the possible accumulation of metals in *Phragmites* plants. Concentrations of metals in the sludge are a major concern for final disposal including such issues as town economics, public safety, and state and federal compliance issues.

The SBWWTP project was chosen for logistical reasons. In 1992, the Shelburne/Buckland community sought the cooperation of the University of Massachusetts' Environmental Services Program (ESP), an organization that works with local towns to provide technological support. The SBWWTP laboratory and Howard Laboratory, which had the initial monitoring contract, were willing to make collected data available. The Shelburne/Buckland Board of Health, the Massachusetts Department of

Environmental Protection (DEP) and the Shelburne/Buckland community were eager to work with the ESP given the support it could provide. Additionally, the proximity, approximately 30 miles to the University of Massachusetts, made it an ideal site for the project.

Objectives

Specific objectives of this project were to:

1. quantitatively show that RBSTS's effectively dewater sludge and are a viable alternative to conventional sludge dewatering technology;

2. measure selected parameters including total suspended solids, biochemical oxygen demand, nitrate-nitrogen, and total phosphorus in the underdrain effluent, and compare, where relevant, to DEP discharge standards; and

3. determine the concentrations of boron, cadmium, chromium, copper, iron, manganese, molybdenum, nickel, lead and zinc in RBSTS sludge biomass at different depths and in *Phragmites* plant tissue to determine the fate of these metals.

CHAPTER 2

MATERIALS AND METHODS

Background

The Shelburne/Buckland wastewater treatment plant (SBWWTP) services the business districts of two towns, along with the densely populated residential areas adjacent to these commercial areas. The facility is located on the south bank of the Deerfield River in the town of Buckland, MA. During dry weather, flows to the plant typically average about 150,000 gallons per day, but during storm events flow rates can exceed 500,000 gallons per day. After initial screening and settling processes, an extended aeration system treats the raw wastewater followed by aerobic digestion of the sludge in an aerated 52,000-gallon above ground tank with a residence time of 25 to 30 days. During that time the volatile solids are reduced to between 60% and 70%. The sludge is then applied to the reed bed for dewatering.

In 1992 the first of three *Phragmites* reed beds went on line to help dewater the towns' sludge. Three reed beds were designed to eventually replace an existing greenhouse and sand filter bed drying operation. The first reed bed, and the focus of this project, was designed by Krueger Engineering of Randolph, Vermont and built by Warner Brothers Construction Company of Sunderland, Massachusetts. The fate of the two other proposed reed beds depended on the performance of the first RBSTS. Data provided by this project along with information provided by other laboratories were presented to the Massachusetts Department of Environmental Protection (DEP). Following a review of the performance data by the DEP the two additional reed beds were approved.

Bed Design

Phragmites were planted in the oldest bed by the Environmental Services Program at the University of Massachusetts Amherst during the fall of 1992. The reed bed is 55 feet wide by 100 feet long with an overall depth of 8 feet (). Each reed bed is lined with an impervious material and has an 8 to 12-inch layer of pea stone or gravel around the 4-inch perforated underdrain pipes. On top of the pea stone is 12 inches of coarse sand. The pea stone and sand are the initial growing medium for the *Phragmites* plants and the primary physical filtration medium for the sludge (Figure 2.2). The rhizomes and root system of *Phragmites* penetrate the growing medium and help channel wastewater flow. The effective depth of sludge storage is 4 feet and the expected length of time between reed bed cleanings, limited by the effective depth of sludge storage, is 8-10 years. The underdrain pipes surrounded by pea stone and underlain by the impervious liner direct the effluent to a concrete cistern where a sump pump forces the effluent from the cistern back to the headworks for chlorinating prior to discharge.

During the first 18 months sludge loading averaged approximately 15,000 gallons/month. The treatment plant went to loading of approximately 24,000 gallons/month during May of 1994. Water quality monitoring and plant tissue and sludge core analysis have been on-going since the fall of 1992 by various subcontracted laboratories.

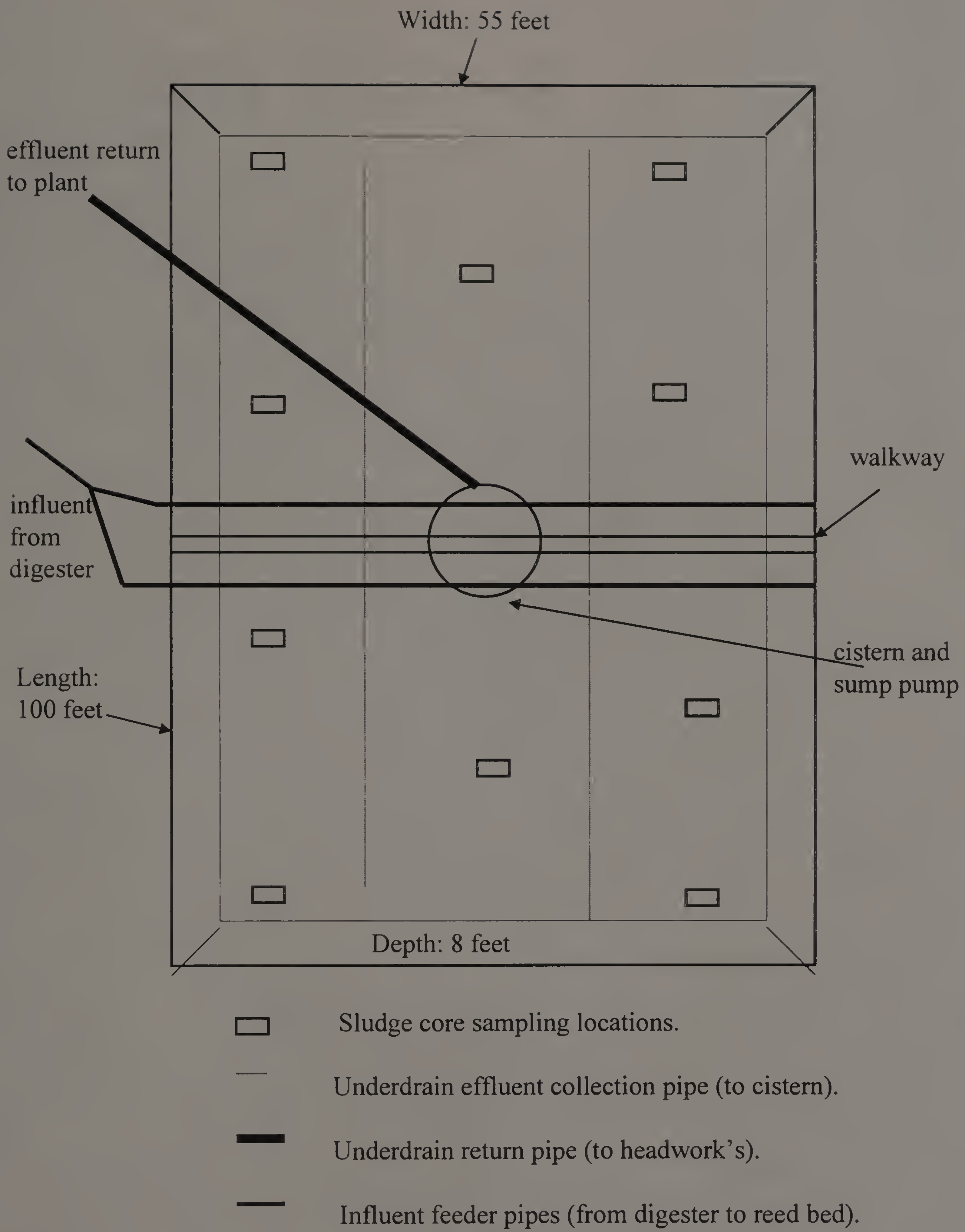

Figure 2.1 Shelburne/Buckland reed bed plan view.

