EVALUATION OF THE SUBSURFACE VEGETATED BED FORM OF CONSTRUCTED WETLANDS FOR DOMESTIC WASTEWATER TREATMENT

by

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for
the degree of Doctor of Philosophy
in
Crop and Soil Environmental Sciences

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September 1995
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(ABSTRACT)

Sixteen small scale Subsurface vegetated beds (SVB) were installed down slope of the residence at the Whitethorne Planation (WP) site. Treatments included three detention times (2.6, 3.9, and 5.9 days), two recirculation ratios (0 and 0.5), and two plant species [woolgrass *(Scirpus cyperinus)* and cattail (*Typha latifolia*)]. Twelve larger scale SVBs were constructed at the Powell River Project (PRP) site, Wise County, VA. Treatment consisted of three detention times (4, 8, 12 days) with the same plant species (cattail and woolgrass).

At the WP site, pollutant removal incresed with detention time for 5-day biochemical oxygen demand (BOD_5), total Kjeldahl nitrogen (TKN), ammonium (NH_4-N), phosphates (PO_4^{3-}-P), redox potential (Eh), and total dissolved solids (TDS). The pollutant removal rates, based on 23 data sets, were: BOD_5 (54-70%); NH_4^+-N (30-61%); TKN (33-52%); PO_4^{3-}-P (7-28%); fecal coliforms (FC) (>99%) and coliphages (>95%). Recirculation appeared to have no apparent benefit. There were no differences in P, S and secondary and trace metals concentrations in the SVBs planted to cattail and woolgrass. Plants could remove 2 -10% of the total N applied and 13-57% of the total P applied to the SVBs if harvested once a year during the growing season.

At the PRP site, differences were observed among the detention times for BOD_5, TKN, NH_4-N, PO_4-P, TDS, pH, EC and Eh. The pollutant removal percentages were: FC (>99%); BOD_5 (30-75%); NH_4^+-N (27-88%); TKN (27-81%); PO_4^{3-}-P (24-46%); and TDS (12-73%). Samples collected from shallow wastewater column exhibited a higher level of treatment. There were no differences in FC, BOD_5, TKN and NH_4^+-N concentrations between

SVBs planted to cattail and woolgrass, and there were no differences in tissue N content between cattail and woolgrass at both sites.

The average NH_3 volatilization rate was 236 mg N/m^2/day, and accounted for 7-37% of total N applied to the SVBs. Average measured denitrification rates ranged from 3.87 to 6.69 mg N_2O / m^2/ h, and accounted for 2-17% of total N applied.

To the appreciation of my God,
for all I have got,
the strength, the courage, the health
and the wisdom I may have.

ACKNOWLEDGEMENTS

I give my sincere thanks to Dr. Raymond B. Reneau, Jr., my major professor and mentor, for his professional guidance, encouragement, patience and his willingness to spend extra time to improve my English. I am honored to be a student of such a knowledgeable scholar. I would like to express my appreciation to the members of my committee, Dr. Duane. F, Berry, Dr. David. C Martens and Dr. Gregory D. Boardman for their helpful guidance, patience and advice. Special thanks go to Dr. Charles Hagedorn, for his guidance and advice on microbiological techniques, and his sense of humor. I also would like to gratefully acknowledge the financial support of the Virginia Department of Health. Special thanks go to Michael Saluta for his readiness to help, his encouragement, patience, and his friendship. I also wish to thank Dr. Gregory Monnett and Jennifer Siebold, Norma Nelson, Hubert Walker, and William G. Keeling, who assisted me in the laboratory, for their time, patience, and both moral and technical support. I also appreciate Nancy Reneau, Sue Brown and Sybil B. Paul, for their all kinds of help in my living. Without their help, I could never image that my dream could come true. In the course of pursuing my goal, I had to leave my home country, my three year old daughter at home, and my husband, Dafang. My husband has been patient and supportive of my study. My daughter, Kathy, has provided me with the inspiration to complete this degree. I know that I owe you too much, my little daughter. My parent, have endlessly supported my goals, all I have belong to you, mom and dad.

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Chapter I:

INTRODUCTION

I. Overview

Wetlands have received wastewater discharges in numerous situations in the past, but only recently have they been recognized as a potential cost efficient treatment alternative to conventional on site wastewater treatment and disposal systems (OSWTDS). Research over the last few years has shown that both natural and constructed wetlands for wastewater treatment can provide high-quality discharge water at relatively low cost. Although some natural wetlands have been effectively used for wastewater quality improvement, more researchers now view natural wetlands as valuable resources that must not be wasted and as such discourage their use for such purposes. There is a growing interest in constructed wetland systems because they represent a simple and inexpensive solution for controlling many water pollution problems without detrimentally affecting our natural wetland resources (TVA, 1987; Hammer, 1989; and Moshri, 1993). Pretreatment of septic tank effluent (STE) may be required prior to application to marginal soils. The subsurface vegetated bed (SVB) form of constructed wetlands is an ideal candidate for both economical and efficient pretreatment of STE from individual homes prior to soil application or perhaps stream discharge in some instances. This project consists of studies conducted in the laboratory and at two field sites, The Powell River Project (PRP), Wise County, VA and The Virginia Tech Research Farm, Whitethorne Plantation (WP), Blacksburg, VA. The primary objective was to evaluate and develop the SVB system, a form of artificial wetlands, as an alternative OSWTDS for domestic wastewater. However, many soils and wetlands may both have limited potential for renovation of domestic wastewater because of soil permeability, high water table, shallow depth to rock, or restricting soil horizons. Although regulations also prohibit discharge of domestic wastewater to natural wetlands in the US, natural wetlands still are an alternative methods for renovation wastewater in developing countries such as China. Therefore, interest is increasing in use of constructed wetlands as a simple, energy efficient, largely passive, highly reliable means of removing nutrient from wastewater without endangering the function or extent of natural wetlands. Two field experimental sites have been installed in conjunction with this project to evaluate and develop the SVB for the practical application of pretreatment of STE prior to spray irrigation, application to marginal soils, or stream discharge. There are, however, many uncertainties entailed in these systems. For example, many mechanisms that modify or immobilize pollutants, especially toxic substances, are poorly understood. In addition, long term accumulation of toxic substances and heavy metals in vegetation may cause bioaccumulation and or biotransport. A major problem in the use of this technology at present is the lack of detailed information from long term experience with these systems.

II. Potential benefits of research

The SVB may be beneficial in small to medium-sized communities to assist in meeting discharge limitations.

* Regions with soil conditions which limit surface disposal. The SVB may be capable of consistently producing effluent which meets discharge standards.

* Regions where transport of pathogens and /or nutrients from OSWTDS present a water quality problem or a potential health hazard. The SVB used for treatment around lake margins and in aquifer recharge areas might significantly improve water quality.

* Regions where cost efficient management systems are needed. The SVB may provide a cost efficient method of protecting public health and water quality.

* Regions where arable land are limited (developing countries). The SVB should be a good

candidate for treatment of wastewater in smaller areas at lower cost.

* Regions with high population densities, such as unsewered towns, or other developments with small lots, where more stringent treatment before disposal would help to protect the public health and water quality.

III. Research objectives

The general purpose of this research project is to provide a thorough, systematic evaluation of the general capabilities of the SVB when treating STE, including the design parameters which may impact its practical workability. The SVB in this project employs wetland-adapted plants [woolgrass *(Scirpus cyperinus)* and cattail (*Typha latifolia*)] in conjunction with an attached growth gravel media substrate for treatment. Therefore, its efficiency is likely to be affected by weather factors such as temperature, humidity and wind, etc. However, the aquatic macrophyte system is expected to adapt to the area of application.

This research is also designed to evaluate the influence of detention time, plant species, and recirculation on:

Objective 1. The potential for the SVB to treat domestic wastewater.
Objective 2. The capacities of pollutant removal in the SVB systems.
Objective 3. The nitrogen (N) balance in the SVB system.

The design parameters being investigated are two plant species, three detention times and two recirculation ratios. The experimental design is completely randomized. Pilot-scale facilities have been constructed at the WP and PRP experimental sites. The rationale for effluent loading rates employed at the two sites are developed in Chapter III. The source of domestic wastewater at each site is from a single family residence. These prototype systems will allow for observation of "real world" performance and any differences imparted by Virginia climate. This is an area where the SVB may be beneficially employed, given the climate, site conditions and access to wetland-adapted plants. The following investigations of the SVB design issues and treatment capabilities with respect to removal of 5-day biological oxygen demand(BOD_5), total suspended solids (TSS), total dissolved solids (TDS), nutrients [N, phosphorus (P), chloride (Cl)], indicator organisms and heavy metals have been conducted since January, 1992. The STE and SVB's effluent were collected and analyzed monthly. Electrical conductivity (EC), redox potentials (Eh) at different depths of the SVB and dissolved oxygen (DO) have been monitored in situ monthly.

Nitrogen is the key element with the greatest potential for surface and ground water contamination. A N balance can help to better understand the primary N removal mechanism and N transformations that have occurred. The N balance has been estimated by analysis of STE and SVBE, denitrification measurement, NH_3 volatilization and plant tissue analysis.

Denitrification potentials of these systems were determined by incubation of the STE and SVBE in the laboratory.

Redox potentials at different depths in the SVB and DO were monitored *in situ* monthly.

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Chapter II:

LITERATURE REVIEW

I. Overview

Additional treatment of STE may offer potential for use in soils that have limited treatment depth (substitution of treatment for soil depth). The SVB form of constructed wetlands is an ideal candidate for both economical and efficient additional treatment of STE from individual homes prior to soil application or perhaps stream discharge in some instances. During recent years, the interest in utilizing constructed wetlands as an alternative method for wastewater treatment has rapidly increased (Brix and Schierup, 1989; Cooper and Hobson, 1989; Hammer, 1989; Moshiri, 1993). Constructed wetlands employed for wastewater treatment takes advantage of the same principals present in natural wetlands, but employ a more controlled environment. Wetlands have been constructed for various wastewater treatment purposes, e.g., domestic wastewater (Wolverton, 1987b; Steiner and Combs, 1993), primary wastewater effluent (Gerberg et al., 1989), animal waste (Maddox and Kingsley, 1989; Payne et al., 1992; Hammer et al., 1993), acid mine drainage (Brodie et al., 1989), industrial wastewater (Litchfield and Schates, 1989), pulp mill effluent (Thut, 1989; Tettleton et al., 1993; Thut, 1993), municipal waste landfill leachate (Trantmann et al., 1989; Martin et al., 1993), petro chemicals (Litchfield, 1993), and nonpoint source pollution (Silverman, 1989; Higgins et al., 1993; Ferlow, 1993). Some large-scale systems have been developed involving multiple use objectives, such as using treated wastewater effluent as a water source for creating or restoring marshes for wildlife use and environmental enhancement (Feierabend, 1989).

Constructed wetland treatment systems with appropriate design, have achieved high removal efficiencies for pollutants such as BOD_5, suspended solids (SS), nutrients and pathogens, but N removal efficiency depends on loss by both ammonia (NH_3) volatilization and nitrification followed by denitrification , and is variable in the SVBs depending upon system design, detention time and oxygen (O_2) present. Constructed wetlands may have greater potential than natural wetlands as wastewater treatment systems, due to their location flexibility, better hydrologic control and pollutants removal capacity. The major disadvantages of constructed wetland treatment systems compared with conventional wastewater treatment are the larger land requirement and the decreased performance during periods of low temperature.

1. Domestic Wastewater Characteristics

Wastewater constraints of concern include bacteria, viruses, nitrates (NO_3^-), synthetic organics, P, metals (Pb, Sn, Zn, Cu, Fe, Cd, and As) and selected other inorganic ions (Na, Cl, K, Ca, Mg, and S). Domestic wastewater constituents are comprised of a complex mixture of mineral and organic matter in many forms, including larger and small particles of solid matter, floating and in suspension; colloidal and pseudocolloidal dispersions; and true solutions. Among the organic substances present in domestic wastewater are carbohydrate, lignin, fats, proteins, soap, synthetic detergents and their decomposition products.

Table 2.1 illustrates the composition of a typical untreated domestic wastewater in the United States. The medium strength wastewater is typical of the wastewater found in developed countries such as the U.S. or Canada where an abundant supply of water is available (Pescod and Arar, 1988). This effluent will be typical of domestic wastewater, unless the system has received industrial wastes.

Table 2.2 summarized the effluent quality from various septic tank studies. The physical and chemical concentrations are representative of a typical STE (Table 2.3). If based on reported efficiencies of soil absorption systems, Canter and Knox (1988) have suggested

Table 2.1. Typical composition of untreated domestic wastewater*

Constituents	Concentration		
	Weak	Medium	Strong
Total Solids (TS, mg L^{-1})	350	720	1200
Total Dissolved Solids (TDS, mg L^{-1})	250	500	850
Suspended solids (mg L^{-1})	100	220	325
Settleable solids (mg L^{-1})	5	10	20
Biochemical oxygen demand, (5 days, 20°C)	110	220	400
Total organic carbon (TOC, mg L^{-1})	80	160	290
Chemical oxygen demand (COD, mg L^{-1})	250	500	1000
Total nitrogen (mg N L^{-1})	20	40	85
Organic nitrogen (mg N L^{-1})	20	15	35
Free ammonia (mg N L^{-1})	8	25	50
Nitrates (mg N L^{-1})	0	0	0
Nitrites (mg N L^{-1})	0	0	0
Total phosphorus (mg N L^{-1})	4	8	15
Organic phosphorus (mg N L^{-1})	1	3	5
Inorganic phosphorus (mg N L^{-1})	3	5	10
Chloride (mg N L^{-1})	30	50	100
Sulfate (mg N L^{-1})	20	30	50
Alkalinity (as $CaCO_3$)	50	100	200
Grease	50	100	150
Total coliform (counts/100 ml)	10^6-10^7	10^7-10^8	10^7-10^9
Volatile organic compounds (VOCs, ug L^{-1})	<100	100-400	>400
Biochemical oxygen demand (mg L^{-1})			

*from Tchobanoglous, G. 1991. *In Wastewater Engineering- Treatment, Disposal, and Resue.* p.109. Third Ed. McGeaw-Hill, Inc. with modification.

Table 2.2 Summary of effluent quality (mg L^{-1}) from various septic tank studies (U.S.EPA, 1980)*

Parameter	7 tanks	10 tanks	19 tanks	4 tanks	1 tank	average
Suspended solids						
mean	49	155**	101	95***	39	77
range	10-695	43-485	-	48-340	8-270	
sample numbers	148	55	51	18	47	
BOD$_5$						
mean	138	138*	140	240**	120	142
range	7-480	64-256	-	70-385	30-280	
sample numbers	150	44	51	21	50	
COD						
mean	327	-	-	-	200	296
range	25-780	-	-	-	71-360	
sample number	152	-	-	-	50	
Total nitrogen						
mean	45	-	36	-	-	42
range	9-125	-	-	-	-	
sample numbers	99	-	51	-	-	

* Canter and Knox, 1985

**calculated from the average values from 10 tanks, 6 series of tests.

*** calculated on the basis of a log-normal distribution of data.

that the following represent typical concentrations entering groundwater are; SS (18 - 53 mg L^{-1}); BOD (28 - 84 mg L^{-1}); COD (57 - 142 mg L^{-1}); NH_4-N (10 - 78 mg L^{-1}); TP (6 - 9 mg L^{-1}). However, the concentrations applied to soils may be overestimated as indicated by comparing Table 2.2 with Table 2.3. The mean values of TSS, BOD_5 and COD of Table 2.3 are much higher than values in Table 2.2.

Table 2.3 Characteristics of Septic Tank Effluent (STE)
(Viraraghavan and Warnock, 1976)*

Characteristics	Range	mean value
pH	6.53 - 7.45	6.90
TSS (mg L^{-1})	68 - 624	176
BOD (mg L^{-1})	140 - 666	280
COD (mg L^{-1})	240- 2026	568
PO_4^{3-}-P (mg L^{-1})	6.25 - 30	11.6
NH_4^+-N (mg L^{-1})	77 - 111	97
NO_3^--N (mg L^{-1})	0 - 0.1	0.026
Total soluble iron (mg L^{-1})	0 - 20.0	73
Cl (mg L^{-1})	37 - 101	53
Soluble organic carbon (mg L^{-1})	24 - 190	

* Canter, L.W and R. C. Knox, 1985.

2. Summary of Subsurface Vegetated Bed System Performance

Pollutant removal efficiencies vary greatly in the SVB systems due to their design and wastewater sources. Design parameters such as wastewater loading, detention time, substrate type, and vegetation type could affect the performances of the SVB system. Table 2-4 summarizes the pollutant removal capacities of existing systems. The experience obtained thus far shows that efficient BOD_5 removal in the SVB ranges from 18 to 96 %, with an average of 67%. In the well designed SVB system, it would not be difficult to achieve 70-90% BOD_5 reduction (Table 2.4). Removal efficiencies for N and P are variable and dependent upon loading rate, substrate type, wastewater characteristics, plant species and local climatic conditions. Fecal coliforms also can be reduced in excess of 87% in the SVB system. The removal of P varied from 2% to 95% and average of 37% in the SVB system. However, the application of the SVBE to soils will remove most of the P present in solution and thus eliminate the potential for P to contaminate ground and surface waters. The major concern of soil application of the SVBE is the potential for biological (fecal coliforms and virus) organisms and NO_3^- to contaminate groundwater. Nitrate in both STE and SVBE was very low (0-0.01 mg L^{-1}) (Huang et al., 1994). Therefore most NO_3^- in the soil resulted from nitrification of NH_4^+ present in the SVBE. According to Duncan's soil column study (1994), there were no fecal coliforms present in the leachates where the SVBE had passed through 30, or 45 cm soil. BOD_5, TKN, NH_4^+ and TDS in leachates were also very low. However, when the SVBE was applied to soil columns, the average NO_3^- concentrations in soil leachates was 10 mg L^{-1}, as compared with an average NO_3^- concentration of 19 mg L^{-1} in the soil leachate when STE was applied to the soil column. Therefore, well designed SVBs can be used as a substitution for soil depth with little or no risk of contamination of groundwater.

II. Environmental Concerns

OSWTDS are a potential nonpoint source of ground water contamination. Use of OSWTDS was introduced into the U.S. in 1884 and have since been the most widely used method of treatment and disposal of domestic wastewater (Canter and Knox, 1985). The number of OSWTDS in the U.S. are estimated at 20 million with more than 70 million

Table 2.4 Performance of gravel based subsurface bed form of constructed wetland systems*

System name	Record	Plant species	Loading	BOD_5	NH_4^+-N	TN	PO_4^{3-}	FC
	year		cm/d	removal %				
Santee, CA	1.3	bulrush	4.68	96	94			99
	1.3	reed	4.68	91	78			
	1.3	cattail	4.68	74	28			96
	1.3	control	4.68	69	11			
Benton, KY	0.7	woolgrass	4.27	52		37	18	98
	0.7	bulrush	7.97	50		12	15	96
Gravesend UK	1.8		8.16	65	14		42	
	1.8		8.16	62	16		40	
	1.8		8.16	73	16		60	
Castleroe, UK	0.8		4.34	66	24		20	
	0.8		4.34	55	9		4	
Midleton, UK	0.6		8.89	73	46		30	
Bluther Burn, UK	0.8		10.1	75	19		70	
Little Stretton, UK	0.4		26	77	-4			
Phillips High School	2		3.74	93	85	87	95	
Denham Spring	1.5		18.5	63	68			
Monterey	1.1		33	61	7			
Kingsron	0.7		2.92	18	42			
"Benton La"	2.8			63	47			
Average	1.21		9.02	67	35.3	41	36.7	95.2
Maximum	2.8		33	94	94	87	95	99
Minimum	0.4		2.92	18	-4	12	2	87

* from Knight, R. L., R. W. Ruble, R. H. Kaddlec, and S. Reed. 1993. Wetland for wastewater treatment: performance database. p.44-48. *In* G. A. Moshiri (Ed.) *Constructed wetlands for water quality improvement*, and Waston, J. T, S. C. Reed, R. H. Kadlec, R. L. Knight, and A. E. Whitehouse. 1989. p.322-327. *In* D. A. Hammer, (Ed.) *Constructed wetland for wastewater treatment*, with modification.

people utilizing OSWTDS. Approximately one third of all existing housing units and about 25% of all new homes being constructed use OSWTDS. Early estimates of wastewater discharged by OSWTDS to the subsurface were about 800 billion gallons annually; however, recent updates of this figure range up to 1,460 billion gallons annually (Canter and Knox, 1985). These systems apply approximately 4 billion gallons of domestic wastewater to United States soils daily. In these systems, wastewater is directed first to a buried tank (septic tank) where scum, grease, and settleable solids are removed from the liquid by gravity separation. The effluent from the septic tank then percolates into the soil and represents a potential source of ground water contamination. OSWTDS that are properly designed, constructed, maintained and located represent an efficient and economical sewage disposal alternative and present a limited threat to ground water resources.

However, in many cases, poor system design, improper construction and maintenance, and unsuitable soils have led to groundwater pollution. Another concern in many locations is that OSWTDS density may be exceeding the natural ability of the subsurface environment to absorb and purify these wastewaters. Excessive OSWTDS densities in many areas have degraded ground water quality with high concentration of NO_3^-, bacteria, and organic contaminants. When pollutants move rapidly through soils, or when soils with high permeability are hydraulically overloaded, accelerated migration of organic and inorganic chemicals and microorganisms may occur. Rapid transport does not allow the soils physical, chemical, and biological removal mechanisms to fully operate on the percolating effluent. The transport and fate of pollutants from the soil absorption system through underlying soils to groundwater is an important consideration in the use of OSWTDS. The transport and fate issue must be addressed for the biological (bacteria and viruses), inorganic (P, N and metals) and organic (synthetic organics and pesticides) contaminants. Therefore, there are possible risks to health and potential damage to the environment. Health consideration are focused on the pathogenic organism that are, or could be present in the effluent and the build-up of toxic materials within the soil as well as in water bodies (surface and ground waters).

III. Subsurface Vegetated Bed (SVB) systems

Constructed wetlands with subsurface flow were developed in Germany in the 1970s (Brix 1993). During recent years, the interest in utilizing SVB as an alternative method for wastewater treatment has rapidly increased all over the world. Some example are, Village of Neshaminy Falls, PA (1979); Iselin, PA and Santee, CA (1983). Ringsted, Denmark (1984); Gravesend and Holtby, England (1986); Marnhull, Castleroe, Little Stretton, and Bluther Burn, England (1987); and Benton, KY (1988) (Watson et al., 1989). In the US, use of constructed wetlands for wastewater treatment is a relatively new practice as compared with the European countries. The subsurface flow (SF) form of constructed wetlands was employed to treat wastewater in 1986 (Brown and Reed, 1994). Since 1991, more than 25 SF system have been operating. A total of 143 communities in the U. S. were identified as using, building, designing, or planning constructed wetlands in 1991 (Brown and Creed, 1994). A total 154 wetlands were actually identified as a few communities had more than one wetland system. To date, there are over 70 constructed wetland systems in operation in the United States, of which 30% are the SVB type (Knight et al., 1993). There are several hundred systems in operation in Denmark, Germany and the U.K. (Brix, 1993). The typical design consists of a bed planted with the aquatic plants, and underlaid by an impermeable liner to prevent seepage. The bed is sloped typically between 0 and 2% (Crites, 1994). The substrate may be soil, sand, or gravel. Wastewater flows laterally about 10 to 15 cm below the medium surface, and is purified during contact with medium surfaces and vegetation root zones. The subsurface zone is saturated and generally anaerobic, but excess O_2 conveyed through the plant root system supports aerobic microsites adjacent to roots and rhizomes. During the treatment of wastewater flow through the rhizosphere of plants, organic matter is decomposed by microorganisms, N may be removed mainly by nitrification/denitrification and NH_3 volatilization, P and heavy metals are fixed or deposited in the medium, and most of pathogens may die off in this unfavorable environment. Experience obtained thus far shows that pollutant removal efficiencies are variable and dependent on loading rate, type of substrate and the characteristics of the wastewater.

Usually, there are five major components in the system: aquatic vegetation, substrate, wastewater column, aerobic and anaerobic microbial populations and invertebrates and vertebrates. The SVB can also considered as a system which is composed of gas, liquid and solid phases.

1. **Aquatic Vegetation**

The SVB vegetation is considered an integral part of the substrate. The emergent or wetland adapted macrophytes have several intrinsic characters that make them a key component of constructed wetlands. The most important functions of the macrophytes, with respect to the wastewater renovation, are the physical and biological effects brought by the presence of plants. Vegetation provides physical filtration, enhanced vertical flow (reduced clogging), insulates against cold weather, and provides a large surface area for attached microbial growth. The plant leaves and stems can also transfer O_2 from the atmosphere to the roots, excess O_2 is then released to the rhizosphere, and thus creates an aerobic/oxidized rhizosphere for organic decomposition and establishment of desired microbial populations such as nitrifiers and denitrifers. The aerobic rhizosphere also allows for nitrification of NH_4^+ to NO_3^- in an otherwise anaerobic environment.

There are numerous reports of aquatic macrophyte systems being effectively used to reduce pollutant levels in water bodies (Wolverton and McDonald, 1979; Gearheart and Finney, 1981; Wolverton, 1981; Wolverton, 1982; Wolverton and McDonald, 1982; Wolverton et al., 1983a; Wolverton et al., 1983b; Gersberg et al., 1985; Wolverton, and McCaleb, 1987; Wolverton, 1987a; Wolverton, 1987b; Wolverton, 1987c; Wolverton, and Bound, 1988; Thut, 1989; Wolverton, 1989; Cooper and Hobson, 1989; Gearheart et al., 1989; Gersberg et al., 1989; Gillette, 1989; McIntyre and Riha, 1991).

Vegetation also helps maintain hydraulic pathways in the substrate (Brix, 1994). Growth of emergent vegetation on gravel has led to significant reductions in substrate mineral nutrient concentration (Roser et al., 1987; Hazen, 1988; Cooper and Hobson, 1989). In addition, selected attractive wetland plant such as the yellow flag iris (*Iris pseudacorus*) make sewage treatment systems aesthetically pleasing (Brix, 1994). Wetland plants take up nutrients with their root system, and considerable amounts of nutrients can be bound in the biomass. However, the amount is insignificant when compared to the quantities applied to constructed wetlands in the wastewater. Nutrients bound in the plant tissue are recycled back in the system upon decay of the plant unless the plants are harvested. The potential of aquatic plants for reducing BOD_5, TSS, N, P, Cl, heavy metals, pathogens and viruses, and to purify the wastewater by direct uptake and assimilation of pollutants is not well documented, and is probably limited.

2. Wastewater Column

Wastewater flows laterally and is purified during contact with medium surfaces and the vegetation root zones. The subsurface zone is saturated and generally anaerobic, but excess O_2 conveyed through the plant root system supports aerobic microsites adjacent to roots and rhizomes. O_2 concentration in the SVBs is important and determines the quantity of organic matter decomposed as well as the balance between nitrification and denitrification in the SVBs. The presence of submerged macrophytes promotes depletion of dissolved inorganic carbon (C) in the water and increases the DO content during the periods of high photosynthetic activity, and results in increased pH, creating favorable conditions for NH_3 volatilization, chemical precipitation of P and organic matter mineralization.

3. Substrate

Many substrates are suitable for subsurface vegetated bed system establishment. The substrates used in the SVB can range from gravel, sand, and mine spoils to soils. Substrates with low nutrient levels may be suitable in the SVB for wastewater treatment if other requirements are met. Substrate water and substrate root interfaces are critical for development of aerobic and anaerobic treatment mechanism. The substrate supports vegetation, provides surface areas for microorganism attachment, and is associated with the physical and chemical treatment mechanisms. The substrates can affect treatment capability through its impact on detention time, and contact surfaces for organisms with the wastewater and O_2 availability. Gravel beds are not homogeneous and will vary in hydraulic conductivity along with the bed length. A range of physical characteristics for mineral soil are shown in Table 2.5 (Hammer, 1989). Substrate depth influences detention time in a subsurface flow system, a 0.6 m depth is common, but substrate depth and vegetation type must be compatible, for example, usually 0.3 m depth is optimal for cattail. Gravel size is selected by using Darcy's law to determine hydraulic conductivity after the required area,

Table 2.5 Range of Physical Characteristics of the media used for constructed wetlands*

Type	Total porosity	Hydraulic conductivity	Bulk density
	%	m/d	g/cm
Gravel	20	100-1000	2.1**
Sand	35-50	1-100	1.2-1.8
clay	40-60	<0.01	1.0-1.6

* Faulkner and Richardson (1989).
** calculated based on porosity.

length/width, cross-sectional area and slope are fixed. For example, for a 0.5 m deep bed, gravel sizes are 12-25 mm diameter for the lower 0.40 m and pea gravel of 6-12 mm diameter for the top 0.10 m to enhance vegetation planting and growth. The inlet zone is relatively short and receives high amounts of SS that accumulate in this part of the SVB.

IV. Subsurface Vegetated Bed (SVB) Design Issues

1. Hydraulic Loading Rates

Hydraulic loading factors are the primary design basis for most constructed wetlands and are based on Darcy's equation, which is:

$$Q = k\,A\,S$$

Where Q = flow rate,
k = hydraulic conductivity,
A = cross-sectional area, and
S = slope of the hydraulic grade line.

Because of various treatment objectives, system types, configurations and performance level, the loading rates vary from 1 to 60 cm/day. However for gravel substrate the loading rates range from 1.26 to 33 cm/day, but are usually less than 10 cm /day (Watson, 1987, Knight et al., 1993).

2. Detention Time (Hydraulic Residence Time)

Treatment for any biologically based process is time-dependent. The time that the wastewater is detained in the SVBs for treatment is determined by the SVB treatment area and wastewater loading rate. Witthar (1993) reported that typical detention times range from 0.25 to 75 days with an average about 5 days . In the SVBs, purity of the filter effluent is not only determined by the length and depth of the filter but also by the detention time. As mentioned by Bavor et al. (1989) first order kinetics were used to model removal of solids, C, P, N, and microorganisms. Reed et al. (1995) has shown that a SVB is not an ideal plug flow reactor, but the response thends to be closer to plug flow that to the complete mix alternative. Thus the hydraulic detention time in this study wasbased on plug flow. The detention time needed for BOD_5 removal can be calculated as follows (Crites, 1994):

$$\ln (Ce/C_o) = - K_T t$$

Where t = hydraulic retention time within macrophyte system, days

C_o = initial BOD_5 concentration, mg/l

Ce = effluent BOD_5 concentration, mg/l

K_T = temperature-dependent first-order reaction rate constant, $days^{-1}$

ln = natural log

The K_T value ranges from 0.8 to 1.1 $days^{-1}$ for sand and gravel (Reed et al, 1988). Typical detention times range from 2-7 days for the SVB type wetlands.

According to Crites (1994), design criteria for nutrient removal needs to be longer than the time needs for BOD_5 and TSS. For NH_4^+ and TKN reduction, both minimum temperature and detention time are important. BOD_5 and TSS removal occurs in 5-10 days detention time, while significant N removal requires from 8-14 days or even more.

3. Recirculation

Recycling treatment effluent will dilute influent BOD_5, TSS, decreases odor potential and increases DO and detention time. Recirculation should enhance nitrification and subsequent N removal. However, recirculation will increase construction cost and maintenance. In most case, recirculation was not required if detention times were greater than 4 days (Zachritz and Jacquez, 1993).

V. Mechanisms of Pollutant Removal

In the gravel based SVB systems, the contaminants are removed by a complex variety of physical, chemical and biological processes. Physical processes include sedimentation, filtration, absorption, and volatilization. Biological processes consist of bacterial metabolism, plant metabolism, plant absorption and natural die-off. Precipitation, absorption, hydrolysis reactions, and oxidation/reduction are included in the chemical processes. The most important removal mechanisms in the SVBs are listed in Table 2.6. The potential N removal mechanism in the SVBs are NH_3 volatilization, denitrification and storage in living biomass such as plant and microbes, detritus and sediments.

Table 2.6 Pollutant removal mechanisms in the SVB systems*

Pollutant	Removal mechanisms
Suspended solids	Sedimentation/filtration
BOD_5	Biological degradation (aerobic and anaerobic)
Nitrogen (N)	Ammonification followed by microbial nitrification and denitrification, ammonia volatilization, plant uptake
Phosphorus (P)	Precipitation with calcium, iron , magnesium, aluminum cations and plant uptake
Pathogens	Sedimentation/filtration, natural die-off, UV radiation. and killed by excretion of antibiotics from roots of macrophytes

* From H. Brix. 1993. Wastewater treatment in constructed wetlands: system design, removal processes, and treatment performance. p. 11. *In* G. A. Moshiri. (Ed.) *Constructed werlands for water quality improvement* with modification.

1. Nitrification

The sequential processes of mineralization, NH_3 volatilization, nitrification and denitrification dominate N cycling and the potential for N removal in the SVBs. Nitrification/denitrification is believed to be the most effective machanism for removal of N in the constructed wetlands (Gersburg et al., 1983). Ammonium is oxidized to NO_3^- by nitrifying bacteria in aerobic microzones, and NO_3^- is converted to N_xO or N_2 by denitrifying bacteria in anoxic microzones. However, these processes are regulated by the presence of microorganisms and environmental conditions such as available substrates, temperature, pH, and Eh. Growth of nitrifying organisms is favored by neutral pH and retarded by pH values less than 5 (Batal et al.,1989).

2. Denitrification

Although the process of denitrification has been of interest to soil scientists and microbiologists for many years, there have been very few field studies with theSVB systems in which denitrification rates have been measured and documented (Chan and Knowles, 1979; Chang and Page, 1985; Devido and Conway, 1989; Oostrom and Russell, 1994). Nitrogen can exit at various oxidation states in nature, N is transformed by organisms along two opposite pathways in the N cycle-reduction (denitrification) and oxidation (nitrification). There are environmental limitations to denitrification. The following four general requirements are necessary for denitrification (Ritter and Eastburn, 1988):

1. Presence of suitable nitrifers which are capable of providing the required enzymes.
2. Suitable C source to fuel the anabolism.
3. Release of O_2 repression of these enzymatic systems.
4. Suitable oxidized N compounds to serve as terminal electron acceptors in place of O_2.

Denitrification is regulated by temperature, pH, Eh, high concentration of heavy metals (Chang et al., 1982) and pesticides (Grant and Payne, 1982). Denitrification was achieved in a simultaneous nitrification and denitrification process and was dependent on mean residence time in the soil, C/N ratio (Bremner and Shaw, 1958; Sikora and Corey, 1976), temperature (Bremner and Shaw, 1958), partial pressure of O_2, and NH_4^+ concentration. The maximum temperature for denitrification is 75 °C (Firestone, 1982) and the minimum temperature for denitrification in land treatment system is 2-5 °C (Crites et al., 1981). Denitrification was very slow at a low pH (4.8, Bremner and Shaw, 1958). The optimum pH for denitrification is 7-8.5, the maximum denitrification rate was reached at a pH of 7.5 (Beccari et al., 1980) and a temperature of 25 °C within a biological solids concentration range of 700 to 1000 mg/l. The average C : N ratio of STE is 10:1 (Sikora and Corey, 1976). N immobilization is limited in the septic tank or in the ponded bed effluent during steady state conditions. Under saturated conditions, NO_3^- would eventually be leached to the ground water, NH_4^+ would also eventually be leached to the ground water after a long period of time due to retardation via the soil CEC.

Stengel and Schultz-Hock (1989) reported that NO_3^- elimination in artificial wetlands might occur throughout all seasons, even at the low temperature (2-4 °C) if specific conditions were fulfilled (low DO concentration in water and available C source). However, most denitrification research has focused on natural wetlands and soil based constructed wetlands. Denitrification may be quite different in the gravel based SVB systems.

3. Ammonia (NH_3) Volatilization

In the freshwater wetlands, N removal by NH_3 volatilization has been considered as a minor factor (Faulkner and Richardson, 1989; Hsieh and Coultas, 1989). Few reports have documented the magnitude of NH_3 volatilization in constructed wetlands. Ammonia volatilization may play an appreciable role in the N cycling in the SVB systems due to the favorable environment present (high pH and available NH_3 sources). Ammonia volatilization from flooded soils has been studied extensively, but there is no consensus on the importance of NH_3 volatilization in N cycling (Vlek and Craswell, 1981). Jayaweera and Mikkelsen (1991) concluded that from 10 to 60% of the amount of N applied was lost via NH_3 volatilization when they assessed NH_3 volatilization from flooded soil systems, and N losses varied depending on water pH, N source, rate (NH_4^+ concentration), time, and method of application (Mikkelsen et al., 1978).

Field ^{15}N balance studies in wetland rice have shown that N loss ranged from 35-60% of urea or ammoniacal-N applied to floodwater (Cao and De Datta, 1984; Fillery et at., 1986; Fillery and Vlek, 1986). The NH_3 volatilization process is directly influenced by floodwater NH_4^+ concentration, pH, temperature, depth of floodwater, and wind velocity (Jayaweera and Mikkelsen, 1990). The pH of floodwater has a tremendous impact on NH_3 volatilization (Mikkelsen et al., 1978; Vlek and Craswell, 1981; Jayaweera and Mikkelesn, 1990). Aqueous NH_3 in floodwater increased about ten fold per unit increased in pH between 7.5 and 9.0 (Vlek and Stumpe, 1978; Vlek and Craswell, 1981), but if the pH value is less than 6.6, there was little to no NH_3 volatilization from a wastewater detention pond (Pano and Middlebrook, 1982). With respect to the effect of temperature on NH_3 volatilization, Vlek and Stumpe (1978) suggested an exponential increase of NH_3 loss with temperature for tropical climates. In the freshwater wetlands, N removal by NH_3 volatilization was considered a minor factor (Faulkner and Richardson, 1989) in N loss, this is probably a result of both low concentration of NH_4^+ and the depth of water column. Murphy and Brownlee (1981), however, observed that NH_3 volatilization in a hypertrophic lake was significant during the periods of high pH and NH_3 concentration, that resulted from the collapse of the algae bloom. In the gravel based SVB systems designed to treat domestic wastewater, NH_3 volatilization may play a significant role in the N cycling due to its favorable environment (high pH and available NH_3 sources).

VI. Reactions and Redox Potential in the SVB Systems

1. pH

After systems have been established for a while, both natural wetland systems and constructed wetland systems will be highly buffered near pH 7.0, and changes in pH in most wetlands have been within two pH units (Porties and Palmer, 1989; Maddox and Kingsley, 1989; Brodie et al., 1989; Waston et al., 1989; Davido and Conway, 1989). Nitrification can not be completed without adequate alkalinity, approximately 7 mg alkalinity is required for oxidation of 1 mg of NH_3-N, the optimum pH is range of 7 to 8 (Waston et al., 1989). Nitrification declines markedly at pH <6.0 and is negligible at pH <5.0 (Hammer and Knight, 1994). Denitrification requires similar pH condition. Ammonia volatilization increases with increased pH and may be appreciable at a pH >8.

2. Redox Potential (Eh)

Redox potential quantitatively measures the tendency of the system to oxidize or reduce susceptible substances. Oxidation is the loss of electron, and reduction is the gain of electrons. A generalized reaction is given in Equation 2.1,

$$Ox + ne^- + mH^+ = Red + H^+ \qquad \text{Eq. 2.1}$$

and Eh can be calculated by Equation 2.2,

$$Eh = E^\circ - 0.059\,(m/n)\,pH + (0.059/n)\log[(oxidant)/(reductant)] \qquad \text{Eq. 2.2}$$

Where E° is the standard potential; m is the number of protons in the reaction; and n is the number of electrons. Nitrate is the first component reduced after O_2, though this process can proceed prior to complete O_2 disappearance, then followed by Mn^{4+} to Mn^{2+}, and Fe^{3+} to Fe^{2+}. Hydrogen sulfate (H_2S) and methane (CH_4) will not appear unless the preceding component has been completely reduced (Cole, 1983).

VII. Subsurface Vegetated Bed (SVB) Limitations

The factor most limiting N removal in the SVB appears to be the supply of O_2 necessary to sustain nitrification. Although O_2 can be transport by plants through their aerenchyma to roots the quantities may be insufficient to satisfy organic O_2 demands. The O_2 demand for nitrification is 4.5 mg O_2 per mg N (Gersberg et al., 1989), O_2 transport rates were estimated at 21 to 120 kg O_2/ha/day for *Phragmites australis* (Brix and Schierup, 1990; Armstrong et al., 1990). For example, if 45 mg TN /L was introduced into a SVB system with an average dosing rate as 10 L/m^2/day, O_2 demand for nitrification only would be more than 2 g /m^2/day (2x10^5 kg O_2/ha/day). When the BOD demand cannot be met, nitrification and O_2 diffusion will be greatly reduced in the SVB system.

The SVBs may be more suitable to treatment of domestic wastewater than the free water surface (FWS) systems due to its greater assimilation capacities, lower land requirement, no visible flow, less potential for nuisance (vector and odors), and increased cold tolerance. However, this technology is still under development and many questions need to be answered before designs can be optimized and performance levels firmly established. There are many uncertainties entailed in these systems. A major problem in the use of this technology is the lack of detailed information that is normally gained from long term experience.

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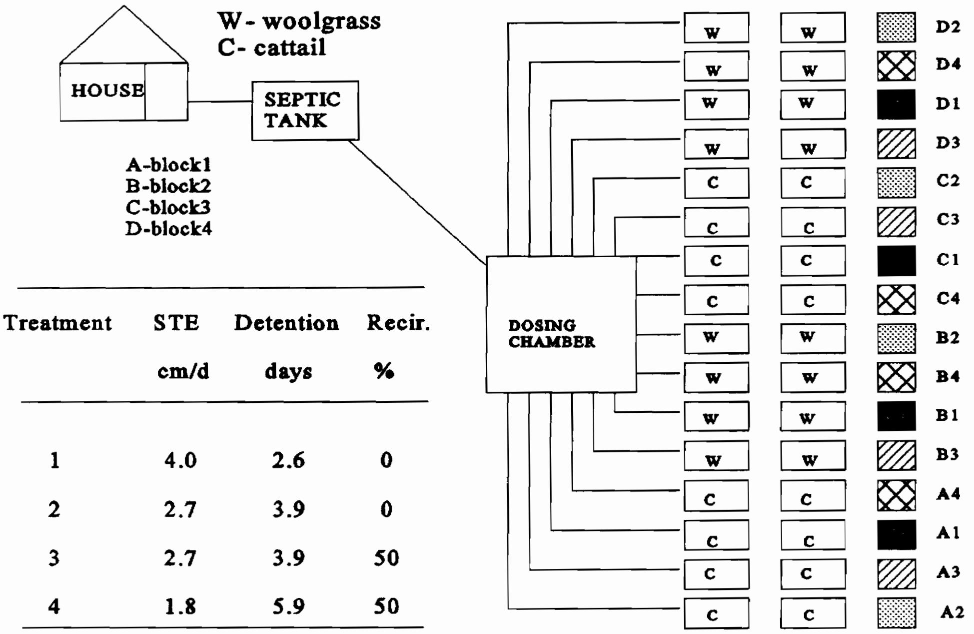
Chapter III:

MATERIALS AND METHODS

I. Field Experiment Design

1. The Whitethorne Plantation (WP) Site

Small SVBs were constructed, as shown in Figure 3.1, at the WP site. The source of domestic wastewater is a single family residence. The experimental design consists of 8 treatments; including three influent detention times; two recirculation ratios; and two plant species (cattail and woolgrass). Septic tank effluent is supplied to the SVBs from a pump chamber placed between the existing septic tank and distribution box. STE is then pumped to a series of dosing chambers that add wastewater, at the rates listed in the Field Experimental Design (Fig. 3.1), to each of the 16 SVBs installed down slope of the residence. Each SVB consists of two plastic containers each measuring 41.5 cm depth x 36 cm width x 52 cm length. Containers are connected at the bottom by a 3.18 cm diameter PVC pipe, and placed in series. The combined surface area for each cell is 0.374 m^2 (4 ft^2) with a total submerged volume of 0.112 m^3 (30 gal). A 30 cm layer of 2.5 to 3.0 cm diameter limestone gravel is placed in the bottom of the SVB to accommodate wastewater flow and root growth. This 30 cm gravel layer is covered with 10 cm of pea gravel (0.5 cm diameter) to support plant growth. To control the water level, each SVB has an attached water level control device constructed from the same size plastic container as used for the SVB construction. Sample wells are placed in each container (Fig. 3.2) to facilitate sample collection and to measure dissolved oxygen (DO). Redox electrodes are installed at 2.5 cm and 25 cm from the bottom of each SVB (Fig. 3.2) so changes in redox potentials (Eh) with depth can be measured over time. A gas distribution pipe is placed at the bottom of each SVB to introduce acetylene (C_2H_2) to facilitate denitrification measurements (Figure 3.2). STE is dosed, automatically, to the SVBs six times daily. These SVBs were installed in June, 1992 and were fully functional by September, 1992. Since September, 1992, samples of influent (STE) and SVBE have been collected and analyzed monthly. Plant tissue samples were harvested once on June 7, 1993.