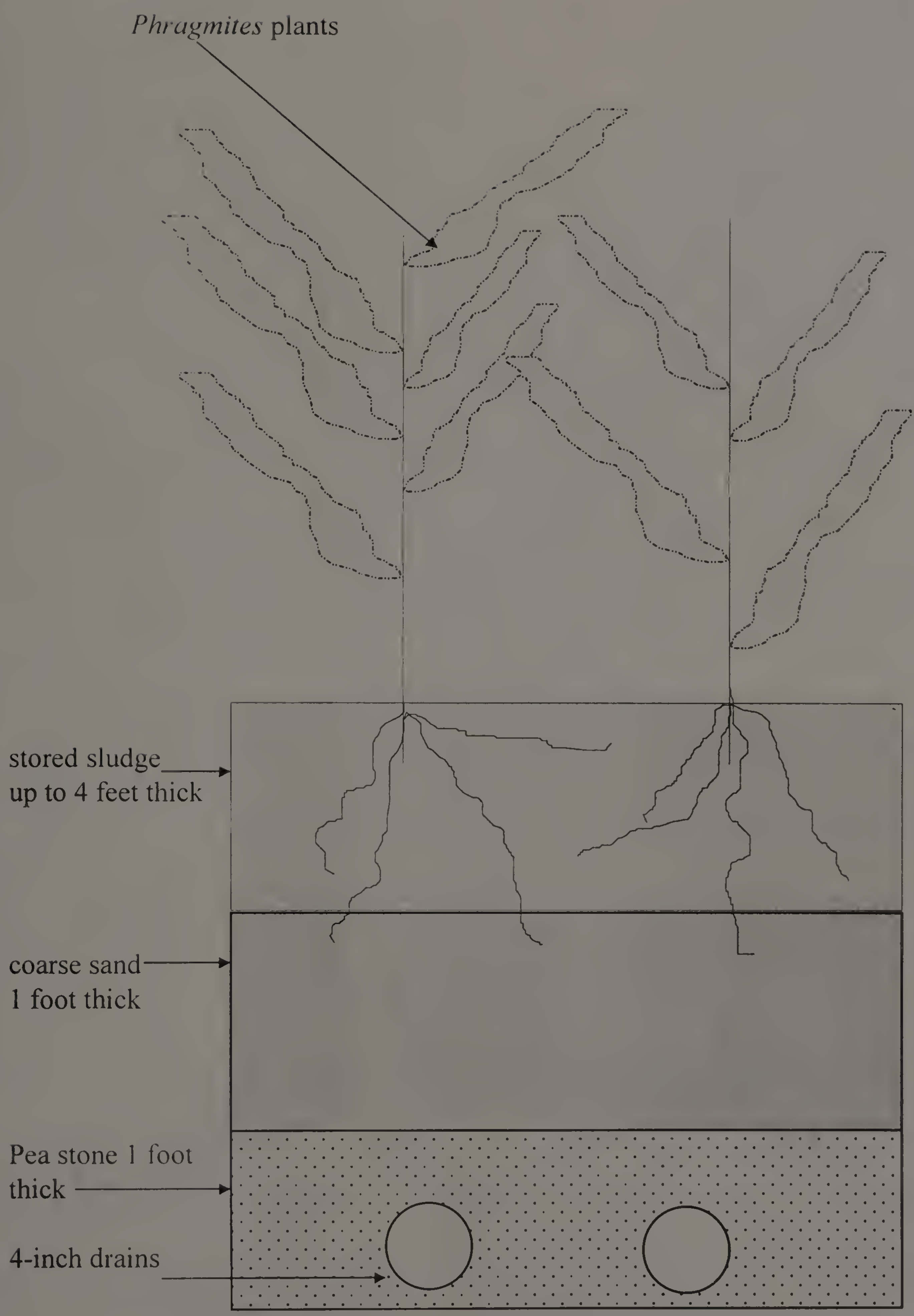

Figure 2.2 *Phragmites* reed bed cross section.

Dewatering Efficiency and Total Suspended Solids

Yearly biomass accumulation data were not recorded. Measurements of reed bed biomass depth were taken in 1995 and 1999 with a yardstick from ten random locations. (Figure 2.1). The measurements were taken in March, when cold nights would sufficiently freeze and harden the surface of the reed bed to allow walking on yet there weren't thick layers of ice and snow to dig through. Reed bed biomass depth was compared to sludge volume data obtained from the treatment plant operator. A mass balance determination relates the applied liquid sludge volume to residual biomass for a six-year period. The sludge volume applied from 1992-1995 was 696,500 gallons (Lavigne, 1996). The volume of sludge applied from 1996-1999 was 714,600 gallons for a total of 1,411,100 gallons applied to the reed bed (see appendix A for data).

Fifteen samples were collected to determine the bulk density of the sludge. The samples were taken with a 2-inch diameter plastic pipe driven into the sludge. The core sample was cut into 1/2-inch discs resulting in a measured volume of 25.7 cubic centimeters. Samples representing different depths were dried at 103-105^0 C until they reached a constant weight and the bulk density was calculated.

Solid content was determined by gravimetric procedures in the laboratory for the sludge influent and the underdrain effluent following Standard Methods (2540 A-G) (Greenberg et al., 1992). A homogenized sample was filtered through a weighed 1-micron glass fiber filter disc using a membrane filter funnel with vacuum applied. The residue retained on the filter disc was then dried to constant weight at 103 to 105 ^{0} C. The increase in weight of the filter represents the amount of total suspended solids.

$$TSS\ (mg/l) = \frac{[\text{mass of dried residue (mg)} + \text{filter mass (mg)}] - \text{filter mass (mg)}}{\text{sample size mass (l)}}$$

$$\%\ TSS\ removal = \frac{\text{influent mg/l} - \text{effluent mg/l}}{\text{influent mg/l}} \times 100$$

Biochemical Oxygen Demand (BOD_5)

For each loading of the reed bed BOD_5 samples were collected from the sludge influent and the underdrain effluent. Influent samples were collected from the reed bed loading pipe and effluent samples were collected from the concrete cistern/sump pump chamber located in the center of the reed bed. The samples were analyzed following Standard Methods 5210 B (Greenberg et al., 1992). Samples were seeded with wastewater and incubated for five days at 20°C. The dissolved oxygen was measured at the beginning of the five-day period with a dissolved oxygen meter (YSI model 51B) and then again at the end of the five-day period. The difference between influent and effluent oxygen contents provide an indication of reed bed treatment efficiency.

Nitrate - Nitrogen and Total Phosphorous

Influent samples were collected from the reed bed loading pipe and effluent samples were collected from the concrete cistern/sump pump chamber located in the center of the reed bed. Nitrate concentrations were determined with a modified colorimetric analysis utilizing a spectrophotometer (Hach model DR- 2000) with cadmium reduction following Standard Method 4500-NO_3-E (Greenberg et al., 1992). Total phosphorus concentrations were determined with a modified colorimetric analysis utilizing a spectrophotometer (Hach model DR- 2000) following a persulfate digestion as described in Standard Method 4500 P B 5 (Greenberg et al., 1992).

Metals

In the spring of 1998, a systematic sampling of sludge biomass was undertaken at five points in the reed bed. Samples were taken following the same procedure used in the 1994 and 1995 samplings, with a 2-inch diameter 48-inch long plastic pipe in a pattern as shown in (Figure 2.1). Each core sample was divided into three, 10-inch long tiers (upper, middle and lower). Samples were dried at 103-105° C until they reached a constant weight. The samples were then digested in nitric acid following Standard Method 3030 E (Greenberg et al., 1992) and analyzed by ICP plasma emission spectrometry following Standard Method 3120 B (Greenberg et al., 1992) to determine the concentrations of selected metals, including, boron, cadmium, chromium, copper, iron, manganese, molybdenum, nickel, lead, and zinc.

Phragmites plants were randomly harvested in December of 1994, 1995, and 1998 from the reed bed (Figure 2.1). The *Phragmites* were severed at the sludge surface. Thirty plants formed a composite sample to be analyzed for metal content. The samples were dried at 100^0 C until they reached constant weight. The dried plant material was milled followed by ashing in a muffle furnace at 500^0 C. The ashed samples were then digested in nitric acid following Standard Method 3030 E (Greenberg et al., 1992) and analyzed by ICP plasma emission spectrometry following Standard Method 3120 B

(Greenberg et al., 1992) to measure the concentrations of the same metals assessed in the sludge. Quality control for sludge and *Phragmites* samples included sample results with duplicates, matrix spikes, and matrix spike duplicates. Laboratory batch quality control included lab fortified blanks and duplicates, standard reference materials and duplicates, and method blanks.

CHAPTER 3

RESULTS AND DISCUSSION

Sludge Dewatering Efficiency

In an earlier study of the Shelburne/Buckland reedbed system during the period of October 1992 to October 1995 dewatering efficiency was 96.9% (Lavigne, 1996) (Table 3.1). After a total of six years of operation the dewatering efficiency is 92.6% (Table 3.2). The sludge volume applied from 1992-1995 was 696,500 gallons (Lavigne, 1996), the volume of sludge applied from 1996-1999 was 714,600 gallons for a total of 1,411,100 gallons (see appendix A for data).

While sludge application and dewatering are year round processes there are approximately 50,000 gallons more per winter month returned to the headworks via the underdrain than during the growing season months. This amount likely represents the evapotranspiration taking place during the summer (see Figure 3.1). This indicates an average evapotranspiration rate during the summer months of 1.3 feet per month. Evaporation and transpiration cause a loss of water from wetland systems. The amounts are generally studied using energy equations such as: $J_n = LE +/- A + S + M$ (Hillel, 1982). Where J_n = net radiation which is the incoming solar flux, less long and short wave reflection and long wave radiation; LE = rate of energy of utilization in evapotranspiration, which is the latent heat of vaporization times the rate of evaporation; A = energy flux going into heating the air; S = rate at which the heat is stored in the wetland components; and M = other miscellaneous energy terms such as photosynthesis and respiration.

Table 3.1 Dewatering efficiency for the Shelburne/Buckland reed bed from the start up in the fall of 1992 to the fall of 1995 (Lavigne, 1996).

Total sludge applied	Existing depth	Efficiency
648,480 gallons		
86,695 cubic feet		
16 feet	0.5 feet	
		96.9 %

Table 3.2 Dewatering efficiency for the Shelburne/Buckland reed bed from the start up in the fall of 1992 to the spring of 1999.

Total sludge applied	Existing depth	Efficiency
1,411,100 gallons		
188,649 cubic feet		
34 feet	2.5 feet	
		92.6 %