Treatment	STE cm/d	Detention days	Recir. %
1	4.0	2.6	0
2	2.7	3.9	0
3	2.7	3.9	50
4	1.8	5.9	50

Figure 3.1 Field Experimental Design at the Whitethorne Plantation (WP) Site (not to scale)

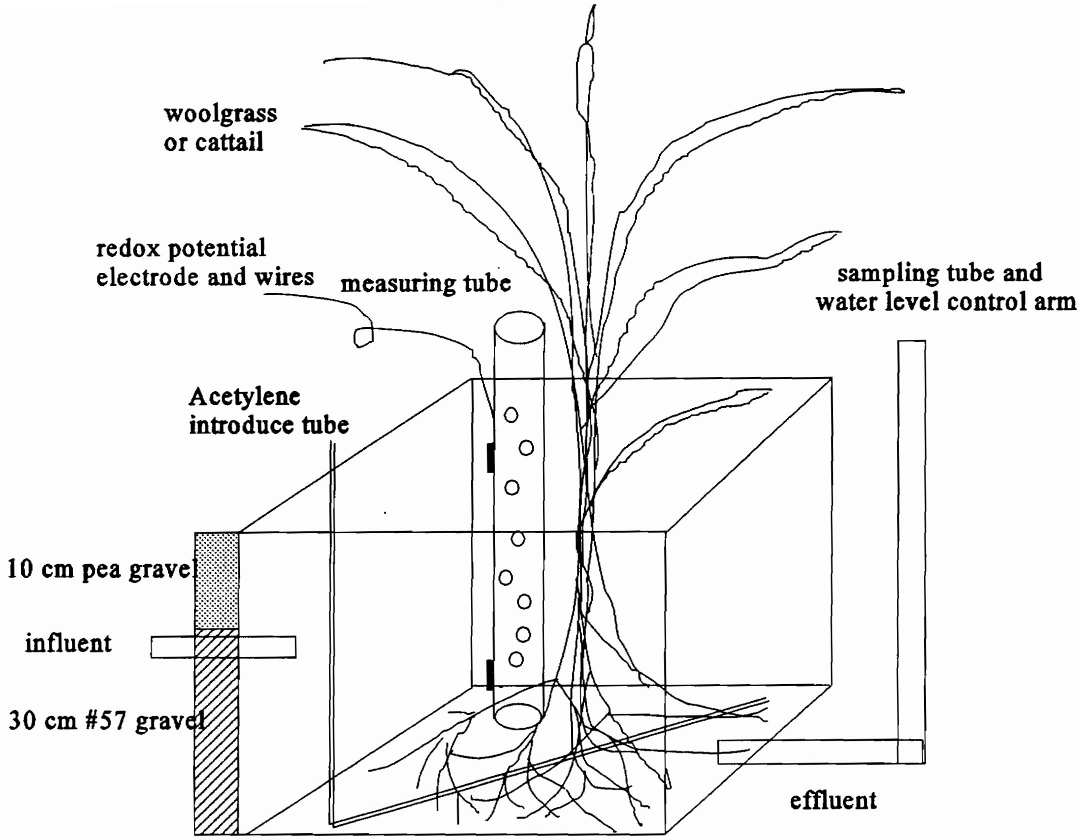


Figure 3.2. Subsurface vegetated bed at the WP site (not to scale)

2. The Powell River Project (PRP) Site

The experimental design consists of three detention times (4, 8, 12 days) and two plant species (cattail and woolgrass), and is replicated two times. The SVB consists of a STE dosing reservoir, a gravel filter with plants, and water level control box (Fig. 3.3 and 3.4). Each SVB has a surface area of 4.32 m^2 (46.5 ft^2) and is 0.45 m (0.3 m for water flow) deep, 1.1 m (3.6 ft) wide, and 3.93 m (12.9 ft) long. These SVBs were much large than the SVBs located at the WP site. A pump chamber was placed between the septic tank and

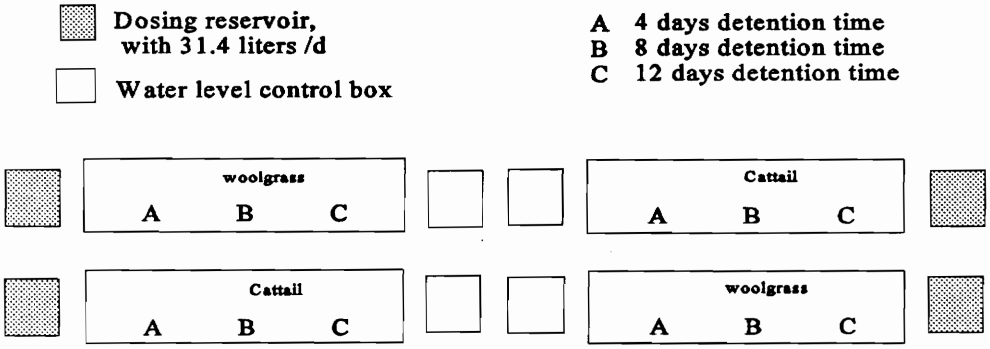


Figure 3.3. Field experimental design at the PRP (Powell River project) site (Wise County, VA not to scale)

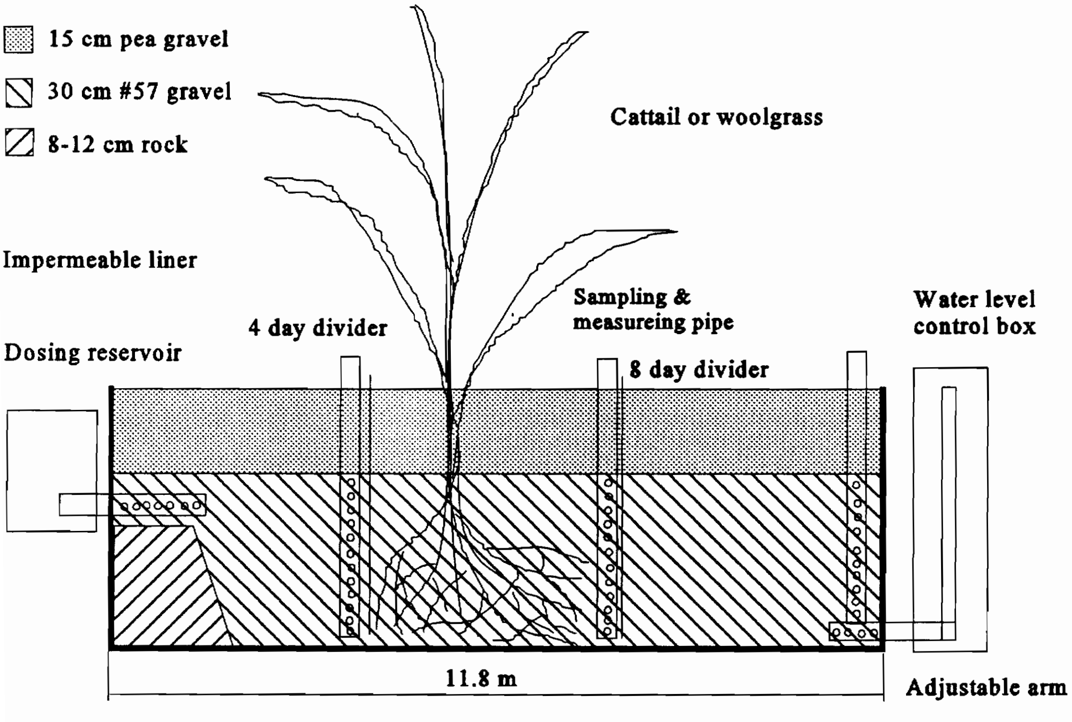


Figure 3.4 Side view of the SVB at the PRP site (not to scale)

the distribution box at a private residence to collect effluent to dose the SVBs. A 30 cm layer of #57 gravel (2 - 10 cm diameter) was placed in the bottom of each SVB and then a 15 cm layer of pea gravel (0.5 cm diameter) was placed on top of the #57 gravel. In order to reduce the potential for clogging, larger stone (7.5 to 12.5 cm diameter), was placed in the inlet (first 1.5 m) section of the SVBs Cattails and woolgrass were planted in the SVBs as shown in the experimental design (Fig. 3.3 and Fig. 3.4). Sample wells were placed in each SVB in order to collect samples and measure DO at varying detention times. A water impermeable liner was placed in all SVBs to eliminate seepage into the soil. Redox potentials were measured at three depths at each detention time, using redox electrodes placed at 2.5, 15, and 25 cm from the bottom of the SVB (Fig. 3.4). Samples were first collected from the SVBs during the winter months (February to April, 1992) prior to planting vegetation. Since January 1992, the quality of STE (raw) and SVBE has been monitored monthly. Water samples have been collected separately from two depths in the SVBs (deep samples-10 cm above the bottom and shallow samples-10 cm below the water column surface) since June 1993.

3. The Rational Of Experimental Design

General design criteria for a SVB is based on following Equations (USEPA, 1988 and TVA, 1991):

Hydraulic residence time can be represented as:

$$t = L\,W\,D\,/\,Q \qquad \text{Eq. 3.1}$$

where,

L = length

W = width

D = depth

Q = average flow rate = $(\text{flow}_{in}+\text{flow}_{out})/2$

This equation represents hydraulic residence time for an unrestricted flow system. In a SVB system, a portion of the available volume will be occupied by plant roots and substrate, so the actual detention time will be a function of the porosity (n), which can be defined as the remaining cross sectional area available for flow.

$n = V_V / V$ Eq. 3.2

where V_V and V are volume of voids and total volume, respectively.

Degradation of BOD_5 follows the 1st order reaction, that is

$\ln Ce/C_0 = - K_T t$ Eq. 3.3

where Ce= effluent BOD_5 mg L^{-1}

C_0= influent BOD_5 mg L^{-1}

K_T= temperature dependent first order reaction rate constant, day^{-1}.

Combining the relationships in Equation (3.1), (3.2) and (3.3) results in Equation 3.4:

$Ce/C_0 = A \exp[(-0.7\, K_T(A_V)^{1.75}\, L\, W\, D\, n) / Q]$ Eq. 3.4

where,

A = fraction of BOD_5 not removed as settleable solids (as decimal fraction)

A_V = specific surface area for microbial activity, m^2 / m^3

L = length, m

W = width, m

D = design depth, m

Q = average hydraulic loading on the system, $m^3\, d^{-1}$

SVB design are based on BOD_5 removal.

3.1. The SVB design for the WP Site

Hydraulic residence time was based on plug flow. Reed et al. (1995) has shown that a SVB is not an ideal plug flow reactor, but the response tends to be closer to the plug flow than complete mix alternative.

3.11 Design based on surface loading rate

TVA (1991) information that states that the optimal loading for SVB is 1.3 ft^2/gpd.

Hydraulic load, Q = 4.0 gpd =4 (gal d^{-1}) X 3.785 (L gal^{-1}) X 1/1000 (m^3 L^{-1})

=0.01514 (m^3 d^{-1}) (0.535 ft^3 d^{-1})

Hydraulic loading criteria = 1.3 (ft^2 gpd^{-1}) = 0.103 (ft d^{-1}) =3.14 (cm d^{-1})

1). As, the SVB cell surface area:

As = 0.01514 (m^3 d^{-1}) / 3.14 (cm $d^{-1)}$ = 0.4822 (m^2) (5.19 ft^2)

2). Ax, the cell cross-sectional area,

Q = Ax * Ks * S

Ks = substrate hydraulic conductivity (259 m d^{-1} or 850 ft d^{-1})

s = hydraulic gradient (assume equivalent to bed slope, 0.0025)

Ax = Q/Ks X S = 0.01514 (m^3 d^{-1}) / [259 (m d^{-1}) X 0.0025]

=0.0234 m^2 (0.252 ft^2)

3). D, bed depth 1 ft (0.305 m) .

4). W, bed width. W = Ax / d = 0.0234 m^2 / 0.305 m = 7.7 cm (0.0252 ft)

5). L, bed length. L = As / w = 0.4822 m^2 /0.077 m = 6.26 m (20.6 ft)

Each PVC container is 36 cm in width, 52 cm in length and 42 cm in depth, each SVB consists two container which is equal to 0.3744 m^2 (4.03 ft ^{2}).

6). t, detention time. t = Vv / Q.

$Vv = L\ W\ D\ n = 1.04\ m\ X\ 0.36\ m\ X\ 0.3045\ m\ X\ 0.35 = 0.04\ m^3\ (1.41\ ft^3)$

$(t = 0.04\ m^3 / 0.01514\ m^3 / d\ = 2.64\ d$

3.12. Design based on BOD$_5$ removal

These design were based on information provided by Reed et al. (1988).

1). The bed depth D=0.3 m (1 ft) for cattail and woolgrass.

2). Slope 0.0025.

3). porosity n = 0.35, which for gravel as substrate .

4). K_T , the first-order temperature-dependent rate constant can be solved using Equation: 3.5

$K_T = K_{20}\ (1.1)^{T-20}$ Eq. 3.5

K_T for winter temperature(0.05 ^0C)

$K_0 = 1.839\ d^{-1}$

K_{20}=1.35 d^{-1} as a average from sand to gravel (EPA, 1988)

$K_T = K_{20}\ (1.1)^{(0.05-20)} = 0.21\ d^{-1}$

5). Ac, bed cross-sectional area,

$Q = 4.0\ gpd\ X\ 3.785\ X\ 10^{-3} = 0.015\ m^3\ d^{-1}$

$Ac = Q/Ks\ X\ S = 0.015 / 500 * 0.0025 = 0.012\ m^2$

6). W, width of bed W = 0.57 m (1.88 ft)

7). As, surface area of system required. Assuming BOD$_5$ of influent (STE) is equal to 95 mg L^{-1}, based on initial measurement of raw sample. Expected BOD$_5$ of the SVB is 20 mg L^{-1}.

$As = Q\ (\ln Co - \ln Ce) / K_T\ X\ d\ X\ n$

$= 0.012\ (\ln 95 - \ln 20) / 0.21\ X\ 0.3\ X\ 0.35$

$= 0.85\ m^2$

8). t, detention time

$L = As/W = 0.72\ m^2 / 0.36\ m = 2.4\ m$

$Vv = L * W * D * n *$

$= 2.4\ m\ X\ 0.36\ m\ X\ 0.3\ m\ X\ 0.35 = 0.089\ m^3$

so $t = Vv/Q = 0.089 / 0.015 = 5.9$ days

The detention time based on hydraulic gradient was 2.6 days and based on winter temperature for BOD_5 reduction to 20 mg L^{-1} was 5 days. Therefore, 2.6, 3.9 and 5.9 days detention times were used in this experiment, which requires loading rates of 4.0, 2.7 and 1.8 cm d^{-1} (40.4, 26.7 and 17.7 L / m^2/d).

3.2. The SVB design for the PRP Site (Wise County, VA):

Rational used for hydraulic residence time employed in section 3.1 was used in following calculations.

3. 21. Design based on surface loading rate

Hydraulic load, $Q = 30\ (gpd)\ X\ 3.785\ (L\ gal^{-1})\ X\ 0.001\ (m\ L^{-1})$

$= 0.1136\ (m^3\ d^{-1})\ (4.01\ ft^3\text{-}d^{-1})$.

Hydraulic loading criteria = 1.3 ft^2/gpd = 3.14 cm d^{-1} (0.103 ft d^{-1})

1). As, the SVB cell surface area:

$As = 0.1136\ m^3 / 0.0314\ m\ d^{-1} = 3.62\ m^2\ (38.8\ ft^2)$

2). Ax, cell cross-sectional area,

$Q = Ax * Ks * S$

Ks = substrate hydraulic conductivity (850 ft d^{-1} or 259 m d^{-1})

s = hydraulic gradient (assume equivalent to bed slope, 0.0025)

$Ax = Q/Ks*S = 0.1136^3\ d^{-1} / (259\ m\ d^{-1}*0.0025) = 0.175\ m^2\ (1.88\ ft^2)$

3). D, cell depth 1 ft or 30.5 cm.

4). W, cell width. W = Ax/d = 0.175 m^2 / 0.3048 m = 0.574 m (1.88 ft)

5). L, cell length. L = As/w = 3.62 m^2 / 0.574 m =6.31 m (20.7 ft)

6). t, detention time. t = Vv / Q.

Vv = L W D n = 3.93 m X 1.1 m X 0.3048 m X 0.35 =0.46 m^3 (13.8 ft^3)

t = 0.46 m^3/ 0.1136 = 4.0 days

so t is deigned for 4.0 days.

3.22. Design based on BOD_5 removal

1). The bed depth D=0.3 m (1 ft) for cattail and woolgrass.

2). Slope 0.0025.

3). porosity n = 0.35, which for gravel as substrate .

4). K_T , the first-order temperature-dependent rate constant can be solved using Equation: 3.5.

$K_T = K_{20} (1.1)^{T-20}$

K_T for winter temperature(0.05 °C)

$K_0 = 1.839\ d^{-1}$ and $K_{20}=1.35\ d^{-1}$

$K_T = K_{20} (1.1)^{(0.05-20)} = 0.21\ d^{-1}$

5). Ac, cell cross-sectional area,

Q = 30 gal/d X 3.785 X 10^{-3} = 0.113 $m^3\ d^{-1}$

Ac = Q/Ks X S = 0.113 / 500 X 0.0025 = 0.09 m^2

6). W, width of cell. W = 0.09 m^2 / 0.3 m = 0.3 m

7). As, surface area of system required. Assuming BOD of influent is equal to 170 mg L^{-1}, which was the initial measurement for STE sample. Expected BOD of the SVBE is 20 mg L^{-1}.

As = Q (ln Co - ln Ce) /K_T X d X n

= 0.113 (ln 170 - ln 20)/ 0.21 X 0.3 X 0.35

= 10.97 m^2

8). t, detention time

$L = As/W = 9.3\ m^2/\ 0.3\ m = 36.6\ m$

$Vv = L\ X\ W\ X\ D\ X\ n$

$= 36.6\ X\ 0.3\ X\ 0.3\ X\ 0.35 = 1.15\ m^3$

so $t = Vv/Q = 1.15\ m^3/0.113\ m^3d^{-1}=10.2$ days

The detention time based on hydraulic gradient was 4 days and based on winter temperature for BOD_5 reduction to 20 mg/L was 10.2 days. Thus beds were split into three even increments 4, 8 and 12 days retention time. Also gives some latitude in case the water level has to be lowered in the winter.

II. Data Analysis

The SVBs were placed in a completely random design. If there was no difference between plant species, then these data were pooled to give a total of four replications. Treatment efficiencies were tested by ANOVA using the Statistical Analysis System (Ray, 1982; Schlotzhauer and Littell, 1987). Duncan's multiple range test ($P<0.05$) was used for testing differences between means (Schlotzhauer and Littell, 1987). The strength of the relation between two selected water parameters was measured by the correlation coefficient (r). If there was a meaningful correlation coefficient between two parameters, then straight-line regression was performed by SAS.

III. Characteristics of Domestic Wastewater

The analysis of STE at both sites indicated that STE varied from time to time. Concentrations for chemical and biological constituents in the STE are listed in Table 3.1. According to Canter and Knox (1985), based on TKN, fecal coliforms and BOD_5 content, wastewater at both sites was classified as medium to strong domestic wastewater. If based on TDS concentrations, wastewater at both sites would be classified as strong wastewater

(Pettygrove and Asano, 1985). The STE at the PRP site was stronger than STE at the WP site. There were no differences between STE at the two sites for pH, NO_3^--N, BOD_5 and fecal coliforms in the STEs ($P \leq 0.01$); however, TKN, NH_4^+-N, TDS, PO_4^{3-}-P, Cl, and EC concentrations in STE at the PRP site were higher than concentrations present in STE at the WP site ($P \leq 0.01$). There was no difference in NO_3^--N between the two sites, however, a larger percentage of TN was present as NH_4^+-N at the PRP site (84%) than at the WP site (75%). Suspended solids were higher at the PRP site than the WP site and this may explain that higher EC and TDS in STE at the PRP site. Concentrations of metals such as K, Mg, and Mn were much higher in STE at the PRP site compared to STE at the WP site, but the Zn concentration was 3 fold higher in STE at the WP site. These differences may be due to differences in the source of the water supply used by the residents.

No differences were observed in biological (FC and BOD_5) and selected chemical parameters (pH, EC, TDS, P, and Cl) in the STE between the summer and fall period and the winter and spring period at either site ($p<0.01$). Therefore, single mean values of these wastewater parameters were used to calculate pollutant removal rates between different seasons.

Table 3.1 Characteristics of septic tank effluent (STE)

Site		Parameters									
		pH	EC	TDS	PO_4-P	Cl	FC	BOD_5	TKN	NH^+_4	NO^-_3
		unit	us/cm	mg/l	mg/l	mg/l	no/100ml	mg/l	mg/l	mg/l	mg/l
Powell River Project	max.	8.1	2448	1492	9.62	191	4500000	217	62.6	71.6	1.42
	Min.	6.74	780	1181	2.9	50.2	170	75	43.8	30.9	0
	Ave.	7.44	1890	1293	5.33	83.2	277245	135	54.8	45.9	0.31
	Sd±	0.3	108	141	1.67	35.6	1025901	37.8	8.5	8.9	0.3
	n	22	23	7	21	21	19	17	10	21	21
Whitethorne	max.	7.74	1372	805	6.91	123.2	7000000	230	69.6	53.9	1.99
	Min.	6.91	853	502	1.73	38.4	10	51.6	32.3	23.1	0.01
	Ave.	7.42	1083	651	3.12	58.8	529178	124	48.3	36.4	0.27
	Sd±	0.24	137	98.6	0.96	19.3	1771136	57.7	11.1	7.9	0.44
	n	22	22	12	22	22	18	20	18	18	18

IV. Evapotranspiration (ET) at the WP site

Evapotranspiration (ET) accounted for most of the daily water loss from the SVBs. Daily water loss (%) was estimated by measuring differences in water levels in the SVBs during a 24 h period without dosing, and percentage of water loss was calculated using equation 3.1.

$$\text{Water loss \% /day} = \text{TWL} * 100 / V_A \qquad \text{Eq. 3.1}$$

where TWL is total water loss within 24 hours (L),

V_A is actural void space in the SVB (L),

V_A is equal to the difference between V_v and V_R., and V_A was detemined by measuring total amont of water added to the SVB subsurface after plant root system was developed. V_V is total void space in the SVBs (L), which can estimated using equation as following, V_V=LDWn. V_v can also be determined by measuring total amount of water was added to the SVB subsurface without plants. V_R is volume occupied by the root system in the SVBs (L), and the difference of V_v and V_A was V_R.

The daily water loss due to ET are shown in Table 3.2. Detention time and plant species had little effect on daily evapotranspiration. Although there were no differences between plant species, plants had a significant impact on water loss in the SVBs. Water loss averaged 20% in vegetated beds as compared to 1-2% daily water losses in beds without plants (Table 3.2). Water loss in the SVBs planted with cattails was slightly higher than the SVBs planted with woolgrass, and 3.9 days detention time with recirculation tended to have the highest water loss in the SVBs for both plant species (Table 3.2).

However, water loss was lower than those repoated by McIntyre and Riha's (1991) where water loss by cattail ranged from 32 to 63%, and water loss by woolgrass ranged from 31 to 47% in the lab research environment. The differences in water loss between plants was related to total leaf surface area of the plants in each SVB. If water loss was based on the total amount of wastewater applied, at least 30 to 60% of applied wastewater was lost via ET daily during the summer and fall periods, the highest water loss rates were found in the SVBs with the longest detention time (Table 3.3).

$$\text{Water loss \% /day} = \text{TWL} * 100 / (V_A) \qquad \text{Eq. 3.2}$$

where TWL is total water loss within 24 hours (L),

V_A is total amount of water applied to the SVBs in 24 hours (L),

Twenty percent water loss average was used to adjust concentrations of pollutants during the summer and fall periods, a very conservative estimate. In the summer, water loss was much higher, and 30% or more of the total wastewater in the SVBs were lost by this process. Water loss via ET was also dependent on weather conditions such as wind velocity, temperature, and humidity. However, during periods of rain, the SVBE may be diluted. Water samples were never collected during the periods of rain due to the difficulty in measuring DO and Eh *in situ*.

Table 3.2 Daily water loss based on total water in the SVBs (Whitethorne Plantation, 1994)@

Treatment			Water loss % via evapotranspirtation						
			SVBs*				SBs**	SVBs	SBs
Detention time (days)	Plant species	Recir. %	July, 25, 1994	Aug., 19, 1994	Aug., 31, 1994	Oct., 6 , 1994		Nov., 30, 1994	
2.6	cattail	0	17.3	18.6	17.0	13.9	1.2	4.7	2.9
3.9	cattail	0	21.9	16.2	11.3	7.5	0.4	3.0	2.4
3.9	cattail	50	25.0	27.5	12.2	5.7	1.6	2.0	2.0
5.9	cattail	50	19.2	9.6	14.2	8.0	1.4	2.2	1.0
2.6	woolgrass	0	15.7	16.4	15.4	12.4		6.2	
3.9	woolgrass	0	14.9	12.9	12.7	10.1		10.2	
3.9	woolgrass	50	19.5	32.7	15.8	14.8		6.3	
5.9	woolgrass	50	14.7	17.0	12.7	5.9		1.6	
mean			19	19	14	10	1.2	3.8	2.1

@ Based on total amount of wastewater in the SVB.

* SVBs, subsurface vegetated beds; **SBs, subsurface beds without plants.

Table 3.3 Daily water loss based on total water applied to the SVBs (Whitethorne Plantation, 1994)@

Treatment			Water loss % via evapotranspirtation						
			SVBs*				SBs**	SVBs	SBs
Detention time (days)	Plant species	Recir. %	July, 25, 1994	Aug., 19, 1994	Aug., 31, 1994	Oct., 6 , 1994		Nov., 30, 1994	
2.6	cattail	0	37	39	44	30	3	12	8
3.9	cattail	0	80	49	45	24	2	12	9
3.9	cattail	50	73	79	32	16	6	9	8
5.9	cattail	50	95	65	84	40	8	13	6
2.6	woolgrass	0	30	35	33	26		16	
3.9	woolgrass	0	49	48	50	33		31	
3.9	woolgrass	50	57	64	62	43		25	
5.9	woolgrass	50	73	58	52	29		10	
mean			62	55	50	30		16	8

@ Based on total amount of wastewater in the SVB.

* SVBs, subsurface vegetated beds; **SBs, subsurface beds without plants.

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Chapter IV:

BIOLOGICAL INDICATORS

ABSTRACT

Studies were conducted at the WP site in Blacksburg, VA, and the PRP site in Wise County, VA, to evaluate the SVB type of constructed wetland. Domestic wastewater was applied to the SVBs from a pump chamber placed between the septic tank and the existing drainfield at both locations. Sixteen small scale SVBs were installed down slope of the residence at the WP site. Treatments included three detention times (2.6, 3.9, and 5.9 days), two recirculation ratios (0 and 0.5), and two plant species woolgrass and cattail. Treatments for the PRP experimental site consisted of three detention times (4, 8, 12 days) and the same plant species (cattail and woolgrass). The investigation of the SVB design variables and treatment capabilities was conducted by monitoring STE and SVBE monthly with respect to fecal coliform (FC) and coliphage populations.

There were no differences among the three detention times for FC and phages in the effluent collected from the bottom of the SVBs at both experimental sites, and more than 99% of FC in the SVBE were removed at both sites. Effluent samples collected from the shallow part of the wastewater column (shallow sample) did not exhibit a higher removal of FC. There was no seasonal impact on the FC and coliphage numbers in the SVBE at the WP site, but FC numbers were higher in the shallow samples during the winter and spring periods at the PRP site. Plant species had no impact on FC and phages in the SVBE at either experimental site.

I. INTRODUCTION

Interest in using the SVB type of constructed wetlands as an alternative method to treat domestic wastewater has been increasing rapidly during recent years, and the SVB systems appear to be reliable and cost efficient in removal of BOD from wastewater (Brown and Reed, 1994). However, a main concern is whether SVB systems provide an acceptable effluent regarding FC and pathogenic viruses. There is a limited data available regarding the fate of FC and pathogenic viruses in the SVB system.

Feierabend (1989) and Gearheart (1989) suggested that fecal coliform (FC) removal can be effectively modeled by first order kinetics The reductions in FC numbers may be attributed to natural die-off in an unfavorable environment, and to the toxic effects of aquatic plant root excretions on enteric organisms. In general, the SVB systems have efficient FC removal rates, and FC removal rates are higher than in free water systems. Herskowitz et al. (1987) reported FC reduction of 94-99%. Wolverton (1989) reported 97% reduction of FC after wastewater passed through over 20 meters in a rock/plant filter employed to treat STE. Gersburg et al. (1989) also reported that constructed wetlands at Arcata, CA and Santee, CA had efficiencies of 90 to 99% in removal of bacterial indicators. However Gearheart et al. (1989) reported an average 86% reduction in FC numbers in constructed free surface wetlands employed to treat wastewater.

Viruses in municipal wastewater range from $1x10^7$-$2.45x10^9$ PFU/100 ml (Siegrist, 1977; Gersburg, 1986) and the average viral content of domestic sewage in the United States is about $7 X 10^4$ PFU/ 100 ml (Melnick, et al.,1978). There are over 100 different kinds of viruses known to be excreted from human feces (World Health organization, 1979), and the minimal infective dose may be as low as one virus particle. However, detection and enumeration of human viruses in wastewaters is a time-consuming and costly process. The physical size and structure of coliphages is similar to human enteroviruses, and the coliphage is also more resistant to environmental stress such as chlorine disinfection (APHA, 1992), heat (Cramer et al., 1976) and sunlight (Kapuscinski and Mitchell, 1983) than coliforms. In addition the coliphage assay is relatively simple, fast (8-16 hr) and inexpensive (Gersberg, et al., 1987). Therefore, coliphage (F-specific phages) have been suggested as an ideal indicator of viral pollution (Kott et al, 1974; Wentsel et al, 1982; Stetler, 1984), and a virus behavior indicator in water hygiene (Havelaar and Pot-Hogeboom, 1989). But there is no consensus on the suitability of a bacteriophage indicator to monitor human enteric viruses. A coliphage is a bacteriophage which infects and replicates in coliform bacteria, and tends to be present where total FC are found. This implies that enteroviruses are not detected unless coliphages are present in wastewater. Berg (1973) concluded that all conventional secondary treatment technologies (trickling filter, activated sludge, and oxidation ponds) could reduce enteric viruses after reviewing the literature on virus removal by wastewater treatment and disinfection processes. Gerba (1980) reported that conventional treatment only removed about 50% of viruses in the wastewater, and concluded that factors known to inactivate viruses include enzymatic attack, denaturation of the protein coat, loss of structural integrity, oxidation and adsorption to surfaces. There is limited information available on fate of viruses in constructed wetlands. Gersburg et al. (1986) reported that vegetated wetland beds with a 5 cm per day primary wastewater loading rate, indigenous F-specific RNA bacteriophages removal was > 99%. Butler et al. (1993) reported that the viruses were removed more efficiently than bacteria in gravel bed hydroponic sewage treatment system. Gersburg et al. (1989) also reported that constructed wetlands at Arcata, CA and Santee, CA had efficiencies of 90 to 99% in removal of viral indicators.

II. MATERIALS AND METHODS

1. Field experiments and Data analysis: Refer to Chapter III.

2. Biological analysis

2.1. Fecal coliforms

The membrane filter procedure was used to determine fecal coliform (FC) numbers (APHA, 1992). If samples were positive using the Colilert test, a presence -absence test by Environetics Inc., Brandford, CT (Edberg et al., 1988), then fecal coliforms and coliphages were enumerated using the following two procedures. A set of 0.1 ml, 1 ml, and 10 ml of effluent sample was filtered though a gridded 0.45 um filter, 47 mm in diameter using a vacuum pump. After the sample passed through the filter, the filter was placed on the surface of a 50 x 12 mm petri dish containing mFC agar. The petri dishes were inverted, placed into a plastic bag, and the plastic bag submerged into a 44.5 °C water bath for 24 h. After 24 h the plastic bag was removed from the water bath, and allowed to cool. The fecal coliform numbers were determined by counting the number of blue colonies present.

2.2. Coliphage

Phage agar concentrate (PAC) bottles were steamed to the liquefy agar, and the temperature then was adjusted to 48 °C in a water bath. Fifty ml of sample was poured into sterile glass container and 0.5 ml of 0.12 M $CaCl_2$ solution added. The sample was adjusted to 48 °C in the water bath, 2.5 ml of overnight host culture added, and sample and culture was mixed at 48 °C for 3 min. PAC and sample-culture mixtures were then combined gently to avoid formation of bubbles, the mixtures were then poured into 100 X 15 mm Petri dishes, and allowed to solidify. Plates were inverted and incubated at 37 °C and plaques counted after 8 h (APHA, 1992).

2.3. Estimating K_T for FC removal

Base on equation 3.3 ($\ln C_e/C_0 = - K_T t$) , the temperature dependent first order reaction rate constant (K_T, d^{-1}) was estimated by using FC numbers in the SVBE (C_e) and in the STE (C_o). The t is the designed influent detention time.

III. RESULTS AND DISCUSSIONS

Monitoring of biological parameters of the SVBE over a three-y period at both experimental sites indicated that biological indicator removal rates in the SVB was >99% for FC and >95% for coliphages.

1. Fecal coliforms

Although FC were reduced by 99% in the effluent collected from bottom of the SVBs at both experimental sites (Tables 4.1 and 4.2), there were no differences in FC numbers among the three detention times (Tables 4.1 and 4.2). This implied that a large reduction in FC numbers occurred within the first 2.6 days detention time. Fecal coliform removal percentages tended to be higher at the PRP site than at the WP site, but the K_T was higher at the WP site, indicating that FC reduction was faster at this site that the PRP site (Tables 4.1 and 4.2). With increased detention time, removal rates were decreased (the longer detention time, the smaller K_T).

There were no differences in FC numbers in effluent collected from the bottom of the SVBs and the middle part of the SVBs at the PRP site (Table 4.3). Fecal coliform numbers

Table 4.1 The impact of detention time on removal rates of biological indicators in the SVBE at the WP (Whitethorne Plantation) site

Detention time	Fecal coliforms			Coliphages	
days	no./100 ml	%	K_T, d^{-1}*	no./100 ml	%
0**	529178			157.7	
2.6	2808 a***	99.46 aa	2.01	3.5 a	97.8 a
3.9	4867 a	99.06 a	1.2	5.4 a	96.6 a
5.9	4135 a	99.22 a	0.82	6.8 a	95.7 a
average	3937	99.25	1.34	5.2	96.7

*K_T, temperature dependent first order reaction rate constant, d^{-1}.

** influent (STE).

***means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 4.2 The impact of detention time on removal rates of biological indicators in the SVBE at the PRP (Powell River Project) site

Detention time	Fecal coliforms			Coliphages
days	no./100 ml	%	K_T, d^{-1*}	no./100 ml
0**	227245			
4	324 a**	99.86 a	1.64	10.9 a
8	81 a	99.96 a	0.99	9.4 a
12	303 a	99.87 a	0.55	20.8 a
average	236	99.9	1.1	13.7

*K_T, temperature dependent first order reaction rate constant, d^{-1}.

** influent (STE).

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 4.3 The impact of detention time on biological indicators in the effluents collected from the different parts of the SVBs at the PRP site

Detention time	Fecal coliforms		Coliphages
days	no./100 ml	%	no./100 ml
STE	227245		
Shallow samples (10 cm below the water level)			
4	454 ab	99.80 ab	
8	22 b	99.99 a	
12	251 ab	99.89 ab	
Deep samples (10 cm above the bottom of the SVBs)			
4	644 a	99.72 b	10.9 a
8	111 ab	99.95 ab	9.4 a
12	268 ab	99.88 ab	20.8 a

*means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

were initially reduced to <1-2% within 2.6 days residence in the SVBs, then these small amount of FC persisted indicating that the FC survive or may undergo after-growth in the SVBs. This result is similar to results of other researchers (Scheuerman et al., 1993).

There was no seasonal impact on FC numbers in the SVBs at the WP site (Table 4.4), however, FC numbers were higher during the winter and spring periods (colder temperature) at the PRP site (Table 4.5) Plant species did not impact on FC numbers in the SVBE at either experimental site (Table 4.6).

2. Coliphage

Viruses in municipal wastewater ranged from $1x10^7$-$2.45x10^9$ FPU/100 ml (Siegrist, 1977; Gersburg, 1986). There were very low phage numbers in the SVBE at both experimental sites (Tables 4.1 and 4.2), which may indicate that at least 99% of viruses had been removed in the SVBE. There were no differences in phage numbers in the SVBE among the three detention times at both experimental sites (Tables 4.1 and 4.2). There was no seasonal impact on phage numbers in the SVBE (Table 4.4). Plant species also did not influence phage numbers in the SVBE at either experimental site (Table 4.6).

Table 4.4 The impact of detention time on biological indicator removal under the different seasons in the SVBE at the WP (Whitethorne Plantation) site

Detention time	Fecal coliforms		Coliphages	
days	no./100 ml	%	no./100 ml	%
0*	529178		157.7	
Summer and fall periods				
2.6	3519 a**	99.3 a	5.3 ab	96.6 ab
3.9	5454 a	99.0 a	8.1 ab	94.9 ab
5.9	2914 a	99.4 a	10.2 a	93.5 b
Winter and spring periods				
2.6	2307 a	99.6 a	2.6 b	98.4 a
3.9	3874 a	99.3 a	4.1 ab	97.4 ab
5.9	6065 a	99.0 a	5.1 ab	96.8 ab

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 4.5 The impact of detention time on FC removal in the SVBE under the different seasons at the PRP site

Detention time	Shallow samples		Deep samples	
days	no./100 ml	%	no./100 ml	%
0*	277245			
Summer and fall periods				
4	432 b**	99.8 a	467 a	99.8 a
8	10 b	99.9 a	28 a	99.9 a
12	29 b	99.9 a	473 a	99.8 a
Winter and spring periods				
4	1973 a	99.1 b	225 a	99.9 a
8	90 b	99.9 a	120 a	99.9 a
12	371 b	99.8 a	210 a	99.9 a

* influent (STE).

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 4.6 The impact of plant species on fecal coliform and coliphage numbers (no./100 ml) in the SVBE

Detention time	PRP site*		Detention time	WP site	
days	Coliphages	Fecal coliforms	days	Coliphages	Fecal coliforms
Cattail					
4	6.2 a**	482a	2.6	5.0 a	2651 a
8	7.4 a	44 a	3.9	5.2 a	6774 a
12	17.8 a	412 a	5.9	6.7 a	2624 a
Woolgrass					
4	15.8 a	541 a	2.6	2.0 a	3327 a
8	11.2 a	96 a	3.9	5.6 a	3302 a
12	23.9 a	82 a	5.9	6.9 a	5961 a

*The PRP site-the Powell River Project site; The WP site-the Whitethorne Plantation site.
**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

IV. CONCLUSIONS

1. The SVB type of constructed wetlands was highly efficient at FC and coliphage removal. It may not be possible to achieve zero FC and coliphage discharge from the SVB..
2. High removal rates of FC and coliphages were achieved in the SVBs within a short period of time (<2.6 -4 days detention time).
3. Fecal coliforms and coliphages may survive longer during the winter and spring periods due to lower temperature, and fecal coliforms and coliphages may undergo after-growth in the SVBs.
4. Depth that samples were collected from the SVB did not affect FC numbers (there were no differences in FC numbers in the SVBE between deep samples and shallow samples).

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Chapter V:

BIOCHEMICAL OXYGEN DEMAND

ABSTRACT

This research consisted of studies conducted at the WP site in Blacksburg, VA and the PRP site in Wise County, VA, to evaluate the SVB form of constructed wetlands. Domestic wastewater was supplied to small scale SVBs from a pump chamber placed between the septic tank and the existing drainfield. Sixteen small scale SVBs were installed down slope of the residence at the WP site. Treatments included three detention times (2.6, 3.9, and 5.9 days), two recirculation ratios (0 and 0.5), and two plant species (woolgrass and cattail). Treatments for the PRP site consists of three detention times (4, 8, 12 days) and the same plant species (cattail and woolgrass). The investigation of the SVB design issues and treatment capabilities was conducted by monitoring STE and SVBE *in situ* monthly for BOD_5, DO and Eh

With increased detention time, DO concentrations at the deep part of the wastewater column (deep sample) were increased at the WP site, but there were no differences in DO concentration at the PRP site. DO concentrations were much higher during the winter and spring periods, especially in shallow part of wastewater column.

Redox potentials (Eh) increased with detention time at both sites. Eh values were higher during the winter and spring periods as compared with the summer and fall periods at both sites, especially for the shallow samples. There was limited seasonal impact on Eh at different depths in the wastewater column in the SVBs. Eh values at the shallow depth in the SVBs planted to woolgrass were higher than the SVBs planted to cattail at both sites. Linear

relationships (regression analysis of detention time with Eh) were present between detention times and Eh values at both sites.

There were differences among the three detention times at the WP site. Recirculation appeared to have no apparent benefit, but BOD_5 removal increased with increased detention time. The 5.9 days detention time (1.7 cm d^{-1} loading rate) had the highest removal capabilities. The BOD_5 removal rates ranged from 54 to 70%. Although there was little seasonal impact on BOD_5 concentrations or treatment efficiencies at the WP site, pollutant removal rates tended to be higher in the summer and fall periods.

At the PRP site, there were differences in BOD_5 concentrations among the three detention times. BOD_5 removal rates ranged from 30 to 75% and shallow samples exhibited a higher level of treatment. Pollutant removal rates were higher during the winter and spring than summer and fall periods. Plant species did not affect DO content and BOD_5 concentration at either site.

The K_t values are influenced by season, sample depth, and site. The average K_T value was 0.24 d^{-1} for BOD_5 removal at the WP site. The K_T value at this site was 0.28 d^{-1} for samples collected during the summer and winter periods, and 0.19 d^{-1} for samples collected during the winter and spring periods. At the PRP site, the K_T value was 0.14 d^{-1} for shallow samples during the summer and fall periods, and 0.20 d^{-1} during the winter and spring periods. However, the K_T value was much smaller for deep samples at the PRP site.

I. INTRODUCTION

In the SVB systems employed to treat domestic wastewater, BOD_5 is the most frequently measured water quality parameter. The experience obtained thus far shows that in properly designed SVB systems, it should not be difficult to achieve 70 to 90% of BOD_5 reduction. According to Knight et al. (1993) and Waston et al. (1989), BOD_5 removal percentage ranged from 18 to 96% in 20 operational SVB systems, with an average removal rate of 67%. While Bastian and Hammer (1993) reported that BOD_5 removal efficiencies in constructed wetlands ranged from 50-90%.

Degradation of BOD_5 integrates the process of organic and chemical oxidation in the wastewater column. BOD_5 removal in the SVB systems has been described as a first-order reaction (EPA, 1988). The decomposition of BOD in the SVB system occurs microbially, and not appreciably by the macrophytes. Based on operational wetland data in the database, Knight et al. (1993) conducted a linear regression to predict BOD_5 concentration in the wetland effluent as a function of BOD_5 inflow concentration and hydraulic loading rate.

$$BOD_{out}=0.097\ HLR+0.192\ BOD_{in} \qquad R^2=0.72 \qquad \text{Eq. 5.1}$$

Where BOD_{out}-BOD_5 outflow concentration, mg/L,

BOD_{in}-BOD_5 inflow concentration, mg/L

HLR-hydraulic loading rate, cm/d.

The BOD_5 degradation process is also an O_2 consuming process. The lower the DO, and the Eh in the SVBs, the slower the BOD reduction in the wastewater column. The main sources of O_2 for the SVB is 1) O_2 diffusion from the atmosphere into the wastewater column and 2) O_2 diffusion via plant structures from the atmosphere to the plant root, then the roots release excess O_2 to the rhizosphere (Brix, 1987). However, it is difficult to determine O_2 change with field equipment. Eh quantitatively measures the tendency of the system to oxidize or reduce susceptible substances. Oxidation is the loss of electrons and reduction is the gain of electrons. A generalized reaction is given in Equation 5.2,

$$Ox + ne^- + mH^+ = Red + H^+ \qquad \text{Eq. 5.2}$$

and Eh can be calculated by Equation 5.2,

$$Eh = E^o - 0.059\ (m/n)\ pH + (0.059/n)\ \log\ [(oxidant)/(reductant)] \qquad \text{Eq. 5.3}$$

Where

E^o is the standard potential;

m is the number of protons in the reaction; and

n is the number of electrons.

As degradation of organic materials occurs in the SVBs, the DO in the wastewater column is depleted and the Eh decreases. BOD_5 can be decomposed under both aerobic and anaerobic conditions, but more rapidly under aerobic conditions. After disappearance of O_2, NO_3^- is the first component reduced (denitrification), although denitrification can proceed prior to the complete disappearance of O_2. After denitrification, then Mn^{4+} is converted to Mn^{2+}, and Fe^{3+} is converted to Fe^{2+}. Hydrogen sulfide and CH_4 do not appear until reduction of the above components. Lower Eh values indicate more anaerobic conditions.

The SVB systems in this experiment were designed, based on BOD_5 removal, to achieve maximum BOD_5 reduction from STE with minimum land requirement and at low cost.

II. MATERIALS AND METHODS

1. Field experiments and data analysis: Refer to Chapter III.

2. Chemical and Biological analysis

2.1. Redox potential (Eh)

Eh values relative to H_2/H^+ were measured at various points in the SVBs before dosing with a pH meter (APHA, 1985). The calomel electrode potential ($Eh = Eh_{reading} + 243$; Jackson, 1975) was added to the initial reading to determine the actual Eh values. Eh values for each SVB were measured at two depths (2.5 and 25 cm from the bottom of the SVB) at the WP site and at three depths (2.5, 15, 25 cm from the bottom of the SVBs) at the PRP site.

2.2. Dissolved oxygen (DO)

Dissolved oxygen concentrations in the SVBs were measured after Eh determination, but prior to dosing. A YIS DO meter was calibrated with distilled water and adjusted for temperature and altitude (APHA, 1985).

2.3. Biochemical oxygen demand (BOD_5)

Samples were collected, in plastic bottles, from the SVBs after dosing. BOD dilution water was a mixture of 1 ml phosphate buffer, 1 ml $MgSO_4$, 1 ml $CaCl_2$ and 1 ml $FeCl_3$ solutions in 1000 ml distilled water. Unfiltered subsamples were diluted with BOD dilution water. BOD_5 was determined using a DO meter to measure the differences between initial and final DO concentrations after 5 days incubation at 20°C. BOD_5 concentrations were calculated based on DO differences and dilution volumes (APHA, 1985).

III. RESULTS AND DISCUSSION

1. Dissolved oxygen (DO)

Aquatic plant growth imports life and activity to the SVB systems. Oxygen is introduced into the SVBs by diffusion and plant transportation. Oxygen transported from the atmosphere to the submerged zone via plant structures not only supply the dissolved O_2 continually in the wastewater column in the SVBs, but also increases the capacity of the system for aerobic bacterial decomposition of pollutants. This occurs because of the large range of O_2 consuming aquatic organisms that are present in the vicinity of root zones and in the shallow part of the wastewater column. Although it is difficult to measure DO differences between planted and unplanted systems with field equipment, Eh can indirectly reflect disappearance of O_2 in the system. There were low DO concentrations at the bottom of the SVBs at both sites (Table 5.1), especially during the summer and fall periods due to high decomposition rates of organic materials and the low O_2 solubilities in the wastewater column (Table 5.2). However, DO concentrations were much higher during the winter and spring periods, especially in the shallow part of the wastewater column SVBs (Table 5.2). These higher values may be a result of the greater concentration of roots in the upper part of the SVBs and diffusion of O_2 from the air into the surface of the wastewater column. The concentration of O_2 in the wastewater column also increases as the water temperature decreases (the lower temperature, the higher saturated O_2 concentration in water).

Plant species did not affect DO content in the deep part of the wastewater column at either site (Table 5.3). Apparently both cattail and woolgrass can transport similar quantities of O_2 from the atmosphere to their root systems, and then release the excess O_2 to the rhizosphere.

Table 5.1 The impact of detention time on dissolved oxygen (DO) and redox potential (Eh) in the SVBs

Whitethorne Plantation site				Powell River Project site				
Detention time (days)	Eh mvolts		DO mg/l	Detention time (days)	Eh mvolts			DO mg/l
	mV		mg L^{-1}		mV			mg L^{-1}
days	shallow*	deep		days	shallow	middle	deep	
2.6	-87b**	-334c	1.0b	4	-210c	-250b	-320b	1.0a
3.9	-29b	-258b	1.3b	8	-112b	-181b	-265a	0.9a
5.9	117a	-211a	1.6a	12	70a	-151a	-246a	0.9a

*shallow, middle and deep -Eh measured at 25, 15, 2.5 cm from the bottom of the SVBs

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 5.2 The impact of detention time on DO concentrations under different seasons in the SVBE

Whitethorne Plantation site		Powell River Project site		
Detention time	DO	Detention time	DO (deep)	DO (shallow)
days	mg/L	days	mg/L	
Summer and fall		Summer and fall		
2.6	0.7 d	4	0.8 b	
3.9	0.8 d	8	0.8 b	
5.9	0.8 d	12	0.8 b	
Winter and spring		Winter and spring		
2.6	1.7 c	4	1.5 a	3.1 b
3.9	2.3 b	8	1.5 a	3.8 a
5.9	3.5 a	12	1.3 a	4.1 a

*Deep samples at the WP site were collected from 2.5 cm above the bottom of the SVBs; Deep samples at the PRP site were collected from 10 cm above the bottom of the SVBs; Shallow samples were collected from 10 below the water surface.