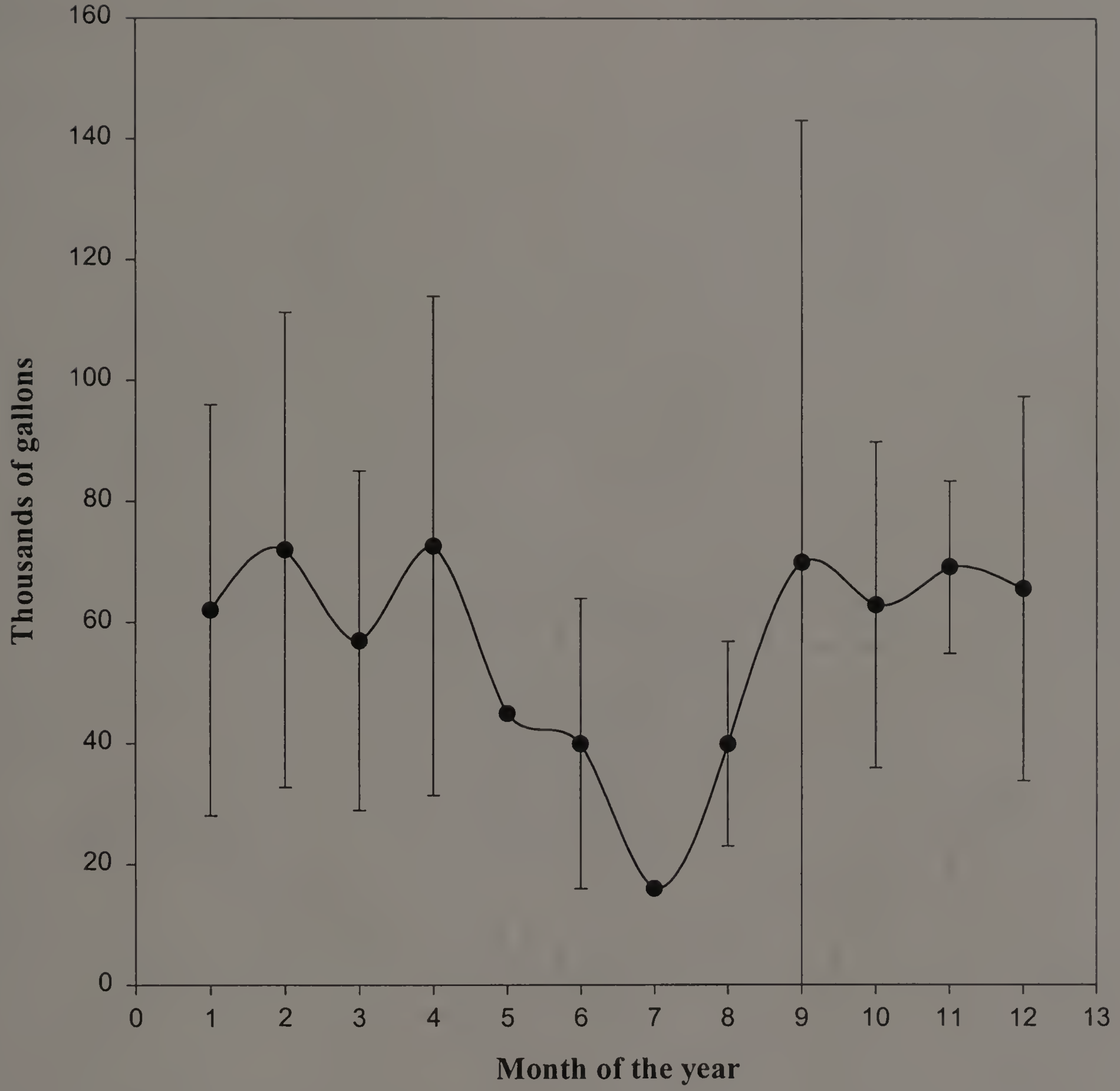

Figure 3.1 Average seasonal variations in the underdrain return flow based on data from the fall of 1995 through the spring of 1999.

Data requirements for energy balancing estimates are extensive, and thus, empirical procedures are favored. Kadlec (1989) states that wetland evapotranspiration, over the growing season is represented by 0.7 times the Class A pan evaporation from an adjacent open site, and that wetland evapotranspiration and lake evaporation are roughly equal. The average yearly Class A pan evaporation for western Massachusetts is 2.4 feet /growing season (Farnsworth, R. E., Thompson, S., and Peck, L.E., 1982). According to Kadlec evapotranspiration for this area should approximate 0.33 feet/month. The measured water loss at the Shelburne/Buckland reed bed was 1.3 feet/month during the growing season and 0.2 feet/month during the winter.

In addition to the influent applied to the reed bed, precipitation, averaging 48 inches a year over the last six years, added approximately 942,857 gallons of water to the reed bed. This volume added to the sludge influent totals 2,353,857 gallons of liquid that was either evapotranspired through the *Phragmites* plants, leaked through a hole in the liner or pumped back to the headworks. Table 3.3 depicts a water balance for the reed bed. The balance shows that 85% of the water is accounted for, there is an unaccounted volume of 363,182 gallons over a six-year period if this was averaged out for the seven months of winter usage per year it would equal 8,647 gallons/month (0.2 feet/month) unaccounted for. Since, during those winter months evaporation still takes place, it is reasonable to conclude that the 0.2 feet/month unaccounted for are evaporated during the winter months. Another possibility is that the liner could be leaking. In order to assess the magnitude of evapotranspiration or to determine whether the liner may have developed a leak, the monthly underdrain records were compared to inflow data (Figure 3.1).

Table 3.3 Water balance Fall 1992 to Spring 1999.

Source	Quantity	Yearly Average
	--gallons--	--gallons--
Influent	1,411,100	235,183
Precipitation	942,857	157,143
Effluent	392,500	65,416
Evapotranspiration	1,800,000	250,000
Sludge water content	98,175	16,362
Unaccounted volume	363,182	60,548

The data showed that 80 % of the total volume of effluent returned to the headworks was returned during the non-growing season when little evapotranspiration is going on. In Figure 3.1 the deep trough represents the average seasonal effect of evapotranspiration on the volume of effluent returned to the headworks as recorded by the underdrain sump pump.

The application of 1,411,100 gallons of sludge over a 6-year period resulted in 2.5 feet of reed bed residual biomass. With a four-foot effective biomass storage depth the bed was designed with a storage life of 8-10 years. Now approaching the seventh year of operation the reed bed has reached 62 % of its storage capacity and it is still maintaining a high dewatering efficiency. While hydraulic conductivity in a reed bed may decrease somewhat over time (Brix , 1997), the dewatering efficiency at the Shelburne/Buckland reed bed remains high. In the literature the reported decrease in hydraulic conductivity is thought to be due to pore spaces filling with solids. With new root growth additional flow channels develop annually helping to extend the life of the porous medium. The decrease in hydraulic conductivity in Shelburne/Buckland is not a major problem as yet, but may present a problem after several 10-year storage cycles if the sand and stone media are not replaced.

Total Suspended Solids

Suspended solids refer to matter suspended in water or wastewater. Solids analyses are important indicators of the effectiveness of biological and physical wastewater treatment processes and for assessing compliance with regulatory wastewater effluent limitations.

The Shelburne/Buckland wastewater treatment plant has a DEP discharge limit for total suspended solids of 30 mg/l, a limit they must meet daily in order to avoid fines and revocation of their permit. The results of this study show that the average red bed influent TSS concentration is 12,352 mg/l with the average effluent TSS concentration 14.2 mg/l, which is well below discharge standards.

The principle of suspended solid removal is filtration through the reed bed. As shown in Table 3.4 removal rates for total suspended solids average over 98%. Winter month removal is almost as effective as that during the summer months (p=.39, one-tailed t-test). Removal rates did not significantly decrease over time, with the Shelburne Buckland RBSTS maintaining a TSS removal efficiency of 99%. Table 3.4 shows the removal efficiencies for 1993 - 1998 (see appendix B for actual data).

Table 3.4 Shelburne/Buckland TSS removal efficiency for the period 1993 - 1998. The winter period is from November through March.

Date	Removal Efficiency	Winter
	-----%-----	-----%-----
1993	99.29	
1994	98.4	
1995	99.7	
1996	95.0	
1997	99.9	
1998	99.9	
Mean	98.7	97.7

Biochemical Oxygen Demand (BOD_5)

The biochemical oxygen demand determination is an empirical test in which standardized laboratory procedures are used to determine the relative oxygen requirements of wastewaters, effluents and polluted waters. The test is used to measure waste loading to treatment plants and in evaluating the efficiency of such treatment systems. The test measures the oxygen utilized during a specified incubation period for the biochemical degradation of organic material (Greenberg et al., 1992).

BOD_5 is a measure of the amount of dissolved oxygen in the waste stream. The large amount of carbon associated with wastewater potentially reduces the amount of oxygen available to aquatic species. Table 3.4 presents typical BOD_5 removal efficiencies for wastewater as reported in the literature. Typical removal efficiencies in reed beds are greater than 90 % (Williams, 1995; Yang et al., 1995).

As an indicator of potential microbial demands, BOD_5 is crucial to treatment plants to discharge renovated wastewater according to state and federal regulations. The state DEP discharge permit for the SBWWTP sets the BOD_5 limit at 30 mg/l. Results from the Shelburne/Buckland BOD_5 data set covering a 3-year period with 43 samplings of the reed bed's influent and effluent show that the reed bed effluent BOD_5 quality consistently passed regulatory standards (see appendix C for actual data). The average reed bed influent BOD5 concentration was 1,342 mg/l and the average reed bed effluent BOD_5 concentration was 6 mg/l, resulting in a BOD_5 treatment efficiency of 99 %.

Table 3.5 BOD5 removal efficiencies for this study compared to typical values reported in the literature. Values represent averages.

Author	Year	BOD_5 Removal Efficiency
		-------%------
Williams et al.	1995	90
Lavigne	1996	97
Yang et al.	1995	90
Yin and Shen	1995	89-97
Persyn et al.	1998	80
This study	1999	99

Nitrate - Nitrogen and Total Phosphorus

Nitrate generally occurs in trace quantities in surface water but may attain high levels in groundwater. In excessive amounts, it may cause methemoglobinemia (blue baby syndrome) in infants. A limit of 10 mg/l nitrate-nitrogen has been imposed on public drinking water to prevent this disorder. Nitrate is found only in small amounts in fresh water but in the effluent of biological treatment plants it may be considerably higher (Greenberg et al., 1992).

Phosphorus occurs in natural waters and wastewaters almost solely as phosphates. These are classified as orthophosphates, condensed phosphates, and organically bound phosphates. Condensed phosphates arise from commercial cleaning processes, orthophosphates are applied as fertilizers, and organic phosphates are formed primarily by biological processes. They are contributed to sewage by body wastes and food residues, and also may be formed from orthophosphates in biological treatment processes. Phosphorus is essential to the growth of organisms and can be the nutrient that limits the primary productivity of a body of water. In instances where phosphorus is a growth-limiting nutrient, the discharge of wastewater to that water body may stimulate the growth of photosynthetic aquatic organisms including algae (Greenberg et al., 1992).

RBSTS's show positive removal capacities for nitrogen and phosphorus with the removal mechanisms ascribed to plant adsorption, plant uptake, or chemical transformation and precipitation (Revitt et al., 1997). Removal efficiencies for nutrients vary considerably and have been reported ranging from 10 to 93 % for total nitrogen and from 9 to 94 % for total phosphorus (Reed, 1990; Yang et al., 1995). Typical values reported in the literature as well as the results of this project are presented in Table 3.6. At the Shelburne/Buckland reed bed nitrate and total phosphorus were not monitored on a regular basis. For purposes of this study, 11 samples were taken over a six-month period (March through October 1998) from the reed bed influent and effluent. The results show a 90% reduction in nitrate-nitrogen and an 80% reduction in total phosphorus (see appendix D for actual data).

Table 3.6 Nitrate-nitrogen and total phosphorus removal rate as reported in the literature and compared to the results of this study.

Author	Year	Nitrate-nitrogen	Total phosphorus
		----%----	----%----
Reed	1990	10-93	14-94
Wood	1995	64	55
Yin and Shen	1995	29	44
Yang et al.	1995	21-45	9-58
This study	1999	90	80

Metals

The effects of metals in water and wastewater can range from beneficial through troublesome to dangerously toxic. Some metals are essential for plant growth, others may adversely affect wastewater treatment systems and receiving waters (Greenberg et al., 1992).

The fate of metals in aquatic systems is strongly influenced by pH. High pH values promote precipitation of the metals and therefore assist in their removal from the aqueous phase. The reverse effect occurs with increasing acidic conditions (Revitt et al., 1997). While the pH at the Shelburne/Buckland reed bed varied due to wastewater quality and amount of rainfall, the pH generally ranged between 6.5-7.5.

It is reasonable to assume that metals associated with a wastewater/sludge stream may concentrate in the biosolids. This may be especially true for reed beds because of the reduction in biomass over time. Sludge core analyses of the RBSTS were used to assess to what extent this happens. It has been documented that metals tend to concentrate in the older or deeper layers of the reed bed biomass (Kim and Smith, 1997). Pollutants concentrated in the reduced biosolids mass could complicate final disposal because the material may exceed regulatory standards.

Friedland (1990) documented that some plants show a tolerance to metal contaminated soils. Research is presently underway to identify high biomass crop plants capable of accumulating heavy metals (Kumar et al., 1995). The ability of plants to renovate contaminated wastewater, also known as rhizofiltration, rhizoextraction, or phytoremediation, is a process whereby the plant extracts and/or accumulates metals and nutrients available in the waste stream (Kumar et al.,1995; Dushenkov et al., 1995).

The results from the Shelburne Buckland RBSTS show an average metal concentration removal rate of 87% (influent to effluent) (Table 3.7). With such a high removal rate, where are the metals ending up? Are they concentrating in the reed bed sludge biomass or in the *Phragmites* tissue? By analyzing influent and effluent in addition to analyzing sludge and plant tissue an attempt was made to determine the fate of metals in the reed bed. The concentrations of metals in the sludge biomass and in the *Phragmites* tissue are indicative of the wastewater quality of the treatment plant influent. In this case the metals concentrations are relatively innocuous as there is little industry in either Shelburne or Buckland. Of the ten metals studied iron consistently had the highest concentration, followed by copper, zinc, nickel, manganese, lead, boron, chromium, cadmium and molybdenum.

This research also examined the concentrations of the metals over time and depth in the reed bed sludge biomass profile. Table 3.8 summarizes these results. For most of the metals the highest concentrations were found in the lower tier of the sludge profile. The metals are more concentrated in the lower tiers because there is a greater degree of microbial decomposition. This along with physical compaction results in higher bulk densities thus increasing the relative amount of metals per unit volume of sludge. The bulk density for the sludge at the Shelburne/Buckland RBSTS in the upper tier is 0.17 g/cm^3, in the middle tier 0.19 g/cm^3 and in the lower tier 0.25 g/cm^3.

Table 3.7 Concentrations and removal efficiencies of selected metals in sludge, plant tissue, and reed bed influent and effluent from the Shelburne/Buckland reed bed. Values represent averages.