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

2. Redox potential (Eh)

Redox potentials of each individual bed have been monitored for over three years, *in situ*, at both sites, and results indicate that the upper part of SVBs are aerobic, but the bottom of the SVBs are anaerobic, actually the Eh values at the bottom of the SVBs (2.5 cm from the bottom of the SVBs) indicate conditions where H_2S and CH_4 might form. In fact, H_2S was present in some samples collected from this depth from the PRP site (rotten egg odor). The Eh values of the wastewater column in the SVBs at the WP site ranged from -87 to +117 mV at the shallow depth, and from -334 to -211 mV at the bottom of the SVBs (Table 5.1). Eh values increased with increased detention time. The Eh values at the shallow depths in the SVBs were higher and would be expected to be associated with the disappearance of NO_3^- and the formation of Mn^{2+} and Fe^{2+} (Cole, 1988). Similar results were observed in the SVBs at the PRP site; Eh values at the bottom (2.5 cm from the bottom of the SVB) of the SVBs were much lower than Eh values at the middle (15 cm from the bottom of the SVB) and the upper portion of the SVBs (Table 5.1). Eh values at the bottom of the SVBs and the upper part of the SVBs (25 cm from the bottom of the SVB) were similar at both sites (Table 5.1). As compared with DO concentrations at both sites, DO in the deep part of the wastewater column was also higher at the WP site (Table 5.1). Maximum detention time in the SVBs at the PRP site (12 days) was almost twice as long as the detention time in the SVBs at the WP site (5.9 days). This indicated that longer detention time did little to improve anaerobic conditions in the deep part of the wastewater column, and the nitrification process was low due to limited DO in the SVBs.

Eh values were higher during the winter and spring periods as compared with the summer and fall periods at both sites, especially when measured at the shallow depth in the wastewater columns (Table 5.4). There was a limited seasonal impact on Eh values at the bottom and middle parts of the SVBs (Table 5.4), which may imply that depth of the SVB system is an important design issue. Eh values in the shallow position of the wastewater

Table 5.3 The impact of plant species on redox potential (Eh) and dissolved oxygen (DO) in the SVBs

Whitethorne Plantation site				Powell River Project site				
Detention time	Eh mV		DO mg L^{-1}	Detention time	Eh mV			DO mg L^{-1}
days	shallow	deep*	deep	days	shallow	middle	deep	deep
	Cattail				Cattail			
2.6	-120c	-330d	1.1bc	4	-194c	-248c	-307cd	1.1a
3.9	-40bc	-273c	1.4abc	8	-196c	-215c	-274bc	1.3a
5.9	251a	-176a	1.5ab	12	-178c	-196bc	-267ab	1.3a
	Woolgrass				Woolgrass			
2.6	37b	-299cd	0.9c	4	-221c	-251c	-330d	0.8a
3.9	65b	-228b	1.1bc	8	27b	-148ab	-257ab	0.8a
5.9	211a	-200ab	1.7a	12	327a	-105a	-224a	1.3a

*Deep at the WP site, Eh and DO were measured at 3 cm above the bottom of the SVBs;
Deep at the PRP site, Eh and DO were measured at 10 cm above the bottom of the SVBs;
Shallow at the WP site, Eh and DO were measured at 25 cm above the bottom of the SVBs;
Shallow at the PRP site, Eh and DO were measured at 25 cm above the bottom of the SVBs;
Middle at the PRP site, Eh and DO were measured at 15 cm above the bottom of the SVBs;
**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

column of the SVBs that were planted to woolgrass were higher than the SVBs planted to cattail at both sites (Table 5.3). Both cattail and woolgrass have special tissues to transport O_2 from the atmosphere to their root systems, then release excess O_2 to the rhizosphere. These oxidized rhizosphere supports microbes capable of facilitating a wide range of biological reactions such as degradation and nitrification processes.

Linear relationships (regression analysis of detention time with redox potential) were present between detention times and Eh values at both sites. At the WP site, the relationship between detention times and redox potential was r =0 .97 for Eh measured at the bottom of the SVBs and r = 0.99 for Eh measured at the middle part of the SVBs (Fig. 5.1 and Table 5.5). There were also linear relationships between detention times and Eh at all three water column depths at the PRP site with the higher correlation coefficients, r = 0.99 for the Eh measured at the upper part of the SVBs, r = 0.98 for Eh measured at the middle part of the SVBs, and r = 0.96 for Eh measured at the bottom of the SVBs (Table 5.5 and Fig. 5.2).

3. Biochemical oxygen demand (BOD_5)

Monitoring of biological parameters of the SVBE in both sites over a three-y period, indicated that the SVB form of constructed wetlands was effective in removing BOD_5, especially at the longest detention time and at the shallow wastewater column depths. Detention time, seasons, and plant species may impact on the BOD_5 removal in the SVBs.

3.1. Detention time

BOD_5 concentration in the SVBE is a function of organic loading rate (or detention time), and largely impacted by temperature. At the WP site, BOD_5 concentrations and detention time could be described using the first order decay equation for both colder and warmer seasons (Fig. 5.3), or a linear relationship between log BOD_5 concentration and

Table 5.4 The impact of detention time redox potential in the SVBs under different seasons

Whitethorne Plantation site			Powell River Project			
Detention time	Eh (mV)		Detention time	Eh (mV)		
days	shallow*	deep	days	shallow	middle	deep
Summer and fall			Summer and fall			
2.6	-173 e**	-369 c	4	-194 c	-248 c	-307 cd
3.9	-156 e	-257 b	8	-196 c	-215 c	-274 bc
5.9	-28 d	-217 b	12	-178 c	-196 bc	-267 abc
Winter and spring			Winter and spring			
2.6	127 c	-244 b	4	-221 c	-252 c	-330 d
3.9	230 b	-242 b	8	-27 b	-148 ab	-257 ab
5.9	492 a	-115 a	12	327 a	-105 a	-227 a

*shallow, middle, deep -Eh measured at 25, 15, 2.5 cm from the bottom of the SVBs

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 5.5 Relationship between detention time and redox potential

Experimental Site	Equation	Position in the SVBs[**]
Whitethorne Plantation (WP)	$Eh^{*}=-445.9 + 115\,X$, $r=0.98$	shallow(cattail)
Whitethorne Plantation (WP)	$Eh=-120.7+ 54.4\,X$, $r=0.97$	shallow (woolgrass)
Whitethorne Plantation (WP)	$Eh=-453.2 + 46.8\,X$, $r=0.99$	deep (cattail)
Whitethorne Plantation (WP)	$Eh=-257.1 + 9.23\,X$, $r=0.93$	Deep (Woolgrass)
Powell River Project (PRP)	$Eh=-205.3 + 2\,X$, $r=0.81$	shallow (cattail)
Powell River Project (PRP)	$Eh=-503.7 + 68.5\,X$, $r=0.99$	shallow (woolgrass)
Powell River Project (PRP)	$Eh=-271.7 + 6.5\,X$, $r=0.98$	middle (cattail)
Powell River Project (PRP)	$Eh=-314 + 18.3\,X$, $r=0.97$	middle (woolgrass)
Powell River Project (PRP)	$Eh=-322.7 + 5\,X$, $r=0.93$	deep (cattail)
Powell River Project (PRP)	$Eh=-376.3 + 13.3\,X$, $r=0.97$	deep (woolgrass)

* Eh-redox potential (mV); X-detention time (days)

** shallow, middle, deep-Eh measured at the 25, 15. 2.5 cm from the bottom of the SVBs.

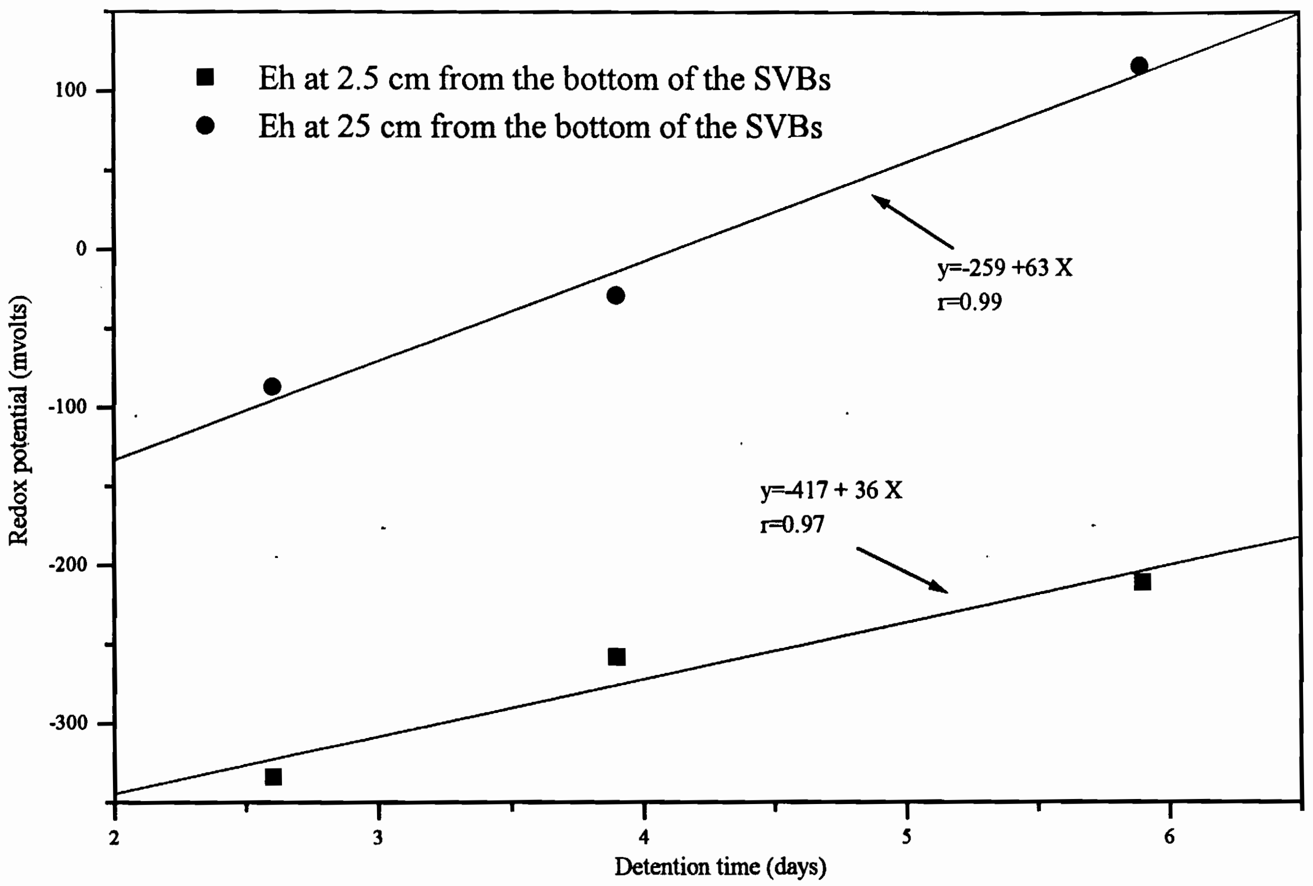

Figure 5.1 Relationship between detention time and redox potential at two depths in the SVBs at the Whitethorne Plantation site

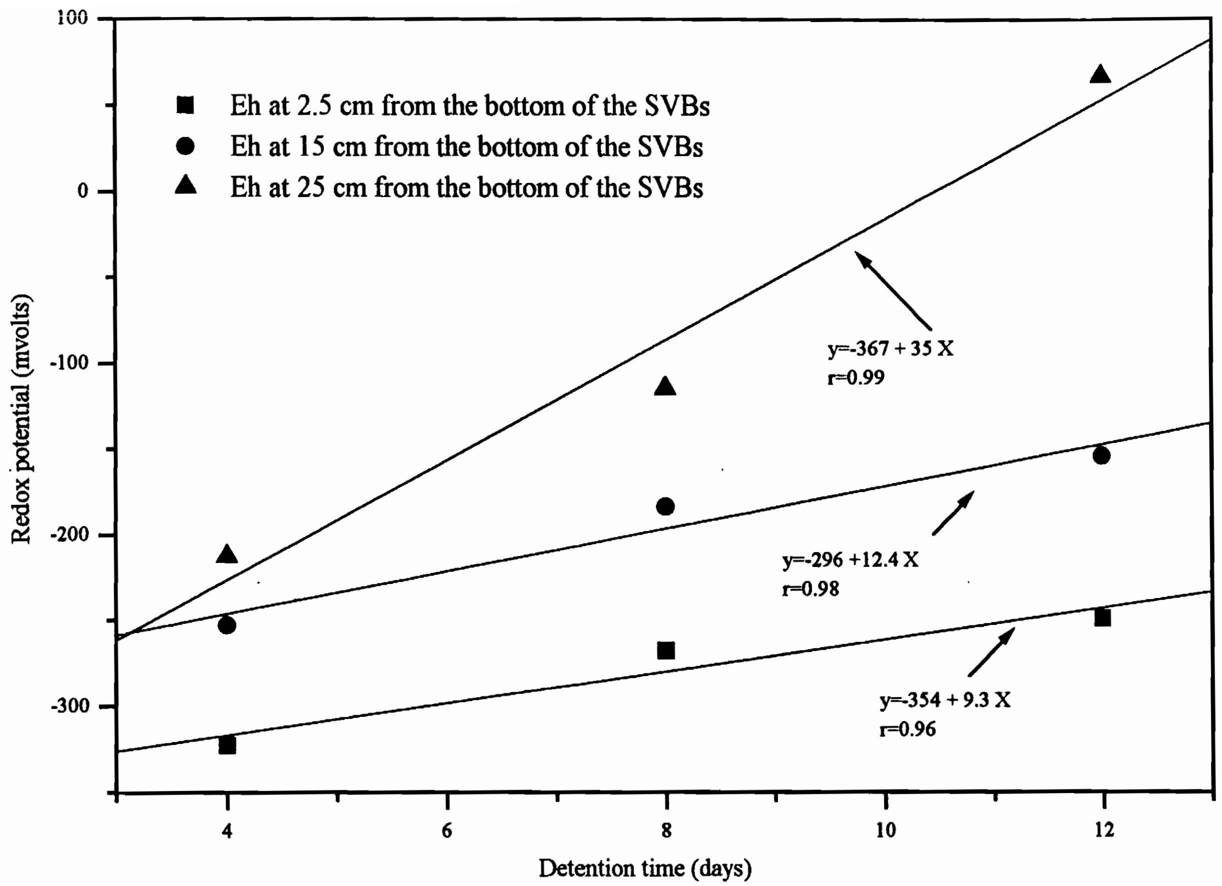

Figure 5.2 Relationship between detention time and redox potential in the SVBs at the Powell River Project site

detention time (Fig. 5.4). At the PRP site, the relationship between BOD_5 concentrations and detention time could be described using the first order decay equation, for shallow samples (Fig. 5.5), while linear relationships described the relationship between BOD_5 concentrations and detention time for the deep samples (Fig. 5.5). Linear equations also can be used to describe relationship between log BOD_5 concentration and detention time (Fig. 5.6). BOD_5 degradation at both sites met the first order reaction kinetics as expected. For shallow samples, more than 50% BOD_5 in the effluent were reduced within 4 days in both colder and warmer seasons. While deep samples, BOD_5 degradation rates maintained the same velocity (the same slope) with increased detention time. This may suggested that readily degradable organic matter was removed within 4 days, and complex organics reside in the deep part of the wastewater column due to insufficient DO (Table 5.2). When BOD_5 removal, in the deep part of the wastewater column, was compared at both sites, the SVB at the WP site was more effective in BOD_5 removal. This may be caused by a 5 cm thicker pea gravel layer at the PRP site, which resulted in lower plant stand densities at the PRP site, and may also decrease the amount of O_2 defusing and transported from atmosphere into system. In addition, BOD_5 concentration in STE (influent) at the PRP site was higher than at the WP site.

3.2 Sampling depths

Although BOD_5 concentrations were reduced 54 to 70% in the SVBE at the WP site, and 30 to 75% at the PRP site, BOD_5 concentrations at the longest detention time (5.9 days and 12 days) were still above the discharge limit (30 mg L^{-1}) at both sites at all seasons (Table 5.6). To compare water quality in the SVBs, effluent samples were collected separately from

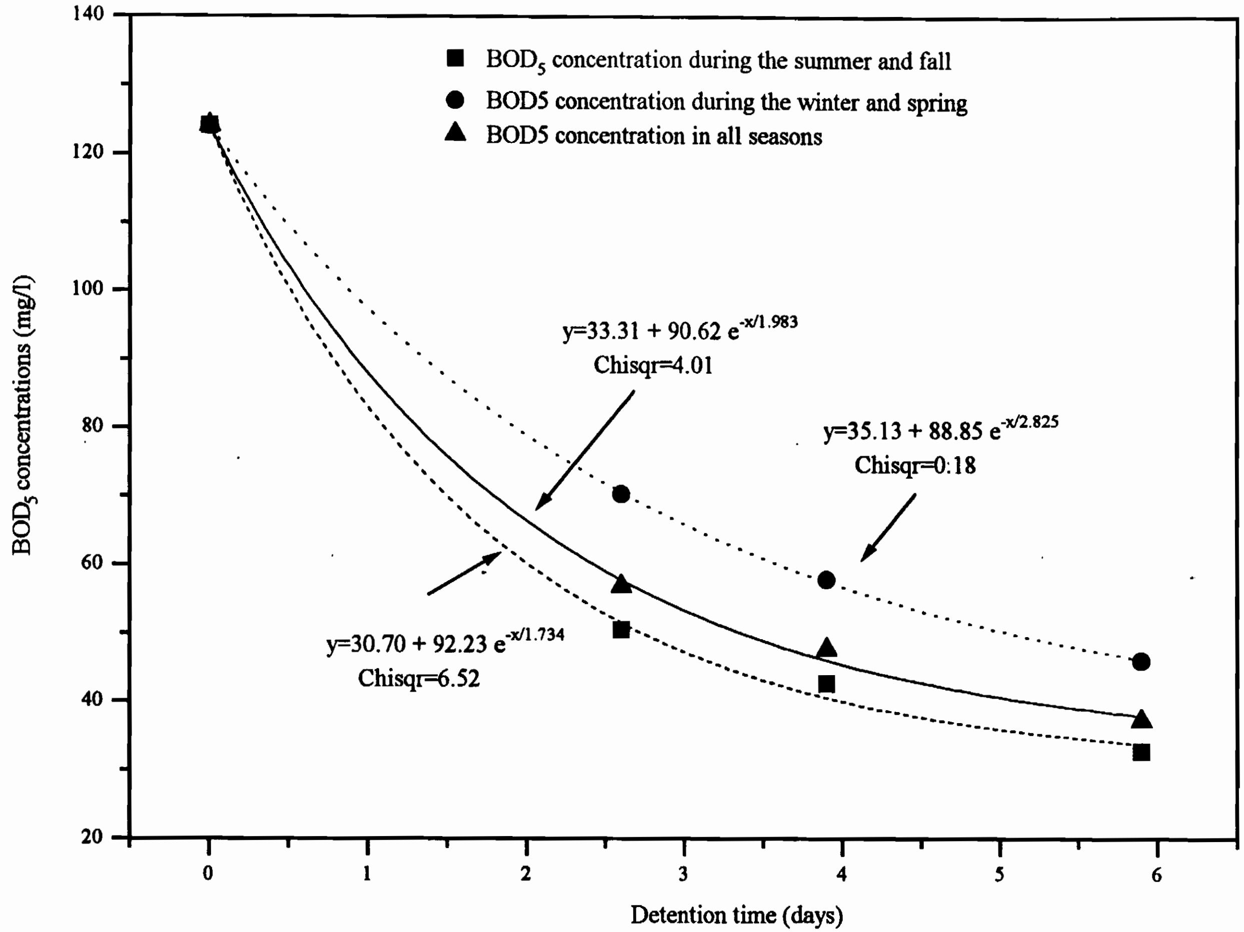

Figure 5.3 The impact of detention time on BOD_5 concentations in the SVBE at the Whitethorne Plantation site

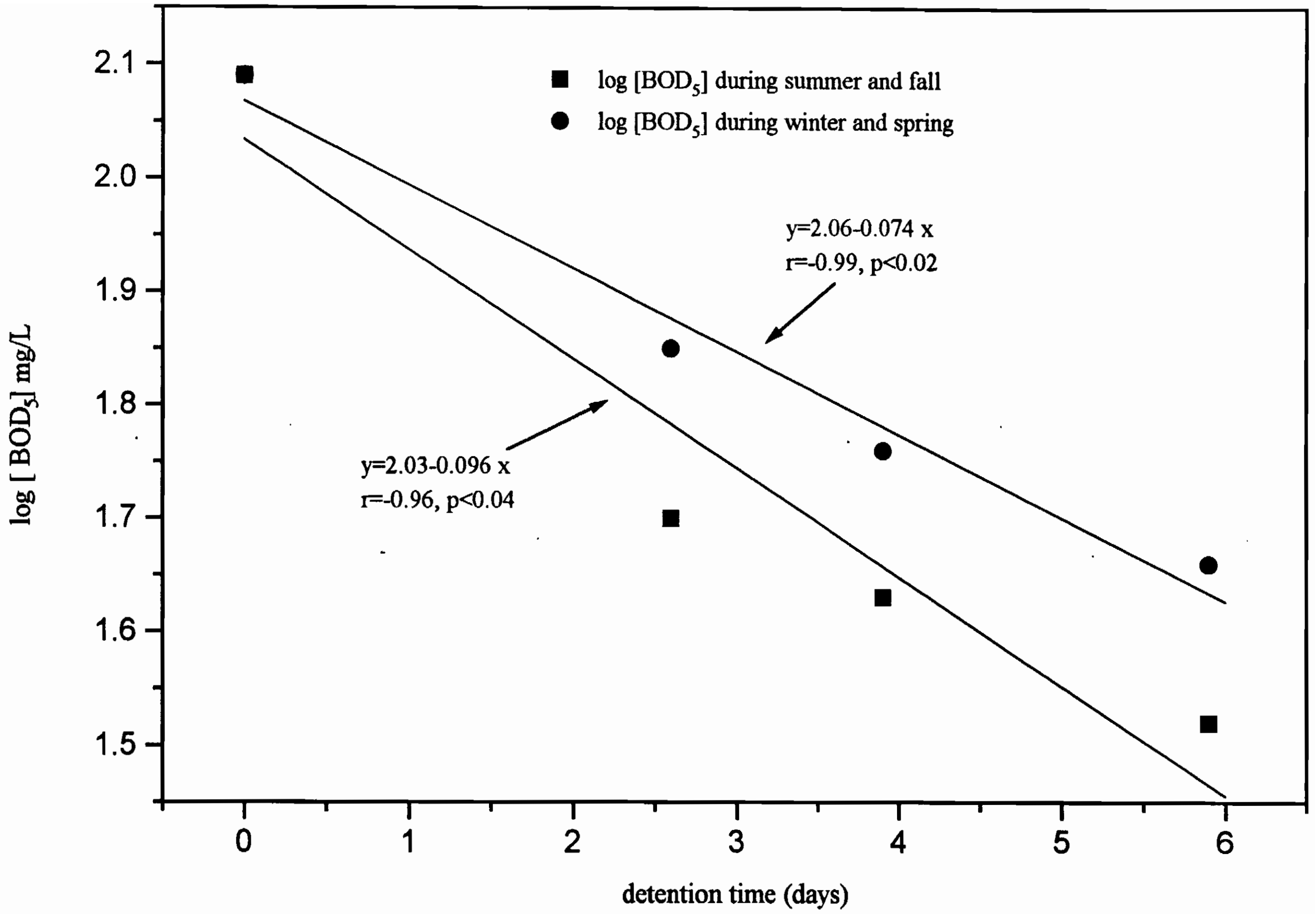

Figure 5.4 Relationship between detention time and BOD$_5$ concentrations in the SVBE at the Whitethorne Plantation site

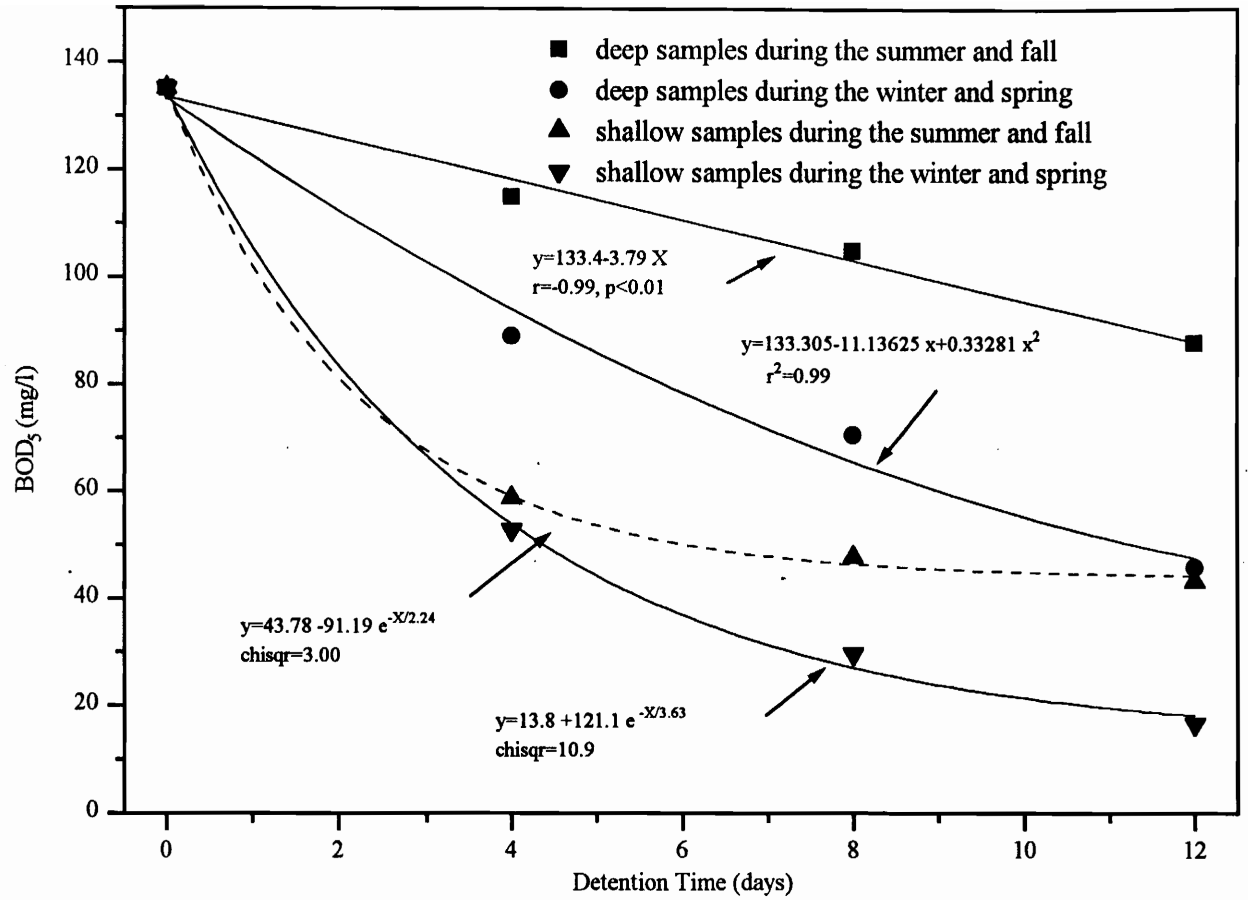

Figure 5.5 The effect of detention time on BOD_5 concentrations in the SVBE under different seasons at the Powell River Project site

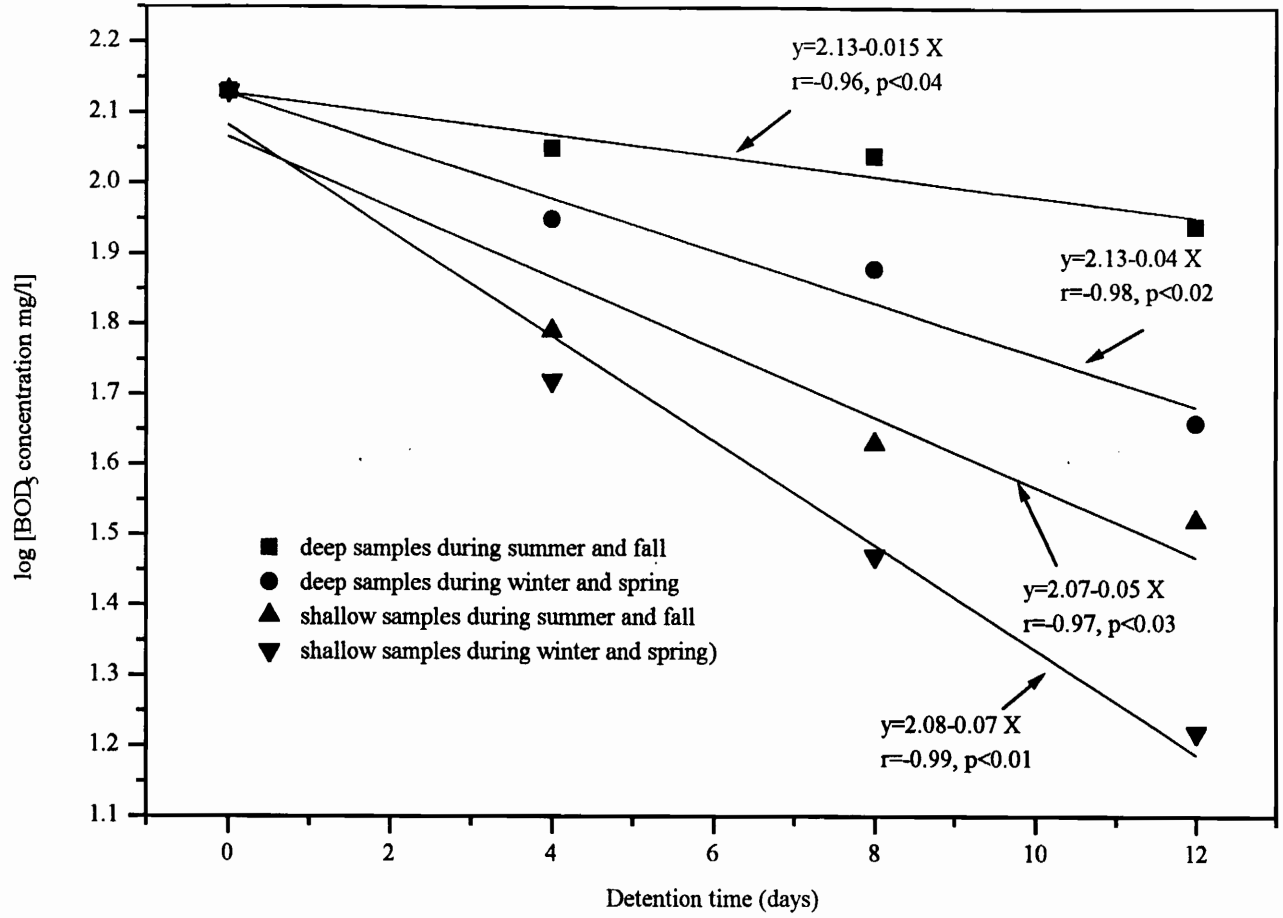

Figure 5.6 Relationship between detention time and BOD_5 concentrations in the SVBE at the Powell River Project site

the bottom of the SVBs (10 cm above the bottom of the SVBs) and from the shallow part of the wastewater column in the SVBs (10 cm below the water surface of the SVBs) at the PRP site. Effluent samples collected from the shallow part of the wastewater column in the SVBs exhibited a higher degree of treatment (Table 5.6). BOD_5 concentrations in the shallow part of the wastewater column were much lower than in the deep part of the wastewater column of the SVBs, therefore removal rates were higher in the shallow part of the wastewater column (59-75%) than in the deep samples (30-56%). Although BOD_5 reduction as high as 70 to 75% could be achieved, the average BOD_5 concentration over a three year period at both sites still would not meet 30 mg L^{-1}. The data indicate that stream discharge limits cannot be met, under the present conditions. Perhaps a longer residence time, a combination of plant materials,

3.3 Seasons

There were seasonal impact on BOD_5 removal rates in the SVBE at both sites. At the WP site, BOD_5 removal rates were higher during the summer and fall periods than during the winter and spring periods at the 2.6 days detention time (Table 5.7). BOD_5 removal percentages ranged from 59 to 74% during the summer and fall periods, and 43 to 63% during the winter and spring periods. At the PRP site, however, BOD_5 removal rates were higher during the winter and spring periods than during the summer and fall periods. In general, anoxic or anaerobic condition may occur during the summer due to low O_2 solubilities and higher O_2 consumption by the biological community (Miller, 1989). In addition, water loss via evapotranspiration during the warm seasons may concentrated the SVBE, therefore, BOD_5 removal rates were actually underestimated. However, at the WP site, BOD_5 removal rates were higher during the summer and fall periods than the winter and spring periods. This may result in shallower depth of the SVBs and higher densities of plants

Table 5.6 The impact of detention time on BOD_5 concentrations and removal percentage in the SVBE

Whitethorne Plantation site			Powell River Project site				
Detention time	BOD_5 (deep samples)*		Detention time	BOD_5 (deep samples)		BOD_5 (shallow samples)	
days	mg/L	Rem.%	days	mg/L	Rem.%	mg/L	Rem.%
0**	124		0	135		135	
2.6	56.8 a***	54 b	4	98.9 a	30 b	57.9 a	59 b
3.9	47.6 ab	62 ab	8	87.7 a	38 b	40.3 b	72 a
5.9	37.2 b	70 a	12	62.3 b	56 a	35.2 b	75 a

*Deep samples at the WP site were collected from 2.5 cm above the bottom of the SVBs; Deep samples at PRP site were collected from 10 cm above the bottom of the SVBs; shallow samples-samples collected from 10 cm below the water level.

** influent (STE).

***means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 5.7 The impact of detention time on BOD_5 concentrations in the SVBE under different seasons

Whitethorne Plantation site			Powell River Project site				
Detention time	BOD_5 (deep samples)*		Detention time	BOD_5 (deep samples)		BOD_5 (shallow samples)	
days	mg/L	Rem.%	days	mg/L	Rem.%	mg/L	Rem.%
0**	124		0	135		135	
Summer and fall			Summer and fall				
2.6	50.4 bc***	59 ab	4	112.9 a	21	58.7 a	59 c
3.9	42.6 bc	66 ab	8	109.8 a	23	47.7 a	66 c
5.9	32.8 c	74 a	12	87.1 b	39	43.2 a	70 bc
Winter and spring			Winter and spring				
2.6	70.3 a	43 c	4	89.0 b	37	52.7 a	63 c
3.9	57.8 ab	53 bc	8	76.6 b	50	29.7 b	79 ab
5.9	46.0 bc	63 ab	12	45.9 c	68	16.6 c	88 a

*Deep samples at the WP site were collected from 3 cm above the bottom of the SVBs; Deep samples at the PRP site were collected from 10 cm above the bottom of the SVBs; shallow samples-samples collected from 10 below the water level.

** influent (STE)

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

in the SVBs. These factors may result in more O_2 being transported from the atmosphere into the SVBs. At the PRP site, during the winter and spring period, BOD_5 removal rates in the shallow part of the wastewater column ranged from 63 to 88%, while BOD_5 removal rates ranged from 59 to 70% during the summer and fall without adjustment of water loss via ET (Table 5.7). Although different seasons had less impact on the deep part of the wastewater column, BOD_5 removal percentages were still higher during the winter and spring than the summer and fall period, BOD_5 removal percentages ranged from 21 to 39% during summer and fall, and ranged from 37 to 68% during winter and spring (Table 5.7).

3.4. Plant species

There were no differences in BOD_5 concentrations between the SVBs planted to cattail and woolgrass at both sites (Table 5.8). This indicated that plant species did not impact on BOD_5 concentrations in the SVBE (Table 5.8).

3.5. Temperature dependent first -order reaction rate constant (K_T, d^{-1})

First order kinetics (Eq. 5.4) was successfully used to model BOD_5 removal in a wetland environment (EPA, 1988; Bavor et al., 1989).

$$C_e/C_o=\exp(-K_T\, t) \qquad \text{Eq. 5.4.}$$

where Ce=effluent BOD_5 concentration, mg/l;

C_o=influent BOD_5 concentration, mg/l;

K_T=temperature dependent first -order reaction rate constant, d^{-1};

$$K_T=K_{20}\, 1.1^{(T-20)} \qquad \text{Eq. 5.5}$$

$K_{20}=0.86\ d^{-1}$ for gravel based system.

t=hydraulic retention time, d;

and t=LWDn/Q

where L=length of the SVB, m;
W=width of the SVB, m;
D=depth of submergence, m;
n=porosity, dimensionless;
Q=average flow rate, $m^3\ d^{-1}$.

The larger K_T, the faster BOD_5 can be removed in the treatment system. The K_T value ranges from 0.8 to 1.1 d^{-1} for sand and gravel (Reed et al., 1988). However, average K_T in the gravel based SVBs studied was much smaller. The temperature dependent first-order reaction rate constant (K_T) for BOD_5 removal at both sites are listed in Table 5.9, based on Eq. 5.6 by using data in Table 5.7.

$$K_T = (\ln C_o - \ln C_e)/t, \qquad \text{Eq. 5.6}$$

At the WP site, average K_T was 0.28 d^{-1} for BOD_5 removal in the SVBE during summer and fall period, and 0.19 d^{-1} during the winter and spring period. The K_T values was much smaller at the PRP site as compared with the WP site (Table 5.8). Average K_T was 0.24 d^{-1} (an average of 0.28 and 0.19 d^{-1}) for BOD_5 removal at the WP site. For a BOD_5 discharge limit of 30 mg L^{-1}, it would require a 5 day detention time to achieve this limit for effluent collected from the bottom of the SVBs during the summer and fall period, and would require a 7.5 day detention time to reach the same limit during the winter and spring period. For the PRP site, it would require 7.5 days detention time for the shallow part of the wastewater column in the SVBs during the winter and spring period, and would require 11 days during the summer and fall period. It may require 17 to 50 days detention time to meet this limit at the bottom of the wastewater column during the summer and fall. This indicated that the SVBs at the WP site were more effictive than the SVBs at the PRP site in BOD_5 removal. Health and density of aquatic plant stands and the depth of the SVBs may play a very important role in pollutant removal.

Table 5.8 The impact of plant species on BOD_5 concentrations in the SVBE at both experimental sites

Whitethorne Plantation site		Powell River Project site		
Detention time	BOD_5 (deep samples)*	Detention time	BOD_5 (deep samples)	BOD_5 (shallow samples)
days	mg/L	days	mg/L	mg/L
0**	124	0	135	
	Cattail		Cattail	
2.6	64.6 ab***	4	101 a	54.2 a
3.9	52.1 abc	8	86.5 ab	35.8 b
5.9	41.1 c	12	57.2 c	31.0 b
	Woolgrass		Woolgrass	
2.6	69.6 a	4	98.8 a	57.2 a
3.9	60.6 abc	8	92.7 a	43.7 ab
5.9	50.0 bc	12	67.6 bc	37.0 b

*Deep samples at the WP site were collected from 3 cm above the bottom of the SVBs;
Deep samples at the PRP site were collected from 10 cm above the bottom of the SVBs;
shallow samples-samples collected from 10 below the water level.

** influent (STE).

***means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

IV. CONCLUSIONS

1. DO concentrations at the bottom of the SVBs increased with detention time at the WP site, but there were no differences in DO concentrations at the PRP site. Plant species had no impact on DO concentrations in the wastewater column in the SVBs.
2. Redox potentials measured at all depths of the SVB increased with detention time, and there was a linear relationship between Eh value and detention time. Eh values were higher during the winter and spring period as compared with the summer and fall period at both sites. Eh values at the shallow wastewater column depths were higher where woolgrass was planted.
3. BOD_5 concentrations in the SVBE decreased with detention time. BOD_5 removal rates ranged 54-70% at the WP site, and 30-75% at the PRP site. Effluent samples collected from the shallow part of the wastewater column exhibited a higher degree of treatment.

4. An average K_T value was 0.17 d^{-1} for BOD_5 removal at the WP site. The K_T value was 0.28 d^{-1} for the samples collected during the summer and fall period, and 0.19 d^{-1} for the samples collected during the winter and spring period.

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Chapter VI:

NITROGEN

ABSTRACT

This research consisted of studies conducted at the WP site in Blacksburg, VA and the PRP site in Wise County, VA, to evaluate the SVB type of constructed wetlands for domestic wastewater treatment. Domestic wastewater was applied to small scale SVBs from a pump chamber placed between the septic tank and the existing drainfield. Sixteen small scale SVBs were installed down slope of the residence at the WP site. Treatments included three detention times (2.6, 3.9, and 5.9 days), two recirculation ratios (0 and 0.5), and two plant species (woolgrass and cattail). Treatments for the PRP site consisted of three detention times (4, 8, and 12 days) and the same plant species (cattail and woolgrass). The investigation of the SVB design issues and treatment capabilities was conducted by monitoring STE and SVBE monthly with respect to total Kjeldahl nitrogen (TKN), ammonium (NH_4^+), and nitrate (NO_3^-) concentrations in the SVBE. To determine the fate of N in the SVB system, denitrification rates, ammonia (NH_3) volatilization rates and plant tissue N contents were determined during 1993.

Data collected from both sites over a three year period, indicated that the SVB form of constructed wetlands had high N removal rates, especially in the shallow samples. There were no differences among detention times for NO_3-N concentrations in the SVBE. There were, however, differences among detention times for TKN and NH_4^+ concentrations in the SVBE. TKN removal percentages ranged from 33 to 52% at the WP site, and 27 to 81%

at the PRP site. NH_4-N removal rates ranged from 30 to 61% at the WP site, and 27 to 87% at the PRP site. Shallow samples had low concentrations of both TKN and NH_4^+-N. There was limited seasonal impact on TKN and NH_4^+ concentrations in the SVBE at the WP site, but there were apparent seasonal differences in TKN and NH_4^+ concentrations in both deep and shallow samples at the PRP site. There were no differences between plant species (cattail and woolgrass) with respect to N removal at either site.

There were no differences among detention times for denitrification rates, however, denitrification rates tended to be higher in the SVBs with 3.9 days detention time compared with the other two detention times. Average measured denitrification rates ranged from 3.87 to 6.69 N_2O mg/m^2/hr (93-161 N_2O mg/m^2/d), and 2-17 % (35-267 N mg/d/m^2) of total N applied to the SVBs could be removed by denitrification in the SVBs. Plant species had limited impact on denitrification rates. Nitrate concentration was the major limiting factor for denitrification in the SVBE. When NO_3^- (12 mg L^{-1}) was added to the STE and SVBE, all the NO_3^- was denitrified indicating that C source did not limit denitrification in the SVBs. A suitable C source may become a limiting factor at high concentration of NO_3^-. There were no differences among detention times for NH_3 volatilization rates. Ammonia volatilization rates ranged from 146 to 221 NH_3 mg/d/m^2. An average 20% of total N applied to the SVBs could be removed by NH_3^+ volatilization.

Nitrogen removal by plant uptake ranged from 2-10% of total N applied to the SVBs annually. Plant uptake was based on the harvest of plant materials once each year.

I. INTRODUCTION

During recent years, the interest in utilizing the subsurface vegetated bed (SVB) form of constructed wetlands as an alternative method for wastewater treatment has rapidly increased due to both cost and energy efficiencies (Hammer, 1989; Moshiri, 1993). The constructed wetlands designed to treat domestic wastewater can be managed to enhance N removal by denitrification. The inorganic N in STE consisted of more than 75% NH_4^+ with very low NO_3^- concentration (Table 3.1). Wastewater flows in the SVBs laterally and is purified during contact with media surfaces and the vegetation root zones. The subsurface zone is saturated and generally anaerobic, but excess oxygen (O_2) conveyed through the plant root system supports an aerobic zone adjacent to roots and rhizomes. According to Bowden (1987), radial O_2 loss from wetland plant roots can range from 0.24 to 9.6 g O_2/m^2/day, and the sequential processes of mineralization, nitrification, and denitrification dominate N cycling in wetlands. Nitrification-denitrification reactions may play an important role in wastewater renovation in the SVBs. Most denitrification research has focused on natural wetlands and soil based constructed wetlands, denitrification may be quite different in the gravel based SVB systems. There are also few data available to quantify N loss via NH_3 volatilization mechanism in the SVBs, this research was proposed to systematically evaluate the roles of denitrification and NH_3 volatilization in removal of N from the gravel based SVB form of constructed wetlands.

II. MATERIALS AND METHODS

1. Field experiments and data analysis: Refer to Chapter III.

2. Chemical analysis

2.1. Total Kjeldahl Nitrogen (TKN)

An unfiltered sample (10 ml) was placed in 100 ml digest tube, and then 1 g of catalyst mixture, 3 ml of concentrated sulfuric acid (H_2SO_4) and a piece of boiling chip were added.

The digestion tubes were placed in a heating block at 200 °C for 2 hours, then the temperature was adjusted to 380 °C for an additional 3 hours. After digestion (mixture turned transparent), the mixture was allowed to cool and diluted to 50 ml with distilled water. Samples were mixed thoroughly, and a three to four ml aliquot was taken for NH_3 analysis using an Orion Scientific autoanalyzer using a colorimetric procedure (USEPA, 1979, methods 352.2).

2.2. Ammonium (NH_4-N) and Nitrate (NO_3-N)

Effluent samples were filtered with a vacuum micro-pore filter with cellulosic 0.45 micron filter paper. Subsamples were collected for NH_4^+-N and NO_3^--N analysis with an Orion Scientific autoanalyzer using a colorimetric procedure (APHA, 1985; and USEPA, 1979).

2.3. Denitrification Rate and Denitrification Potentials

Denitrification rate

Denitrification rates were measured *in situ* using the C_2H_2 block technique (Chan and Knowles, 1979), N_2O samples were collected from the head space of measuring tubes, and determined with a gas chromatograph (GC) equipped with an electron capture detector. A 2 m long porapak-Q column with 2 mm inside diameter, 6 mm outside diameter and 80/100 mesh size was used. The gas chromatograph was operated at an inlet temperature of 60°C, a column/oven temperature of 390 °C, and a detector temperature of 340°C. N_2O peaks are separated under these condition at a retention time of approximately 1.3 minutes. Samples were injected directly into the GC, and concentration of N_2O in each was calculated against a standard curve, which was plotted from a set of N_2O standard concentrations (10^{-12}, 10^{-10},

10^{-8}, and 10^{-6} moles N_2O/0.5 ml).

Denitrification potential

The estimation of denitrification potential in the SVBs was conducted by incubating the STE and SVBE in airtight bottles under room temperature (25-27°C). Nitrate (KNO_3) and C ($C_6H_{12}O_6$) concentrations were added to the effluent to determine the denitrification potential, and C_2H_2 gas was injected into the bottle to block the transformation of N_2O to N_2. Gas samples were collected from the head space in the bottles, and N_2O concentrations determined with a gas chromatograph as described earlier. To estimate denitrification potential in the STE and SVBE, 4 treatments including 2 levels of NO_3^- (0 and 12 mg L^{-1} for the first experiment, and 0 and 84 mg L^{-1} for the second experiment) and 2 levels of $C_6H_{12}O_6$ (0, and 1800 mg L^{-1}) concentrations were added to the STE or the SVBE. One hundred and twenty samples of STE and SVBE were incubated under room temperature, 25-27 °C after addition of different levels of NO_3^- and $C_6H_{12}O_6$ to the airtight bottles. Fifteen ml of C_2H_2 gas were injected into bottle to block N_2O transformation to N_2. Gas samples were collected from the head space in the bottles (50 ml). In order to maintain pressure in the bottle, the volume of gas removed from the bottles was replaced with He.