Parameter	Sludge	*Phragmites*	Method Detection Limit	Influent	Effluent	Average Removal Efficiency
	mg/kg	mg/kg	mg/l	mg/l	mg/l	%
Boron	60	10	0.05	0.41	0.11	73
Cadmium	3	2	0.02	BDL	BDL	100
Chromium	42	10	0.02	0.140	BDL	97
Copper	1906	155	0.02	11	0.17	98
Iron	11592	3263	0.02	19	0.07	98
Lead	154	32	0.02	0.5	0.29	40
Manganese	457	1443	0.025	2	0.29	86
Molybdenum	4	1	0.0015	0.09	BDL	100
Nickel	23	9	0.02	0.82	0.17	80
Zinc	684	453	0.02	3	0.14	95
Mean removal rate of all metals combined:						86.7

Table 3.8 Metal concentrations in the reed bed sludge by depth. Each tier is 10 inches long. Values represent averages.

Parameters	Upper Tier	Middle Tier	Lower Tier
	----mg/kg----	----mg/kg----	----mg/kg----
Boron	58	69	51
Cadmium	2.7	3.5	3.7
Chromium	36	45	53
Copper	957	2117	2483
Iron	9251	11021	12419
Lead	159	185	178
Manganese	385	555	561
Molybdenum	4	5	5
Nickel	25	26	25
Zinc	635	738	796

Table 3.9 is a statistical evaluation of the sludge core data showing a significant difference, for most metals, between the upper, middle and lower tiers. This suggests that the metals mostly concentrate in the lower sludge tier. The statistical testing was done with a one-sided, difference of means t-test. The null hypothesis was that there was no difference between tiers. The alternative hypothesis was that the higher tier was less concentrated than the lower tier. The probability value shows the chance that a difference as great as observed in the sample would occur by chance in repeated sampling. I chose p=.10 as the significance level. In general, the null hypothesis was rejected. In most cases there was a clear and significant top-to-bottom gradient. Table 3.9 shows two exceptions. Nickel showed very little difference between the various tiers. For boron, there is a highly significant (p=.01) difference between the middle and lower tiers with boron most heavily concentrated in the middle of the sludge. This may be due to differences in physical and chemical properties of boron as compared to the rest of the selected metals. Since the periodic law states that, "The physical and chemical properties of the elements are periodic functions of their atomic numbers" (Metcalfe, Williams, and Castka, 1970). The periodic table indicates that boron has a lower atomic weight than the rest of the selected metals and exhibits the fewest metallic properties for the metals analyzed. None of the metals showed maximum accumulations in the upper third of the sludge reed bed.

Metals can be taken up by vegetation. In discussing lead accumulation in *Brassica* species, Kumar et al. (1995) concluded that all species tested concentrated lead in their roots. Kumar (1995) cites several author's who reached similar conclusions. Adcock

Table 3.9 Difference of means (t-test) testing of selected metals by depth in the sludge reed bed. If the probability is less than 0.10, two tiers are "significantly" different. A probability higher than 0.10, means that concentrations are not significantly different.

Chromium

	U	M	L
U *36*	-	.011	.012
M*45*		-	.057
L *53*			-

Cadmium

	U	M	L
U*2.7*	-	.001	.000
M*3.5*		-	.164
L *3.7*			-

Lead

	U	M	L
U*159*	-	.012	.029
M*185*		-	.185
L1*78*			-

Iron

	U	M	L
U*9251*	-	.021	.000
M*11021*		-	.020
L1*2419*			-

Molybdenum

	U	M	L
U*4.2*	-	.040	.000
M*4.9*		-	.404
L*5.0*			-

Nickel

	U	M	L
U*24.7*	-	.079	.470
M*25.5*		-	.237
L*24.8*			-

Boron

	U	M	L
U*58*	-	.072	.132
M*69*		-	.010
L*51*			-

Manganese

	U	M	L
U384	-	.005	.006
M555		-	.468
L561			-

Copper

	U	M	L
U957	-	.010	.010
M2117		-	.108
L2482			-

Zinc

	U	M	L
U635	-	.032	.000
M738		-	.078
L796			-

Concentration in milligrams per kilogram for upper (U), middle (M), and lower(L) tiers respectively.

and Ganff (1994) in examining the distribution of biomass in *Phragmites* reported that more than 75% of the plants biomass is in the root core and rhizomes. Accumulation of metals in roots therefore may be quite significant.

At the Shelburne/Buckland treatment plant the roots and rhizomes were not harvested nor analyzed. During regular operation only the upper part of the P*hragmites* plants are harvested, thus the contribution of the root biomass to metal attenuation can be ignored. The contribution of metals contained in the upper portion of the *Phragmites* plants also can be ignored as the standard operating procedure at the Shelburne/Buckland treatment plant for disposal of the upper portion of the *Phragmites* plants is to burn them right in the reed bed with the residual ash incorporated into the reed bed sludge biomass.

Metal Mass Balance

A mass balance for metal concentrations was calculated based on a total volume of 1,411,100 gallons of sludge applied to the reed bed and 392,500 gallons of effluent pumped from the underdrain to the headworks. The mass of the sludge in the reed bed was determined by measuring the bulk density and multiplying this value by the volume of sludge. The metal mass balance for the SBRBSTS was calculated as follows:

Total Incoming Metal Mass(kg): volume of influent (l) x metal concentration(mg/l) x 10^{-6}

Total Outgoing Metal Mass(kg): volume of effluent (l) x metal concentration(mg/l) x 10^{-6}

Metals in sludge (kg): mass of sludge (kg) x metal concentration (mg/kg) x 10^{-6}.

The theoretical results of the mass balance and the actual results obtained do not equal each other. In 8 out of 10 cases there is more of the metal in the effluent and sludge than was applied in the influent. In 2 cases, nickel and molybdenum, there is less of the metal in the effluent and sludge than was applied in the influent. The difference in the results may be due to the low concentration of the metals in the influent, this concentration also varies from day to day due to the waste stream. In addition, the concentration of the metals in the effluent is diluted by approximately 48 inches of rainfall each year. What the results do show is that for the most part the metals tend to concentrate more in the reed bed sludge biomass than in the *Phragmites* plants. Table 3.10 summarizes the mass balance.

Sludge Quality

Table 3.11 compares the Shelburne/ Buckland reed beds composite sludge and *Phragmites* samples to standards set (where applicable) by the DEP for land application of Type 1 sludge as defined in Massachusetts DEP publication 310 CMR 32.12. Type 1 sludge can contain various metals as long as they do not exceed the limits set forth in Table 3.10. Metals accumulated in the *Phragmites* are below Type 1 sludge standards and don't appear to present any disposal problems. Disposal of the sludge from the Shelburne/ Buckland RBSTS presents one problem as the current concentration of copper exceeds the state limit for land application. This is a common problem in municipal sludge where the source of the copper is copper pipe used for water supply lines in most homes and businesses. In order to alleviate this problem sodium hydroxide was added to the water supply to raise the pH and make the water less aggressive to the copper pipes. This seems to be working as the upper tier of the sludge biomass has less of a concentration of copper than the lower tiers.

Table 3.10 Metal mass balance. Values in parenthesis can not be determined accurately because the effluent concentrations were below detectable limits.

Parameter	Influent	Effluent	Sludge	Difference from expected mass balance
	--kg--	--kg--	--kg--	--kg--
Boron	2.2	0.16	4.9	2.8 >
Cadmium	BDL	BDL	0.25	(0.25)
Chromium	0.7	BDL	3.4	(2.7)
Copper	58.5	0.25	142	83.5 >
Iron	101	0.10	836	735 >
Lead	2.6	0.43	13.3	10.7 >
Manganese	10.6	0.43	38.4	27.8 >
Molybdenum	0.5	BDL	0.87	(0.37)
Nickel	4.4	0.25	1.9	2.5 <
Zinc	15.9	0.2	55.4	39.5 >

BDL = Below detection limit. > = greater than influent total. < = less than influent total.

Table 3.11 Metal concentrations in Shelburne/Buckland reed bed sludge and *Phragmites* tissue as compared to DEP regulatory limits for Type 1 sludge. Values represent averages.

Parameter	DEP Limit	Reed Bed Sludge	*Phragmites* Tissue
	----mg/kg----	----mg/kg----	----mg/kg----
Boron	300	59	10
Cadmium	14	3	2
Chromium	1000	45	10
Copper	1000	1852 *	155
Iron	no limit	10897	3263
Lead	300	174	32
Manganese	no limit	500	1443
Molybdenum	10	4	1
Nickel	200	25	9
Zinc	2500	723	453

* = exceeds state limit.

CHAPTER 4

CONCLUSIONS

The primary purpose for the installation of the reed bed in Shelburne/Buckland was to utilize a cost effective, environmentally sound method to dewater the sludge. The reported costs at the Shelburne/Buckland wastewater plant for conventional sludge dewatering compared to the costs associated with reed bed technology are approximately $40.00/square foot for conventional methods and $12.00/square foot for reed bed technology (Krueger, 1991).

The dewatering efficiency of the Shelburne/Buckland reed bed system after a 6-year period is 93%. This agrees with data reported in the literature. The Shelburne/Buckland reed bed system has performed well enough that the town received regulatory approval for 2 additional reed beds. This will prove to be important during evacuation of the first reed bed as it will give the plant operators an alternative effluent dumping location. Of the 1,990,675 gallons of sludge and rain received over a six-year period, 1,500,000 gallons are lost due to evapotranspiration during the growing season, 392,500 gallons were returned to the headworks, approximately 98,175 gallons of water was held in the sludge biomass which leaves approximately 363,182 gallons unaccounted for. While the *Phragmites* plants do not lose significant amounts of water due to transpiration during the winter months there is still water loss from the reed bed due to evaporation. To account for the remaining 363,182 gallons we estimate that winter evaporation would have to equal approximately 8,647 gallons/month (0.2 feet/month).

Regulatory approval of alternative technology systems such as RBSTS's require monitoring of the effluent being produced. The effectiveness of the filtration of solids into the reed bed system was determined by measuring total suspended solids. The SBWWTP's discharge permit for TSS is 30 mg/l.

The average TSS concentration leaving the Shelburne/Buckland reed bed was 14.2 mg/l, a 99 % reduction from the influent average concentration of 12,350 mg/l.

Another important measure of effluent quality is the biochemical oxygen demand which has a regulatory discharge limit of 30 mg/l. The Shelburne/ Buckland reed bed effluent had an average BOD_5 of 6 mg/l, a 99 % reduction from the influent concentration of 1,300 mg/l.

TSS and BOD_5 effluent concentrations are well under the regulatory standards, showing that reed beds can produce an effluent of high quality that needs no further treatment and could be discharged directly to our waterways.

With less transpiration taking place in the winter months there was a greater amount of effluent returned to the headworks, however there was no significant difference in TSS and BOD_5 treatment results for winter or summer months (see appendix B and C). This clearly shows that, even when located in northern climates, reed bed technology is a viable alternative to conventional sludge treatment.

Nitrate-nitrogen reduction was 90% and total phosphorus reduction was 80%, these results are encouraging and seem to follow reports in the literature. Further study is needed in order to draw any significant conclusions from the data presented.

The overall average metal removal efficiency was 87 %. The results of the mass balance varied from metal to metal but the general conclusion is that the metals tend to concentrate in the reed bed sludge biomass and not in the *Phragmites* plant tissue.

Of the selected metals analyzed only boron showed a significantly higher concentration in the middle tier than in any other tier of the sludge samples. This may be due to differences in physical and chemical properties of boron as compared to the rest of the selected elements. Boron has a lower atomic weight than the rest of the selected metals and exhibits the fewest metallic properties for the metals analyzed. The rest of the elements showed a significantly higher concentration in the lower tier of the sludge samples except for nickel, which showed no significant difference between the various tiers.

All metal concentrations in the sludge bed biomass except for copper meet DEP standards for Type 1 sludge, suitable for land application. Copper concentrations in the sludge pose a potential disposal problem. To alleviate this problem the towns drinking water is presently treated with sodium hydroxide to make it less aggressive to the copper pipes. This seems to be effective as the residual copper concentrations in the upper tier of the sludge biomass are less concentrated than those in the lower tiers.

The metal concentrations in the *Phragmites* plants are below the disposal standards set by the DEP and do not pose a problem if disposed of separately from the sludge.

The data presented in this paper confirm the reported success of RBSTS in cold climates and show that while RBSTS are not a panacea for all parameters of wastewater treatment, they are certainly a viable alternative to current technology.

With new RBSTS coming on line every year, the operation and maintenance of the reed beds will soon be fine-tuned to successfully provide treatment for not only municipal wastewater but for different wastewater streams as well.

APPENDIX A

SLUDGE VOLUME AND TOTAL SUSPENDED SOLIDS DATA FOR THE SHELBURNE/BUCKLAND WASTEWATER TREATMENT PLANT

Appendix A. Sludge dewatering data and total suspended solids data for 1996 and 1997.

Date	Sludge Applied	TSS
	----gallons----	----mg/l----
1/96	36360	12942
2/96	24480	12413
3/96	12240	11625
4/96	25920	12438
5/96	12240	12350
6/96	28800	12233
7/96	24480	11540
9/96	12240	10075
10/96	40320	10745
11/96	12240	11000
12/96	28800	11000
1996 Total	258120	128361
1996 Mean	21368	11669
1996 Standard Deviation	10097	886
1/97	28800	11750
2/97	12240	12740
3/97	28080	12000
4/97	25200	12412
5/97	12600	13275
6/97	24480	14962
7/97	13050	13050
8/97	25040	14225
9/97	12960	12750
10/97	23780	12250
11/97	12960	13725
12/97	9900	1375
1997 Total	229090	156714
1997 Mean	17737	13059
1997 Standard Deviation	7202	3486

Appendix A. Sludge dewatering and total suspended solids data for 1998 and 1999.