2.4. Ammonia Volatilization Rate

NH_3 trapping and collecting

Ammonia which volatilized from each SVB was trapped using a two-layer polyurethane plastic foam discs, which had a diameter of 7.5 cm, and a thickness of 2.56 cm and a density of 0.025 g/cm^3 (Nommik, 1973). The discs were washed with 1M phosphoric acid (H_3PO_4), then rinsed with distilled water. Dried discs were soaked in acid solution (5%

H_3PO_4 and 10% glycerol). The excess solution was removed by squeezing the discs. The disc retained about 7-10 ml solution after this procedure. Two discs were placed in a measuring tube in the SVBs. After 3-4 h (daytime) exposure to NH_3 escaping from the SVB, the bottom disc was removed and replaced by a new reloaded disc.

NH_3 determination

The amounts of NH_3 trapped by plastic foam discs were displaced with several successive portion of 1 M KCl, then brought to 50 ml volume. The NH_3 in this solution was analyzed colorimetrically, with an Orion Scientific autoanalyzer using the indophenol blue procedure (U.S.EPA, 1979). This information was used to calculate the quantity of NH_3 volatilized.

2.5. Plant tissue N content

Plant tissue TKN was determined by a modified micro-Kjeldahl digestion procedure (Mckenzie and Wallace, 1954; Bremner and Mulvaney, 1982). A 0.1000 [illegible]g of tissue sample was first placed in 100 ml digest tube, and then add 0.75 g of catalyst mixture, 1.25 ml of concentrated H_2SO_4 and a boiling chip. Digestion tubes were placed in a heating block at 200 °C for 30 min, and then adjusted to 410 °C for additional 3 more hours. After digestion, tubes were allowed to cool and then diluted to 50 ml with distilled water. Samples were mixed thoroughly. Three to four ml of aliquot was taken for NH_3 analysis using an Orion Scientific autoanalyzer with colorimetric procedure (USEPA, 1979, methods 352.2).

III. RESULTS AND DISCUSSION

1. Total Kjeldahl Nitrogen (TKN)

The N cycle in the SVB is greatly influenced by microbial activities, which involves a complex interaction of mineralization, oxidation, and reduction. In the SVBs, the source of N is STE. Total Kjedahl Nitrogen (TKN) concentrations in the SVBE included both N (NH_4^+-N and organic N) from STE and organic N from plant and microbial detritus. In the SVBs, TKN removal is mainly NH_4-N reduction since more than 75% of TKN in the influent (STE) was present in the NH_4^+ form at the WP site, and more than 84% at the PRP site (Table 3.1, Chapter III).

1.1. Detention time

First order kinetics were used to model N removal (Bavor, 1989). Detention time and temperature in the wastewater column were major factors for TKN reduction in the SVBs. There were differences in TKN concentrations in the SVBE among the three detention times at the WP site, and TKN concentrations in the SVBE decreased with increased detention time. However, at the PRP site, there were differences in TKN concentrations between 4 and 8 days detention times in the shallow samples (effluent collected from 10 cm below the water surface), while there were no differences in TKN concentrations between 8 and 12 days detention time in the shallow samples. In the deep samples (effluent collected from 10 cm above the bottom of the SVBs), there were no differences in TKN concentrations between 4 and 8 days detention time, however there were differences in TKN concentration in the wastewater column between 8 and 12 days detention time. This indicated that TKN reduction was faster in the shallow part of wastewater column. With increased detention time, TKN concentrations in the SVBE decreased at both sites, and TKN removal percentages ranged from 33 to 52% at the WP site, and 27 to 81% at the PRP site (Table 6.1).

1.2 Sampling depth

TKN concentrations in deep samples (10 cm above the bottom of the SVBs) were double those in shallow samples (10 cm below the water surface) (Table 6.1) at the PRP site. Relationship between detention time and TKN concentrations in the shallow samples can be described as the first order decay equation (Fig. 6.1), but in the deep samples, the relationship between detention time and TKN concentration was linear (Fig. 6.2 and 6.3). TKN was removed very rapidly during the first 4 days of detention time in the shallow samples, followed by a slow reduction. In the deep samples, TKN concentrations decreased with increased detention time.

1.3 Seasons

Seasons had an impact on TKN removal at the longest detention time (5.9 days) at the WP site (Table 6.2 and Fig. 6.4). There were also differences in TKN concentrations between colder and warmer seasons at the PRP site, and TKN concentrations in both shallow and deep samples were higher during the summer and fall period than during the winter and spring periods, especially at the longest detention times (Table 6.3, Figs. 6.1 and 6.2). It should be noted that, after 12 days residence in the SVB, TKN concentration was as low as 6.0 mg L^{-1} in the shallow samples during the winter and spring periods. This was a 89% removal of TKN. However, during the summer and fall periods, TKN concentration in the shallow samples was higher, this may result, partially, from the water loss via ET and the higher decomposition rates of organic matter during the warm seasons.

1.4 Plant species

Plant species did not impact on TKN concentrations or TKN removal in the SVBE at both sites (Tables 6.4 and 6.5).

2. Ammonium (NH_4^{+}) and Nitrate (NO_3^{-})

Ammonium and NO_3^- are the most active components of the N cycle in the SVBs. Biological nitrification followed by rapid denitrification is believed to the primary N removal process (Reed et al., 1994). Nitrification can occur if aerobic conditions are present, sufficient alkalinity and suitable temperature (Reed et al., 1995). The nitrifying organisms are thought to attach to the aerobic substrate surface (root and gravel surface). In the SVBs, the limiting factor is the availability of DO, and theoretical relationships indicate that ratio of O_2/NH_4^+ is 4.6 for complete nitrification, which implies that oxidization of 36 mg/L NH_4^+ in STE would require at least 166 mg/L DO in the SVBs. However NH_3 volatilization may also removed NH_4^+ directly from the SVBs. Assuming NH_3 volatilization could account for 20-40% of NH_4^+ loss, 99-132 mg/L of O_2 would still be required to oxidize NH_4^+ to NO_3^-. It is impossible to transfer this much O_2 in the SVBs since it has been estimated that emergent plant species can transfer between 5-45 g of O_2 per day per square meter (Reed et al., 1995). Thus approximately 0.05-0.43 g O_2 L^{-1} d^{-1} could be transferred to the SVBs at the WP site. One must also consider that much of O_2 was consumed by BOD in the SVBs.

Table 6.1 The impact of detention time on N concentrations in the SVBE and removal percentages at both sites

Site	Detention	TKN	Removal	NH_4^+	Removal	NO_3^-	NH_4/TKN
WP*	days	mg/l	%	mg/l	%	mg/l	%
	0**	48.3		36.4		0.27	75.4
	Deep samples (2.5 cm from the bottom of the SVBs)						
	2.6	32.2 a***	33 c	25.6 a	30 c	0.13 a	79.5
	3.9	27.7 b	43 b	19.8 b	46 b	0.13 a	71.5
	5.9	23.3 c	52 a	14.3 c	61 a	0.13 a	61.4
PRP	0	54.8		45.9		0.31	83.8
	Shallow samples (10 cm below the water surface)						
	4	19.6 b	63 bc	17.2 c	63 b	0.29 a	87.8
	8	14.7 cd	73 ab	9.4 d	80 a	0.26 a	63.9
	12	10.3 d	81 a	6.2 d	87 a	0.18 a	60.2
	Deep sample (10 cm above the bottom of the SVBs)						
	4	39.3 a	27 d	33.8 a	27 d	0.25 a	86.0
	8	34.9 a	35 d	27.9 b	40 c	0.25 a	79.9
	12	25.3 b	53 c	18.6 c	60 b	0.22 a	73.5

* WP-the Whitethorne site; PRP-the Powell River Project site.

** influent (STE)

***means within the same column followed by the same letter at the same site are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 6.2 The impact detention time on N concentrations in the SVBE under different seasons at the Whitethorne Plantation site

Detention	TKN		NH_4^+		NO_3^-
days	mg/l	removal %	mg/l	removal %	mg/l
0*	48.3		36.4		0.27
Summer and fall periods					
2.6	36.6 a**	24 c	28.8 a	21 c	0.12 b
3.9	31.7 abc	34 abc	22.8 b	38 b	0.14 ab
5.9	26.3 c	46 a	13.6 c	55 a	0.13 ab
Winter and spring periods					
2.6	33.6 ab	31 bc	25.4 ab	30 bc	0.17 a
3.9	31.0 bc	36 ab	23.6 b	35 b	0.14 ab
5.9	28.5 b	41 ab	21.5 b	41 b	0.14 ab

* influent (STE)

** means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

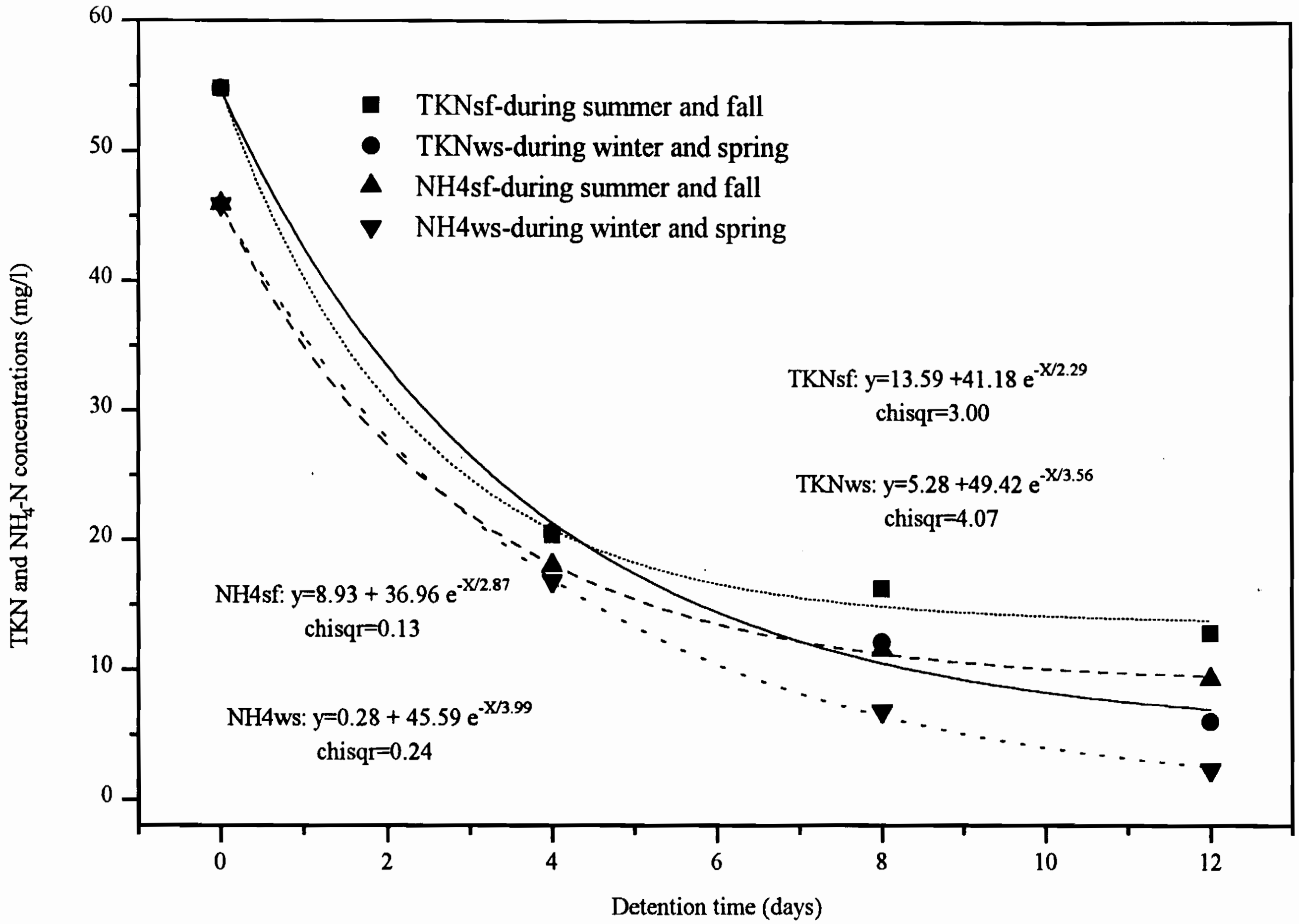

Figure 6.1 The effect of detention time on the TKN and NH$_4$-N in the samples collected from the shallow wastewater column in the SVBs at the Powell River Project site

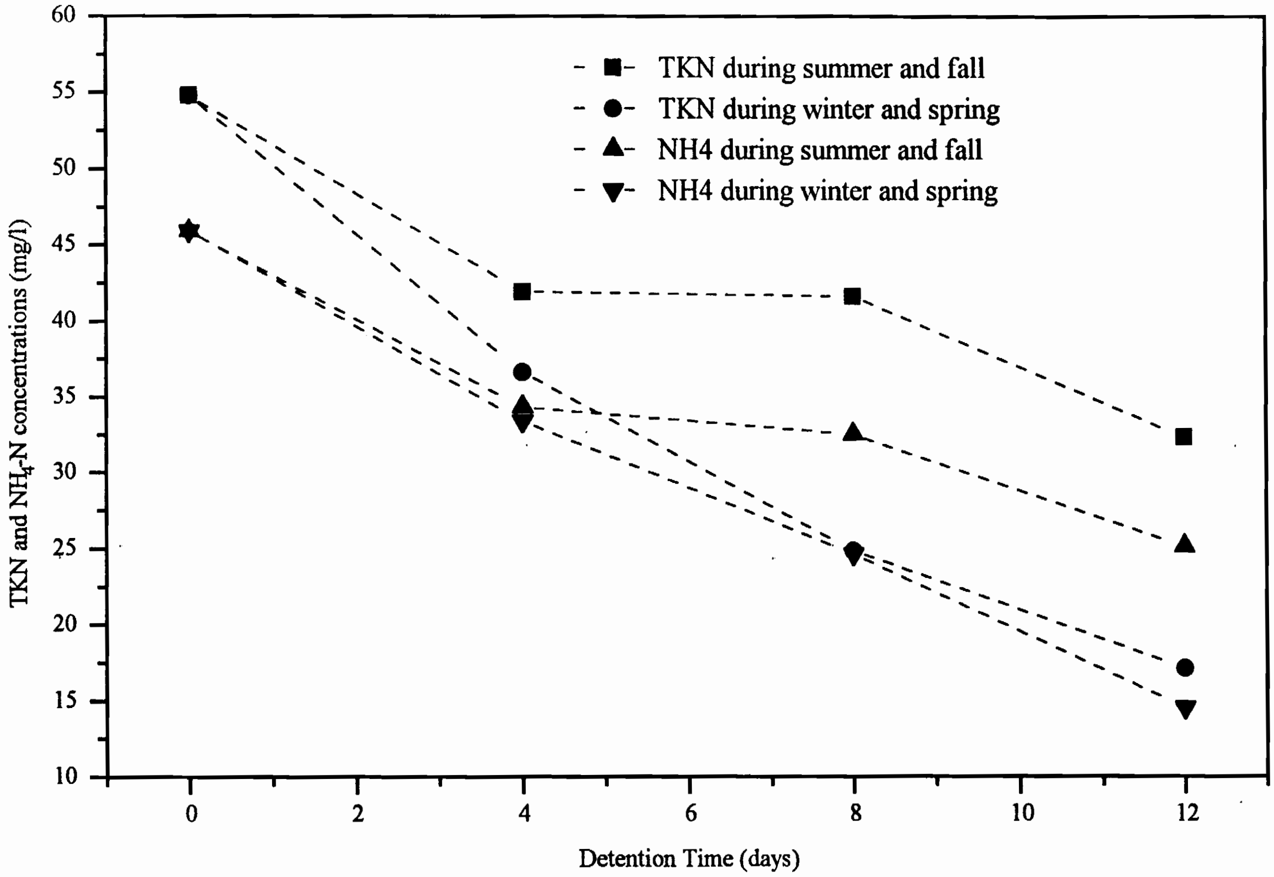

Figure 6.2 The effect of detention time on TKN and NH_4-N concentrations in the samples collected from the bottom of the SVBs at the Powell RiverProject site

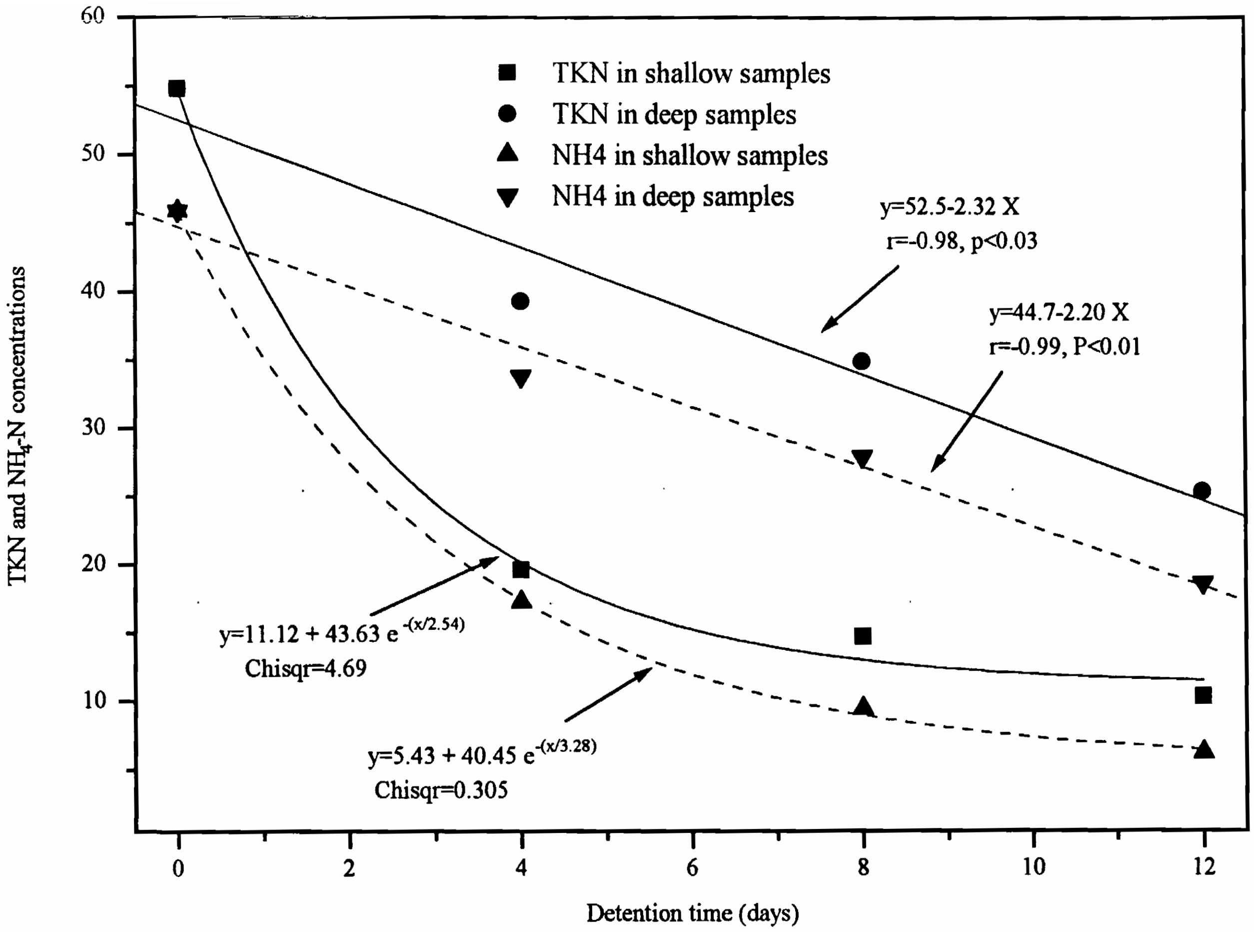

Figure 6.3 The effect of detention on TKN and NH_4-N concentrations in the samples collected from different depths of the SVBs at the Powell River Project site

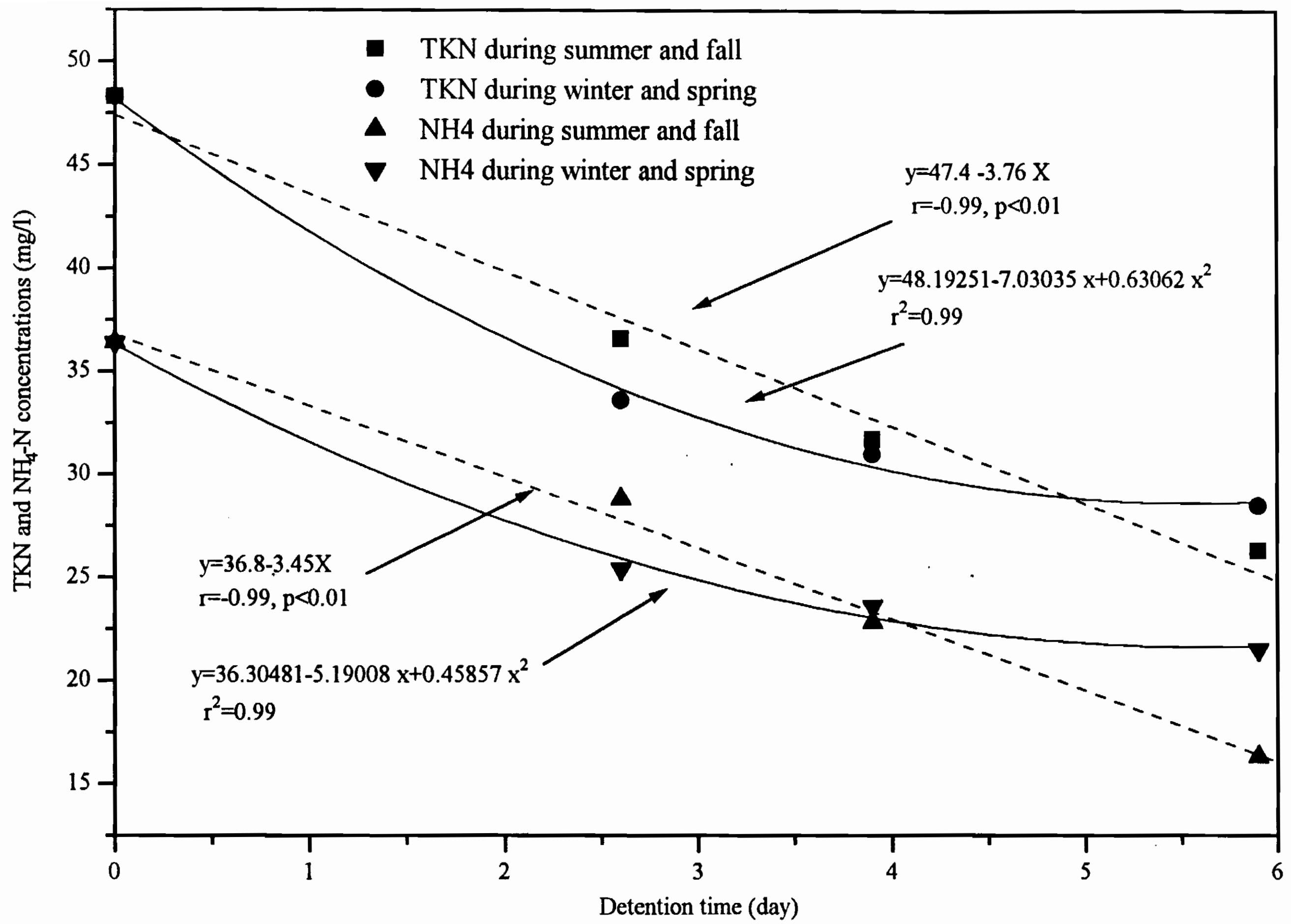

Figure 6.4 The effect of detention time on TKN and NH_4-N concentrations in the SVBE under different seasons at the Whitethorne Plantation Site

2.1. Detention time

There were differences in NH_4^+-N concentrations in the SVBE among detention times at both sites (Table 6.1). With increased detention time, NH_4^+ concentrations in the SVBE decreased rapidly at both sites (Table 6.1). Relationships between detention time and NH_4^+ concentration in the SVBE were similar to relationships between detention time and TKN concentrations in the SVBs (Figs.6.1, 6.2, 6.3 and 6.4), this is not unexpected since most of the TKN is present as NH_4^+-N. Nitrate concentrations were very low in both STE and SVBE (Table 6.1), and detention time did not influence NO_3^-concentrations in the SVBE. This may be resulted by anaerobic condition in the SVBs (low DO and Eh) and NO_3^- removed by denitrification instantaneously.

2.2 Sampling depth

Ammonium concentrations were higher in deep samples (10 cm above the bottom of the SVBs) than in shallow samples (10 cm below the water surface) (Table 6.1) at the PRP site. Also NH_4^+/TKN ratios were higher in the deep samples than in the shallow samples. This may indicated that more NH_4^+ was removed in the shallow part of the wastewater column with increased detention time. This is not unexpected since NH_3 volatilization mainly occurs near the water surface. Sampling depths did not affect NO_3^- concentration in the wastewater column. However, NO_3^- concentrations in the shallow samples tended to be higher than the concentration in the deep samples at the PRP site (Table 6.1). This may resulted from the higher DO in the shallow part of the wastewater column in the SVBs due to a higher root density closer to the surface, and also higher O_2 concentrations via diffusion from atmoshere.

Table 6.3 The impact of detention time on N concentrations in the SVBE under different seasons at the Powell River Project site

Detention	Shallow samples*					Deep samples				
	TKN		NH_4^+		NO_3^-	TKN		NH_4^+		NO_3^-
days	mg/l	rem. %	mg/l	rem.%	mg/l	mg/l	rem.%	mg/l	Rem.%	
STE	54.8		45.9		0.31	54.8		45.9		0.31
Summer and fall periods										
4	20.4 a**	62 c	18.0 a	61 d	0.33 a	41.9 a	22 d	43.3 a	27 c	0.25 a
8	16.2 ab	70 bc	11.5 b	75 c	0.27 a	41.6 ab	23 cd	32.5 a	30 c	0.22 a
12	12.8 b	76 b	9.3 bc	80 bc	0.17 a	32.3 bc	40 bc	25.1 b	46 b	0.19 a
Winter and spring periods										
4	20.6 a	62 c	16.8 a	64 d	0.18 a	36.6 ab	32 cd	33.4 a	28 c	0.25 a
8	12.1 bc	74 ab	6.8 c	85 b	0.24 a	24.8 bc	54 ab	24.6 b	47 b	0.28 a
12	6.0 c	89 a	2.3 d	95 a	0.19 a	17.1 d	68 a	14.5 c	69 a	0.24 a

* shallow samples-collected from 10 cm below the water surface; Deep samples-collected from the bottom of the SVBs.

** means followed by the same letter within the same row are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 6.4 The impact of plant species on N concentrations and removal percentages in the SVBS at the Whitethorne Plantation site

Detention time	Deep samples (2.5 cm from the bottom of the SVBs)				
	TKN		NH_4^+		NO_3-
days	mg/L	Removal %	mg/L	Removal %	mg/L
0*	48.3		36.4		0.27
	Cattail				
2.6	34.5 ab**	29 d	28.1 a	23 d	0.15 a
3.9	30.7 bcd	37 abc	22.7 c	38 b	0.15 a
5.9	26.8 d	45 a	17.6 d	52 a	0.14 a
	Woolgrass				
2.6	36.6 a	24 a	27.4 ab	25 cd	0.13 a
3.9	32.2 abc	33 bcd	23.4 bc	36 bc	0.13 a
5.9	27.3 d	43 ab	18.3 d	50 a	0.13 a

* influent (STE).

** means followed by the same letter within the same row are not significantly different at 5% level, determined by Duncan multiple range test.

Table 6.5 The impact of plant species on N concentrations and removal percentages in the SVBS at the Powell River Project site

	Shallow samples					Deep samples				
Detention	TKN		NH_4^+		NO_3^-	TKN		NH_4^+		NO_3^-
days	mg/l	rem. %	mg/l	rem.%	mg/l	mg/l	rem.%	mg/l	rem.%	mg/l
0*	54.8		45.9		0.31	54.8		45.9		0.31
					Cattail					
4	19.8 a**	63 b	17.5 a	62 b	0.39 a	38.3 ab	29 bc	33.1 ab	29 d	0.29 ab
8	14.5 ab	73 ab	10.1 b	79 ab	0.34 a	32.6 bc	39 bc	27.8 b	40 c	0.30 ab
12	9.6 b	82 a	5.3 b	89 a	0.19 b	22.0 c	59 a	15.4 d	67 a	0.32 a
					woolgrass					
4	19.4 a	64 b	16.8 a	64 b	0.19 b	40.3 a	25 c	34.5 a	26 d	0.22 ab
8	14.8 ab	72 ab	8.8 b	81 a	0.18 b	37.5 ab	30 bc	27.9 b	40 c	0.19 ab
12	10.9 b	80 a	7.0 b	85 a	0.18 b	28.4 bc	47 ab	21.8 c	53 b	0.12 b

* influent (STE).

** means followed by the same letter within the same row are not significantly different at 5% level, determined by Duncan's multiple range test.

2.3 Seasons

There was a seasonal impact on NH_4^+ concentrations in the SVBE at both sites (Tables 6.2 and 6.3). The NH_4^+ concentrations were higher at the longest detention time during the winter and spring period at the WP site, and lower at the PRP site during this season. At the WP site, NH_4^+ concentration in the SVBE were higher during the winter and spring than the summer and fall periods, which may be caused by a lower NH_3 volatilization rate during the colder seasons. At the PRP site, NH_4^+ concentrations in both the shallow and deep samples were higher during the summer and fall period than the winter and spring period, which may be a result of water loss via ET during the warmer seasons and dilution from precipitation during the cooler seasons. This is not unexpected since NH_4^+ would become more concentrated at the longer detention times because of ET. The STE source and the plant densities at the two sites may also contribute to the seasonal affect observed. STE at the PRP site had higher NH_4^+/TKN ratio than STE at the WP site (Table 6.1). There were no differences in NO_3^- concentrations between seasons.

2.4 Plant species

Plant species did not impact on NH_4^+ and NO_3^- concentrations in the SVBE at the WP site (Table 6.4). There were no differences in NH_4^+ concentrations in shallow samples between the SVBs planted to cattail and woolgrass (Table 6.5), but NH_4^+ concentration in deep samples was higher in the SVBs planted to woolgrass than cattail (Table 6.5). The NO_3^- concentrations in both shallow and deep samples were higher in the SVBs planted to cattail than those planted to woolgrass. This may imply that cattail's root system transported more O_2 deeper into the wastewater column. The higher Eh values at the deeper depths in the SVBs planted to cattail compared to those planted to woolgrass supports the above observations.

3. Denitrification

Nitrogen can exist at various states in nature and is transformed by organisms along two opposite pathways in the N cycle-reduction (denitrification) and oxidation (nitrification). Ammonium is converted to NO_3^- primarily by *Nitosomonas* and *Nitrobacter* bacteria, then denitrification bacteria utilize NO_3^- as a terminal electron acceptor for their respiration under anaerobic condition thus converting NO_3^- into N_2O and N_2. The SVB form of constructed wetlands provides an environment that is well suited to foster this process, thus N can potentially be removed from the SVB systems. However, there are several environmental limitations to denitrification. Following are four general requirements imposed by microorganism on denitrification (Ritter and Eastburn, 1988): 1. Presence of suitable bacteria which are capable of providing the required enzymes; 2. Suitable C source to fuel the anabolism; 3. Release of O_2 repression of these enzymatic systems; 4. Suitable N oxides compounds to serve as terminal electron acceptors in place of O_2. Denitrification is influenced by temperature, pH, Eh, high concentration of heavy metals (Chang et al., 1982; Smith, et al., 1983) and pesticides (Grant and Payne, 1982). In the soil, denitrification is achieved in a simultaneous nitrification and denitrification system, and was dependent on mean residence time, C/N ratio, temperature (Bremner and Shaw, 1958; Panganinan, 1985), partial pressure of O_2, and NH_4^+ concentration (Firestone, 1982). The optimum range for many denitrifying organisms is between pH 5 and 9 (Focht and Verstraete, 1977; Delwiche and Bryan, 1976). The rate of denitrification increased rapidly with rise in temperature from 2 to 25 °C. The C:N ratio of an average STE was 10:1, and a C:N ratio of 4:1 was optimal to produce satisfactory denitrification (Sikora and Corey, 1976). Nitrogen in the SVBs is removed primarily by denitrification and NH_3 volatilization. Plant uptake accounts for a minor portion of the observed N removal. There is limited data available to quantify N loss via denitrification; however, a recent study reported 25-30 kg/ha/year of N loss as gaseous N (N_2 and N_2O) with an appreciable amount diffusing through aerechymal structures into the atmosphere (Faulkner and Richardson, 1989). Stengel et al. (1989) employed the acetylene blockage technique to estimate denitrification rate in an artificial wetlands, and reported from 75 to 90% of the decrease in NO_3-N corresponded to N_2O in the effluent.

Although the denitrification processes have been of interest to soil scientists and microbiologists for many years, few field studies have been conducted with gravel based SVB systems to determined N loss via this mechanism because of the difficulty in making *in situ* measurements. In the SVB environment, conditions are favorable for denitrification during the warm seasons such as adequate C, suitable pH, and oxidizing microzones in an otherwise anaerobic environment with the exception of low NO_3-N concentration present, but low NO_3-N concentration might also indicate immediate loss of NO_3-N via denitrification. The Eh values ranged from -87 to +117 mV at the shallow depth, and from -334 to -211 mvolts at the deeper depth. Lower Eh values indicate more anaerobic conditions (Table 5.1). According to Good and Patrick, (1989), NO_3^- is reduced when the Eh reaches approximately 220 mV (assuming pH=7) in the water-sediment interface, then NO_3^-reduction is followed by manganic manganese (200 mV), Fe^{3+} (120 mV), SO_4^{2-} (from -75 to -150 mV), and CO_2 (from -250 to -300 mV). The Eh values at the shallow depth were higher and normally associated with the disappearance of NO_3^- and formation of Mn^{2+} and Fe^{2+}, and the Eh values at the deeper depths indicate conditions where H_2S and CH_4 might form. Chan and Knowles (1979) reported that the rate of 2.2 and 2.6 mg of N/m^2/day (800-950 mg/m^2/year) would likely represent the *in situ* rates of denitrification of fresh sediments in the presence and absence of macrophytes in fresh sediments. While Bowen (1987) reported the potential reduction of N by denitrification ranged from 55 to 219 mg N/m^2/day (20-80 g /m^2/year) in freshwater wetlands. Bowen's values are closer to the denitrification rates measured in this study (33-267 mg N/m^2/day, Table 6.6).

3.1 Detention time

There was little difference among detention times except for denitrification rates measured on June 4, 1993, which were higher at the 2.6 days detention times. However, all 14 replications including both cattail and woolgrass were consistent for denitrification rates (Table 6.6). Denitrification rates tended to be higher at 3.9 days detention time than the other two detention times (Table 6.6). Denitrification rates decreased after 4 days detention time (Table 6.6). It should also be noted that designed detention times would become shorter after plant root systems fully developed. Having adjusted for the volume occupied by root systems, the actual detention times were approximately 2.1, 3.0, and 5.0 days for three designed detention times, respectively. Since plant stands were better in the SVBs with 3.9 days than that of the 2.6 days and 5.9 days detention times, biomass of roots were also higher in the SVBs with 3.9 days detention times. This indicated that favorable environment for plants might also be beneficial to microorganisms. It is interesting to note that denitrification rates measured on the four different dates were very close, the one exception was for the highest denitrification rate measured on June 4, 1993 at 2.6 days detention time (Table 6.6). Temperature might have some impact on denitrification in the SVBs, but it is probably not the major factor. All measurements were conducted between 12 noon to 3 pm, which means small variation in the maximum daily air temperature. However on the June 4, 1993, the temperature was higher than on any other date (Table 6.7), and denitrification rate was also higher at 2.6 days detention time.

3.2 Plant species

With respect to the effect of plant species on denitrification, the results suggested that there were little difference in denitrification rates among the SVBs planted to cattail and woolgrass in the same treatment, and denitrification rates would vary depending on seasonal conditions (Table 6.7). However, it is still unknown which factor impacted denitrification during a particular measuring period, measured denitrification rates only reflect the instantaneous rate at that time. Both cattail and woolgrass have a large quantity of root biomass, which can provide biological reaction sites for microorganisms to facility all kinds of biological reaction within the SVBs. Both plant species can transport O_2 from the atmosphere to roots, and release excess O_2 to the rhizosphere, which facilitates the transform of NH_4^+ to NO_3^-. Denitrification occurs when NO_3^- produced in the aerobic rhizosphere diffuses into the anaerobic zones surrounding the rhizosphere. It should be noted that denitrification rates were 6 time higher at the 2.6 days detention time on June 4, 1993. This may indicate the potential for denitrification under a favorable environment.

4. Denitrification Potential

Denitrification has been shown to be an important process for removal of N in wetlands. To determine the potential for wetlands to remove NO_3^-, laboratory studies were conducted where the NO_3^- and C concentrations were varied. It is impossible to determine these values in the SVBs because of the very low NO_3^- concentrations present. When NO_3^- is supplied at large concentrations, denitrification may still be limited if energy (C source) becomes a limiting factor. Therefore, high concentration of C (1800 mg/L of $C_6H_{12}O_6$) was added into the STE and SVBE to estimate denitrification potentials. The differences in denitrification potentials in the SVBE and STE were estimated by conducting experiments with addition of different NO_3^- concentrations to the STE and SVBE. Denitrification increased dramatically when NO_3^- was added to the SVBE and STE (Table 6.8, Figs. 6.5, and 6.6). In the first experiment where low concentrations (12 mg/L) of NO_3^- was added to the effluent, denitrification potentials tended to be much higher than the treatments that received no NO_3^-. In the second experiment where high concentration of NO_3^- was added to the effluent, denitrification potentials tended to be higher than treatments that recieved lower

Table 6.6 The effect of detention time on denitrification rates in the SVBs at the Whitethorne Plantation site

Detention (days)		Denitrification rate ($N_2O/m^2/hr$)				
designed	actual	11/18/92 (16.7 °C)*	6/4/93 (26.7 °C)	9/24/93 (24.4 °C)	3/30/94 (11.4 °C)	average
2.6	2.1	2.46 (12)* a#	17.5 (14) a	2.47 (13) a	4.32 (8) a	6.69
3.9	3.0	4.98 (28) a	5.95 (29) b	3.96 (30) a	4.77 (16) a	4.92
5.9	5.0	3.93 (16) a	2.85 (14) b	2.66 (14) a	2.18 (7) a	3.87

* number of replications.

\# means followed with the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 6.7 The effect of treatment on denitrification rate in the SVBs at the Whitethorne Plantation site

Treatment			Denitrification rate			
Loading rate	Detention time	Recirc ratio	N_2O mg/m^2/day			
			11/18/92	6/4/93	9/24/93	3/30/94
cm/d	days	%	16.7 °C[**]	26.7 °C	24.4 °C	11.4 °C
			Cattail			
4.00	2.6	0	2.51 a[*] (8)[#]	13.7 ab (6)	1.11 b (6)	1.07 a (4)
2.65	3.9	0	8.25 a (8)	5.28 b (6)	2.07 b (7)	9.79 a (4)
2.65	3.9	50	8.15 a (8)	3.00 b (8)	3.52 ab (8)	0.99 a (4)
1.75	5.9	50	6.67 a (8)	3.82 b (6)	1.47 b (8)	1.91 a (4)
			Woolgrass			
4.00	2.6	0	2.33 a (4)	20.3 a (8)	3.64 ab (6)	3.65 a (4)
2.65	3.9	0	0.67 a (8)	7.06 b (7)	6.08 a (7)	4.33 a (4)
2.65	3.9	50	0.71 a (8)	8.41 ab (8)	4.20 ab (8)	3.94 a (4)
1.75	5.9	50	1.19 a (4)	2.13 b (7)	4.26 a (6)	6.68 a (4)

* means followed with the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test. **numbers of replications.

**Maximum atmosphere temperature; # numbers of replications;

Table 6.8 Denitrification potential in the STE and SVBE from the Whitethorne Plantation site, April, 1994

Effluent type	Experiment 1 4/4/94	Accumulated N_2O mg d^{-1}	Experiment 2 4/14/94	Accumulated N_2O mg d^{-1}
STE	Control	0.01	Control	0.013
SVBE (2.6 d)		0.014		0.044
SVBE (3.9 d)		0.01		0.066
SVBE (5.9 d)		0.009		0.048
STE	$C_6H_{12}O_6$ (1800 mg L^{-1}) addition	0.004	$C_6H_{12}O_6$ (1800 mg L^{-1}) addition	0.008
SVBE (2.6 d)		0.008		0.012
SVBE (3.9 d)		0.008		0.013
SVBE (5.9 d)		0.008		0.012
STE	NO_3^- (12 mg L^{-1}) addition	0.618	NO_3^- (84 mg L^{-1}) addition	7.56
SVBE (2.6 d)		0.903		6.75
SVBE (3.9 d)		1.27		6.27
SVBE (5.9 d)		1.13		5.96
STE	$C_6H_{12}O_6$ (1800 mg L^{-1}) NO_3^- (12 mg L^{-1}) addition	0.933	$C_6H_{12}O_6$ (1800 mg L^{-1}) NO_3^- (84 mg L^{-1}) addition	9.53
SVBE (2.6 d)		1.54		8.77
SVBE (3.9 d)		1.89		8.33
SVBE (5.9 d)		1.42		8.06

STE-septic tank effluent;
SVBE-subsurface vegetated bed effluent;
2.6, 3.9, 5.9 d are STE residence time (detention time) in the SVBs.

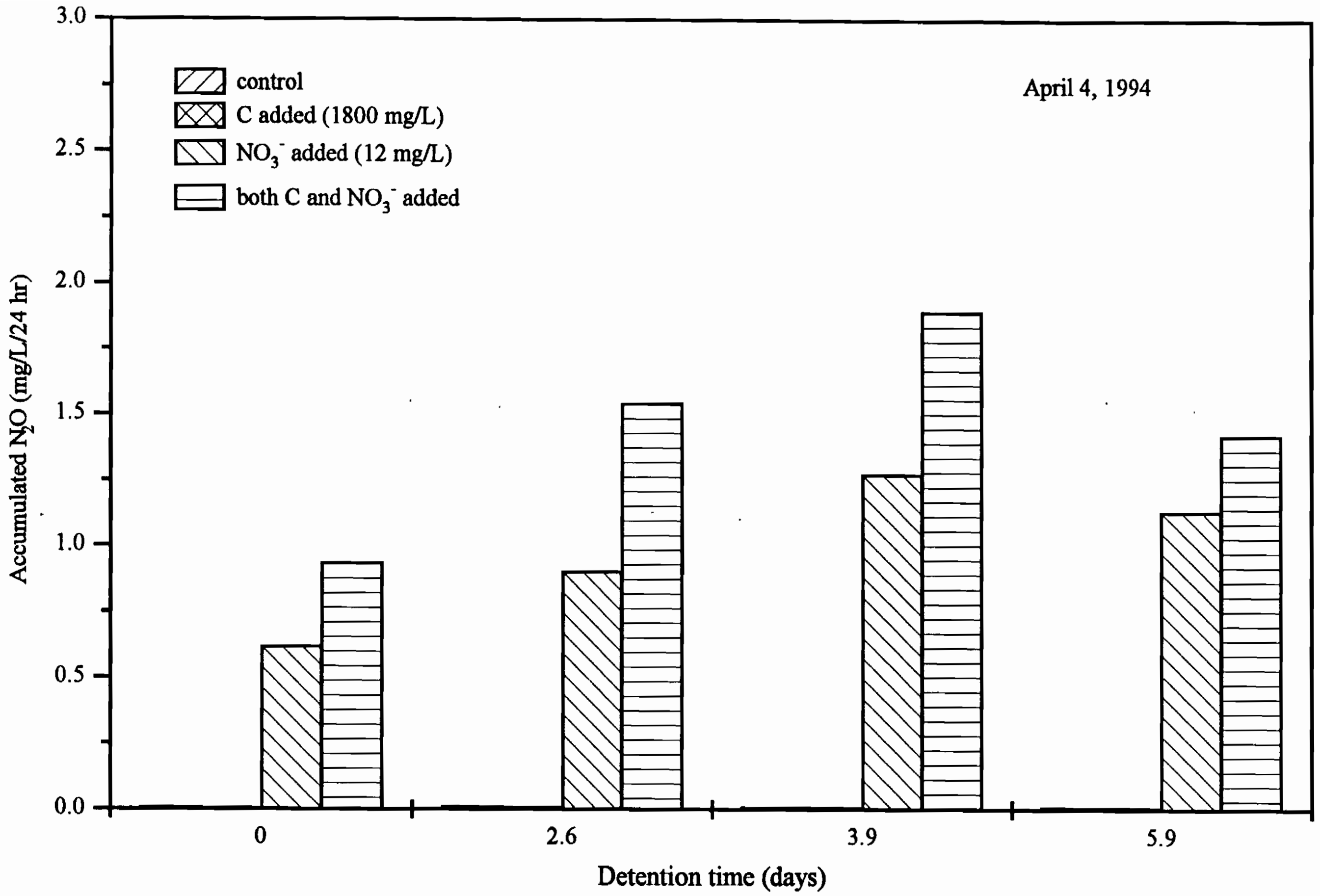

Figure 6.5 Denitrification potential in the STE and SVBE at the Whitethorne Plantation site

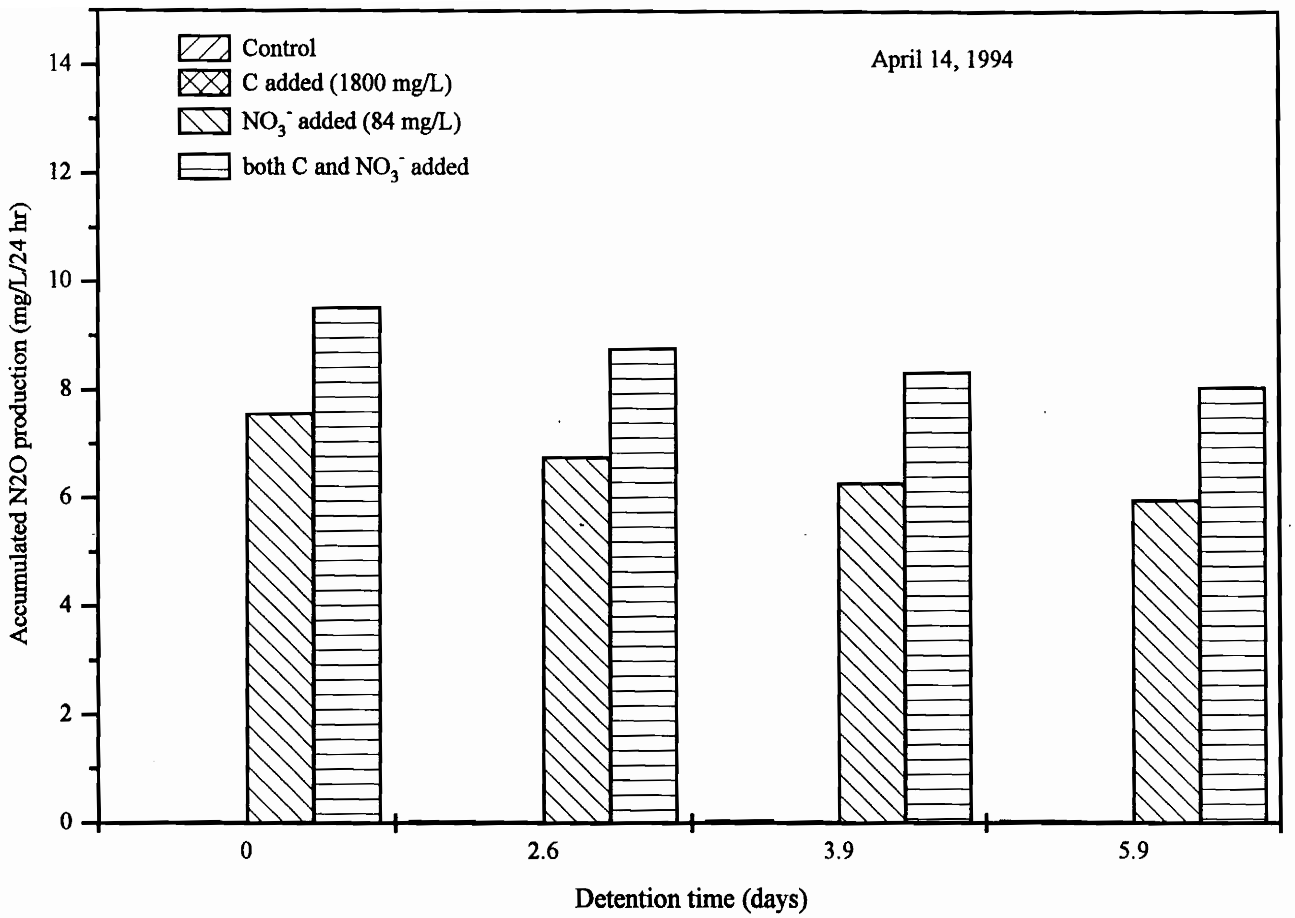

Figure 6.6 Denitrification potential in the STE and SVBE at the Whitethorne Plantation site

additions of NO_3^-. Addition of C without addition of NO_3^- to both STE and SVBE did not increase the denitrification potential. Effluent that received both NO_3^- and C tended to have higher denitrification potentials than effluent that received NO_3^- only. These results indicate that NO_3^- concentration is the major limiting factor which controls the denitrification process in the SVBs, and that C concentration is not the limiting factor at low NO_3^- level (<12 mg/L). However, this result can not be interpreted as the actual potential of the SVBE denitrification capacity in the field. In this study, denitrification potentials were measured in an ideal closed system. According to Reed et al. (1994), a ratio of BOD/NO_3-N from 5 to 9 is required for complete denitrification, which means that STE at the WP site, with an average 124 mg BOD L^{-1} would have a maximum denitrifying capacity of 13-24 mg NO_3^- L^{-1} and 15-29 mg NO_3^- L^{-1} for the PRP site (135 mg L^{-1} BOD in the STE).

5. Ammonia Volatilization

The sequential processes of mineralization, nitrification, and denitrification have been thought to dominate N cycling in natural wetlands (Bowden, 1987), and N loss via NH_3 volatilization was considered as a minor process (Faulkner and Richardson, 1989). The amount of DO in the gravel based SVB system is limited, especially at the bottom of the SVBs, which is normally anaerobic (Huang et al., 1994). Therefore, nitrification was restrained. Nitrate concentration in the STE is also very low (Huang et al., 1994). Sequentially, low NO_3-N content may become a limiting factor for denitrification in the SVB system. High N removal rates in the some SVB systems have been reported during recent years (Knight et al., 1993; Waston et al., 1989), which implied that NH_3 volatilization might be partially responsible for N removal in the SVB systems. Ammonia volatilization from flooded soils has been studied for years, but there is no consensus on the importance of NH_3 volatilization in N cycling (Vlek and Craswell, 1981). Jayaweera and Mikkelsen (1991) concluded that from 10 to 60% of the N applied was lost via NH_3 volatilization from flooded soil systems, and N losses varied depending on water pH, N source, rate (NH_4^+ concentration), time, and method of application (Mikkelsen et al., 1978). Field ^{15}N balance studies in wetland rice have shown that the loss of N ranged from 35-60% after application of urea or ammoniacal-N in floodwater (Cao and De Datta, 1984; Fillery et at., 1986; Fillery and Vlek, 1986). The NH_3 volatilization process is directly influenced by floodwater NH_4^+ concentration, pH, temperature, depth of floodwater, and wind velocity (Jayaweera and Mikkelsen, 1990). The pH of floodwater has a tremendous impact on NH_3 volatilization (Mikkelsen et al., 1978; Vlek and Craswell, 1981; Jayaweera and Mikkelesn, 1990). Aqueous NH_3 in floodwater increase about ten fold per unit increase in pH between 7.5 and 9.0 (Vlek and Stumpe, 1978; Vlek and Craswell, 1981), but if the pH value is less than 6.6, there was little to no NH_3 volatilization from a wastewater detention pond (Pano and Middlebrook, 1982). With respect to the effect of temperature on NH_3 volatilization, Vlek and Stumpe (1978) suggested an exponential increase of NH_3 loss with temperature for tropical climates. In freshwater wetlands, N removal by NH_3 volatilization was considered to be a minor factor (Faulkner and Richardson, 1989), that may be caused by both low concentration of NH_4^+ and the long distance between sediment and surface. Murphy and Brownlee (1981), however, observed that NH_3 volatilization in a hypertrophic lake was significant during the periods of high pH and NH_3 concentration, that resulted from the collapse of the algae bloom. In the gravel based SVBs designed to treat domestic wastewater, NH_3 volatilization may play a significant role in the N cycling due to its favorable environment (high pH and available NH_3 sources).

Most NH_3 volatilization research has focused on N loss from agricultural activities such as fertilization of NH_4^+ fertilizers, animal manures, and compost of organic manures. Few field studies with SVB systems have determined N loss via NH_3 volatilization mechanism due to difficulty associated with *in situ* measurement.

5.1 Detention time

In the SVB environment, conditions are favorable for NH_3 volatilization such as suitable pH (>7.4), and high NH_4^+ concentrations (Table 6.1). There were no differences in NH_3 volatilization (Table 6.9) among the three detention times and NH_4-N concentrations, this might indicate that there were abundant sources of NH_3 in the system. According to Thurston et al. (1979), if fresh water temperature is 25°C, and pH is 7.4, and it has a low total dissolved solids (200-300 mg/l), the ratio of NH_4^+ to NH_3 concentration is 1: 0.0141. Therefore, where concentrations of NH_4^+ in the SVBs were 23.3 to 32.2 mg L^{-1}, about 0.33-0.45 mg L^{-1} of NH_3 might be expected in the SVBs, which means that each SVB would contain up to 13 -18 mg NH_3 at equilibrium. Therefore, once NH_3 volatilization occurred, the driving force [(difference in partial pressure of NH_3 between the atmosphere and the water column (γG)] would continue to drive the reaction toward NH_3, NH_3 would then diffuse to the atmosphere. In addition, weather conditions such as high wind speed, and high air temperature would enhance this diffusion process. However natural wetlands and freshwater wetlands are different from the SVBs, the equilibrium of NH_4^+ and NH_3 in the system might be different due to higher salinity and total dissolved solids. Higher salinity and total dissolved solids will decrease the percentage of NH_3 in the waters column (Thurston et al., 1979). Although there were no differences among detention times, the longest detention times tend to have higher NH_3 volatilization rates. This could result from increased percentage of NH_3 in the wastewater column due to lower salinity and total dissolved solids concentrations at 5.9 days detention time compared with the other two detention times (Huang et al., 1994). Two different sampling dates gave similar results for NH_3 volatilization, this may have resulted from similar weather conditions (air temperature and relative humidity) at the two measuring dates.

5.2 Plant species

There were no differences between the two plant species in NH_3 volatilization rates (Table 6.10). Ammonia volatilization is mainly a chemical or physical-chemical process instead of biological process, so plant species would be expected to have limited impact on NH_3 volatilization. However, different plant species could transport varying amounts of O_2 from air to the root zones, thus enhancing nitrification and decreasing the quantity of NH_3 lost to the atmosphere via aerachymal structures.

6. Nitrogen Uptake By Plants

Nitrogen removed by plant uptake is a non-significant factor unless plants are harvested. It is not feasible to remove or harvest plant biomass in large scale constructed wetlands. However, it is easy to harvest the aerial parts of plant during the growing season from the prototype SVBs employed in this study (Table 6.11). There were no differences in tissue N content among detention times and between plant species. However, N content in plant tissue in both species were higher at the WP site than at the PRP site, this may result from different harvest dates for the two sites. Plant tissues were harvested at the WP site on June 9, 1993, while plant tissues were collected at the PRP site on June 29, 1993. In addition, the plants harvested at the PRP site were more mature than plants harvested at the WP site.

7. Nitrogen Budget In the SVBs

The N budget in SVBs can be estimated by calculation of total N input and total N concentration in the SVBE. Total N includes the reduced form (measured as TKN) and oxidized forms (measured as NO_3^-). Total N input can be estimated by dosing rate (L/d) multiples TKN and NO_3^- concentration in the STE. Assuming water balance, total N in the effluent also can be estimated by N concentration in the SVBE. Denitrification and NH_3 volatilization rates were determined during the same period of time.

Nitrogen removal by NH_3 volatilization is shown in Table 6.12. Nitrogen removal percentages increased with detention time, and removal rates ranged from 7 to 37% with an average removal rate of 20% based on total N applied to the SVBs. The NH_3 volatilization rates and total quantities of N loss via this process were similar between years when measured during the same season (similar maximum temperature and humidity) (Table 6.9), but N via NH_3 volatilization removal percentages based on total N applied to the SVBs were different (Table 6.12). This may imply that the NH_3 volatilization rate would achieve the maximum rate when NH_4^+ concentration in the SVB was high enough, and then NH_3 volatilization would be time dependent.

Nitrogen removal by denitrification is listed in Table 6.13. Nitrogen removal rates ranged from 2-17 % with an average of 5% of total N applied to the SVBs. Losses via denitrification were similar except for the denitrification rates measured in the 2.6 day detention time SVBs on June 4, 1993 (Table 6.13). This suggested that the denitrification process was limited by NO_3^- concentration in the SVBE, but if environment conditions were favorable for both nitrification and denitrification, denitrification rates as high as 267 N mg /d/m^2 (100 N mg/d/SVB) could be achieved.

It should be noted that total N removed by denitrification and NH_3 volatilization only accounted for 30-48% of total N removal in the September, 1993. This indicated that more than 50% of N loss was unaccounted for. Although plant uptake and microorganisms may fix certain percentage of N in their biomass, and some organic N would retain in sediment at the bottom of the SVBs, gaseous N (NH_3, N_2 N_2O, and NO etc.) loss via aerachymal structures may account for large percentage of unaccounted N loss. Because plant root and leaf surface areas were much greater than the SVB surface areas. Therefore N loss via denitrification and NH_3 volatilization may be underestimated based on surface areas of the

SVBs.

Plant uptake of N is considered to account for a minor portion of the N removal in the SVB system, because N immobilization by plant tissue would recycle back to the system unless plant biomass were harvested. However in the small scale SVBs, the upper portion of plant tissues can be harvested during the growing season (late May or early June). If plant tissue was only harvest once a year, plant uptake N could accounted for 6 to 19% of total N removal annually for cattail, and 5-9% for woolgrass (Table 6.14). A N budget conducted for the SVBs during September 1993, indicated that only 3-5% of the N budget could be attributed to plant uptake (Tables 6.15 and 6.16).

Nitrogen losses attributed to NH_3 volatilization were greater than losses from denitrification in the SVBs. Volatilization of NH_3 is undesirable in N rich environments where it just transfers pollutant from liquid phase to gaseous phase. However, in N deficient plant systems the addition of N from NH_3 volatilization may be beneficial. Denitrification is a desirable process when the final product is N_2, which is a primary component of the atmosphere. To enhance denitrification in the SVBs, increasing NO_3^- concentrations in the influent may be the only economic feasible method. For instance, it is possible to increase NO_3^- concentrations by cycling a portion of the wastewater through a sand filter, and then introducing the nitrified effluent into the constructed wetland.

Table 6.9 The effect of detention time on ammonia volatilization rate in SVBs at the Whitethorne Plantation site

Detention time (days)		Ammonia volatilization rate NH_3 mg/m^2 /d	
designed	actual	Sep., 13, 1993 (8-27.5°C) (36-101 % RH*)	Aug., 8, 1994 (15.2-27.4 °C) (50-101% RH)
2.6	2.1	158.7 a* (8**)	160.1 a (4)
3.9	3.0	156.7 a (16)	145.9 a (8)
5.9	5.0	169.9 a (8)	220.6 a (4)

* means followed with the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

** number of replications.

Table 6.10 The effect of treatment on ammonia volatilization rates in the SVBs at the Whitethorne Plantation site

Treatment			Ammonia volatilization rate (NH_3 mg/m^2/d)	
loading rate	detention time	recirculation ratio	Sep., 13, 1993	Aug., 8, 1994
			8-27.5 °C, 36-110% RH*	15.2-27.4 °C, 50-101% RH
cm/d	days	%		
			Cattail	
4.0	2.6	0	156.8 a** (4)***	150.6 b (2)
2.7	3.9	0	165.2 a (4)	112.7 b (2)
2.7	3.9	50	175.1 a (4)	169.8 b (2)
1.8	5.9	50	161.3 a (4)	225.6 a (2)
			Woolgrass	
4.0	2.6	0	160.6 a (4)	169.8 b (2)
2.7	3.9	0	147.5 a (4)	142.6 b (2)
2.7	3.9	50	145.7 a (4)	158.1 b (2)
1.8	5.9	50	178.2 a (4)	215.3 a (2)

*RH-relative humidity;

** means followed with the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

*** numbers of replications.

Table 6. 11 Nitrogen content in plant tissues in 1993

Whitethorne Plantation Site			Powell River Project Site		
Treatment		N content	Treatment		N content
Detention (days)	Plant species	%	Detention (days)	Plant species	%
2.6	cattail	3.20 a	4	cattail	2.51 a
3.9	cattail	2.98 ab	8	cattail	2.27 ab
5.9	cattail	2.95 ab	12	cattail	2.03 ab
2.6	woolgrass	2.98 ab	4	woolgrass	1.99 ab
3.9	woolgrass	3.08 ab	8	woolgrass	1.95 ab
5.9	wwolgrass	3.00 ab	12	woolgrass	1.80 b

* means within the same column followed by the same letter are not significantly different, determined by Duncan's multiple range test.

Table 6.12 Total N removed by ammonia volatilization in the SVBs at the Whitethorne Plantation site

Detention time	STE in	TN[a] in	TN[b] out	TN[c] removed		TN removed by NH_3 volatilization	
days	l/d	mg/d	mg/d	N mg/d	%	N mg/d	%
September 13, 1993							
2.6	15.1	861.8	505.8	356.0	41.3	59.4	6.9
3.9	10.0	570.7	315.8	254.9	44.7	58.7	10.3
5.9	6.62	377.8	192.3	185.5	49.1	63.6	16.8
August 7, 1994							
2.6	15.1	506.8	337.7	169.1	33.4	59.9	23.1
3.9	10.0	335.6	217.7	117.9	35.1	54.6	23.2
5.9	6.62	222.2	129.7	92.7	41.7	82.6	37.1

a- Total N applied to the SVBs as TKN + NO_3^-;

b- Total N in the SVBE.

c-Total N removed in the SVBs daily.

Table 6.13 Total N removed by denitrification in the SVBs at the Whitethorne Plantation site

Detention time	STE in	TN[a] in	TN[b] out	TN[c] removed		TN removed by denitrification	
days	l/d	mg/d	mg/d	mg/d	%	mg/d	%
			November 18, 1992				
2.6	15.1	436.4	284.3	152.1	34.9	14.0	3.2
3.9	10.0	289.0	174.3	114.7	39.7	28.5	9.9
5.9	6.62	191.3	67.4	123.9	64.8	22.6	11.8
			June 4, 1993				
2.6	15.1	595.8	358.5	237.3	39.8	100.0	16.8
3.9	10.0	384.6	144.4	240.2	62.5	34.0	8.6
5.9	6.62	261.2	53.4	207.8	79.6	16.3	6.2
			September 24, 1993				
2.6	15.1	735.4	488.2	247.2	33.6	14.2	1.9
3.9	10.0	486.2	278.3	207.9	42.8	22.6	4.6
5.9	6.62	321.5	154.4	167.1	52.0	15.2	4.7
			March 30, 1994				
2.6	15.1	1051	775.2	275.8	26.4	24.7	2.4
3.9	10.0	697.5	465.8	231.7	33.2	27.3	3.9
5.9	6.62	461.7	254.3	207.4	44.9	12.5	2.7

a- Total N applied to SVBs as TKN + NO_3^-;

b- Total N removed by denitrification;

c- Removed percent;

Table 6.14 N removed by plant tissues in the SVBs at the Whitethorne Plantation site in 1993

Treatment		TN in	TN out	TN Rem	Plant biomass	N in tissue	N removed by plant tissues	
Detention (days)	Plant species	g/year				%	g/year	removal %
2.6	cattail	268	153	115	201	3.2	6.4	2.4
3.9	cattail	177	90	87	390	2.98	11.6	6.6
5.9	cattail	117	52	65	410	2.95	12.1	10.3
2.6	woolgrass	268	162	106	185	2.98	5.5	2.1
3.9	woolgrass	177	94	83	236	3.08	7.3	4.1
5.9	woolgrass	117	53	64	198	3	5.9	5.0

Table 6.15 Denitrification and ammonia volatilization in the SVBs during the same measuring period at the Whitethorne Plantation site, September, 1993

Detention time	TKN	NO_3^-	Denitrification rate	NH_3 volatilization rate
days	mg/L		N_2O mg/m^2/day	NH_3 mg/m^2 /day
0*	56.9	0.17		
2.6	33.3	0.19	59.3 a** (13)	158.7 a (8)
3.9	29.6	0.20	95.0 a (30)	156.7 a (16)
5.9	28.8	0.25	63.8 a (14)	169.9 a (8)

* influent (STE)

**means followed by the same latter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 6.16 N budget in the SVBs at the Whitethorne Plantation site, September, 1993

Detention days	STE in	TN[a] in	TN[b] out	TN[c] Rem.	NH_3[d] Rem	N_2O[e] Rem	Total N removed %			
designed	l/d	as N mg/d					total	NH_3[f]	N_2O[g]	NH_3+ N_2O[h]
2.6	15	735	490	245	59	14	33	8.0	1.9	10
3.9	10	486	279	207	59	23	43	12.1	4.7	17
5.9	6.6	322	155	167	64	15	52	19.9	4.7	25

a-Total inputed TKN and NO_3^-based on N;
b-Total TKN and NO_3^- in the SVB effluent based on N;
c-Total N removed in the SVBs;
d-Total N removed by NH_3 volatilization;
e-Total N removed by denitrification.
f-Total N removal rate by NH_3 volatilization based on total N applied.
g-Total N removal rate by denitrification based on total N applied.
h-Total N removed by denitrification and NH_3 volatilization

IV. CONCLUSIONS

1. TKN removal rates ranged 33-50% at the WP site, and 27-81% at the PRP site. NH_4^+-N reduction ranged from 30 to 61% at the WP site, and 27-87% at the PRP site. Both TKN and NH_4^+ removal percentages increased with detention time at both sites. Nitrate concentrations were very low in the SVBE at both sites. Water quality exhibits a higher level of treatment in the shallow wastewater column as compared to the deeper wastewater column at the WP site.
2. There was little seasonal impact on N removal at the WP site; however, there was a seasonal impact on N removal at the PRP site. Higher TKN and NH_4-N removal rates were observed during the winter and spring period than during the summer and fall period in both deep and shallow samples.
3. Denitrification was limited by the low NO_3^- concentration in the SVBs. N removed via denittrification ranged 35 to 267 N mg/d/m^2, N removed via denitrification process ranged 2-17% of total N applied. The SVBs had a higher potential for denitrification if a suitable concentration of NO_3^- was present in the system. Carbon would not limit denitrification in the SVBs as long as NO_3^- concentration remained low.
4. Ammonia volatilization was high during the warmer seasons and accounted for 7-37% of total N applied to the SVBs, N removed via NH_3 volatilization process ranged 147-221 N mg /d/m^2.
5. If plant tissues were harvested once a year during the growing season, N removal by cattail ranged from 2-10%, and woolgrass accounted for 2 - 5% of the total N applied to the SVBs annually.

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Chapter VII:

SELECTED CHEMICAL PARAMETERS

ABSTRACT

The SVB type of constructed wetland has been studied and documented for renovation of various wastewaters (Hammer, 1989 and Moshiri, 1993). However, most of these documents are case reports, and lack systematic investigation and long-term observation. This research consisted of studies conducted with prototype systems at the WP site and the PRP site to evaluate the SVB form of constructed wetlands. Domestic wastewater was applied to the SVBs at the WP site from a pump chamber placed between the septic tank and the existing drainfield. Sixteen small scale SVBs were installed down slope of the residence. Treatments for the small scale field experiment included three detention times (2.6, 3.9, and 5.9 days), two recirculation ratios (0 and 0.5), and two plant species (woolgrass and cattail). Treatments for the SVB experiment at the PRP site consisted of three detention times (4, 8, and 12 days) and the same plant species (cattail and woolgrass). The investigation of the SVB design issues and treatment capabilities was conducted by monitoring STE and SVBE monthly with respect to selected chemical parameters including pH, EC, TDS, PO_4^{3-}, and Cl.

At the WP site, there were differences among treatments for P, EC, and TDS concentrations in the SVBE. Recirculation, however, appeared to have no apparent benefit on the SVBE quality. Pollutant removal increased with increased detention time. Removal percentages ranged from 7 to 28% for P, and from -4 to 7% for Cl, while TDS accumulated from 6 to 25%. After adjustment for evapotranspiration (ET) of 20%, total water loss in the SVB, P removal ranged from 25 to 43%; Cl from 17 to 26%; and TDS from 0 to 15%. There were no differences among detention times for Cl concentrations in the SVBE, however, with

increased detention time, Cl concentration tended to increase because of water loss via ET.

Shallow samples (collected from 10 cm below the water surface) exhibited higher levels of treatment than deep samples (collected from 10 cm above the bottom of the SVBs) at the PRP site. The pollutant removal percentages ranged from: 24 to 46% for P; 18 to 50% for Cl; and 12 to 73% for TDS for deep samples. In contrast, 50 to 78% of P, 50 to 77% of Cl and 52 to 72% of TDS were removed in the shallow samples without adjustment for water loss due to ET. TDS and EC of the SVBE at both experimental sites were highly correlated.

There were no differences in the chemical parameter in the SVBE between plant species at the PRP site, but EC, P, Cl, and TDS levels tended to be higher in effluents collected from the SVBs planted to woolgrass at the WP site. Different seasons (based on plant growth) had limited impact on the SVBs treatment of wastewater at the WP site, however, P, Cl and TDS concentrations in the SVBE were unexpectedly lower during the winter and spring periods than summer and spring periods at the PRP site.

There were no differences among treatments for concentrations of K, Ca, Mg, S, Zn, Cu, Mn, Pb, Ni, and Cd in the SVBE at the WP site. There were also no differences among treatments in P, Zn and Fe contents in plant tissues, but cattail tissues tended to have higher K, Ca, Mg, S, and Cl contents than woolgrass tissues. Plant tissue accounted for 13-57% of applied P removal if harvested once a year during the growing season.

At the WP site, there were linear relationships between the detention time and EC, and TDS . Curvilinear relationships were present between detention time and P. At the PRP site, polynomial equations were used to describe relationships between detention time and EC and P concentrations in the SVBE.

I. MATERIALS AND METHODS

1. Field Experiments And Data Analysis: Refer to Chapter III.

2. Chemical Analysis

Effluent samples were collected in plastic bottles from the SVBs as it was displaced by STE application. Unfiltered samples were analyzed for pH, EC, and TDS, K, Ca, Mg, Mn, Cu, Fe, Zn, Pb, Co, Cd and S. Samples were filtered for P and Cl determination using a cellulosic 0.45 micron filter paper.

2.1. Electrical conductivity (EC) and total dissolved solids (TDS)

Electrical conductivity, TDS, and pH were determined on unfiltered samples. Electrical conductivity and TDS of effluent were measured with a conductivity bridge using the procedure described by USEPA (Method 120.1, 1979).

2.2. pH

SVBE and STE pH values were determined by a glass electrode paired with a reference electrode. Double standard pH buffer solutions (pH 4 and pH 7) were used to calibrate the pH meter prior to measurement (USEPA, Method 150.1, 1979)

2.3. Ortho-phosphates (PO_4^{3-})

Phosphorus concentrations of the SVBE and STE were measured using the L$^+$-ascorbic acid colorimeteric procedure (USEPA, 1979). Under reductive condition in the presence of ascorbic acid, PO_4^{3-} forms a deep blue colored complex with addition of antimony and molybdate. The intensity of blue color increases with increased PO_4^{3-} concentration in the sample. A Hitachi Spectrophotometer was used to measure the intensity of blue color in the sample (USEPA, 1979).

4. Chloride (Cl)

Samples for Cl determination were filtered as described above. Chloride concentrations were determined by a potentiometric titration performed with a digital chloridometer (APHA, 1985). Samples were mixed with an acid solution and a gelatin reagent before analysis. The acid solution contained 6.4 ml concentrated nitric acid and 100 ml glacial acetic acid in 1000 ml volume of distilled water. Three ml of sample were combined with 1 ml acid mixture and 4 drops gelatin reagent in a glass vial for automatic titration by a Buchler Digital Chloridometer. A standard curve was prepared from a set of known standard concentrations of Cl^-.

5. Sulfate, Secondary Elements And Trace Metals Concentration In Effluent

Unfiltered effluent sample was analyzed for K, Ca, Mg, Mn, Fe, S, Pb, Co, Cu, Cd, Ni and Zn by an inductively coupled argon plasma emission spectroscopy (ICAP) on an ICAP 61 System. The ICAP operating conditions were a 27.12 MHz frequency, 1.15 kW forward, less than 5 W reverse, and 17 mm observation height. The plasma gases flow were set at 17 liters per min. for plasma, 0.62 liters per min for nebulizer, and 1.41 ml per min. for sample flow rate (TJAC,1988).

6. Phosphorus, Secondary Elements, And Trace Metals In Plant Tissue

Plant tissue phosphorus, secondary elements, and heavy metals content were determined by a perchloric acid digestion procedure (Martens, 1993). A 1.0000 g tissue samples was first placed into a 50 ml Folin Wu digestion tube, 8.0 ml of concentrated nitric acid (HNO_3), was added into digestion tube, and then the sample was placed into a fume hood overnight. The following morning, 2 ml of concentrated perchloric acid was added to the tube, and then the tube was placed in a heating block in a perchloric acid hood. The temperature was set at 120 °C until the red fume of nitric acid in the digestion tube had disappeared, and the temperature was set at 160 °C until white fumes of perchloride acid had disappeared, and then the temperature to was set to 200 °C (<203 °C) until digestion tube contained approximately 1ml solution. After digestion, the tube was allow to cool, and the digested sample was brought to 50 ml volume with 1.2 N Hydrochloride acid (HCl). After filtering the sample through acid-washed Whatman number 42 filter paper, the sample was transferred into a plastic bottle. The concentration of P, S, K, Ca, Mg, Cu, Fe, Zn, and Mn in the solution was determined by a Jarrell Ash ICAP61 as described earlier (TJAC, 1988).

7. Tissue Chloride Content

Total Cl in plant tissue was determined by a modified Dry Ashing procedure (Chapman and Pratt, 1961). A 1.0000 g of ground plant material was placed in a porcelain evaporating dish, the sample was mixed with 0.25 g of calcium oxide and sufficient water to give a thin paste, and then the sample was ashed in a muffle furnace. The temperature in the muffle furnce was gradually raised from room temperature to 550 °C, and then kept this temperature for at least 90 min. After ashing, the sample was removed from the muffle furnace allowed to cool. After the sample was cooled, 15 ml of hot water was added to the sample, the sample was placed on a hot plate, the ash was blroke into a fine powder with a , and then filtered into 250 ml Erlenmeyer flask. The residue was washed with five, 10ml portions of hot water. Concentration of Cl in the solution was determined by titration with a Buchler Digital Chloridometer as mentioned earlier.

II. RESULTS AND DISCUSSION

Data collected over a three year period indicated that the SVBs have a potential for removal of certain chemical pollutants. The results indicated that the SVB form of constructed wetlands used for wastewater renovation was efficient at both experimental sites, especially for effluent samples collected from the shallow part of wastewater column at the PRP site. Although cattail and woolgrass stands at the PRP site did not appear as vigorous as those at the WP site, the root systems were well developed, especially where 12 day detention times were employed. Both cattail and woolgrass roots were white in color and penetrated to the bottom of the SVBs (Photoes 1 and 2). Therefore pollutant levels were lower than expected (Tables 7.1 and 7.2) when compared with the quality of the SVBE at the WP site (Tables 7.3 and 7.4). The reduced plant stand at the PRP site may have been caused by a deeper (15 cm) layer of pea gravel cover when compared with plants at the WP site (10 cm layer of pea gravel cover). The increased depth to liquid at the PRP site may have impeded young plant growth.

1. pH Values

The pH value reflects a balance of biological and chemical reactions occurring in the SVBs. Both natural or constructed wetlands are well buffered near pH 7.0 after ecosystems (plants and microorganisms) are established, and changes in pH within most wetlands have been within two units (Porties and Palmer, 1989; Maddox and Kingsley, 1989; Brodie et al., 1989; Waston et al., 1989; David and Conway, 1989; Kingsley et al., 1989).

Although there were no differences among treatments in pH values of the SVBE at the WP site, pH values of the SVBE (Table 7.4 and Fig. 7.1) were lower than STE (an average of pH 7.42) over time, with increased detention time, pH values tended to decrease slightly with increased detention time (Tables 7.3 and 7.4) at the WP site. The pH values of the wastewater in the SVBs, at the PRP site, were higher than the pH values in the STE, and decreased with increased detention time (Tables 7.1, 7.2, and Fig. 7.2). This may result from more anaerobic conditions at the lower detention times and more aerobic conditions at the longer detention times. The SVBE at the PRP site also had higher organic solids concentrations (Tables 7.1 and 7.2).

There were seasonal variations in pH values in the SVBE at both experiment sites. The pH values were higher during the winter and spring periods than during the summer and fall periods (Tables 7.1, 7.3, and 7.5 and Fig. 7.2). The reason may be higher DO in the wastewater column during the winter and spring, which not only increased redox potential, but also increased water pH values. Higher O_2 concentration would drive the following reaction to the right direction, $O_2 + 4e + 4H^+ = 2H_2O$ (E°_{red}=+1.23 volts). Eh values support this hypothesis.

There were no differences in the SVBE with respect to pH values at both experimental sites as a result of plant species (Tables 7.4 and 7.6). The physiological effect of pH on plant roots are diverse and are often confounded with other changes in the system associated with pH values. Root transpiration, and nutrient uptake such as Ca^{++} and K^+ would release H^+ to the system (James et al., 1974). Some reactions increase the pH, while others lower it. Both types may occur within the system. Nitrification, for example, decreases water pH ($NH_4^+ + 3/2\ O_2 = NO_2^- + H_2O + 2\ H^+$, $NO_2^- + 1/2\ O_2 = NO_3^-$), but denitrification would increase the pH ($NO_3^- + H^+ = NO_2^- + OH^-$, $NO_2^- + 2H^+ = N_2\ (NO_2) + 2OH^-$). The measured pH values are an instantaneous balance of all the chemical and biological reactions occurring in the system. The pH also affects chemical and biochemical reactions such as deposition, complex formation, mineralization, nitrification, and denitrification processes. Wastewater column pH values might affect disposition of P (H_2PO_4-, HPO_4^{2-} and PO_4^{3-}) with cations in the system. Higher pH values might form more cation-P complexes. Nitrification can not be completed without adequate alkalinity, approximately 7 mg alkalinity is required for oxidation of 1 mg of NH_3-N. Waston et al. (1989) reported that the optimum pH for nitrification is 7 to 8.

Photo 1. Cattail root system at the Whitethorne Plantation Site

(August 23, 1994)

Photo 2. Woolgrass root system in the Powell River Project Site

(August 25, 1993)

Table 7.1 The impact of detention time on selected chemical parameters in the SVBE under different seasons at the Powell River Project site

Detention	pH	EC	PO_4-P		Cl		TDS	
days		uS/cm	mg/L	Removal %	mg/L	Removal %	mg/L	Removal %
0*	7.44	1890	5.33		83.2		1293	
Summer and fall periods (May, June, July, August, September, October)								
4	7.92 ab**	1494 a	4.56 a	14 e	52.3 b	37 b	1067 a	16 c
8	7.77 c	1308 ab	4.36 ab	18 de	49.9 b	40 b	714 b	44 b
12	7.63 d	1217 b	3.47 bc	35 cd	33.2 c	60 a	616 b	52 b
Winter and spring periods (November, December, January, February, March, April)								
4	7.98 ab	1431 a	2.81 cd	47 bc	72.5 a	13 c	715 b	44 b
8	8.01 a	1115 b	1.94 de	64 ab	53.1 b	36 b	517 bc	59 ab
12	7.87 bc	869 c	1.12 e	79 a	31.7 c	62 a	309 c	76 a

* influent (STE)

** means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

EC-electrical conductivity; TDS-total dissolved solids; PO_4^{3-}-P-Ortho-phosphorus; Cl-chloride;

Table 7.2 The impact of detention time on selected chemical parameters in the effluents collected from different parts of the SVBs at the Powell River Project site

Detention	pH	EC	PO_4^{3-}-P		Cl		TDS	
days		uS/cm	mg/L	removal %	mg/L	removal %	mg/L	removal %
0*	7.44	1890	5.33		83.2		1293	
Shallow samples (10 cm below the water surface)								
4	7.94 a**	1133 c	2.73 bc	48 bc	41.9 b	47 c	621 bc	50 bc
8	7.79 b	808 d	2.24 c	57 b	34.7 b	56 b	423 cd	66 ab
12	7.73 b	785 d	1.17 d	78 a	19.5 c	75 a	304 d	73 a
Deep samples (10 cm above the bottom of the SVBs)								
4	8.02 a	1591 a	4.02 a	23 d	68.4 a	13 c	1161 a	6 d
8	7.95 a	1390 b	3.46 ab	34 cd	58.3 a	26 c	777 b	37 c
12	7.78 b	1192 c	2.89 bc	45 bc	41.7 b	47 b	521 bcd	58 abc

* influent.

** means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

EC-electrical conductivity; TDS-total dissolved solids; PO_4^{3-}-P-ortho-phosphorus; Cl-chloride;

Table 7.3 The impact of detention time on selected chemical parameters in the SVBE under different seasons at the Whitethorne Plantation site

Detention time (days)	Chemical parameters							
	pH	EC	PO_4-P		Cl		TDS	
		uS/cm	mg/L	Removal %	mg/L	Removal %	mg/L	Removal %
0*	7.42	1083	3.12		58.8		651	
Summer and fall periods								
2.6	7.22 b**	1429 a	2.83 ab	9 b	54.4 bc	8 ab	709 abc	-9 abc
3.9	7.18 b	1297 ab	2.43 bc	22 ab	61.9 ab	-5 bc	806 ab	-23 bc
5.9	7.17 b	1228 b	1.99 c	36 a	99.2 a	-18 c	879 a	-38 c
Winter and spring periods								
2.6	7.42 a	1003 c	3.03 a	3 a	54.6 bc	7 ab	633 bc	3 ab
3.9	7.37 a	1000 c	2.82 ab	10 bc	51.1 bc	13 ab	623 bc	4 ab
5.9	7.36 a	959 c	2.59 ab	17 bc	48.6 c	17 a	576 c	12 a

* influent.

** means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

EC-electrical conductivity; TDS-total dissolved solids; PO_4^{3-}-P-ortho-phosphorus; Cl-chloride;

Table 7.4 The effect of treatments affect on selected chemical parameters in the SVBE at the Whitethorne Plantation site

Treatment			pH	EC	PO_4^{3-}-P	Cl	TDS
Detention time (days)	Plant species	Recir. %		uS/cm	mg/L		
0*			7.42	1083	3.12	58.8	651
2.6	cattail	0	7.29 a**	1074 c	2.80 bc	47.3 c	654 c
3.9	cattail	0	7.23 a	1111 c	2.38 bc	48.4 c	672 c
3.9	cattail	50	7.29 a	1077 c	2.47 bc	48.0 c	662 c
5.9	cattail	50	7.22 a	1071 c	2.05 c	46.6 c	643 c
2.6	woolgrass	0	7.31 a	1198 bc	3.02 a	61.6 b	726 bc
3.9	woolgrass	0	7.27 a	1222 bc	2.66 ab	65.1 ab	873 abc
3.9	woolgrass	50	7.25 a	1292 ab	2.84 ab	69.7 ab	871 abc
5.9	woolgrass	50	7.27 a	1400 a	2.42 bc	76.1 a	990 a

* influent (STE).

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

EC-electrical conductivity; TDS-total dissolved solids; PO_4^{3-}-P-ortho-phosphorus; Cl-chloride;

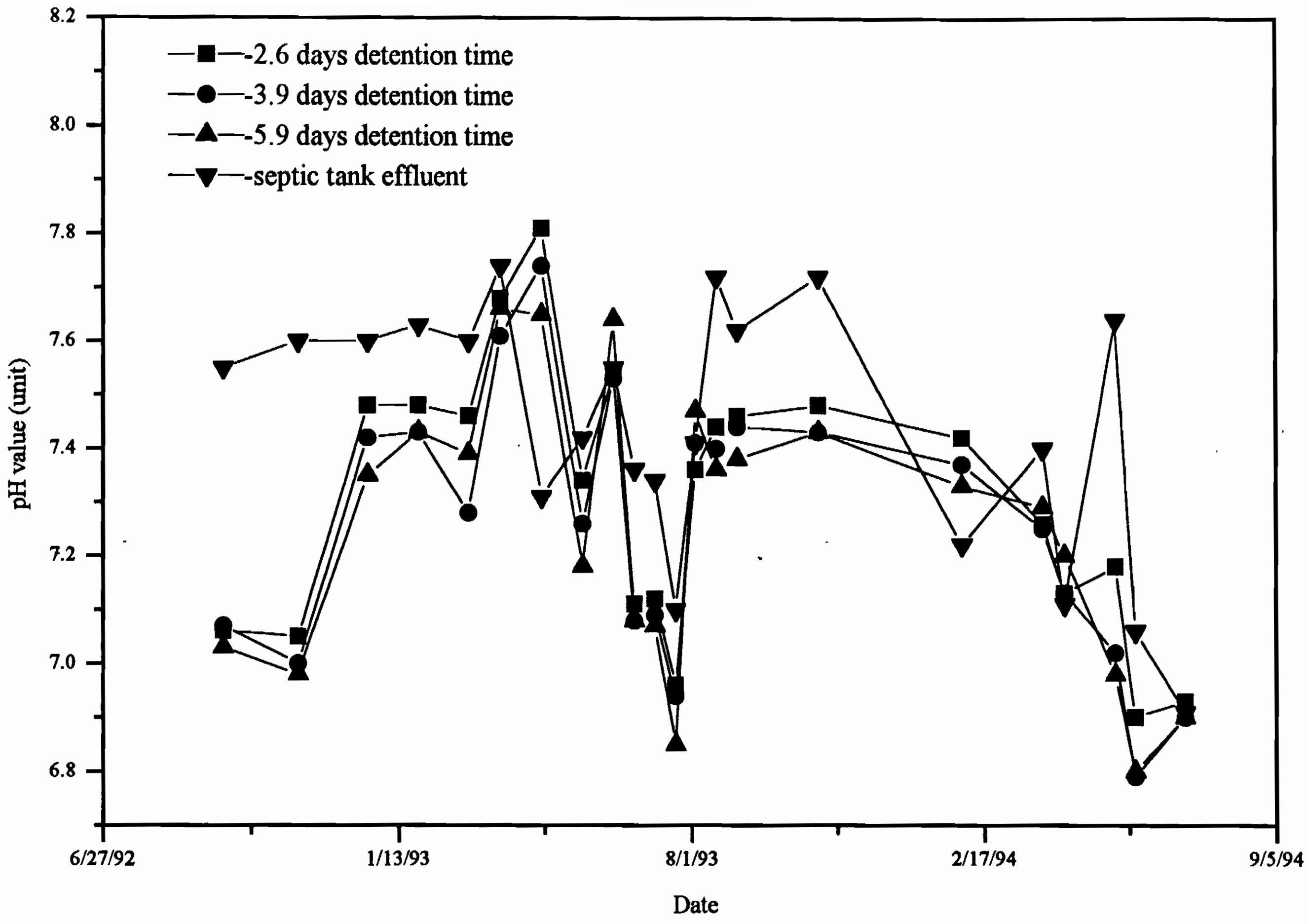


Figure 7.1 pH value in the STE and the SVB effluents at the Whitethorne Plantation site

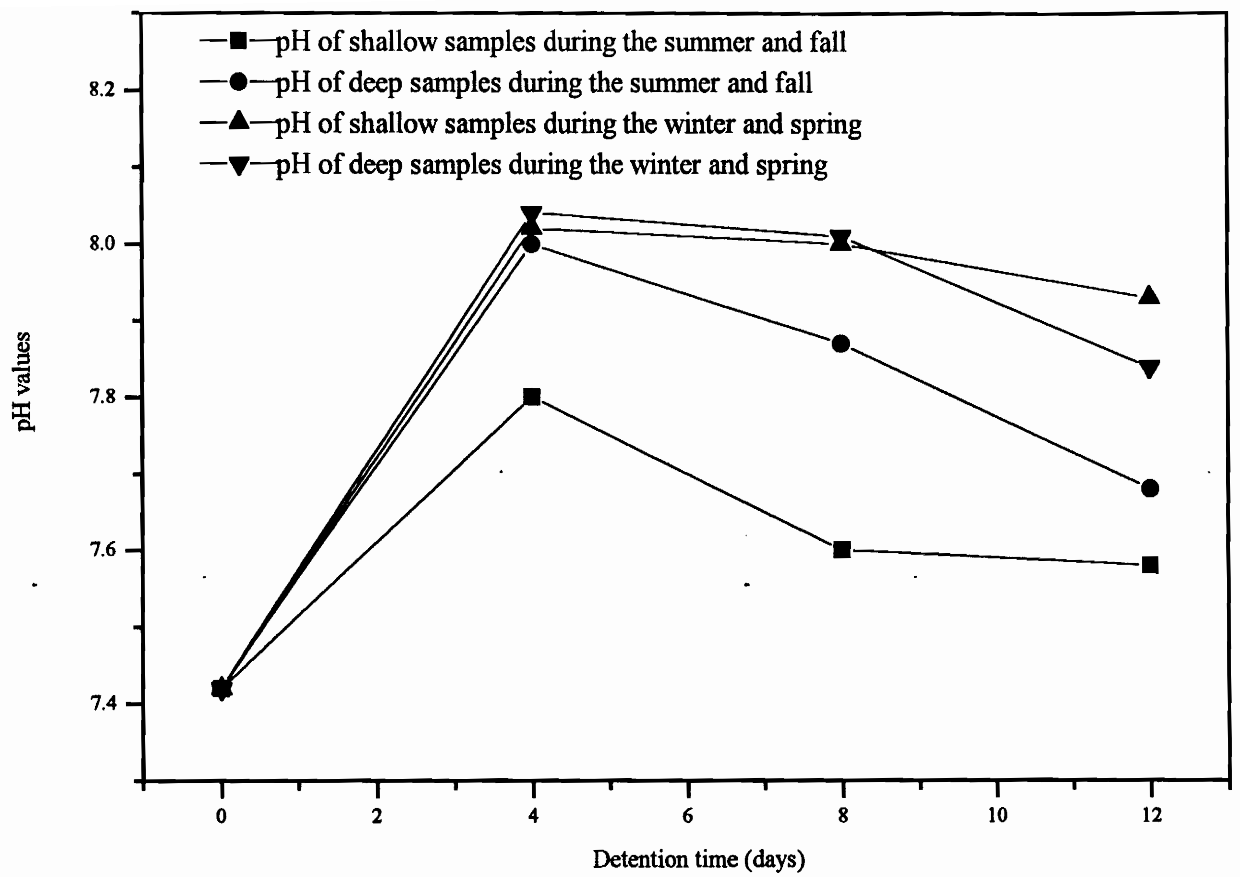


Figure 7.2 The effect of detention time on the pH values of the SVBE at the Powell River Project site

Table 7.5 The impact of detention time on selected chemical parameters in the samples collected from different depths in the SVBs under different seasons at the Powell River Project site

Detention	pH	EC	PO_4^{3-}-P		Cl		TDS	
days		uS/cm	mg/L	removal %	mg/L	removal %	mg/L	removal %
Shallow samples (10 cm below the water surface) during the summer and fall periods								
4	7.80 cd	1165 cd	3.48 b	34 d	36.0 cd	54 ab	694 bc	44 bc
8	7.60 e	920 d	3.43 b	35 d	44.5 cd	56 ab	550 bcd	56 abc
12	7.58 e	938 d	1.66 de	68 ab	20.2 d	74 ab	526 bcd	58 abc
Deep samples (10 cm above the bottom of the SVBs) during the summer and fall periods								
4	8.00 abc	1688 a	5.20 a	1 e	61.9 ab	21 cd	1440 a	-16 d
8	7.87 bcd	1529 ab	4.88 a	7 e	59.0 ab	25 cd	878 b	29 c
12	7.68 de	1482 ab	5.29 a	1 e	46.2 ab	41 bc	707 bc	43 bc
Shallow samples (10 cm below the water surface) during the winter and spring periods								
4	8.02 a	1092 cd	1.79 cde	66 abc	58.8 ab	25 cd	541 bcd	56 abc
8	8.02 ab	653 e	0.81 e	85 ab	35.1 cd	55 ab	344 cd	73 ab
12	7.93 abc	603 e	0.54 e	90 a	17.0 d	78 a	223 d	82 a
Deep samples (10 cm above the bottom of the SVBs) during winter and spring periods								
4	8.04 a	1514 ab	3.12 bc	41 cd	75.6 a	4 d	909 b	27 c
8	8.01 ab	1283 c	2.35 bcd	55 bcd	57.7 ab	26 cd	701 bc	43 bc
12	7.84 bcd	1006 d	1.41 de	73 ab	36.9 bc	53 ab	400 cd	68 ab

* means followed by the same letter within the same column are not significantly difference at 5% level, determined by Duncan's multiple range test.

EC-electrical conductivity; TDS-total dissolved solids; PO_4^{3-}-P-ortho-phosphorus; Cl-chloride;

2. Electrical Conductivities / Total Dissolved Solids (EC/TDS)

Both EC and TDS can be used to indicate salinity of effluent since EC and TDS are highly correlated. Oster and Rhoades (1985) reported that the value of EC and TDS are interchangeable within an accuracy of about ±10%, with equations as follows:

$$\text{EC (dS/m) X 640=TDS (mg/l)} \qquad \text{Eq. 7.1}$$

$$\text{TDS (mg/l) X 0.00156=EC(dS/m)} \qquad \text{Eq. 7.2}$$

Salinity is an important parameter in determining the suitability of wastewater for irrigation or soil application. TDS consists of ions such as Ca, K, Na, Mg, Cl, and sulfates in various forms. TDS also includes dissolved small molecular organic compounds such as amino acids, fatty acids, etc. Excessive salinity may damage some crops, and specific ions such as Cl, Na, and B can be toxic. Excess Na also may pose soil permeability problems. Salinity of water can be determined by measuring its EC, TDS, or concentration of B, Cl, bicarbonate, Na, Ca and Mg. Values for salinity are also reported as TDS of water.