Date	Sludge Applied	TSS
	----gallons----	----mg/l----
1/98	12240	12900
2/98	12240	11890
3/98	12240	13025
4/98	10080	13375
5/98	12240	14100
6/98	12240	8125
7/98	12240	18975
8/98	12240	15175
9/98	12240	13550
10/98	25200	11863
11/98	23050	12188
12/98	12240	17013
1998 Total	168490	162179
1998 Mean	13483	13515
1998 Standard Deviation	4773	2730
1/99	17400	8675
2/99	23050	10175
3/99	18450	9225
1999 3-month Total	58900	28075
1999 3-month Mean	19487	9358
1999 Standard Deviation	3005	759
1996-1999 Totals	714600	475329
Overall Mean	17764	12509
Overall Standard Deviation	3078	3005

APPENDIX B

TOTAL SUSPENDED SOLIDS IN THE SLUDGE BED UNDERDRAIN EFFLUENT OF THE SHELBURNE/BUCKLAND WASTEWATER TREATMENT PLANT

Appendix B. Total suspended solids data for 1993, 1994, 1995 and 1996.

Date	Influent	Effluent
	----mg/l----	----mg/l----
10/93	11330	1
10/93	12780	1
11/93	13040	2
12/93	17330	4
12/93	9500	1
1993 Mean	12796	2
1993 Standard Deviation	2900	1
1/94	18200	1
2/94	20700	1
3/94	14900	1
3/94	12500	20
4/94	20100	1
5/94	15000	1
5/94	13000	20
6/94	10000	10
8/94	10000	30
9/94	8200	0
10/94	8300	0
11/94	24100	10
12/94	9500	20
1994 Mean	14192	9
1994 Standard Deviation	5202	10
2/95	11200	10
3/95	11400	10
4/95	10000	40
5/95	10200	10
6/95	13200	30
8/95	10500	10
1995 Mean	11083	18
1995 Standard Deviation	1174	13
8/96	12500	10
9/96	12600	20
10/96	9500	10
11/96	13200	50
1996 Mean	11950	22
1996 Standard Deviation	1662	19

Appendix B. Total suspended solids data for 1997 and 1998.

Date	Influent	Effluent
	----mg/l----	----mg/l----
1/97	1600	10
2/97	16400	50
3/97	16100	20
4/97	18300	20
5/97	11800	10
6/97	13200	30
7/97	14300	30
8/97	10900	20
9/97	13900	40
10/97	15800	0
10/97	16800	20
11/97	11900	10
12/97	15500	10
1997 Mean	13576	3
1997 Standard Deviation	4213	14
2/98	14000	10
3/98	11600	30
4/98	14300	10
4/98	14100	20
5/98	11500	0
6/98	11200	20
6/98	13600	20
7/98	13600	0
8/98	16000	50
9/98	13800	30
9/98	13300	10
10/98	14800	10
10/98	12100	20
11/98	14800	10
12/98	13200	20
Annual Mean	13460	17
Standard Deviation	1414	13
Overall Mean	12353	14.2
Standard Deviation	70991	102

APPENDIX C

BIOCHEMICAL OXYGEN DEMAND

Appendix C. Data for 1996 and 1997.

Date	Influent	Effluent
	----mg/l----	----mg/l----
1/96	1550	7
2/96	1450	3
3/96	1560	7
3/96	1450	3
4/96	2360	3
5/96	1480	6
5/96	1300	8
6/96	1020	5
6/96	1070	11
7/96	1140	8
8/96	820	12
8/96	920	3
9/96	1000	4
9/96	1040	3
Annual Mean	1297	6
Standard Deviation	394	3
10/97	1100	7
10/97	1200	3
11/97	1520	8
12/97	1680	4
Annual Mean	1375	5
Standard Deviation	271	2

Appendix C. Data for 1998 and 1999.

Date	Influent	Effluent
	----mg/l----	----mg/l----
1/98	1160	3
1/98	2816	12
2/98	1875	8
2/98	1150	4
3/98	1560	15
3/98	1260	5
4/98	1170	6
5/98	870	6
5/98	940	10
6/98	720	6
6/98	880	4
7/98	1260	3
8/98	1350	2
9/98	1660	1
9/98	1620	3
10/98	1500	14
11/98	1685	7
11/98	940	4
12/98	1500	14
12/98	1680	14
Annual Mean	1379	7
Standard Deviation	470	5
1/99	940	7
1/99	1060	5
2/99	1660	4
2/99	1260	6
3/99	1580	14
1999 3-month Mean	1300	5
1999 3-month Standard Deviation	315	4
Overall Mean	13421	6
Overall Standard Deviation	422	4

APPENDIX D

NITRATE-NITROGEN AND TOTAL PHOSPHORUS

Appendix D. Nitrate-nitrogen data in 1998.

Date	Influent	Effluent
	----mg/l----	----mg/l----
3/98	379	38
4/98	492	25
4/98	100	12
5/98	395	35
6/98	437	37
6/98	435	39
7/98	416	38
8/98	292	27
9/98	389	34
9/98	369	32
10/98	391	33
1998 Mean	372	32
1998 Standard Deviation	103	8

Appendix D. Total phosphorus data in 1998.

Date	Influent	Effluent
	----mg/l----	----mg/l----
3/98	342	17
4/98	392	20
4/98	136	12
5/98	387	19
6/98	299	17
6/98	374	18
7/98	398	20
8/98	354	14
9/98	416	20
9/98	375	17
10/98	363	16
1998 Mean	349	17
1998 Standard Deviation	77	3

APPENDIX E

CONCENTRATIONS OF SELECTED METALS IN THE SLUDGE,

PLANT TISSUE AND REED BED INFLUENT AND EFFLUENT.

Appendix E. Data based on samples from 1994, 1995 and 1998. Values are averages.

Parameter	Sludge	*Phragmites*	Influent	Effluent	MDL
	----mg/kg----	----mg/kg----	----mg/l----	----mg/l----	----mg/l----
Boron	60	10	0.41	0.11	0.05
Cadmium	3	2	BDL	BDL	0.02
Chromium	42	10	0.140	BDL	0.02
Copper	1906	155	11	0.17	0.02
Iron	11592	3263	19	0.07	0.02
Lead	154	32	0.5	0.29	0.02
Manganese	457	1443	2	0.29	0.025
Molybdenum	4	1	0.09	BDL	0.0015
Nickel	23	9	0.82	0.17	0.02
Zinc	684	453	3	0.14	0.02

MDL = Method detection limit; BDL = Below detection limit.

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