However, Oster and Rhoades's equations (Eqs. 7.1 and 7.2) were not suitable for either the STE or the SVBE in this research. There was a correlation between EC and TDS in the STE at the WP site (Table 7.7). EC and TDS were also highly correlated in the SVBE, but varied from site to site (Table 7.7, and Figs. 7.3 and 7.4). The relationship between detention time and EC and TDS in the SVBE at both experimental sites is shown in the Table 7.8 and Figs. 7.5, 7.6, 7.7, and 7.8.

Salinity has an impact on the use of the SVBE for irrigation or assimilation into soils. EC in irrigation water usually ranges from 0 to 3000 uS cm^{-1}, while TDS ranges from 0 to 2000 mg L^{-1} (Westcot and Ayers, 1985). Higher salinity wastewater used for irrigation could decrease crop yield and soil permeability (infiltration). Westcot and Ayers (1985) suggested that in wastewater with an EC <0.7 mS cm^{-1} (700 uS cm^{-1}), salinity was not a problem and no

Table 7.6 The effect of plant species on chemical parameters in the SVBE at both sites

	Powell River Project site					Whitethorne Plantation site				
Plant species	pH	EC	PO_4-P	Cl	TDS	pH	EC	PO_4-P	Cl	TDS
		uS/cm	mg/L				uS/cm	mg/L		
	Deep samples (10 cm above the bottom of the SVBs)					Deep samples (3 cm above the bottom of the SVBs)				
Woolgrass	7.92 a*	1476 a	3.76 a	60.7 a	878 a	7.27 a	1727 a	2.73 a	68.1 a	856 a
Cattail	7.94 a	1354 a	3.31 a	55.8 a	852 a	7.26 a	1083 b	2.43 b	47.6 b	678 b
	Shallow samples (10 cm below the water surface)									
Woolgrass	7.81 a	914 a	2.28 a	32.4 a	473 a					
Cattail	7.82 a	902 a	1.76 a	31.4 a	450 a					

* means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

EC-electrical conductivity; TDS-total dissolved solids; PO_4^{3-}-P-ortho-phosphorus; Cl-chloride;

Table 7.7 The relationship between total dissolved solids (TDS) and electrical conductivity (EC) in the SVBE and STE

Site	Source	Relationship between EC and TDS	r^2	p	n
WP	SVBE	TDS (mg/l) = -195.5+0.71 EC (uS/cm)	0.90	<0.001	354
PRP	SVBE	TDS (mg/l) = 3.92 + 0.50 EC (uS/cm)	0.98	<0.001	235
WP	STE	TDS (mg/l) = -15.13 +0.552 EC (uS/cm)	0.69	<0.001	19

WP-Whitethorne Plantation; PRP-Powell River Project;
TDS-total dissolved solids; EC-electrical conductivity;
n-observation number;

Table 7.8 The relationship between detention time and electrical conductivity (EC) and total dissolved solids (TDS) in the SVBE

Site	Parameter*	Relationship	r^2	position**	seasons***
WP	EC	$y=1619.5 - 100.5\ X$	0.88	deep	S & F
WP	EC	$y=1053-22.0\ X$	0.81	deep	W & S
WP	TDS	$y=543 + 85\ X$	0.98	deep	S & F
WP	TDS	$y=696.2-28.5\ X$	0.88	deep	W & S
PRP	EC	$y=1884.3-112.3\ X + 4.76\ X^2$	0.99	deep	S & F
PRP	EC	$y=1886.4-124.4\ X + 3.33\ X^2$	0.99	deep	W & S
PRP	TDS	$y=1312.1-83.6\ X + 2.0\ X^2$	0.98	deep	S & F
PRP	TDS	$y=1273.5 - 148.1\ X + 5.78\ X^2$	0.98	deep	W & S
PRP	EC	$y=1883.5-228.6\ X + 11.5\ X^2$	0.99	shallow	all seasons
PRP	EC	$y=1885.3-76.3\ X + 1.58\ X^2$	0.99	deep	all seasons
PRP	TDS	$y=1273-190.1\ X + 9.59\ X^2$	0.99	shallow	all seasons
PRP	TDS	$y=1309.2 - 49.8\ X - 1.33\ X^2$	0.99	deep	all season

*EC-electrical conductivity (uS/cm; TDS-total dissolved solids (mg/l); X-detention time (days).

**deep-effluent samples collected from 10 above the bottom of the SVBs,
shallow-effluent samples collected from 10 cm below the SVBs water surface.

***S & F-summer and fall periods; W & S -winter and spring periods.

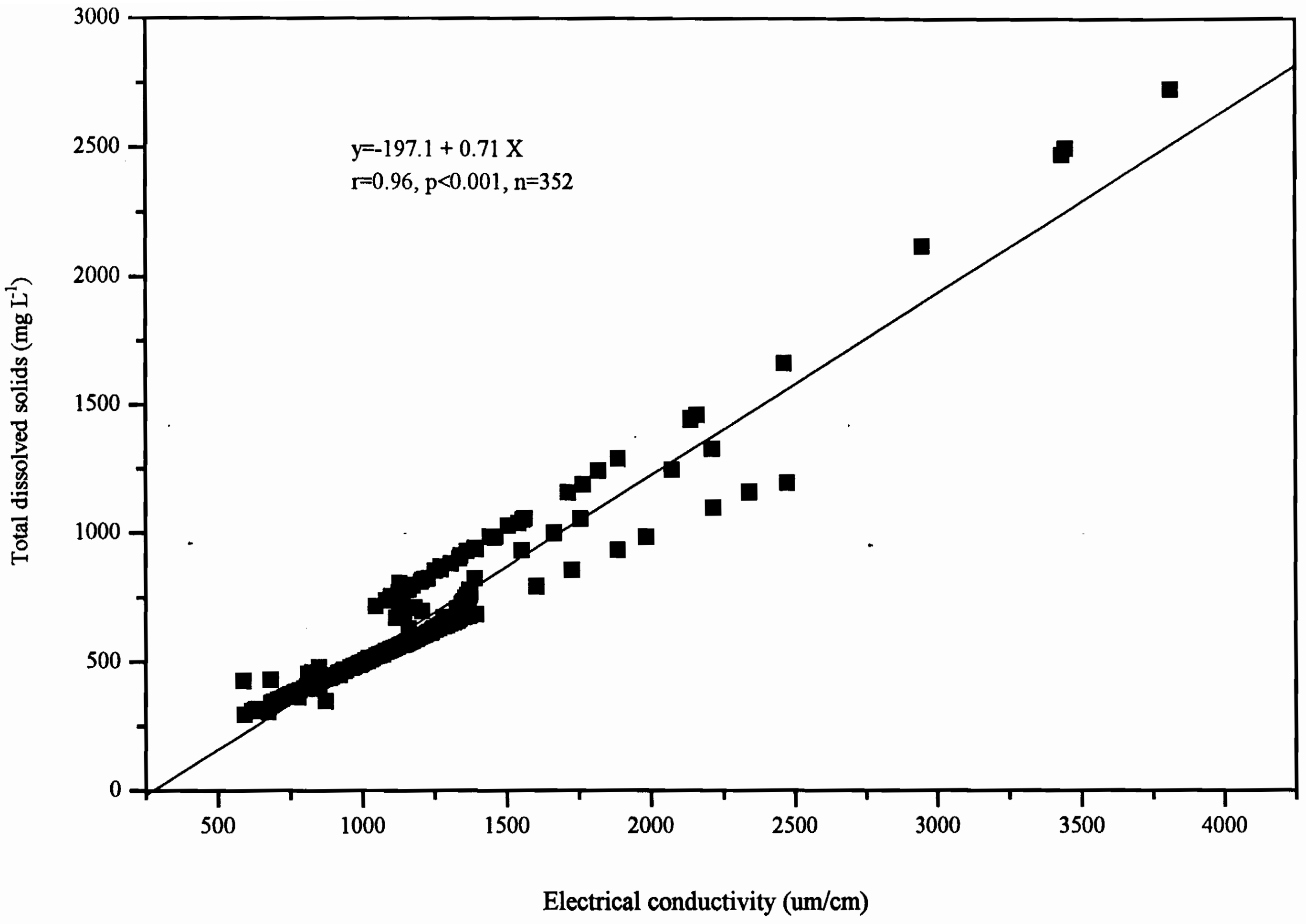


Figure 7.3 Relationship between electrical conductivity and total dissolved solids in the SVBE at the Whitethorne Plantation site

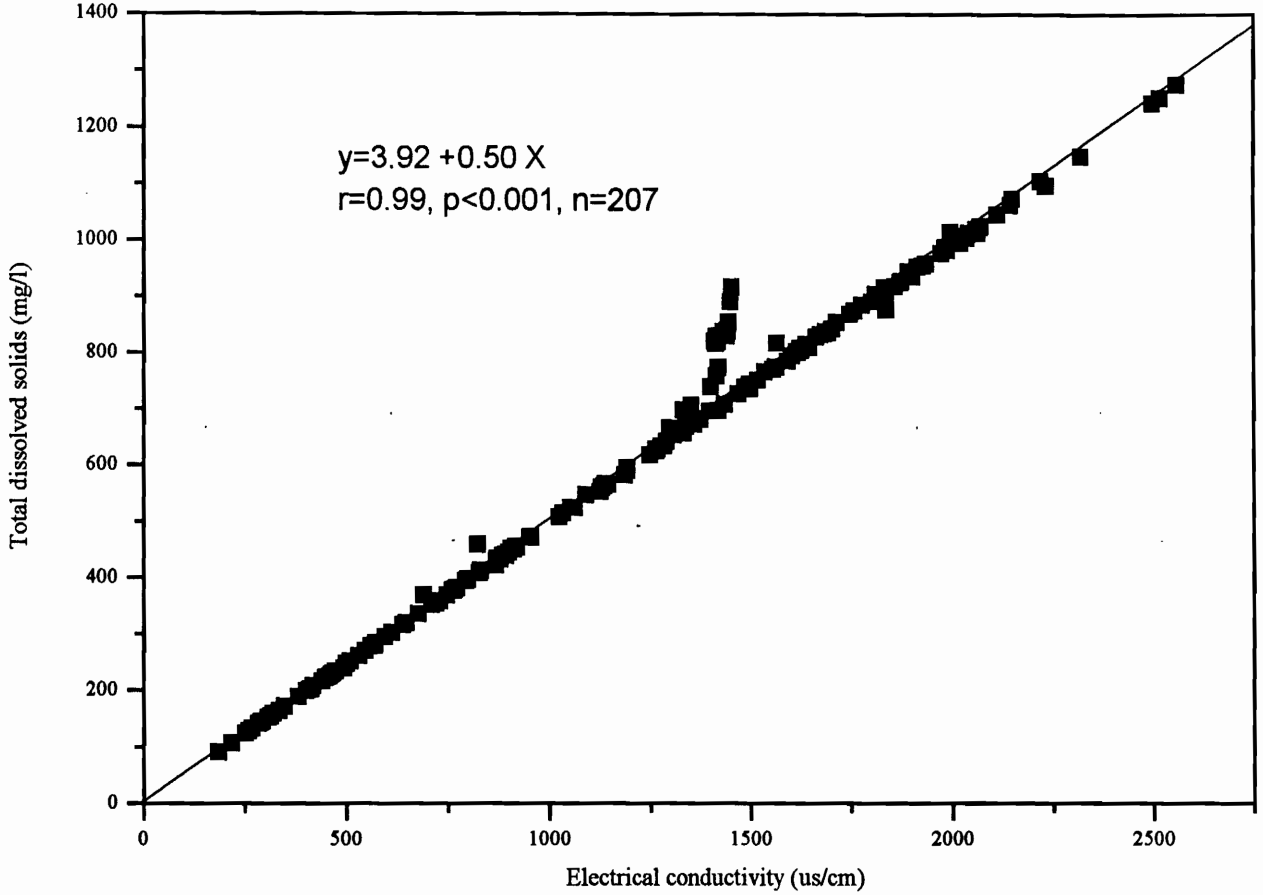


Figure 7.4 Relationship between electrical conductivity and total dissolved solids in the SVBE at the Powell River Project site

special management practices are required. But irrigation water in the 0.7 to 3.0 mS/cm range (slight to moderate salinity) may require special practices. The EC of effluent collected from the bottom of the SVBs at both sites have little restriction for irrigation purposes.

At the WP site, there were differences among treatments for EC and TDS values in the SVBE (Table 7.4). Treatments 2 and 3 had the same loading rate and differ only with respect to recirculation ratios. There was no difference between treatments 2 and 3 for EC and TDS, indicating that recirculation did not result in additional contaminate reduction in the SVBE.

One major concern with the SVB systems for wastewater treatment is pollutant reduction efficiency during the winter (low temperature periods). Both EC and TDS values were higher during the summer and fall periods as compared with the winter and spring periods (Table 7.4). This was attributed to differences in water loss via ET between warm seasons and cold seasons. Although EC and TDS values were higher during the warmer seasons than the cooler seasons, when concentrations were adjusted by 20% (Table 3.2, Chapter III) to account for water loss during the summer and fall periods, the pollutant removal percentages were actually higher than reported (Table 7.9). For instance, TDS concentrations decreased instead of exhibiting accumulation after ET was taken into consideration. This also can explain the lower levels of P, Cl and TDS in the SVBE during the winter and spring than during the summer and fall. At the PRP site, there were differences among the three detention times for both EC and TDS in the SVBE during the fall and summer periods (Table 7.1). With increased detention time, both EC and TDS values decreased during the winter and spring periods, and decreased slightly during the fall and summer periods due to water loss and higher rates of degradation of organic materials. EC values in the SVBE decreased rapidly with increased detention time in both deep and shallow samples at the PRP site, and EC values were higher during the fall and summer periods than the winter and spring periods (Tables 7.1, 7.2, and 7.5). TDS also decreased with increased detention time in both deep and shallow samples, and TDS concentrations in the shallow

Table 7.9 The impact of detention time on pollutant concentrations and removal in the SVBE at the Whitethorne Plantation site

Detention time	PO$_4$-P	Cl	TDS	PO$_4$-P^a	Cl^b	TDS^c
days	overall concentration (mg/l)					
0*	3.12	58.8	651	3.12	58.8	651
2.6	2.91 a**	54.5 a	690 b	2.33	43.6	553
3.9	2.59 b	57.8 a	760 ab	2.07	46.2	608
5.9	2.23 c	61.3 a	815 a	1.78	49	652
	overall removal (%)					
2.6	7 c	7 a	-6 a	25	26	15
3.9	17 b	2 a	-17 ab	34	21	7
5.9	28 a	-4 a	-25 b	43	17	0

* influent (STE).

**means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

PO$_4^{3-}$-P-ortho-phosphorus; TDS-total dissovled solids; Cl-chloride;
a, b, c -adjusted by an average water loss via evapotranspiration rate of 20 %
for the summer and fall periods.

Table 7.10 **Plant tissue P content (%) at both experimental sites (June, 1993)**

Powell River Project site			Whitethorne Plantation		
Detention time (days)	Plant species		Detention time (days)	Plant species	
	Cattail	Woolgrass		Cattail	Woolgrass
4	1.38 a	1.12 d	2.6	1.08 a	0.96 a
8	1.34 a	1.14 cd	3.9	1.04 a	1.08 a
12	0.90 e	1.24 bc	5.9	1.04a	0.95 a
average	1.21	1.17	average	1.05	1.0

* means followed by the same letter within the same site are not significantly different at 5% level, determined by Duncan multiple range test.

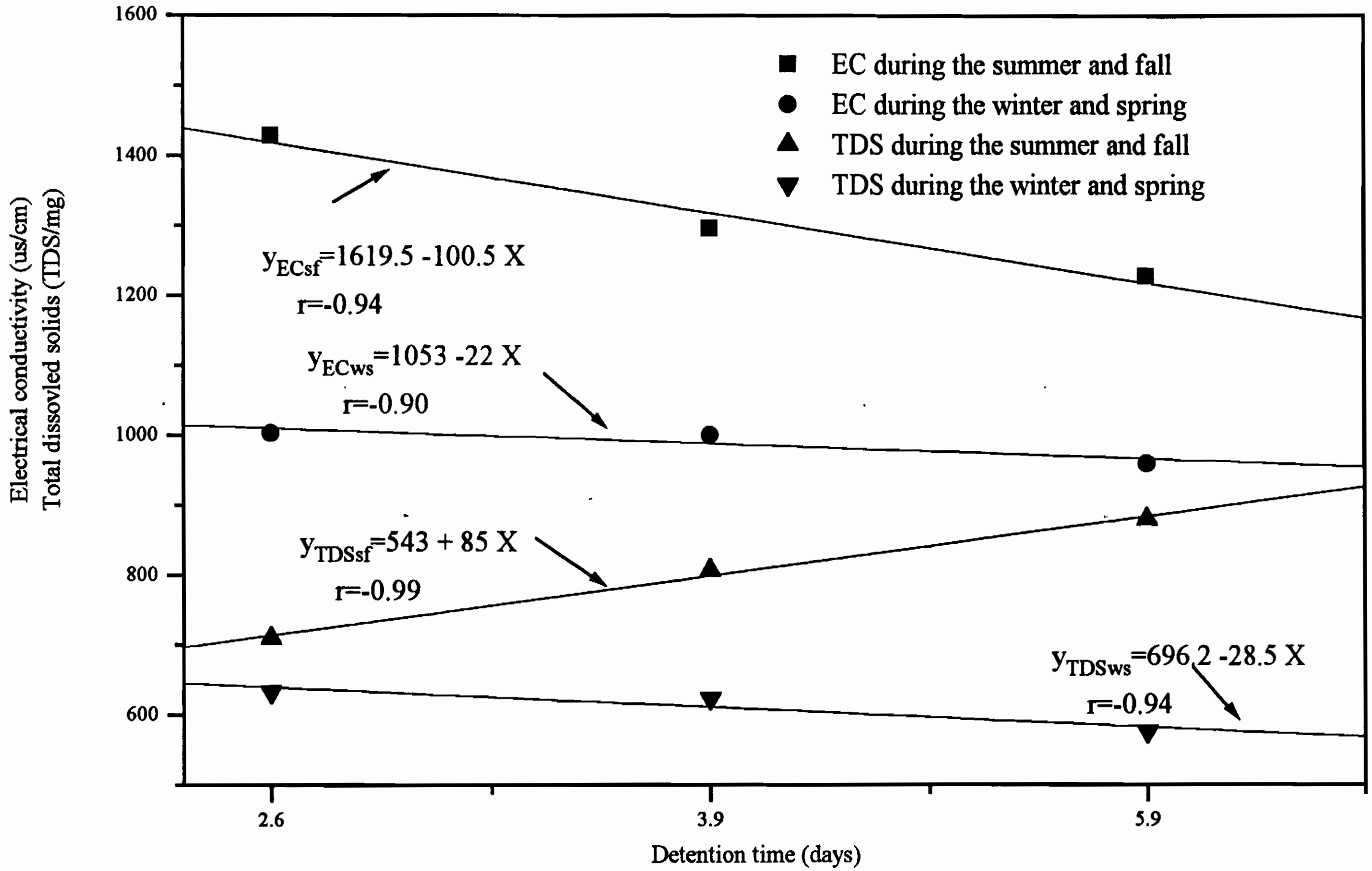


Figure 7.5 Relationship between detention time and electrical conductivity and total dissolved solids in the SVBE at the Whitethorne Plantion site

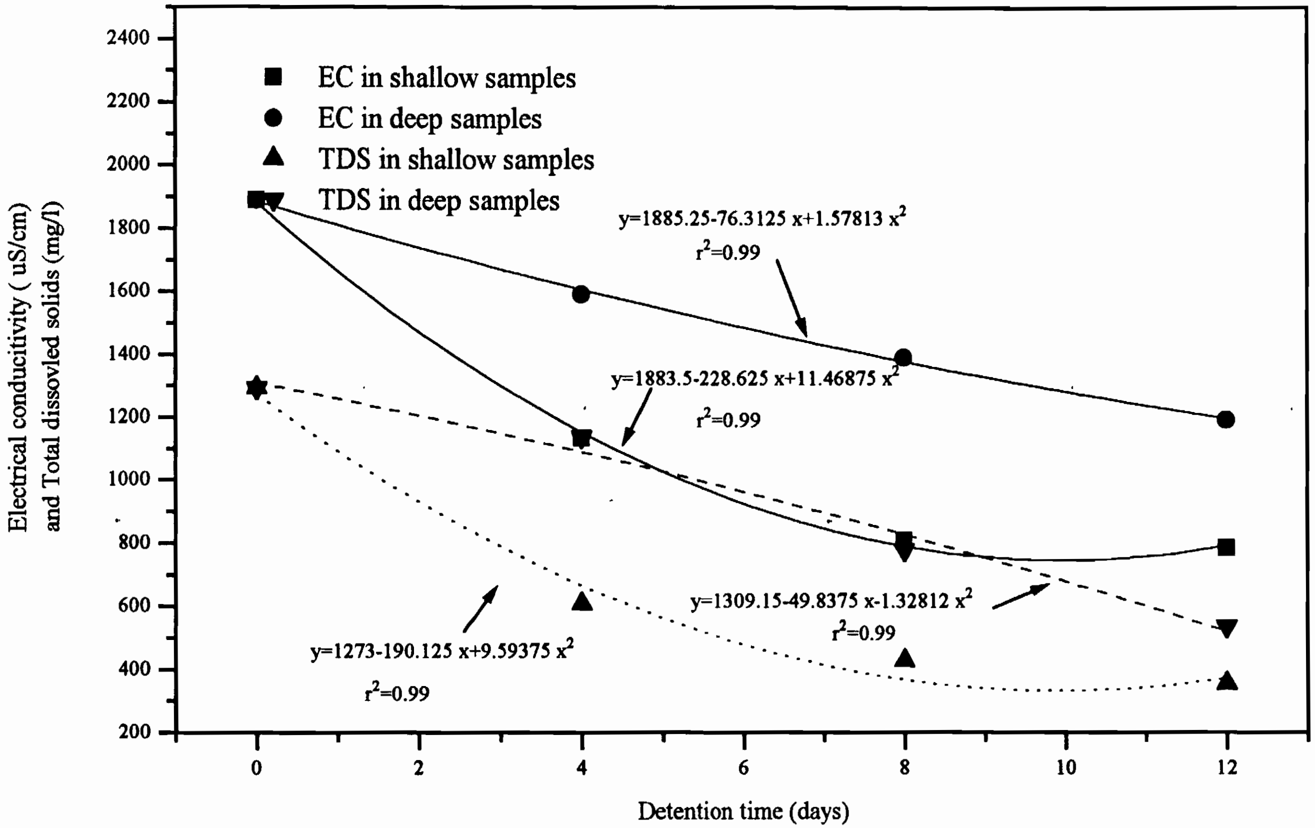


Figure 7.6 The effect of detention time on eclectrical conductivity and total dissovled solids at the Powell River Project site

samples were 50% lower than the deep sample (Tables 7.1 and 7.2). This shows that the wastewater in the shallow part of column is of higher quality and thus better suited for soil application (Fig. 7.6).

Although the SVBs at the PRP site had twice the detention times as the SVBs at the WP site, EC values of the SVBE in both sites were similar (Tables 7.1 and 7.3), while TDS concentrations were higher in the SVBE at the WP site. This difference may have been caused by the difference in plant biomass in the SVBs and STE strength at the two sites. As mentioned earlier, higher plant densities were present in the SVBs at the WP site as compared to the SVBs at the PRP site. This may have increased water loss during the fall and summer periods, thus concentrating TDS in the SVBE. In addition, large amount of plant biomass in the SVBs decompose and the plant root systems vigorously metabolize during the fall and summer periods, byproducts from these activities may increase the release of exudates and add TDS to the SVBE.

Detention time was the major factor which controlled EC and TDS in the SVBs. There were no differences among the three detention times for EC in the SVBE at the WP site, but with increased detention time, EC values and TDS concentrations of the SVBE tended to increase at the WP site (Tables 7.3 and 7.9). This may result from the water loss via evapotranspiration. After adjustment of 20% for water loss, TDS was reduced from 0 to 15% (Table 7.9). At the PRP site, high rates of TDS removal were observed in both deep and shallow samples of the SVBE, namely 8-57% in the deep samples and 51-72% in the shallow samples (Table 7.5).

There were no differences for EC and TDS in the effluents between the SVBs planted with cattail and woolgrass at the PRP site (Table 7.6). However, plant species had an impact on the EC and TDS concentrations in the SVBE at the WP site. EC and TDS concentrations in the effluent samples were lower in the SVBs planted to cattail than those planted to woolgrass (Table 7.6). This may be a result of the differences in plant densities between the two experimental sites.

Linear relationships were present between detention times and EC in the SVBE at the WP site (Fig. 7.5 and Table 7.7). EC decreased with detention time during both warm and cold seasons, and EC decreased faster during the warmer seasons as compared with the colder seasons (Fig. 7.5). The TDS increased with detention time during the summer and fall, and decreased with detention time during the winter and spring periods (Fig. 7.5).

Polynomial equations can be used to describe the relationship between detention time and EC and TDS concentrations in the SVBE at the PRP sites (Figs. 7.6, 7.7, and Table 7.8). However, the constants for the equations were different due to seasonal impact and samples collected from various depths of the SVBs. At the PRP site, unlike the WP site, both EC and TDS in the SVBE decreased with detention time in samples collected from both depths during all seasons (Figs. 7.6, 7.7, and Table 7.5). The EC and TDS reduction rates in the SVBE were much higher at the PRP site as compared with the WP site (Figs. 7.5, 7.6, and 7.7).

3. Ortho-Phosphorus (PO_4^{3-}-P)

Ortho-P removal rates in the SVB form of constructed wetlands varies from case to case (Knight et al., 1993). Waston et al. (1989) reported total P reduction ranged from 4% to 70%. P removal rates in the present study, over a two year monitoring period, ranged from 23 to 78% at the PRP site (Table 7.2), and 7 to 28% at the WP site (Table 7.9). Detention time was the factor most closely related to P removal. This is not surprising since P removal mechanisms are time-dependent. Organic P was decomposed by mineralization, then removed mainly by precipitation with Ca^{++} and $Mg^{++}$and by plant uptake.

The removal percentage was based on average annual concentrations of effluent collected from the bottom of the SVBs for the WP site. However, the PO_4^{3-}-P concentrations in the shallow samples were much lower than the deep samples at the PRP site. The average

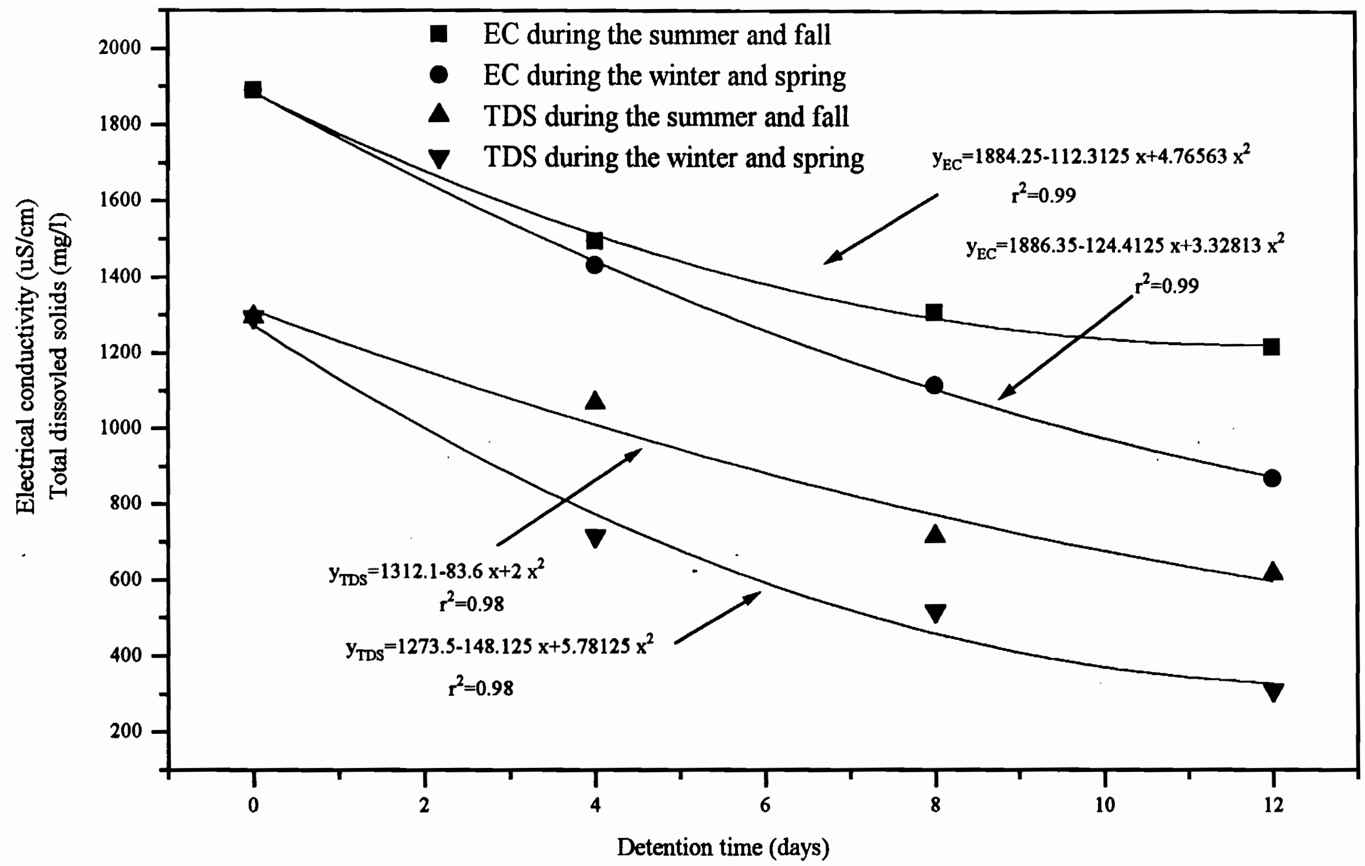


Figure 7.7 Relationship between detention time and electrical conductivity, and total dissolved solids in the SVBE under different seasons (Powell River Project site)

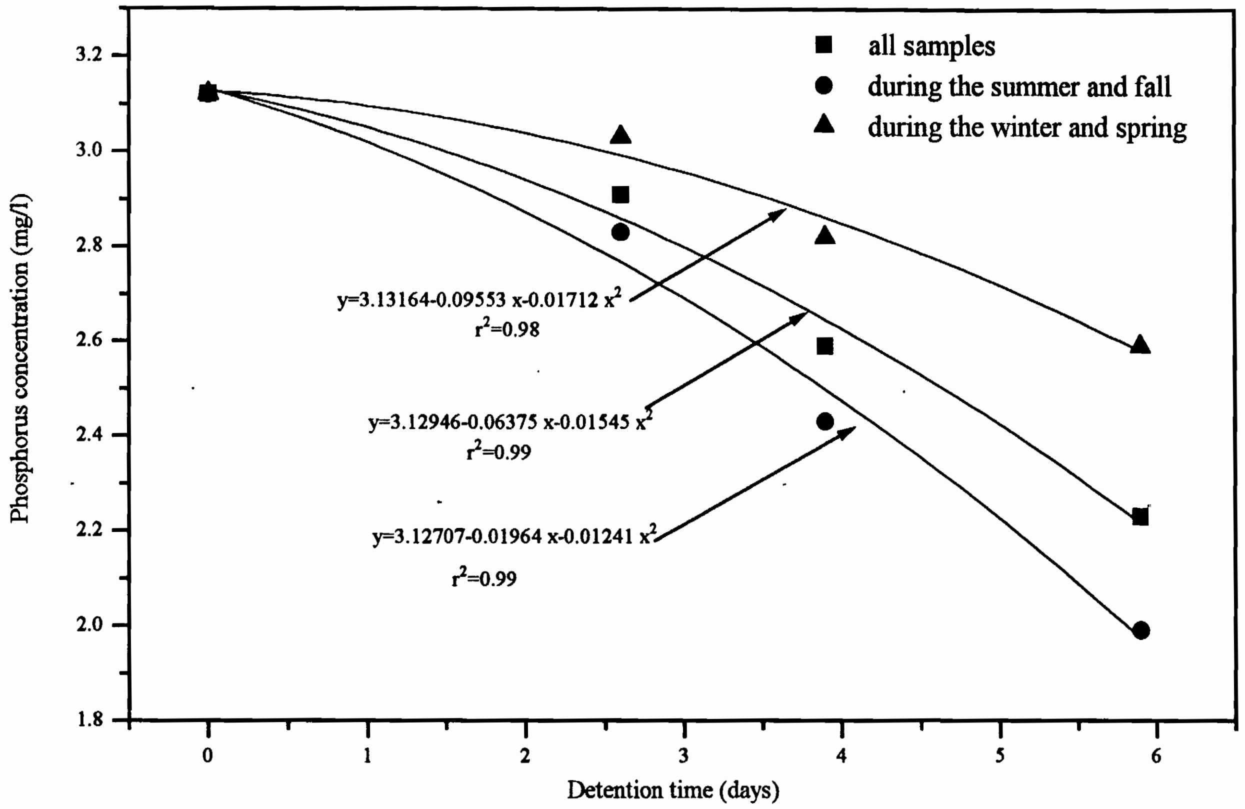


Figure 7.8 Relationship between detention time and phosphorus concentration in the SVBE at the Whitethorne Plantation site

PO_4^{3-}-P reduction rates in the shallow samples ranged from 34 to 90% (Table 7.6). This may have been caused by greater plant uptake in the shallow part of the SVB where a larger number and more active plant roots existed. As discussed earlier, if water loss via ET during the warmer seasons is considered, pollutant removal rates were actually higher than reported.

There was little seasonal impact on PO_4^{3-}-P removal by the SVBs. However, during the winter and spring periods, PO_4^{3-}-P concentrations in the SVBE tended to be higher than PO_4^{3-}-P concentrations during the fall and summer periods at the WP site (Table 7.3 and Fig. 7.8). During the warmer seasons, chemical and biological reactions would occur more rapidly. Also, the microbial population and plants would be more active due to favorable environmental conditions. Although the upper portion of the plants were inactive or dormant during colder seasons, plant roots remained alive, and organisms associated with the root system remained active. In addition, the microbes in the SVBs remain active as long as the water temperature is above 5 °C. It should be noted that PO_4^{3-}-P concentrations in the SVBE at the PRP site during the winter and spring periods, were lower than during the fall and summer periods (Table 7.1 and Fig. 7.9). This may have been partially caused by fertilization when additional cattails and woolgrass were replanted in June 1993. Unlike N, the PO_4^{3-} removal process is slow and time-dependent, and removal rates increased with detention time.

There were no differences between PO_4^{3-} concentrations presented in the SVBE in both shallow and deep samples as a result of vegetation types (Table 7.6) at the PRP site. However, there were differences between PO_4^{3-} concentrations in the SVBs planted to cattail and woolgrass at the WP site (Table 7.6). Although cattail and woolgrass are quite different plant species, there were no differences between the two plant species in water loss via evapotranspiration (Table 3.2, Chapter III). The same type of media (limestone, gravel), was used. therefore, these differences may result from the differences of plant uptake and cation concentrations in the STEs. Plant biomass (tissue) was harvested once at both experimental sites, in June 1993 (June 9, 1993 for the WP site and June 29, 1995 for the PRP site). Both

Table 7.11 Annual P budget in the SVBs at the Whitethorne Plantation site (1993)

Treatment		P* (loading)	P ** (out)	Removed	Plant biomass	P in tissue	Plant uptake	
Detention (days)	Plant species	g/year				%	g/year	removal %
2.6	cattail	17.24	13.15	4.09	201	1.08	2.23	12.9
3.9	cattail	11.4	7.55	3.85	390	1.04	4.06	35.6
5.9	cattail	7.54	4.21	3.33	410	1.04	4.26	56.5
2.6	woolgrass	17.24	14.19	3.05	185	0.98	1.81	10.5
3.9	woolgrass	11.4	8.54	2.86	236	1.08	2.55	22.4
5.9	woolgrass	7.54	4.97	2.57	198	0.95	1.88	24.9

*P loading=P concentration (mg/L) in STE X loading rate (L/d) X 365 d/y;

** P out=P concentration (mg/L) in STE X loading rate (L/d) X 0.85 X 365 d/y, based on 15% water loss via ET.

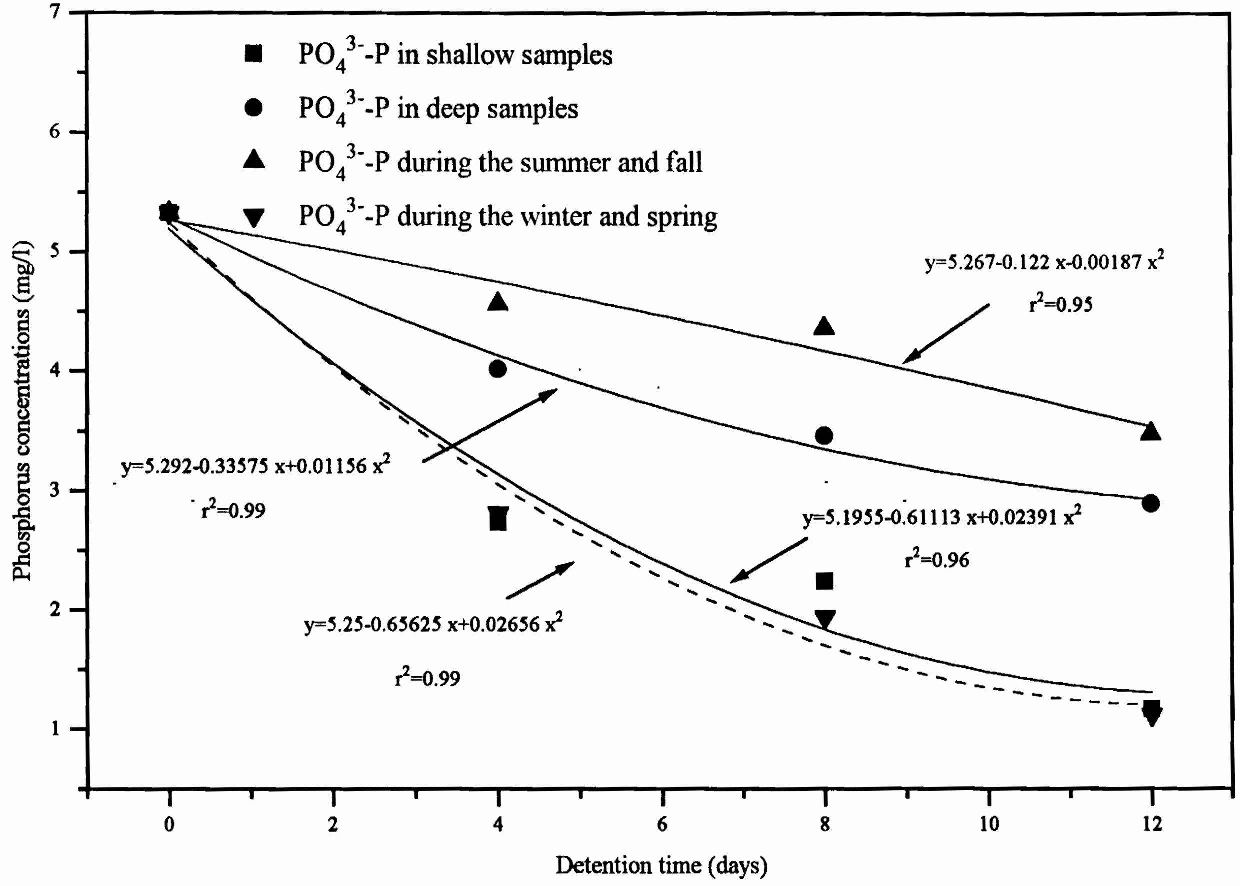


Figure 7.9 The effect of detention time on phosphorus concentrations in the SVBE at thePowell River Project site

cattail and woolgrass contained the same amount of PO_4^{3-} in the tissue within the same site, but average tissue P content at the PRP site tended to be higher than tissue P at the WP site (approximately 1.03% at the WP site, and 1.20% at the PRP site) (Table 7.10). Plant uptake of P in the SVBs, during 1993 at the WP site, accounted for at least 13% of the total P removed (Table 7.11). However, plant uptake is a significant part of the P budget only when the biomass is harvested. Phosphorus may also be controlled by chemical deposition within the SVBs by forming complexes with Ca, Mg, Fe, Al, and Mn. Calcium and Mg complexes may have dominated in the system due to higher pH ($P \geq 7.30$). In addition Ca, Mg, and Mn concentrations in the STEs were much higher at the PRP site than at the WP site (Tables 7.12 and 7.13).

A polynomial equation can be used to describe the relationship between detention time and PO_4^{3-}-P concentrations in the SVBE of both experimental sites. The relationship between detention times and PO_4^{3-}-P concentrations in the SVBE at the WP site (Fig. 7.8) was:

$$PO_4\text{-}P\ (mg/l) = 3.13 - 0.064X - 0.015\,X^2\ (r^2=0.99) \qquad \text{Eq. 7.3}$$

For the SVBs at the PRP site, the relationship between detention times and PO_4^{3-}-P concentrations are shown in Fig. 7.9. The relationship between PO_4^{3-}-P concentration and detention time during the winter and spring was very similar to the relationship between PO_4^{3-}-P and detention time in samples collected from the shallow parts of the wastewater column in the SVBs. This might indicate that there was more P uptake by plants in the shallow part of wastewater column.

4. Metals and Trace Elements

The occurrence of metals and trace elements in the wastewater is related to the water sources and human activities. Trace elements are used in industrial processing and manufactured goods. Many products may also be contaminated by trace elements during the manufacturing and storage processes. The water supply equipment and facilities can also contribute some trace elements to the drinking water supply. Therefore, trace elements are always found in domestic wastewater. Some heavy metals accumulate in the environment and are toxic to plants and animals. Their presence may limit the suitability of the wastewater for irrigation or discharge. Copper and Cd concentrations in the STE at the WP site and Zn at both sites (Tables 7.12 and 7.13) were much higher than recommended criteria for irrigation (Westcot and Ayers, 1985). After treatment in the SVBs, more than 80% of Cu and 75% of Cd was removed, and Cd concentrations were below the recommended irrigation criteria at the 2.6 days detention time. Zn removal ranged from 79 to 95% in the SVBs. The Pb, Co, and Ni concentrations in both STE and SVBE were lower than recommended irrigation limits. Plant species planted into the SVBs had no effect on Ca and Mg concentrations in the SVBE at the PRP site (Table 7.13). However, in the SVBs planted to woolgrass, effluent concentrations for Ca and Mg tended to be higher than those planted to cattails at the WP site (Table 7.12). There were also no differences among the SVBs planted to cattail or woolgrass for K, S, Mn, Pb, Ni, Cu, Cd, and Co concentrations in the SVBE, but Zn concentrations in the SVBE were higher in the SVBs planted to cattails as compared to the SVBs planted to woolgrass.

Based on plant tissue analysis, there were no differences among treatments for Zn and Fe concentrations in plant tissue, but cattail tissues contained more K, Ca, Mg, S, and Cl than woolgrass tissues. This probably reflects genetic differences associated with the ion uptake process for these plant species (Table 7.14).

5. Chloride (Cl)

Chloride can be used as an indicator of dilution or concentration in the SVBs. This is because Cl is chemically and essentially biologically inert (plants may uptake small amounts of Cl) under normal conditions. Comparing the Cl concentrations of effluent with STE can be used as an indicator of dilution or concentration of water samples in the SVBs under natural weather conditions. With increased effluent detention time, Cl concentration in the SVBE tended to increase in the SVBs at the WP site (Tables 7.3, and 7.9 and Fig. 7.10). This increase is probably due to increased ET with increased detention time. In contrast, with increased detention time, Cl concentration was decreased in the effluent collected from both the shallow and deep part of wastewater columns of the SVBs at the PRP site (Table 7.2 and Fig. 7.10), and removal rates ranged from 13 to 75%. Plant tissue contained a very small percentage of Cl (Table 7.14).

Table 7.12 Secondary and trace element concentrations in septic tank effluent (STE) and subsurface vegetated bed effluents (SVBE) at the Whitethorne Plantation site

Treatment			K	Ca	Mg	S	Mn	Pb	Ni	Zn	Cu	Cd	Co
Detention time (days)	Plant species	Recir. (%)	mg/l						ug/l				
STE			13.2	67.6	32.4	8.7	0.05	0.1	0.1	84	13	8	3
2.6	Cattail	0	13.1 a*	67.6 b	33.6 a	3.9 a	0.05 a	<0.1 a	<0.1 a	22.8 a	2.5 a	<2 a	<3 a
3.9	Cattail	0	10.2 a	70.8 ab	34.7 a	3.76 a	0.09 a	<0.1 a	<0.1 a	17.8 a	2.0 a	<2 a	<3 a
3.9	Cattail	50	8.8 a	70.6 ab	35.0 a	4.12 a	0.06 a	<0.1 a	<0.1 a	21.0 a	2.0 a	<2 a	<3 a
5.9	Cattail	50	6.2 a	74.2 ab	36.6 a	4.31 a	0.04 a	<0.1 a	<0.1 a	5.5 b	2.0 a	<2 a	<3 a
2.6	Woolgrass	0	7.4 a	83.8 ab	38.3 a	3.27 a	0.08 a	<0.1 a	<0.1 a	4.8 b	2.0 a	<2 a	<3 a
3.9	Woolgrass	0	8.17 a	78.4 ab	36.3 a	3.81 a	0.18 a	<0.1 a	<0.1 a	11.3 b	2.0 a	<2 a	<3 a
3.9	Woolgrass	50	8.28 a	76.0 ab	35.5 a	2.61 a	0.06 a	<0.1 a	<0.1 a	4.5 b	2.0 a	<2 a	<3 a
5.9	Woolgrass	50	6.94a	84.7 a	39.0 a	2.95 a	0.13 a	<0.1 a	<0.1 a	14.3 b	2.0 a	<2 a	<3 a

*means within the same column followed by the same letter are not significantly different at 5% level, determined by Duncan's multiple range test.

Table 7.13 The impact of detention time on selected metal concentrations in the SVBE at the Powell River Project site

Detention time (days)	K	Ca	Mg	Mn	Zn
	mg/l	mg/l	mg/l	mg/l	ug/l
0*	20	171	76.8	1.96	27.0
4	16.9 a**	140.3 a	60.4 a	0.38 a	19 a
8	11.9 a	119.5 a	56.7 a	0.13 a	24 a
F***	13.4 a	124.5 a	55.6 a	0.15 a	23 a
removal %					
4	15.3 a	17.9 a	21.4 a	80.4 a	29.6 a
8	40.6 a	30.1 a	34.0 a	93.2 a	11.1 a
F	32.9 a	27.2 a	27.7 a	92.3 a	14.8 a

* influent (STE).

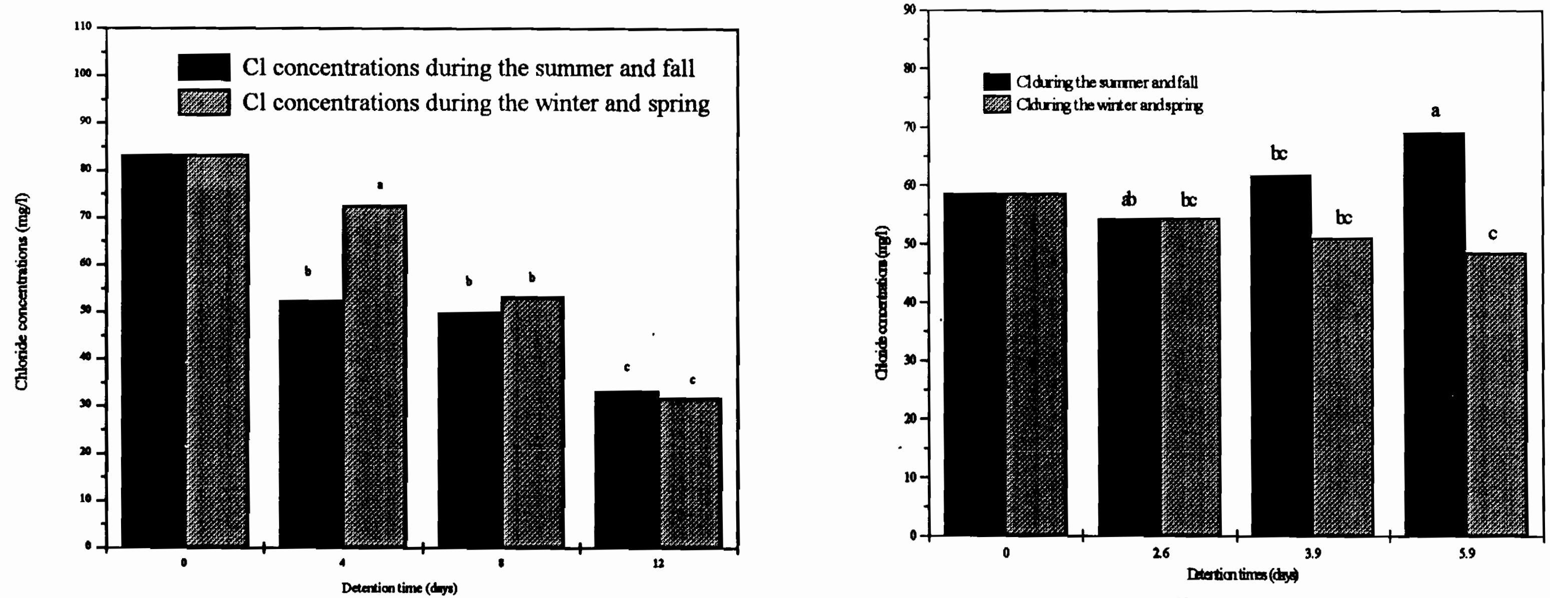
** means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan's multiple range test.

*** mixed samples collected from the bottom of the SVBE.

Table 7.14 Nutrient and metals in the plant tissue (Whitethorne Plantation, June, 1993)

Treatment		K	Ca	Mg	Cl	S	Zn	Cu	Fe
Detention time (days)	Plant species	%					mg/kg		
2.6	cattail	0.93 a	0.82 a	0.31 b	0.91 a	0.41 a	0.30 a	0.07 ab	0.8 a
3.9	cattail	0.81 b	0.84 a	0.35 a	0.83 a	0.37 b	0.31 a	0.07 ab	0.7 a
5.9	cattail	0.84 b	0.85 a	0.35 a	0.80 a	0.34 c	0.28 a	0.05 b	0.6 a
2.6	woolgrass	0.65 c	0.39 b	0.28 c	0.19 b	0.23 d	0.25 a	0.07 ab	0.9 a
3.9	woolgrass	0.59 cd	0.41 b	0.28 c	0.16 b	0.21 d	0.24 a	0.08 a	0.8 a
5.9	woolgrass	0.61 cd	0.39 b	0.27 c	0.19 b	0.20 d	0.28 a	0.08 a	0.8 a

* means followed by the same letter within the same column are not significantly different at 5% level, determined by Duncan multiple range test.



(Powell River Project)

(Whitehorne Plantation)

Figure 7.10 The effect of detention time on chloride concentrations in the SVBE at both experimental sites

III. CONCLUSIONS

1. The efficiency of chemical pollutant removal in the SVBs was high at both experimental sites. Without adjustment of water loss via ET, P removal rates ranged from 7-28% for the WP site, and 24-78% for the PRP site. TDS were accumulated from 6 to 43% at the WP site, but TDS were reduced from 12 to 73% at the PRP site.
2. Detention time was the major factor which affected pollutant removal efficiency. Six to 8 days detention time was suitable for individual domestic wastewater treatment.
3. There were no differences in K, Ca, Mg, Zn, Cu, Pb, Ni, Cd, and S concentrations in the SVBE at the WP site, and these metal concentrations in the SVBE were lower than recommend irrigation criteria
4. Aquatic plants introduced into subsurface beds may be essential for an active and functional system. Both cattail and woolgrass are suitable for constructed wetlands.
5. The depth of the SVB was an important design issue.
6. Plant tissue accounted for 13-57% of applied P removal if harvested once a year during the growing season.

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APPENDIX: DATA

I. Whitethorne Plantation site

1. Fecal coliforms (FC/ no./100 ml)

Field no.	Lab. no.	12/23/92	3/2/93	3/24/93	4/21/93	5/19/95	6/9/930	7/8/93
C2	1	<10	<10	230	<10	109000	0	560
C3	2	<10	<10	<10	1	1500	780	760
C1	3	<10	1	<10	<10	100	100	770
C4	4	<10	1	<10	<10	1200	0	310
W3	5	1	<10	<10	1	6000	630	140
W1	6	1	1	<10	1	2600	180	280
W4	7	1	<10	<10	<10	4000	0	120
W2	8	1	<10	<10	1	2000	0	700
C4	9	<10	1	<10	<10	1000	260	270
C1	10	1	1	<10	<10	17000	0	<10
C3	11	<10	<10	150	<10	700	0	<10
C2	12	500	1	<10	<10	300	0	<10
W3	13	1	<10	<10	<10	2000	0	140
W1	14	1	<10	<10	<10	7000	0	<10
W4	15	1	1	<10	<10	1500	0	<10
W2	16	<10	<10	<10	<10	500	0	110
STE	17	230	<10		<10	2700	800	1920

Fecal coliforms (cont.)

Field no.	Lab. no.	8/4/93	9/1/93	10/27/ 93	2/2/94	3/29/94	4/13/94	5/18/94	6/1/94
C2	1	1000	<10	<10	72000	3700	670	2900	20000
C3	2	1680	120	130	11800	1230	440	21000	3500
C1	3	1060	260	300	10500	42000	830	21800	7500
C4	4	1510	<10	<10	11000	1700	380	15100	21000
W3	5	300	<10	<10	16800	820	2700	1410	18000
W1	6	1100	350	<10	11700	15500	490	15400	17000

W4	7	1190	340	360	10200	10400	910	2120	15000
W2	8	8300	110	<10	2000	115000	1020	23600	10900
C4	9	380	<10	<10	9100	4800	9800	6000	1500
C1	10	1050	300	<10	7800	22000	3800	5600	1400
C3	11	340	140	<10	9800	1190	450	12700	1090
C2	12	660	<10	<10	3000	7400	2700	2150	840
W3	13	750	<10	<10	12300	880	460	3000	920
W1	14	7000	400	500	13300	1730	1020	9200	1380
W4	15	4500	<10	<10	3200	5800	220	2700	540
W2	16	1100	<10	<10	3700	59000	5400	3800	820
STE	17	9600	1850	12700	70000	95000	13000	64000	23000

Fecal coliforms (cont.)

Field no.	Lab. no.	7/5/94	Field no.	Lab. no.	1/25/95	2/22/95	6/21/95	
C2	1	110	I2	1	1300	6900	<10	
C3	2	400	I3	2	3900	14700	<10	
C1	3	310	I1	3	11000	6600	930	
C4	4	360	I4	4	15400	9600	1330	
W3	5	540	B3	5	67000	2600	200	
W1	6	160	B1	6	10500	13300	1840	
W4	7	<10	B4	7	5700	9500	1200	
W2	8	300	B2	8	6200	3600	<10	
C4	9	850	C4	9	5800	3400	1100	
C1	10	1100	C1	10	21500	9500	690	
C3	11	3700	C3	11	8600	9300	1800	
C2	12	16000	C2	12	22700	4000	<10	
W3	13	3200	W3	13	9100	2400	<10	
W1	14	5200	W1	14	84000	12600	<10	
W4	15	3900	W4	15	26000	1200	<10	
W2	16	2200	W2	16	65000	13700	<10	
STE	17	4000	STE	17	216000	23000	13400	

2. Coliphages (no./100 ml)

Field no.	Lab. no.	3/24/93	4/21/93	5/19/93	6/9/93	7/8/93	6/21/95
C2	1	0	7.8	0	0	28.5	
C3	2	0	4	0	0	14.2	
C1	3	0	19	0	0	7.1	
C4	4	0	18	0	0	24	
W3	5	0	16	0	0	29.6	
W1	6	0	12	0	0	56.6	
W4	7	0	20	0	0	46.4	
W2	8	0	20	0	0	25	
C4	9	0	21.6	0	0	18.5	
C1	10	0	12	0	0	16	
C3	11	0	24	0	0	10	
C2	12	0	25.8	0	0	10	
W3	13	0	8	0	0	21.4	
W1	14	0	0	0	0	21.4	
W4	15	0	21.6	0	0	0	
W2	16	0	21	0	0	40	
STE	17	0		0	0		157.7

3. 5 days biochemical oxygeb demand (BOD$_5$, mg/L)

Field no.	Lab. no.	9/16/92	11/6/92	12/23/92	1/27/93	3/2/93	3/24/93	4/21/93
C2	1	31.7	24.3	37.5	77.3	43.5	15.0	19.5
C3	2	46.0	18.0	38.1	76.5	36.8	16.5	21.0
C1	3	45.0	23.0	42.0	89.5	43.5	12.8	16.5
C4	4	32.3	6.0	19.5	57.0	36.0	7.5	18.0
W3	5	43.1	37.5	14.3	75.0	35.4	10.0	18.0
W1	6	59.5	22.5	31.5	79.5	46.5	7.5	18.0
W4	7	48.0	12.3	30.0	63.8	34.8	13.5	16.5
W2	8	55.0	12.8	27.8	83.3	43.8	5.3	16.5
C4	9	25.5	1.5	24.8	57.8	30.8	10.5	16.5
C1	10	46.3	19.5	37.5	84.0	42.0	14.3	15.0
C3	11	31.5	9.0	9.8	67.5	53.3	21.0	15.8

C2	12	39.5	14.3	30.0	77.3	35.3	13.5	20.3
W3	13	32.3	15.8	4.5	84.8	34.5	12.0	25.5
W1	14	56.7	14.6	45.0	84.0	44.3	12.8	18.0
W4	15	60.5	6.0	18.5	58.5	30.8	18.0	18.0
W2	16	33.0	13.0	41.3	81.0	30.8	15.0	22.5
STE	17	83.3	85.5	81.0	104.3	51.6		208.5

BOD$_5$ (cont.)

Field no.	Lab. no.	5/19/93	6/9/93	6/23/93	7/8/93	7/21/93	8/4/93	8/18/93
C2	1	46.0	15.0	21.0	47.5	94.5	12.0	16.5
C3	2	42.0	15.8	26.3	40.0	75.0	18.0	23.5
C1	3	58.5	19.3	34.5	64.0	98.6	18.0	28.0
C4	4	35.5	7.5	10.5	31.5	67.6	21.8	21.0
W3	5	45.0	19.3	15.0	62.0	105.6	61.5	30.0
W1	6	54.0	39.8	42.8	26.0	99.1	57.0	31.5
W4	7	34.5	13.5	32.3	14.0	66.6	35.3	37.0
W2	8	40.0	14.3	39.0	23.0	107.6	72.0	28.0
C4	9	30.0	39.8	16.5	15.0	67.6	9.8	15.5
C1	10	39.0	52.5	38.3	39.5	91.6	16.5	28.5
C3	11	34.5	35.3	15.8	20.0	64.6	22.5	29.0
C2	12	43.5	43.5	15.8	34.5	90.6	21.8	28.0
W3	13	44.3	54.0	15.0	18.0	126.6	58.8	71.0
W1	14	48.0	42.0	40.5	22.0	78.6	39.8	54.0
W4	15	25.5	44.3	19.5	9.5	74.6	32.2	35.0
W2	16	33.0	48.3	25.5	14.0	70.6	47.3	
STE	17	84.0	77.5	99.0	72.5	126.1	84.0	70.0

BOD$_5$ (cont.)

Field no.	Lab. no.	9/1/93	10/27/93	2/2/94	4/13/94	5/18/94	6/1/94	7/5/94	8/11/94
C2	1	22.5	19.0	128	197	83.3	141	178	27.0
C3	2	33.0	29.5	61	182	82.5	143	113	8.3
C1	3	36.0	34.5	141	183	120	160	146	24.8
C4	4	25.5	12.5	52.5	176	57.0	88.5	109	15.0
W3	5	27.0	12.5	46.5	186	118	191	145	11.3

W1	6	28.7	30.5	140	216	152	194	165	18.0
W4	7	29.0	16.5	60.0	162	99	94.2	131	14.3
W2	8	38.5	27.5	43.0	213	164	168	126	19.5
C4	9	23.0	6.0	64.0	182	69	113	106	12.8
C1	10	25.5	1.0	140	230	146	183	161	28.5
C3	11	22.0	19.0	89.0	211	99.8	156	129	4.5
C2	12	25.5	12.5	20.0	224	103	165	114	17.3
W3	13	45.5	15.5	74.5	217	152	197	166	15.0
W1	14	54.0	32.5	120	216	173	206	183	15.8
W4	15	55.0	9.5	25.0	164	93.3	137	103	10.5
W2	16	53.0	16.0	59.5	212	98.3	173	134	15.0
STE	17	141	128.0	143.0	230	191	225	201	

BOD$_5$ (cont.)

Field no.	Lab. no.	9/12/94	10/6/94	11/30/94	12/14/94	1/25/95	4/5/95	5/10/95
I2	1	30.0	13.0	25.5	78.0	61.3	141	75.0
I3	2	21.8	21.0	25.5	78.0	51.8	98.3	46.5
I1	3	25.5	16.0	27.8	107	74.5	121	90.0
I4	4	19.5	6.0	18.0	60.0	63.0	106	80.3
B3	5	21.0	13.0	15.0	111	54.8	110	75.0
B1	6	27.0	24.0	25.5	94.5	48.8	155	105.0
B4	7	18.0	3.0	18.8	93.5	62.3	122	70.5
B2	8	23.3	5.0	18.8	141	77.5	119	93.8
C4	9	23.3	29.5	18.8	88.5	51.8	117	70.0
C1	10	26.3	37.0	30.0	72.0	91.5	108	98.1
C3	11	22.5	13.5	18.0	79.5	63.0	132	80.0
C2	12	21.7	9.0	21.8	39.0	54.8	123	84.8
W3	13	27.0	18.5	17.3	57.0	71.3	138	84.8
W1	14	24.0	34.0	20.3	87.0	63.0	109	82.5
W4	15	15.8	11.0	13.5	30.8	40.0	109	72.0
W2	16	31.5	10.0	13.5	36.0	58.5	125	77.5
STE	17	43.5	32.0	50.3	102	105	159	106.5

BOD$_5$ (cont.)

Field no.	Lab. no.	6/21/95	7/19/95				
I2	1	63.8	17				
I3	2	51.8	82.5				
I1	3	84	24				
I4	4	55.5	12				
B3	5	67.5	15				
B1	6	104	33				
B4	7	75	20.3				
B2	8	75	39				
C4	9	75.8	21.8				
C1	10	76.8	57				
C3	11	66.8	34				
C2	12	65.8	25.5				
W3	13	60	25				
W1	14	64.5	60.8				
W4	15	52.5					
W2	16	61.5	13.5				
STE	17	94.5	67.5				

4. Total Kjeldahl Nitrogen (TKN, mg/L)

Field no.	Lab. no.	1/27/93	3/2/93	3/24/93	5/19/95	6/9/930	6/23/93	7/8/93	7/21/93
C2	1	27.5	27.5	25.7	22.9	12.6	17.2	30.6	32.7
C3	2	30.1	25.5	26.6	25.5	10.8	23.6	36.2	28.4
C1	3	26.3	27.5	25.9	30.8	25.1	25.7	39.0	34.1
C4	4	26.6	23.9	24.8	15.7	7.61	7.4	27.8	32.0
W3	5	25.4	25	24.6	20.7	18	19.2	31.5	33.5
W1	6	28.7	30.7	25.9	24.7	21.5	16.2	37.1	34.8
W4	7	20.7	23.6	23.4	11.2	10.5	20.4	20.3	22.0
W2	8	24.2	25.2	10.2	13.7	5.5	5.4	33.4	34.1
C4	9	30.1	22.1	31.4	16.2	9	20.4	24.1	27.1
C1	10	34.3	26.8	31.6	26.3	28.3	2.0	35.3	35.6
C3	11	31.6	25.5	25.5	14.3	7.3	8.3	30.6	32.0

C2	12	25.7	26.8	25	19.3	6.2	11.2	36.2	34.8
W3	13	33.9	27.7	27.7	21	9.8	20.4	33.4	30.0
W1	14	35.7	28.9	24.3	25.2	19.8	28.9	39.0	36.3
W4	15	22.5	28	26.1	13.2	4.8	7.4	25.9	24.9
W2	16	23.9	27.5	22.7	17.3	5.8	18.3	35.3	32.0
STE	17	40.1	34.3	32.3	35.2	39.4	38.6	48.3	46.2

TKN (cont.)

Field no.	Lab. no.	8/4/93	8/18/93	9/1/93	10/27/93	2/2/94	3/29/94	4/13/94	5/18/94	6/1/94
C2	1	23.3	29.7	32.1	26.1	42.8	41.2	40.8	57.1	57.1
C3	2	32.1	28.6	36.1	29.1	27.9	42.2	43.5	52.9	52.9
C1	3	35.1	31.7	32.9	35.2	42.3	44.4	40.8	53.8	53.8
C4	4	24.1	28.7	24.8	21.8	27.6	38.7	38.1	46.1	46.1
W3	5	30.9	28.6	36.1	33.4	33.5	35.9	39.5	61.4	60.0
W1	6	31.7	31.7	34.5	45.7	38.7	41.4	41.6	61.4	63.9
W4	7	24.9	37.8	39.4	29.1	34.6	31.8	36.7	46.1	46.1
W2	8	30.1	25.9	29.7		36.4	40.3	35.9	61.4	61.4
C4	9	10.5	21.8	16.6	19.3	25.3	46.9	34.9	38.5	38.5
C1	10	25.6	27.2	29.7	26.7	36.1	55.1	37.5	46.1	46.1
C3	11	18.8	19.4	21.6	15.0	30.4	51.6	38.1	43.6	43.6
C2	12	24.3	25.1	24.0	23.0	27.9	52.8	40.4	45.3	45.3
W3	13	21.6	25.5	31.3	30.3	35.6	49.7	35.5	41.9	41.9
W1	14	29.6	31.7	36.1	38.3	36.1	63.4	37.2	51.2	51.2
W4	15	13.1	34.1	34.5	24.8	25.0	35.4	33.7	38.5	38.5
W2	16	29.0	36.8	37.7	33.1	28.4	57.1	36.4	48.7	48.3
STE	17	34.1	41.5	56.9	61.0	52.6	69.6	44.9	63.1	63.1

TKN (cont.)

Field no.	Lab. no.	7/5/94	8/11/94	Field no.	Lab. no.	9/12/94	10/6/94	11/30/94	12/14/94
C2	1	46.7		I2	1	11.3	18.9		
C3	2	50	23.4	I3	2	15	17.4		
C1	3	50	18.1	I1	3	15	14.3		
C4	4	50	9.2	I4	4	14.4	16.1		

W3	5	50	26.5	B3	5	18.1	10.7		
W1	6	56.7	22.8	B1	6	16.3	18.9		
W4	7	40	26.5	B4	7	11.3	9.8		
W2	8	53.3	24.4	B2	8	22.5	14.3		
C4	9	43.3	24.9	C4	9	15	15.2		
C1	10	50	25.5	C1	10	16.3	14.8		
C3	11	46.7	13.9	C3	11	18.8	15.2		
C2	12	46.7	18.1	C2	12	18.8	15.2		
W3	13	48.3	29.7	W3	13	17.5	17		
W1	14	58.3	22.3	W1	14	13.8	15.2		
W4	15	46.7	17.1	W4	15	13.8	15.2		
W2	16	53	15	W2	16	11.3	18.9		
STE	17	60	33.4	STE	17	26.3	20.7		

5. Ammonium (NH_4^+, mg/L)

Field no.	Lab. no.	9/16/92	11/6/92	3/24/93	4/21/94	5/19/94	6/9/94	7/8/93	7/21/93
C2	1	0.49	14.9	24.4	27.6	17.9	3.8	32.7	24.3
C3	2	6.5	12.4	23.0	26.3	20.4	16.6	31.9	29.6
C1	3	11.4	16.5	24.9	27.9	25.1	21.4	36.0	33.8
C4	4	1.9	7.5	22.9	25.9	10.4	3.5	21.7	23.8
W3	5	5.8	17.3	22.2	25.0	14.1	11.6	24.5	22.2
W1	6	9.4	4.2	22.9	26.4	19.8	17.6	29.9	26.9
W4	7	0.6	11.6	22.1	22.2	6.8	1.1	15.0	9.6
W2	8	2.6	11.7	9.2	27.4	13.2	4.1	25.8	23.3
C4	9	0.7	6.7	24.9	26.7	9.5	2.8	10.7	14.3
C1	10	12.2	21.4	24.4	28.1	24.6	16.3	29.5	31.2
C3	11	3.6	13.2	24.6	27.4	14.6	3.4	21.3	24.3
C2	12	2.8	15.7	25.1	27.9	19.1	3.7	22.9	27.5
W3	13	2.8	13.2	25.6	23.8	13.8	9.0	18.9	19.0
W1	14	12.5	18.1	213.7	27.4	22.8	17.9	22.5	31.2
W4	15	0.54	6.7	24.9	25.6	7.4	2.3	5.7	10.6
W2	16		13.2	24.8	27.4	13.2	2.0	22.5	19.0
STE	17	32.0	23.1	25.3	30.5	31.3	35.8	40.5	41.2

NH_4^+(cont.)

Field no.	Lab. no.	8/4/93	8/18/93	9/1/93	10/27/93	2/2/94	3/29/94	4/13/94	5/18/94
C2	1	21.6	20.6	21.5	16.2	34.7	20.1	36.9	39.5
C3	2	27.3	27.8	28.9	27.7	26.9	17.7	50.7	43.4
C1	3	30.1	31.4	30.8	32.3	20.7	21.1	42.3	38.6
C4	4	21	20.4	18.8	11.2	19.7	19.2	31.5	29.5
W3	5	24.5	26.6	29.6	28.5	24.7	18.4	37.1	36.2
W1	6	27.9	29.9	31.7	32.3	33.7	16.5	34.7	38.6
W4	7	18.4	25.6	32	25	22.5	17.7	34.1	36.2
W2	8	27.3	23.8	28.2	27.7	24.7	19.6	39.1	41.0
C4	9	10.5	13.3	9.4	5.5	19.7	16.5	30.3	26.1
C1	10	25.6	25.3	23	23.5	33.4	19.6	39.1	37.6
C3	11	18.8	19	15.3	8.9	27.3	17.2	33.3	30.4
C2	12	24.3	24.2	22.4	12.8	21	20.4	34.3	29.5
W3	13	21.6	22.9	27.4	25.8	33.1	18.7	33.3	30.4
W1	14	29.6	30.6	31.7	32.7	32.8	22	36.2	35.7
W4	15	13.1	31.2	29.3	18.1	21.9	17	28.0	43.4
W2	16	29	33.5	34.8	27.1	26.6	19.6	34.9	31.9
STE	17	34.1	36.4	37.3	26.3	41.5	23.5	41.6	45.8

NH_4^+ (Cont.)

Field no.	Lab. no.	6/1/94	7/5/94	8/11/94	Field no.	Lab. no.	9/12/94	10/6/94	11/30/94
C2	1	35.8	38.9	17.9	I2	1	11.6	5.4	11.6
C3	2	37.0	38.9	15.0	I3	2	12.8	5.7	12.1
C1	3	35.5	40.5	15.5	I1	3	16.1	8.8	16.8
C4	4	35.2	30.6	19.1	I4	4	12.8	6.3	10.7
W3	5	35.8	38.9	19.4	B3	5	12.6	8.2	14.8
W1	6	42.4	41.5	17.1	B1	6	15.1	6.9	15.1
W4	7	35.2	34.3	15.7	B4	7	8.7	6.3	15.3
W2	8	38.1	35.8	16.2	B2	8	12.0	6.9	19.5
C4	9	29.6	36.3	15.3	C4	9	11.0	8.8	13.1
C1	10	42.7	51.4	17.4	C1	10	16.9	11.8	21.2
C3	11	33.2	33.2	19.0	C3	11	14.1	10.5	17.8

C2	12	31.6	33.7	18.3	C2	12	15.1	11.8	16.0
W3	13	30.2	35.8	20.2	W3	13	16.3	12.2	17.5
W1	14	37.1	37.9	14.8	W1	14	14.9	10.1	17.0
W4	15		24.9	17.6	W4	15	11.2	8.4	9.7
W2	16	35.5	36.9	17.2	W2	16	13.2		8.7
STE	17	53.9	45.2	26.3	STE	17	21.2	14.3	26.8

NH_4^+ (cont.)

Field no.	Lab. no.	12/14/94	2/22/95	4/5/95	6/21/95	7/19/95	8/23/93
I2	1	14.8	52	34.6	36.1	25.4	27.2
I3	2	14.4	57.6	32.0		9.7	14.4
I1	3	18.4	73.5	41.5	41.4	33.4	42.1
I4	4	14.8	76.1	37.7	31.3	14.3	26.9
B3	5	18.1	78.6	39.2	29.9	33.8	31.3
B1	6	19.2	82	44.1	42.3	41.0	37.4
B4	7	15.3	73	38.1	38.0	38.9	37.4
B2	8	15.3	62.2	48.1	36.6	41.9	38.0
C4	9	14.6	43.8	39.2	41.8	34.3	33.3
C1	10	18.6	54.6	41.8	32.7	39.8	44.5
C3	11	17.2	46.4	44.9	39.4	35.1	39.4
C2	12	13.2	48.4	45.1	29.9	35.5	44.8
W3	13	17.4	55.6	46.2	37.1	33.4	43.5
W1	14	18.6	49.9	42.6	22.2	37.6	46.8
W4	15	9.3	53	43.4	30.3	33.8	28.5
W2	16	11.9	54.8	40.1	51.9		42.8
STE	17	23.4	62.2	55.1		46.1	49.5

5. Nitrate (NO_3^-, mg/L)

Field no.	Lab. no.	9/16/92	11/6/92	3/24/93	4/21/93	5/19/93	6/1/93	6/23/93	7/8/93
C2	1	0.09	0	0.09	0.19	0.08	0.11	0.10	0.11
C3	2	0.09	0	0.12	0.19	0.09	0.06	0.08	0.06

C1	3	0.07	0	0.09	0.19	0.03	0.07	0.08	0.03
C4	4	0.07	0	0.09	0.15	0.07	0.11	0.07	0.07
W3	5	0.09	0	0.07	0.14	0.07	0.09	0.08	0.06
W1	6	0.09	0	0.11	0.12	0	0.06	0.09	0.05
W4	7	0	0	0.05	0.15	0.12	0.07	0.07	0.06
W2	8	0.05	0	0.01	0.12	0.13	0.07	0.08	0.06
C4	9	0.07	0	0.09	0.11	0	0.09	0.06	0.05
C1	10	0.07	0	0.13	0.13	0.03	0.05	0.08	0.04
C3	11	0.05	0	0.09	0.12	0	0.10	0.07	0.04
C2	12	0.05	0	0.14	0.12	0	0.08	0.10	0.04
W3	13	0.05	0.08	0.12	0.13	0	0.11	0.13	0.04
W1	14	0.05	0.08	0.12	0.12	0.01	0.08	0.09	0.04
W4	15	0.07	0	0.11	0.13	0	0.09	0.08	0.05
W2	16	0.05	0	0.14	0.12	0	0.07	0.10	0.05
STE	17	0.23	0	1.99	0.25	0.05	0.06	0.12	0.06

NO_3^- (cont.)

Field no.	Lab. no.	7/21/93	8/4/93	8/18/93	9/1/93	10/27/93	2/2/94	3/29/94	4/13/94
C2	1	0.25	0.13	0.26	0.23	0.24	0.27	0.26	0.26
C3	2	0.19	0.21	0.24	0.22	0.19	0.23	0.24	0.17
C1	3	0.17	0.15	0.32	0.21	0.17	0.36	0.31	0.29
C4	4	0.16	0.19	0.31	0.39	0.19	0.23	0.16	0.27
W3	5	0.20	0.20	0.24	0.22	0.17	0.19	0.29	0.25
W1	6	0.13	0.16	0.25	0.19	0.15	0.28	0.26	0.23
W4	7	0.16	0.20	0.23	0.27	0.15	0.19	0.29	0.24
W2	8	0.16	0.18	0.24	0.16	0.16	0.13	0.23	0.23
C4	9	0.15	0.14	0.21	0.17	0.14	0.15	0.23	0.20
C1	10	0.13	0.13	0.23	0.20	0.14	0.22	0.24	0.23
C3	11	0.11	0.22	0.20	0.20	0.14	0.19	0.23	0.22
C2	12	0.13	0.17	0.21	0.20	0.12	0.12	0.22	0.23
W3	13	0.15	0.29	0.17	0.24	0.15	0.09	0.19	0.22
W1	14	0.13	0.21	0.21	0.18	0.13	0.15	0.23	0.23
W4	15	0.11	0.22	0.16	0.17	0.14	0.09	0.15	0.24
W2	16	0.16	0.16	0.22	0.10	0.14	0.07	0.21	0.21
STE	17	0.13	0.25	0.20	0.17	0.26	0.13	0.15	0.19

NO_3^- (Cont.)

Field no.	Lab. no.	5/18/94	6/1/94	7/5/94	8/11/94	Feld no.	Lab. no.	9/12/94	10/6/94
C2	1	0.47	0.20	0.12	0.16	I2	1	0.12	0.21
C3	2	0.41	0.20	0.07	0.18	I3	2	0.13	0.28
C1	3	0.28	0.20	0.07	0.21	I1	3	0.17	0.25
C4	4	0.26	0.20	0.04	0.20	I4	4	0.07	0.21
W3	5	0.24		0.05	0.16	B3	5	0.10	0.30
W1	6	0.25	0.26	0.02	0.15	B1	6	0.10	0.23
W4	7	0.22	0.20	0.01	0.17	B4	7	0.07	0.21
W2	8	0.24	0.20	0.02	0.16	B2	8	0.05	0.21
C4	9	0.21	0.18	0.01	0.16	C4	9	0.12	0.14
C1	10	0.19	0.21	0.01	0.12	C1	10	0.13	0.14
C3	11	0.20	0.19	0.01	0.19	C3	11	0.12	0.14
C2	12	0.19	0.16	0.01	0.20	C2	12	0.12	0.16
W3	13	0.18	0.20	0	0.17	W3	13	0.12	0.19
W1	14	0.12	0.19	0	0.18	W1	14	0.15	0.23
W4	15	0.17	0.19	0.01	0.15	W4	15	0.12	0.21
W2	16	0.17	0.19	0.01	0.15	W2	16	0.13	0.16
STE	17	0.28	0.24	0.01	0.16	STE	17	0.36	0.19

NO_3-N (cont.)

Field no.	Lab. no.	11/30/94	4/5/95	5/10/95	6/21/95	7/19/95	8/23/95	
I2	1	0.29	0.21	0.11	0.24	0	0.22	
I3	2	0.18	0.17	0.19	0.33	0	0.20	
I1	3	0.25	0.20	0.26	0.36	0	0.17	
I4	4	0.17	0.10	0.16	0.22	0	0.16	
B3	5	0.19	0.08	0.16	0.24	0	0.21	
B1	6	0.26	0.13	0.26	0.29	0	0.16	
B4	7	0.23	0.14	0.21	0.27	0	0.17	
B2	8	0.17	0.19	0.28	0.29	0	0.18	
C4	9	0.2	0.17	0.19	0.36	0	0.18	
C1	10	0.24	0.22	0.16	0.27	0	0.15	
C3	11	0.22	0.19	0.16	0.29	0	0.13	

C2	12	0.15	0.09	0.08	0.24	0	0.12	
W3	13	0.18	0.12	0.05	0.27	0	0.13	
W1	14	0.27	0.15	0.08	0.31	0	0.13	
W4	15	0.18	0.14	0.08	0.33	0	0.14	
W2	16	0.23	0.09	0.08	0.36	0	0.14	
STE	17	0.19	0.06	0.08	0.79	0	0.14	

7. pH (unit)

Field no.	Lab. no.	9/16/92	11/6/92	12/23/92	1/27/93	3/2/93	3/24/93	4/21/93	5/19/93
C2	1	7.05	7.00	7.40	7.42	7.39	7.65	7.75	7.25
C3	2	7.10	7.10	7.40	7.52	7.42	7.70	7.80	7.36
C1	3	7.00	7.20	7.60	7.53	7.47	7.76	7.87	7.39
C4	4	7.00	7.00	7.30	7.42	7.46	7.86	7.77	7.07
W3	5	7.05	6.80	7.40	7.40	7.37	7.55	7.64	7.29
W1	6	7.10	6.70	7.30	7.46	7.48	7.63	7.73	7.35
W4	7	7.00	6.80	7.30	7.35	7.29	7.50	7.43	7.18
W2	8	7.00	6.80	7.40	7.40	7.36	7.25	7.63	7.34
C4	9	7.10	6.90	7.40	7.57	7.37	7.57	7.73	7.18
C1	10	7.10	7.20	7.50	7.47	7.45	7.69	7.89	7.23
C3	11	7.10	7.10	7.50	7.41	7.36	7.63	7.80	7.16
C2	12	7.05	7.10	7.50	7.45	7.38	7.71	7.85	7.26
W3	13	7.03	7.10	7.40	7.41	7.35	7.60	7.73	7.24
W1	14	7.05	7.00	7.50	7.47	7.45	7.62	7.75	7.38
W4	15	7.02	7.20	7.40	7.43	7.43	7.72	7.65	7.27
W2	16	7.00	7.00	7.40	7.39	7.37	7.67	7.75	7.21
STE	17	7.55	7.60	7.60	7.63	7.60	7.74	7.31	7.42

pH (cont.)

Field no.	Lab. no.	6/9/93	6/23/93	7/8/93	7/21/93	8/4/93	8/18/93	9/1/93	10/27/93
C2	1	7.43	7.14	6.98	6.99	7.33	7.51	7.38	7.33
C3	2	7.59	7.31	7.16	7.05	7.55	7.61	7.56	7.77
C1	3	7.52	7.19	7.18	7.00	7.43	7.48	7.53	7.57
C4	4	7.62	7.00	7.04	6.90	7.32	7.31	7.35	7.33

W3	5	7.60	7.08	6.94	6.82	7.42	7.37	7.44	7.35
W1	6	7.67	7.09	6.93	6.84	7.35	7.58	7.37	7.40
W4	7	7.71	7.13	7.10	6.90	7.71	7.44	7.57	7.67
W2	8	7.62	7.02	7.10	6.92	7.48	7.40	7.58	7.57
C4	9	7.65	7.00	7.04	6.79	7.22	7.21	7.21	7.24
C1	10	7.44	7.03	7.09	6.98	7.26	7.32	7.44	7.38
C3	11	7.44	7.01	7.05	6.88	7.20	7.27	7.27	7.24
C2	12	7.38	7.02	7.01	6.96	7.23	7.25	7.30	7.21
W3	13	7.56	6.99	7.00	6.92	7.48	7.46	7.54	7.53
W1	14	7.51	7.12	7.07	7.02	7.40	7.39	7.51	7.57
W4	15	7.60	7.18	7.27	6.97	7.61	7.49	7.39	7.48
W2	16	7.58	7.09	7.16	7.01	7.56	7.36	7.45	7.43
STE	17	7.55	7.36	7.34	7.10	7.41	7.72	7.62	7.72

pH (cont.)

Field no.	Lab. no.	2/2/94	3/29/94	4/13/94	5/18/94	6/1/94	7/5/94	8/11/94
C2	1	7.20	7.19	7.19	6.94	6.69	6.96	6.95
C3	2	7.39	7.39	7.26	7.18	6.97	7.07	7.14
C1	3	7.32	7.23	7.12	7.01	6.93	6.94	7.03
C4	4	7.35	7.28	7.23	6.99	6.85	6.89	7.09
W3	5	7.48	7.21	7.10	6.99	6.98	5.87	7.01
W1	6	7.35	7.23	7.08	7.01	6.93	6.89	6.96
W4	7	7.40	7.33	7.31	7.08	6.86	6.94	7.01
W2	8	7.42	7.28	7.10	7.17	6.87	6.97	7.05
C4	9	7.41	7.29	7.13	6.90	6.69	6.85	6.93
C1	10	7.35	7.32	7.06	6.92	6.91	6.84	6.91
C3	11	7.29	7.27	7.17	6.94	6.70	6.79	7.13
C2	12	7.28	7.22	7.06	6.90	6.64	6.86	6.93
W3	13	7.46	7.20	7.14	6.94	6.74	6.83	6.96
W1	14	7.30	7.25	7.24	7.68	6.83	7.04	7.08
W4	15	7.15	7.26	7.14	6.94	6.78	6.92	7.03
W2	16	7.42	7.23	7.03	7.06	6.73	6.85	6.93
STE	17	7.22	7.40	7.11	6.94	7.06	6.91	7.18

pH (Cont.)

Field no.	Lab. no.	9/12/94	10/6/94	11/30/94	12/14/94	1/25/95	2/22/95	4/5/95	5/10/95
I2	1	6.72	6.72	7.01	7.62	7.28	7.85	6.99	6.84
I3	2	6.85	6.83	7.01	7.74	7.43	7.69	7.02	6.73
I1	3	6.88	6.93	7.12	7.98	7.50	7.25	7.13	6.91
I4	4	6.91	6.87	6.97	7.75	7.62	7.63	7.05	6.80
B3	5	7.31	7.34	7.82	7.85	7.65	7.65	7.17	7.14
B1	6	7.16	7.30	7.49	7.85	7.62	7.62	7.19	7.04
B4	7	7.29	7.41	7.43	7.86	7.65	7.60	7.18	7.10
B2	8	7.26	7.51	7.57	7.82	7.66	7.58	7.12	7.07
C4	9	6.83	6.79	7.07	7.86	7.58	7.70	7.08	6.97
C1	10	6.84	7.01	7.23	7.88	7.56	7.56	7.01	7.23
C3	11	6.87	7.06	7.32	7.87	7.61	7.74	7.03	6.97
C2	12	6.89	6.97	7.15	7.66	7.44	7.53	7.09	6.92
W3	13	6.85	7.00	7.14	7.81	7.53	7.56	7.13	6.94
W1	14	6.84	6.93	7.14	7.80	7.53	7.52	7.06	6.88
W4	15	7.00	7.02	7.10	7.80	7.40	7.89	7.15	6.99
W2	16	6.83	7.24	6.86	7.67	7.38	7.69	6.96	6.85
STE	17	6.81	7.17	7.50	7.95	7.58	7.76	7.07	7.70

8. Phosphorus (PO_4^{3-}, mg/L)

Field no.	Lab. no.	9/16/92	11/6/92	12/23/92	1/27/93	3/2/93	3/24/93	4/21/93	5/19/93
C2	1	2.56	2.36	1.62	3.17	2.92	2.73	2.91	2.29
C3	2	3.43	2.37	1.54	3.24	2.90	2.90	2.78	2.59
C1	3	3.32	2.75	2.40	3.35	2.95	2.80	2.98	3.01
C4	4	3.00	1.64	1.79	3.12	2.86	2.75	2.79	1.19
W3	5	3.58	2.17	1.63	3.02	2.74	2.61	2.61	1.63
W1	6	3.53	1.48	1.33	3.15	2.93	2.53	2.81	2.18
W4	7	4.21	1.17	1.54	2.82	2.79	2.64	2.32	0.76
W2	8	4.09	1.93	1.68	3.05	2.84	1.15	2.70	1.45
C4	9	2.31	1.24	1.87	2.78	2.77	2.82	2.81	1.11
C1	10	3.15	2.76	2.12	2.84	3.02	2.45	2.95	3.02
C3	11	2.72	1.76	2.20	2.83	2.93	3.01	2.89	1.55

C2	12	3.25	2.32	2.17	3.27	2.91	2.94	2.88	2.38
W3	13	3.80	1.93	1.90	3.02	2.71	2.96	2.45	1.54
W1	14	3.26	2.34	2.23	2.74	2.95	2.60	2.78	2.66
W4	15	3.25	1.39	1.75	2.85	2.87	2.81	2.55	0.88
W2	16	3.27	1.77	1.91	3.08	2.61	2.85	2.71	1.53
STE	17	2.97	2.80	2.17	3.37	3.02	2.94	6.91	3.59

PO_4^{3-}(cont.)

Field no.	Lab. no.	6/9/93	6/23/93	7/8/93	7/21/93	8/4/93	8/18/93	9/1/93	10/27/93
C2	1	0.34	1.07	2.08	3.53	2.33	1.86	1.96	0.76
C3	2	1.72	2.15	2.28	3.23	3.51	3.40	3.23	2.88
C1	3	1.80	2.11	2.35	3.17	3.17	2.49	2.83	2.39
C4	4	0.30	0.24	0.92	2.29	2.43	2.20	1.93	1.22
W3	5	1.12	0.96	1.54	2.89	5.08	4.77	5.16	2.46
W1	6	1.82	1.76	1.74	2.98	4.96	4.35	4.36	2.29
W4	7	0.08	0.12	0.07	1.07	2.49	4.35	6.09	3.43
W2	8	0.36	1.21	1.56	3.09	5.96	5.93	5.26	2.35
C4	9	0.12	0.16	0.29	0.95	0.76	5.57	0.69	0.30
C1	10	1.46	1.75	1.75	2.63	2.47	1.07	1.89	1.35
C3	11	0.31	0.24	0.72	1.84	2.02	2.20	1.21	0.42
C2	12	0.40	0.51	0.96	2.24	2.21	1.55	1.95	0.71
W3	13	0.56	0.54	1.51	1.41	2.94	1.82	5.82	3.52
W1	14	1.86	1.98	2.11	3.31	4.21	3.71	3.69	2.50
W4	15	0.06	0.01	0.03	0.39	2.06	4.33	4.70	1.53
W2	16	0.15	0.38	0.56	1.12	5.61	6.24	5.17	2.34
STE	17	3.48	3.07	2.52	3.56	3.37	6.21	3.26	2.58

PO_4^{3-} (cont.)

Field no.	Lab. no.	2/2/94	3/29/94	4/13/94	5/18/94	6/1/94	7/5/94	8/1194
C2	1	3.47	3.11	3.23	2.50	2.59		1.09
C3	2	4.13	3.21	3.24	3.19	3.08		1.34
C1	3	7.62	3.49	4.94	2.96	2.70		0.95

C4	4	4.11	3.71	3.30	2.67	2.56		2.14
W3	5	6.84	3.03	3.19	3.19	3.10		1.62
W1	6	2.52	2.83	3.16	3.27	2.94		0.83
W4	7	3.00	2.95	3.25	3.31	3.07		1.87
W2	8	3.61	3.48	3.26	3.04	2.81		0.86
C4	9	1.98	2.25	2.99	2.19	2.20		1.55
C1	10	2.46	2.76	3.00	2.57	2.95		2.01
C3	11	2.60	2.99	3.24	2.63	2.41		1.12
C2	12	2.90	2.65	3.20	2.55	2.50		1.50
W3	13	2.97	2.90	3.13	3.09	3.02		1.28
W1	14	2.46	2.80	2.97	2.98	2.74		0.80
W4	15	2.55	2.19	2.93	3.38	3.31		2.13
W2	16	3.35	3.19	3.36	3.67	3.13		2.32
STE	17	1.73	2.67	2.88	2.97	2.94		

PO_4^{3-}(cont.)

Field no.	Lab. no.	9/12/94	10/6/94	11/30/94	12/14/94	1/25/95	2/22/95	4/5/95	5/10/95
I2	1	1.41	0.89	1.27	4.17	4.79	3.74	4.65	4.61
I3	2	1.35	0.66	1.30	4.19	4.45	3.84	4.45	4.56
I1	3	1.39	1.18	1.76	4.72	5.21	3.94	5.19	5.10
I4	4	1.62	0.76	1.17	4.59	4.90	3.80	5.11	3.60
B3	5	1.65	1.51	2.09	5.20	5.15	3.92	4.98	5.12
B1	6	1.60	1.41	2.08	5.08	5.22	3.93	5.35	5.66
B4	7	2.03	1.50	2.20	5.39	5.78	3.99	5.14	5.69
B2	8	2.09	1.37	2.08	5.37	5.16	3.87	5.36	5.74
C4	9	1.06	0.95	1.53	4.10	4.72	3.84	4.74	5.31
C1	10	1.41	1.24	2.27	4.67	5.07	3.95	4.44	3.44
C3	11	1.01	1.20	2.05	4.44	5.11	4.09	5.23	5.38
C2	12	1.33	1.16	1.86	3.72	4.89	3.86	5.12	5.65
W3	13	1.35	1.15	1.81	4.31	4.85	3.75	4.90	4.99
W1	14	1.35	0.99	1.78	4.43	4.92	3.69	4.78	5.01
W4	15	0.98	0.69	1.10	2.75	3.62	3.10	4.86	5.31
W2	16	0.97	1.26	0.87	3.21	4.30	3.39	4.59	5.21
STE	17	1.74	1.49	2.41	5.23	5.56	3.77	5.27	5.25

PO_4^{3-}(cont.)

Field no.	Lab. no.	6/21/95	7/19/95	8/23/95					
I2	1	4.68	3.42	2.95					
I3	2	1.57	1.41	1.84					
I1	3	4.79	4.55	4.43					
I4	4	4.29	2.28	3.73					
B3	5	4.71	5.28	4.66					
B1	6	5.43	5.45	4.65					
B4	7	5.20	5.34	4.73					
B2	8	5.29	5.34	4.34					
C4	9	4.57	4.37	5.16					
C1	10	5.06	5.07	5.57					
C3	11	4.54	4.65	4.02					
C2	12	5.03	4.64	4.37					
W3	13	3.43	4.18	5.93					
W1	14	4.64	4.14	5.13					
W4	15	3.16		5.33					
W2	16	3.73	4.43	5.96					
STE	17	5.43	5.41	4.18					

9. Chloride (Cl, mg/L)

Field no.	Lab. no.	9/16/92	11/6/92	12/23/92	1/27/93	3/2/93	3/24/93	5/19/93
C2	1	34.2	50.7	64.8	42.3	47.8	40.2	52.1
C3	2	28.0	46.9	60.0	37.1	60.1	57.2	46.6
C1	3	36.5	50.7	65.0	34.5	62.6	51.7	43.3
C4	4	34.7	55.7	54.0	33.2	49.0	51.7	31.2
W3	5	17.1	52.0	54.0	30.7	44.1	57.4	56.6
W1	6	51.7	50.7	74.3	38.4	47.8	60.3	54.3
W4	7	52.2	65.8	42.0	30.7	49.0	58.9	43.3
W2	8	44.4	45.7	40.8	43.6	49.0	31.5	51.0
C4	9	57.9	46.9	58.9	44.9	40.4	48.8	23.4
C1	10	16.8	50.7	71.9	39.7	56.4	73.3	44.4
C3	11	38.4	53.2	69.6	41.0	55.2	51.7	23.4

C2	12	23.2	52.0	44.4	38.4	53.9	60.3	33.4
W3	13	24.8	52.0	45.6	39.7	60.1	56.0	47.7
W1	14	52.7	53.2	60.0	43.3	47.8	58.9	53.2
W4	15	52.7	45.7	30.4	32.0	52.7	50.2	52.1
W2	16	55.2	41.9	56.4	41.0	47.8	61.7	46.6
STE	17	46.2	52.0	74.3	50.0	70.0	71.8	61.6

Cl$^-$(cont.)

Field no.	Lab. no.	6/9/93	6/23/93	7/8/93	7/21/93	8/4/93	8/18/93	9/1/93	10/27/93
C2	1	19.6	33.3	40.8	38.6	33.4	48.8	46.9	56.7
C3	2	34.2	40.5	39.8	40.6	39.9	53.9	56.9	49.3
C1	3	30.5	33.6	35.8	40.4	42.5	44.1	44.1	42.8
C4	4	16.7	12.1	40.0	38.6	38.5	58.0	51.2	85.6
W3	5	89.4	53.0	72.5	80.6	144.1	93.7	81.0	55.3
W1	6	84.3	47.9	59.4	65.8	92.0	68.7	82.4	44.9
W4	7	120.4	86.8	112.7	108.2	240.4	125.0	117.8	67.2
W2	8	100.1	54.6	64.9	81.0	111.5	90.4	96.5	44.9
C4	9	58	4.93	20.9	34.5	41.2	47.1	44.1	80.5
C1	10	30.0	29.2	36.4	36.0	43.8	39.6	48.3	49.3
C3	11	8.6	5.70	25.9	32.2	37.3	48.3	45.5	92.4
C2	12	15.3	14.4	28.2	40.9	41.2	45.9	48.3	56.8
W3	13	84.0	54.6	69.2	78.0	218.3	122.9	163.2	71.6
W1	14	76.4	49.6	53.1	55.7	69.8	60.7	71.0	40.4
W4	15	127.4	78.1	53.1	109.9	269.1	113.4	116.4	70.1
W2	16	103.1	61.7	106.2	78.7	164.9	102.0	116.4	55.3
STE	17	48.0	38.4	81.6	39.4	34.7	40.0	59.7	39.0

Cl$^-$ (cont.)

Field no.	Lab. no.	2/2/94	3/29/94	5/28/95	6/1/94	7/5/94	8/11/94
C2	1	63.4	56.6	59.9	61.9	63.3	20.4
C3	2	47.4	56.6	62.6	65.1	63.3	18.1
C1	3	50.3	65.1	68.0	65.1	66.7	18.4
C4	4	56.1	57.8	50.5	57.1	61.6	27.9
W3	5	46.0	55.4	59.9	76.3	70.1	26.8

W1	6	48.9	73.7	73.3	79.5	71.8	20.6
W4	7	47.4	46.8	72.0	63.5	71.8	26.2
W2	8	43.1	49.2	55.9	61.5	66.7	25.0
C4	9	54.7	61.4	41.1	60.3	65.0	21.3
C1	10	46.0	62.7	51.9	63.5	66.7	20.9
C3	11	63.4	62.7	43.8	53.9	73.5	25.0
C2	12	66.3	63.9	49.2	55.5	70.1	19.4
W3	13	38.7	56.6	62.6	74.7	75.2	22.5
W1	14	50.3	52.9	51.9	58.7	80.3	20.6
W4	15	48.9	39.5	62.2	86.0	82.0	28.1
W2	16	44.5	52.9	61.3	73.1	70.1	23.5
STE	17	72.1	70.0	50.5	61.9	66.7	10.8

Cl (cont.)

Field no.	Lab. no.	9/12/94	10/6/94	11/30/94	12/14/95	1/25/95	2/22/95	4/5/95	5/10/95
I2	1	16.6	4.24	38.2	35.2	24.6	19.0	31.1	28.8
I3	2	16.6	3.74	36.9	15.4	26.0	18.4	31.4	
I1	3	12.8	4.98	42.1	23.9	24.6	19.5	30.5	29.7
I4	4	16.3	4.54	33.0	19.7	24.6	20.4	29.9	21.5
B3	5	15.3	5.48	39.5	33.8	19.1	22.3	28.9	26.1
B1	6	16.3	5.07	39.5	18.3	26.0	22.5	27.8	34.3
B4	7	16.6	2.12	35.6	12.5	26.0	23.6	26.6	29.1
B2	8	18.2	4.61	35.6	14.0	21.9	20.1	27.0	29.1
C4	9	14.1	5.62	39.5	16.8	30.1	26.1	28.3	30.4
C1	10	16.0	6.49	40.8	32.4	30.1	28.0	58.8	27.2
C3	11	17.3	6.03	49.9	38.8	31.5	30.3	31.1	46.1
C2	12	16.9	6.08	43.4	49.4	31.5	31.1	27.7	29.1
W3	13	19.5	17.1	40.8	38.8	24.6	22.9	22.0	26.1
W1	14	17.9	16.8	44.7	22.5	23.2	22.3	27.0	28.4
W4	15	22.4	30.4	39.5	48.0	27.4	29.4	26.1	29.2
W2	16	21.8	33.1	36.9	16.8	24.6	21.5	28.4	27.3
STE	17	16.6	14.7	47.3	33.0	24.6	23.4	28.4	25.7

Cl (cont.)

Field no.	Lab. no.	6/21/95							
I2	1	23.8							
I3	2								
I1	3	23.5							
I4	4	21.1							
B3	5	21.7							
B1	6	23.2							
B4	7	21.1							
B2	8	20.5							
C4	9	19.8							
C1	10	22.9							
C3	11	18.6							
C2	12	23.8							
W3	13	13.5							
W1	14	17.4							
W4	15	19.8							
W2	16	22.3							
STE	17	22.0							

10. Electrical conductivity (um/cm)

Field no.	Lab. no.	9/16/92	11/6/92	12/23/92	1/27/93	3/2/93	3/24/93	4/21/93	5/19/93
C2	1	779	908	778	848	1180	834	1025	52.1
C3	2	740	908	732	849	802	809	1041	46.6
C1	3	740	903	723	873	727	873	1063	43.3
C4	4	760	828	702	822	932	880	1030	31.2
W3	5	838	918	743	907	975	918	1043	56.6
W1	6	779	973	691	819	998	897	897	54.3
W4	7	955	948	667	868	955	824	1040	43.3
W2	8	906	906	707	828	983	754	1054	51.0
C4	9	740	855	693	822	938	906	1011	23.4
C1	10	779	938	670	839	989	958	1060	44.4
C3	11	740	896	744	888	974	968	1034	23.4

C2	12	779	910	754	798	969	965	1053	33.4
W3	13	886	906	788	887	973	926	1028	47.7
W1	14	799	921	790	890	993	928	1058	53.2
W4	15	838	928	681	846	977	956	1052	52.1
W2	16	828	812	754	897	962	891	1027	46.6
STE	17	906	973	853	901	988	992	953	61.6

EC (cont.)

Field no.	Lab. no.	6/9/93	6/23/93	7/8/93	7/21/93	8/4/93	8/18/94	9/1/93	10/27/93
C2	1	1183	1167	1177	1139	1129	1385	1213	1072
C3	2	1117	1083	1150	1117	1101	1318	1120	1051
C1	3	1074	1100	1133	1133	1121	1295	1130	1030
C4	4	1117	1103	1208	1130	1161	1354	1156	1152
W3	5	1557	1341	1565	1667	2463	1987	1677	1177
W1	6	1497	1253	1391	1553	1765	1728	1416	1068
W4	7	2100	1888	2141	2076	3451	2343	1991	1284
W2	8	1180	1363	1454	1665	2141	1887	1637	1065
C4	9	1238	1138	1141	1131	1337	1323	1248	1192
C1	10	1138	1048	1101	1147	1227	1332	1182	1038
C3	11	1132	1126	1204	1179	1394	1208	1312	1239
C2	12	1080	1046	1217	1182	1308	1374	1221	1068
W3	13	1551	1443	1558	1542	3439	2474	2410	1372
W1	14	1420	1271	1274	1390	1462	1605	1286	1064
W4	15	2230	1818	2161	2212	3817	2343	1916	1373
W2	16	1637	1508	1714	1757	2951	2218	1913	1158
STE	17	1083	1077	1092	1123	1087	1274	1117	1056

EC (cont.)

Field no.	Lab. no.	10/27/93	2/2/94	3/29/94	4/13/94	5/18/94	6/1/94	7/5/94	8/11/94
C2	1	1072	1086	1263	1375	1158	1166	1200	733
C3	2	1051	923	1248	1371	1163	1157	1132	692
C1	3	1030	999	1270	1376	1176	1174	1166	707
C4	4	1152	885	1148	1350	1115	1138	1147	763
W3	5	1177	966	1180	1369	1212	1231	1216	846

W1	6	1068	1017	1203	1372	1199	1227	1218	770
W4	7	1284	885	1009	1345	1173	1195	1187	866
W2	8	1065	970	1183	1366	1208	1197	1202	801
C4	9	1192	936	1194	1345	1099	1121	1177	856
C1	10	1038	1011	1275	1376	1179	1394	1235	770
C3	11	1239	1099	1282	1363	1129	1147	1320	823
C2	12	1068	1065	1233	1357	1157	1166	1280	825
W3	13	1372	1030	1249	1363	1255	1282	1238	875
W1	14	1064	1009	1232	1372	1208	1194	1202	742
W4	15	1373	917	1141	1329	1305	1194	1242	971
W2	16	1158	1003	1259	1363	1244	1161	1240	833
STE	17	1056	1041	1366	1372	1162	1178	1155	617

EC (cont.)

Field no.	Lab. no.	9/12/94	10/6/94	11/30/94	12/14/95	1/25/95	2/22/95	4/5/95	5/10/95
I2	1	733	630	862	1213	1095	875	969	986
I3	2	737	628	880	1212	1060	866	943	855
I1	3	853	633	923	1285	1165	894	1019	1012
I4	4	741	632	831	1216	1115	877	992	942
B3	5	707	675	841	1245	1145	869	991	937
B1	6	777	617	868	1310	1154	917	1027	1055
B4	7	686	592	860	1216	1080	874	1034	988
B2	8	714	592	806	1216	1120	900	1033	1036
C4	9	767	722	892	1244	1168	922	991	1017
C1	10	783	696	971	1337	1205	957	1017	1103
C3	11	775	684	925	1280	1191	959	1019	1014
C2	12	800	751	910	1226	1185	937	1029	1058
W3	13	874	808	981	1290	1192	950	1033	1083
W1	14	796	729	1027	1309	1169	933	1019	1083
W4	15	915	1012	991	1137	1091	885	1030	1029
W2	16	880	957	1029	1185	1139	888	1021	1096
STE	17	778	676	1019	1379	1197	945	1030	1058

EC (cont.)

Field no.	Lab. no.	6/21/95	7/19/95						
I2	1	1145	1348						
I3	2	868	1312						
I1	3	1173	1364						
I4	4	1062	1197						
B3	5	976	1225						
B1	6	1159	1334						
B4	7	1055	1216						
B2	8	1126	1296						
C4	9	1103	1301						
C1	10	1169	1372						
C3	11	1050	1308						
C2	12	1153	1354						
W3	13	1109	1443						
W1	14	1268	1738						
W4	15	1072							
W2	16	1238	1544						
STE	17	1200	1427						

11. Total dissolved solids (TDS, mg/L)

Field no.	Lab. no.	6/23/93	7/8/93	7/21/93	8/4/93	8/18/93	10/27/93	2/2/94	3/29/94
C2	1	798	795	682	805	685	529	540	637
C3	2	738	778	670	740	652	521	449	626
C1	3	752	765	680	751	641	510	493	642
C4	4	754	815	678	780	671	570	438	567
W3	5	913	1056	1000	1662	984	582	478	586
W1	6	853	942	931	1188	854	529	503	597
W4	7	1289	1447	1245	2499	1158	637	438	500
W2	8	930	982	999	1439	933	526	481	587
C4	9	778	771	679	899	658	587	463	594
C1	10	715	743	688	824	658	513	501	645
C3	11	769	808	708	936	697	612	544	652
C2	12	716	821	711	880	679	530	527	615

W3	13	984	1051	1037	2474	1196	677	509	629
W1	14	868	860	824	983	793	525	500	615
W4	15	1241	1460	1327	2729	1159	679	454	565
W2	16	1027	1156	1054	2117	1097	572	496	629
STE	17	736	737	673	730	630	521	502	735

TDS (Cont.)

Field no.	Lab. no.	4/13/94	5/18/94	6/1/94	7/5/94	8/1194	Field no.	Lab. no.	9/12/94
C2	1	762	577	579	957	364	I2	1	365
C3	2	748	578	573	563	344	I3	2	366
C1	3	778	586	583	581	351	I1	3	394
C4	4	732	554	566	570	379	I4	4	369
W3	5	757	603	613	606	421	B3	5	352
W1	6	765	597	610	605	382	B1	6	363
W4	7	726	584	596	591	433	B4	7	341
W2	8	758	601	596	598	394	B2	8	355
C4	9	726	547	558	586	426	C4	9	381
C1	10	778	587	693	614	383	C1	10	389
C3	11	752	564	570	657	409	C3	11	385
C2	12	747	575	580	637	410	C2	12	397
W3	13	757	623	637	616	435	W3	13	345
W1	14	778	601	594	598	369	W1	14	396
W4	15	706	649	594	618	483	W4	15	456
W2	16	757	619	628	617	415	W2	16	437
STE	17	805	579	586	575	307	STE	17	386

TDS (Cont.)

Field no.	Lab. no.	10/6/94	11/30/94	12/14/94	1/25/95	2/22/95	4/5/95	5/10/95	6/21/95
I2	1	312	429	605	545	435	482	490	569
I3	2	312	437	602	525	435	469	425	431
I1	3	316	459	640	577	442	507	504	584
I4	4	314	414	604	553	436	494	469	528
B3	5	306	419	622	569	434	487	466	485
B1	6	307	432	652	573	456	511	524	577

B4	7	295	428	605	540	435	513	491	524
B2	8	293	400	604	557	447	514	516	560
C4	9	358	444	625	579	459	493	505	549
C1	10	345	483	665	599	476	506	549	583
C3	11	338	459	637	590	478	507	505	523
C2	12	374	453	610	589	467	513	527	573
W3	13	403	487	642	593	477	514	539	551
W1	14	362	511	653	580	463	506	538	630
W4	15	501	493	567	543	439	512	511	534
W2	16	477	512	589	565	438	513	546	616
STE	17	337	507	687	596	473	512	526	596

12. Dissolved oxygen(DO, mg/L, first cell)

Field no.	Lab. no.	11/6/92	1/27/93	3/2/93	3/24/93	4/21/93	5/19/93	6/9/93	6/23/93
C2	1	1.0	2.6	2.9	1.9	0.8	1.0	1.2	1.1
C3	2	1.4	2.2	2.6	2.0	1.2	0.8	0.9	0.9
C1	3	0.6	2.0	2.4	1.5	0.9	0.7	0.6	0.6
C4	4	1.5	2.2	1.4	1.4	1.4	0.6	0.6	0.5
W3	5	1.1	1.5	1.9	1.8	0.9	0.6	0.5	0.8
W1	6	1.1	1.2	1.2	1.8	0.8	0.5	0.35	1.2
W4	7	1.2	1.3	1.1	1.3	1.0	0.4	0.5	0.6
W2	8	1.2	1.2	1.2	2.3	1.0	0.5	0.35	0.6
C4	9	1.8	1.5	2.2	1.9	1.2	0.4	0.3	0.7
C1	10	1.1	1.5	1.3	1.1	1.6	0.4	0.3	0.7
C3	11	1.8	1.3	1.1	0.7	1.2	0.5	0.6	0.6
C2	12	0.9	1.4	1.5	1.2	2.0	0.4	0.4	0.5
W3	13		1.0	1.0	1.3	1.0	0.6	0.45	0.5
W1	14	1.5	1.0	1.1	1.4	0.8	0.4	0.45	0.5
W4	15	1.2	1.0	0.8	1.6	1.4	0.4	0.30	0.7
W2	16	1.2	1.4	1.0	1.5	1.0	0.3	0.30	0.7

DO (cont.)

Field no.	Lab no.	7/21/93	8/4/93	8/18/93	9/1/93	10/27/93	5/18/94	6/1/94	7/5/94
C2	1	2.8	1.9	1.5	1.4	1.25	0.6	0.9	0.9

C3	2	2.7	1.2	0.9	0.7	1.2	0.7	0.8	0.9
C1	3	2	1.1	0.5	0.5	0.5	0.7	0.6	1
C4	4	1.4	0.9		0.6	0.8	0.8	0.8	0.9
W3	5	1.2	0.8	1	0.5	1	0.6	0.8	0.8
W1	6	1.1	0.9	0.6	1.2	0.7	0.8	0.4	0.9
W4	7	1.1	0.8	0.7	1.1	1	0.9	0.4	0.7
W2	8	1.1	0.7	0.6	0.3	0.7	0.18	0.3	0.7
C4	9	0.8	0.7	0.6	0.5	0.9	1	0.4	0.7
C1	10	0.4	0.8	1.1	0.3	0.9	1.1	0.4	0.9
C3	11	0.8	0.7	0.6	0.3	1.2	0.8	0.4	0.8
C2	12	0.8	0.7	0.7	0.4	0.8	0.8	0.5	0.5
W3	13	0.6	0.7	0.5	0.4	0.85	0.9	0.5	0.6
W1	14	0.9	0.7	0.7	0.3	0.7	0.8	0.4	0.5
W4	15	1	0.7	0.5	0.3	1	0.8	0.4	0.6
W2	16	1	0.7	0.5	0.4	0.7	0.8	0.5	0.4

DO (cont.)

Field no.	Lab. no.	10/6/94	11/8/94	1/25/95	2/22/95	4/5/95	5/10/95	6/21/95	7/19/95
I2	1	1.6	1.7	1.4			1.20		0.60
I3	2	1.3	1.3	1.8			1.25		0.70
I1	3	1.0	0.9	1.2			0.70		0.50
I4	4	0.9	0.9	1.8			0.60		0.45
B3	5	0.9	0.9	1.5			0.40		0.40
B1	6	0.7	0.7	1.3			0.30		0.40
B4	7	0.6	0.9	1.2			0.40		0..30
B2	8	0.6	0.9	1.3			0.40		0.40
C4	9	0.5	0.8	1.3			0.40		0.40
C1	10	0.5	0.8	1.2			0.50		0.35
C3	11	0.8	0.6	1.4			0.50		0.20
C2	12	0.5	0.7	1.7			0.50		0.30
W3	13	0.5	0.7	1.0			0.50		0.45
W1	14	0.6	0.7	1.1			0.40		0.50
W4	15	0.4	0.7	1.0			0.50		0.50
W2	16	0.5	0.8	1.2			0.50		0.30

DO (mg/L, second cell)

Field no.	Lab. no.	11/6/92	1/27/93	3/2/93	3/24/93	4/21/93	5/19/93	6/9/93	6/23/93
C2	1	1.2	32.	3.0	3.1	1.4	1.1	1.6	1.2
C3	2	1.1	4.0	3.2	3.9	1.3	0.9	1.0	1.1
C1	3	1.2	2.4	2.8	2.4	1.8	0.6	0.6	0.4
C4	4	1.9	3.2	2.5	2.7	1.4	0.8	0.7	0.5
W3	5	1.5	1.8	1.9	2.9	1.2	0.6	0.5	0.8
W1	6	1.1	1.7	1.5	2.5	1.0	0.5	0.4	0.9
W4	7	1.4	4.8	5.0	5.6	2.2	0.5	0.65	0.7
W2	8	1.4	1.6	1.8	2.6	1.8	0.5	0.4	0.5
C4	9	2.0	6.0	4.4	4.2	1.8	0.4	0.65	0.9
C1	10	1.4	1.5	1.4	0.9	2.0	0.5	0.4	1.0
C3	11	1.9	3.9	1.5	4.2	2.8	0.4	0.65	0.8
C2	12	1.5	2.0	2.0	1.9	2.3	0.4	0.4	0.6
W3	13	1.4	2.3	1.6	2.3	1.8	0.5	0.55	0.7
W1	14	1.8	1.6	1.2	1.8	1.0	0.4	0.55	0.4
W4	15	1.3	6.0	5.1	6.2	2.3	0.5	0.3	0.8
W2	16	1.4	2.3	2.9	2.4	1.8	0.5	0.3	0.6

DO (cont.)

Field no.	Lab no.	7/21/93	8/4/93	8/18/93	9/1/93	10/27/93	5/18/94	6/1/94	7/5/94
C2	1	2.2	1.5	0.9	0.4	1.7	0.7	0.9	1.2
C3	2	2.3	1.2	0.7	1.2	0.9	0.8	0.8	1.1
C1	3	1.7	1.0	0.6	0.5	0.7	0.7	0.7	0.8
C4	4	1.2	0.9	0.6	2.2	0.9	0.7	0.7	0.8
W3	5	1.0	0.9	0.6	0.5	1.2	0.7	0.5	0.8
W1	6	1.2	0.8	0.7	1.0	1.0	0.7	0.5	1.0
W4	7	0.9	0.8	0.5	0.9	1.0	0.8	0.4	0.6
W2	8	0.9	0.8	0.6	0.4	0.9	1.1	0.3	0.7
C4	9	0.8	0.8	0.6	0.4	1.0	1.2	0.3	0.8
C1	10	0.8	0.8	0.7	0.6	0.9	0.9	0.5	0.8
C3	11	0.6	0.8	0.5	0.5	1.3	1.2	0.4	0.7
C2	12	0.5	0.7	0.5	0.5	0.9	1.2	0.4	0.7

W3	13	0.8	0.8	0.5	0.5	0.96	0.8	0.6	0.5
W1	14	1.0	0.7	0.5	0.5	0.8	0.7	0.4	0.5
W4	15	1.1	0.8	0.6	0.5	0.9	0.5	0.5	0.3
W2	16	0.9	0.7	0.6	0.5	1.0	0.8	0.5	0.6

DO (cont.)

Field no.	Lab. no.	10/6/94	11/08/94	1/25/95	2/22/95	4/5/95	5/10/95	6/21/95	7/19/95
I2	1	1.4	1.5	1.6			1.25		0.6
I3	2	1.1	1.4	1.8			0.90		0.7
I1	3	1.2	1.0	1.6			0.75		0.5
I4	4	0.9	1.0	1.5			0.50		0.40
B3	5	0.8	1.0	1.7			0.60		0.70
B1	6	0.9	0.9	1.3			0.40		0.40
B4	7	0.6	0.8	1.2			0.50		0.40
B2	8	0.6	0.9	1.2			0.50		0.45
C4	9	0.7	0.8	1.4			0.40		0.45
C1	10	0.7	0.8	1.7			0.30		0.40
C3	11	0.4	0.7	1.0			0.70		0.30
C2	12	0.5	0.5	1.1			0.40		0.40
W3	13	0.6	0.7	1.0			0.50		0.30
W1	14	0.4	0.7	1.1			0.50		0.40
W4	15	0.5	0.9	1.0			0.50		
W2	16	0.6	0.9	1.2			0.50		0.30

13. Redox potential (Eh=relative values + 243 mvolts)

Field no.	Lab. no.	9/16/92				11/6/92			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-467	-456	-468	-399	-475	-493	-485	-544
C3	2	-457	-464	-452	-451	-409	-509	-495	-495
C1	3	-495	-501	-488	-484	-504	-508	-481	-502
C4	4	-488	-476	-64	-436	-502	-497	+293	-461
W3	5	-475	-486	-399	-460	-488	-491	-185	-480
W1	6	-478	-484	-416	-481	+109	-498	-52	-482

W4	7	-484	-476	-268	-464	-443	-474	+281	-476
W2	8	-470	-327	-208	-467	-479	-485	-49	-474
C4	9	-494	-480	-110	-393	-208	-554	+225	+52
C1	10	-476	-488	-489	-489	-509	-506	-501	-504
C3	11	-307	-481	-440	-462	-141	-492	-388	-473
C2	12	-416	-480	-474	-483	-179	-505	-423	-488
W3	13	-332	-496	-462	-464	-488	-497	-471	-478
W1	14	-485	-407	-487	-477	-498	-501	-478	-483
W4	15	-474	-492	-471	-471	-491	-491	+39	-472
W2	16	-471	-480	-467	-369	-481	-493	-+230	-484

Redox potential (cont.)

Field no.	Lab. no.	11/6/92				12/23/92			
		Ehd-1*	Ehs-1	Ehd-2	Ehs-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-462	-331	-580	-340	-50	-473	-661	-61
C3	2	-235	-330	-442	-406	-496	-502	-500	+90
C1	3	-485	-493	-525	-486	-498	-491	-643	-337
C4	4	-444	-379	-471	+280	-490	-500	-487	+304
W3	5	-420	-437	-457	+150	-470	-507	-529	+197
W1	6	-455	+186	-591	-45	+283	-529	-525	+69
W4	7	-540	+9	+190	+1013	+52	-539	-471	+392
W2	8	+44	+63	-338	+275	-432	-503	-473	+255
C4	9	-549	-475	-498	+ 261	-465	-576	-461	+285
C1	10	-204	-197	-539	-506	-468	-524	-508	-375
C3	11	-300	+55	-465	+32	-437	-502	-466	+265
C2	12	-219	-188	-519	-479	-461	-479	-532	-79
W3	13	-489	-461	-500	+46	-453	-514	-477	+119
W1	14	-102	-72	+24	+695	-461	-489	-497	+173
W4	15	-+40	+482	-486	+63	-282	-488	-467	+114
W2	16	-492	+15	-471	+301	+36	-478	-461	+374

Redox potential (cont.)

Field no.	Lab. no.	3/2/93				3/24/93			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	+49	-329	-27	-656	-31	-364	+23	-570
C3	2	-475	-488	+127	-496	-86	-500	-56	-485
C1	3	-469	-348	-210	-525	-196	-422	+4	-420
C4	4	-455	-479	+276	-453	-201	-495	+215	-335
W3	5	-151	-479	+144	-489	+21	-407	+137	-467
W1	6	+290	-504	+50	-521	+291	-258	+50	-362
W4	7	+36	-476	+385	-465	+28	-538	+357	-461
W2	8	-465	-455	+320	-448	-190	-78	+319	-424
C4	9	-300	-604	+190	-338	+45	-479	+263	-333
C1	10	-462	-470	-420	-476	-237	-486	-241	-492
C3	11	-444	-535	+72	-470	-447	-524	+120	-381
C2	12	-444	-475	+32	-466	-188	-491	-70	-452
W3	13	-456	-535	-13	-480	-439	-500	+44	-473
W1	14	-234	-268	+163	-450	-447	-366	+264	-443
W4	15	-105	-486	+44	-432	+2	-400	+156	273
W2	16	-88	-463	+360	-466	-60	-439	+450	-382

Redox Potential (cont.)

Field no.	Lab. no.	4/21/93				5/19/93			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	+107	-347	+156	-505	-400	-502	-360	-640
C3	2	+174	-403	-168	-401	-300	-466	-466	-506
C1	3	-262	-209	+444	-219	-403	-503	-230	-655
C4	4	-199	-336	+213	-355	-513	-475	-343	-478
W3	5	+240	-234	+105	-469	-452	-478	-310	-455
W1	6	+233	-270	+77	-396	+31	-570	-72	-638
W4	7	+300	-389	+393	-450	-262	-450	-307	-482
W2	8	-376	-277	+350	-330	-494	-439	-286	-478
C4	9	-259	-618	+317	-431	-488	-508	-443	-457
C1	10	-331	-425	-320	-478	-357	-448	-483	-615

C3	11	+176	-394	-230	-480	-454	-631	-133	-465
C2	12	+150	-450	+17	-422	-116	-464	-315	-480
W3	13	-206	-454	-380	-478	-450	-560	-426	-468
W1	14	-438	-448	+130	-486	-344	-466	-437	-560
W4	15	-459	-432	+245	-230	-411	-337	-228	-474
W2	16	+203	-187	+328	-493	-453	-473	-376	-473

Redox Potential (cont.)

Field no.	Lab. no.	6/9/93				6/23/93			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-19	-429	-206	-507	+99	-507	-106	-575
C3	2	+36	-494	-351	-518	-72	-514	-482	-534
C1	3	-498	-573	-28	-650	-506	-584	-459	-661
C4	4	-399	-483	-49	-407	-479	-479	-27	-433
W3	5	-433	-474	-224	-484	-475	-503	-343	-481
W1	6	-330	-624	-17	-636	-428	-556	-351	-627
W4	7	+33	-384	+320	-486	-323	-509	-485	-503
W2	8	-466	-537	-410	-486	-477	-546	-462	-479
C4	9	-502	-652	+33	-433	-497	-654	+127	-279
C1	10	-486	-611	-458	-615	-500	-613	-478	-623
C3	11	-449	-609	-13	-443	-311	-603	-120	-464
C2	12	-340	-482	-309	-405	-335	-482	-457	-454
W3	13	-487	-624	-454	-461	-432	-625	-473	-291
W1	14	-297	-487	-472	-529	-493	-489	-461	-582
W4	15	-419	-481	-207	-455	-408	-505	-142	-456
W2	16	-479	-555	-413	-481	-485	-629	-449	-458

Redox Potential (cont.)

Field no.	Lab. no.	7/8/93				7/21/93			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-506	-608	-488	-657	-524	-637	-370	-456
C3	2	-489	-514	-500	-614	-522	-544	-493	-643
C1	3	-511	-595	-497	-673	-522	-602	-510	-677

C4	4	-500	-545	-412	-465	-513	-552	-308	-505
W3	5	-489	-498	-460	-489	-502	-518	-499	-512
W1	6	-476	-522	-375	-633	-326	-549	-403	-635
W4	7	+5	-500	-459	-508	-2	-520	-434	-482
W2	8	-495	-525	-400	-486	-500	-525	-18	-509
C4	9	-507	-661	+228	-327	-518	-671	-2	-472
C1	10	-493	-610	--483	-630	-510	-630	-509	-636
C3	11	-469	-636	-443	-476	-507	-644	-455	-493
C2	12	-475	-494	-492	-483	-493	-505	-517	-515
W3	13	-477	-633	-416	-491	-502	-646	-496	-490
W1	14	-496	-499	-486	-613	-507	-508	-494	-608
W4	15	-460	-517	-249	-485	-499	-537	-302	-500
W2	16	-493	-555	-454	-460	-505	-660	-425	-471

Redox Potential (cont.)

Field no.	Lab. no.	8/4/93				8/18/93			
		Ehs-1[*]	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-514	-644	-513	-673	-483	-629	-513	-661
C3	2	-508	-603	-504	-634	-313	-617	-400	-617
C1	3	-453	-594	-473	-677	-500	-585	-469	-661
C4	4	-528	-578	-469	-483	-297	-527	-228	-458
W3	5	-519	-535	-513	-514	-493	-519	-477	-518
W1	6	-504	580	-507	-642	-493	-577	-478	-639
W4	7	+84	-588	+122	-526	+258	-543	-486	-523
W2	8	-309	-526	-89	-506	-406	-498	-64	-489
C4	9	-502	-658	-451	-488	-239	-644	-112	-475
C1	10	-516	-603	-485	-616	-521	-587	-352	-597
C3	11	-491	-621	-506	-490	-482	-600	-480	-460
C2	12	-475	-498	-498	-509	-445	-468	-480	-503
W3	13	-497	-650	-523	-507	-465	-660	-483	-486
W1	14	-521	-527	-500	-632	-490	-491	-489	-637
W4	15	-502	-635	-256	-510	-472	-523	-392	-503
W2	16	-507	-670	-321	-509	-487	-648	-475	-481

Redox Potential (cont.)

Field no.	Lab. no.	9/1/93				3/29/94			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-468	-616	-519	-662	-138	-400	-248	-636
C3	2	-609	-618	-472	-627	-19	-619	+53	-654
C1	3	-365	-538	-402	-662	-506	-627	-495	-674
C4	4	-491	-482	-279	-458	-481	-556	-56	-505
W3	5	-491	-525	-483	-518	-497	-598	-418	-502
W1	6	-493	-574	-481	-641	-448	-481	-52	-644
W4	7	+126	-581	-14	-492	+249	-500	+207	-509
W2	8	-437	-505	-278	-487	+438	-493	+181	-494
C4	9	-435	-776	-142	-445	+89	-504	+205	-478
C1	10	-497	-593	-397	-592	+505	-642	-40	-642
C3	11	-607	-593	-490	-465	-490	-612	-425	-457
C2	12	-464	-452	-485	-482	-492	-493	-11	-475
W3	13	-479	-654	-511	-494	-484	-595	-123	-584
W1	14	-489	-488	-485	-641	-505	-509	-439	-661
W4	15	-487	-522	-488	-491	-483	-508	-14	-513
W2	16	-477	-652	-483	-479	-498	-492	-454	-505

Redox Potential (cont.)

Field no.	Lab. no.	5/18/94				6/1/94			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	+12	-633	-336	-688	-424	-631	-459	-686
C3	2	-186	-637	-130	-608	-514	-654	-495	-670
C1	3	-509	-630	-502	-675	-512	-617	-483	-670
C4	4	-525	-606	-403	-499	-540	-627	-375	-486
W3	5	-504	-593	-522	-596	-506	-589	-504	-530
W1	6	-492	-495	-500	-660	-496	-493	-496	-654
W4	7	+71	-577	-497	-550	+16	-589	-500	-517
W2	8	-218	-503	+90	-639	-471	-374	-270	-499
C4	9	-167	-541	-471	-482	-477	-585	-471	-483
C1	10	-478	-562	-474	-603	-493	-628	-473	-589

C3	11	-537	-641	-416	-471	-512	-639	-468	-473
C2	12	-49	-497	-393	-481	-495	-484	-468	-477
W3	13	-499	-681	-544	-529	-486	-677	-550	-618
W1	14	-519	-540	-492	-669	-510	-527	-505	-664
W4	15	-509	-504	-494	-592	-518	-514	-496	-500
W2	16	-492	-590	-495	-488	-496	-695	-498	-488

Redox Potential (cont.)

Field no.	Lab. no.	7/5/94				8/11/94			
		Ehs-1*	Ehd-1	Ehs-2	Ehd-2	Ehs-1	Ehd-1	Ehs-2	Ehd-2
C2	1	-200	-418	-364	-528	-450	-497	-503	-672
C3	2	-333	-405	-333	-356	-104	-541	-490	-60
C1	3	-433	-414	-483	-667	-502	-594	-500	-657
C4	4	-537	-673	-496	-502	-514	-636	-482	-504
W3	5	-509	-517	-503	-522	-501	-575	-470	-536
W1	6	-501	-493	-504	-655	-465	-517	-478	-631
W4	7	+82	-582	-507	-544	+70	-582	-488	-518
W2	8	-492	-514	-396	-495	-378	-504	-126	-586
C4	9	-467	-644	-481	-580	-478	-637	-573	-589
C1	10	-503	-646	-488	-562	-529	-636	-477	-550
C3	11	-508	-656	-502	-481	-250	-614	-445	-439
C2	12	-379	-490	-494	-497	-483	-481	-475	-496
W3	13	-505	-663	-558	-608	-486	-503	-555	-613
W1	14	-504	-522	-505	-666	-511	-500	-494	-653
W4	15	-526	-514	-516	-546	-500	-510	-500	-524
W2	16	-609	-699	-511	-536	-513	-625	-493	-493

14. Minerals and metals in the STE and SVBE (mg L^{-1}, Nov., 6, 1992. Whitethorne Plantation site)

Lab. no.	Field no.	K	Mg	Ca	S	Zn	Mn
1	C2	18.5	34.2	71.0	2.42	0.046	0.089
2	C3	9.8	34.6	68.6	2.80	0.031	0.059

3	C1	12.8	33.2	67.3	2.46	0.101	0.047
4	C4	6.4	36.1	73.6	2.63	0.08	0.038
5	W3	10.4	33.7	72.1	2.28	0.06	0.044
6	W1	3.1	42.5	94.2	1.83	0.7	0.065
7	W4	8.1	37.6	83.5	1.73	0.39	0.111
8	W2	7.1	36.8	79.1	1.85	0.04	0.045
9	C4	5.9	37.1	74.8	4.68	0.03	0.029
10	C1	13.4	33.8	67.8	2.68	0.02	0.045
11	C3	7.8	35.4	72.5	3.14	0.03	0.054
12	C2	11.8	34.7	70.5	3.31	0.04	0.077
13	D3	8.2	27.3	79.9	1.84	0.02	0.065
14	D1	11.6	34.0	73.3	2.23	0.04	0.077
15	D4	5.8	40.3	85.9	2.81	0.02	0.146
16	D2	9.3	35.8	77.6	2.36	0.03	0.311
17	STE	13.2	33.4	68.7	2.25	0.101	0.054

Minerals and metals in the STE and SVBE (cont.)
(mg L^{-1}, June 9, 1992. Whitethorne Plantation site)

Lab. no.	Field no.	K	Mg	Fe	S	Zn	Al
1	C2	2.02	45.7	0.23	3.30	0.127	0.059
2	C3	5.82	38.0	0.09	3.33	0.043	0.049
3	C1	6.76	37.2	0.124	3.12	0.065	0.049
4	C4	0.80	44.8	0.237	4.12	0.074	0.069
5	W3	1.08	48.9	0.162	2.29	0.064	0.079
6	W1	2.42	44.0	0.162	2.03	0.068	0.079
7	W4	0.21	76.9	0.491	2.97	0.069	0.118
8	W2	0.86	51.0	0.245	2.06	0.045	0.089
9	C4	0.58	48.0	0.282	3.38	0.058	0.079

10	C1	4.14	36.5	0.117	2.82	0.037	0.079
11	C3	0.63	46.4	0.211	3.36	0.109	0.089
12	C2	1.26	41.1	0.195	3.50	0.061	0.079
13	D3	0.57	55.5	0.226	2.13	0.058	0.108
14	D1	2.88	44.6	0.222	2.07	0.047	0.079
15	D4	0.12	73.5	0.280	2.97	0.048	0.089
16	D2	0.29	58.2	0.258	2.11	0.076	0.099
17	STE	11.3	32.8	0.095	4.03	0.038	0.089

Minerals and metals in the STE and SVBE (cont.)
(mg L^{-1}, Sep., 1, 1992. Whitethorne Plantation site)

Lab. no.	Field no.	Ca	Mg	S	Zn	Cu	Fe
1	C2	83.8	43.6	5.56	0.017	0.003	0.127
2	C3	72.2	36.3	6.25	0.036	0.002	0.041
3	C1	72.2	35.6	57.6	0.075	0.002	0.130
4	C4	80.7	41.3	5.18	0.004	0.002	0.081
5	W3	123.7	61.0	3.50	0.006	0.002	0.131
6	W1	98.9	48.0	4.04	0.004	0.002	0.102
7	W4	143.2	73.5	4.54	0.004	0.002	0.092
8	W2	117.6	57.5	5.22	0.007	0.002	0.072
9	C4	83.2	41.1	4.76	0.007	0.002	0.118
10	C1	83.2	41.0	4.71	0.004	0.002	0.116
11	C3	99.9	51.6	4.28	0.014	0.002	0.244
12	C2	86.7	52.9	3.75	0.004	0.002	0.163
13	D3	170.9	97.0	2.82	0.004	0.002	0.187
14	D1	88.8	41.5	4.99	0.004	0.002	0.087
15	D4	155.4	72.9	2.70	0.012	0.002	0.490
16	D2	70.8	32.1	5.82	0.031	0.002	0.165

17	STE	67.6	32.4	8.70	0.084	0.002	0.233

Trace metals in the STE and SVBE (cont.)
(mg L^{-1}, Sep., 1, 1992. Whitethorne Plantation site)

Lab. no.	Field no.	Pb	Cd	Ni	Co
1	C2	<0.1	<0.002	<0.1	0.003
2	C3	<0.1	<0.002	<0.1	0.003
3	C1	<0.1	<0.002	<0.1	0.003
4	C4	<0.1	<0.002	<0.1	0.003
5	W3	<0.1	<0.002	<0.01	0.003
6	W1	<0.1	<0.002	<0.1	0.003
7	W4	<0.1	<0.002	<0.1	0.008
8	W2	<0.1	<0.002	<0.1	0.003
9	C4	<0.1	<0.002	<0.1	0.003
10	C1	<0.1	<0.002	<0.1	0.003
11	C3	<0.1	<0.002	<0.1	0.003
12	C2	<0.1	<0.002	<0.1	0.003
13	D3	<0.1	<0.002	<0.1	0.004
14	D1	<0.1	<0.002	<0.1	0.005
15	D4	<0.1	<0.002	<0.1	0.003
16	D2	<0.1	<0.002	<0.1	0.003
17	STE	<0.1	<0.008	<0.1	0.003

Ehs-2-- Eh values measured at 25 com from the bottom of the second cell;
*Ehd-1-- Eh values measured at 2.5 com from the bottom of the first cell;
Ehd-2-- Eh values measured at 25 com from the bottom of the second cell;
C1-treatment 1 with cattail; C2-treatment2-with cattail;
C3-treatment 3 with cattail; C4-treatment 4 with cattail;
W1-treatment 1 with woolgrass; W2-treatment2-with woolgrass;
W3-treatment 3 with woolgrass; W4-treatment 4 with woolgrass;
I1-treatment 1 with iris; I2-treatment2-with iris;
I3-treatment 3 with iris; I4-treatment 4 with iris;

II. Powell River Project Site

1. Fecal coliform numbers (no./ 100 ml)

Field no.	1/1792	2/19/92	3/20/92	4/27/92	6/23/92	7/30/92	9/2/92
STE	450000	310000	6700	2800	1700	170	200
R1	110000	4000	760	10	0	0	
R2	7000	170	140	200	10	0	
R3	7000	200	30	10	10	0	
HR1A		260	80	10	10	10	0
HR1B			1	10	10	0	1
HR1F			10	10	60	10	1
HR2A		720	520	10	0	10	1
HR2B		670	10	10	0	10	1
HR2F		60	1	10	10	10	1
HR3A		320	1	10	0	10	0
HR3B		280	1	10	0	0	0
HR3F		310	0	10	10	10	1
HR4A		430	230	10	0	10	1
HR4B		1200	20	10	10	10	1
HR4F		840	1		10	10	1

FC (cont.)

Field no.	9/23/92	11/3/92.	12/3/92	1/12/93	2/10/93	6/29/93
STE	1132	17063	393	1900	1280	1570
R1	20	0	0	160	0	160
R2	0	0	0	0	121	10
R3	0	0	0	0	0	120
HR1A		0	24	0	0	0

HR1B		0		0	0	10
HR1C				0	0	10
HR1F		3		0	0	310
HR2A		2		0	0	270
HR2B		4		0	0	0
HR2C				0	0	10
HR2F				0	0	520
HR3A	0			0	11	10
HR3B	0			0	0	10
HR3C				0	0	0
HR3F	0			0	0	10
HR4A	0			0	0	10
HR4B	0			0	0	170
HR4C				0	0	10
HR4F	0			0	0	0

FC (cont.)

Field no.	7/27/93	8/25/93	9/13/93	10/12/93	11/11/93	2/9/94
STE	19000	3400			27100	82000
R1	830	10	10	16300	5000	4300
R2	10	10	10	2000		1700
R3	0	0				17200
HR1Ad	10	10	10	10	140	1820
HR1As	0	0	10	430	120	9800
HR1Bd	10	10	10	10	10	170
HR1Bs	0	0	0	10	10	0
HR1Cd	7500	0	10	10	10	0
HR1Cs	0	0	0	0	10	0
HR1F	10	10		10	10	10

HR2Ad	13600	10	10	10	10	2200
HR2As	7000	0	10	0	100	1070
HR2Bd	170	10	10	10	10	620
HR2Bs	0	0	10	0	10	760
HR2Cd	180	0	10	10	10	10
HR2Cs	0	0	10	0	10	0
HR2F	10	10		10	10	120
HR3Ad	200	10	10	260	410	60
HR3As		10	10	310	220	10000
HR3Bd	360	10	10	10	10	720
HR3Bs	0	0	10	0	270	330
HR3Cd	830	10	10	10	4300	990
HR3Cs	520	0	10	0	4100	0
HR3F	10	10		10	10	10
HR4Ad	410	10	10	440	10	920
HR4As	0	0	10	180	10	2100
HR4Bd	220	10	10	10	10	1030
HR4Bs		0	10	0	10	0
HR4Cd	10	830	10	0	230	270
HR4Cs	0	0	10	10	10	1780
HR4F	10	10		10	10	320

FC (cont.)

Field no.	3/15/94	4/21/94	6/15/94	1/11/95		
STE	77000	40000	210000	1040000		
R1	8400	1840		12100		
R2	1220	540		7200		
R3	450	220		1760		
HR1Ad	10	420	10	1560		

HR1As	10	250	210	2000		
HR1Bd	10	10	10	400		
HR1Bs	0	10	130	330		
HR1Cd	0	10	0	800		
HR1Cs	0	0	10	750		
HR1F	10	10	10	280		
HR2Ad	10	220	10	2900		
HR2As	10	110	10	2000		
HR2Bd	10	10	10	1850		
HR2Bs	0	10	10	730		
HR2Cd	10	10	10	300		
HR2Cs	0	0	10	10		
HR2F	10	10	10	790		
HR3Ad	100	310	330	240		
HR3As	220	320	10	400		
HR3Bd	10	10	10	260		
HR3Bs	10	10	10	10		
HR3Cd	10	10	10	10		
HR3Cs	10	10	0	0		
HR3F	10	10	10	10		
HR4Ad	230	10	10	0		
HR4As	10	110	0	0		
HR4Bd	10	10	10	0		
HR4Bs	10	0	0	0		
HR4Cd	10	10	10	10		
HR4Cs	0	0	0	420		
HR4F	10	10	10	0		

2. Five days biochemical oxygrn demand ($BOD_{5,}$ mg/l)

Field no.	2/19/92	3/20/92	4/27/92	7/30/92	9/2/92	9/23/92
STE	103	168	113	147.7	145.3	132.8
R1	113	88		114	100.7	
R2	110	90		56	67.7	
R3	106	79	146	97	68.7	
HR1A	93	73	119.5	108.3	107.3	95.3
HR1B	105	62	92	73	96.7	106.5
HR1F	104	66	102	127	93	72.8
HR2A	87	72	106	123.7	84	90.0
HR2B	90	78	90	110	96.3	80.3
HR2F	83	57	73	123.7	132	51.8
HR3A	64	75	104	108	83.5	120.0
HR3B	23	56	25	59	53	126.8
HR3F	77	61	62.5	120	84.7	35.3
HR4A	53	78	123	85	117.8	79.5
HR4B	64	62	108.5	102.7	80	
HR4F	102	89	11.5	131	83.7	27.0

BOD_5 (cont.)

Field no.	12/3/92	1/12/93	2/10/93	3/10/93	6/29/93
STE		121.5	75.0	34.5	131
R1	126	132.8	46.5		72.8
R2	78.8	79.0	43.5		62.3
R3	136.5	61.5	22.5		57.8
HR1A	120.5	86.0	20.3	27.8	56.3
HR1B	69.0	61.5	28.5	21.8	28.5
HR1Cd	80.3	27.8	18.0		18.0
HR1Cs					7.5

HR1F	132.8	56.3	31.5	33.0	6.8
HR2A	126.8	80.3	16.2	23.0	60.0
HR2B	57.0	41.3	21.0	23.3	70.5
HR2Cd	109.5	70.5	21.0		49.5
HR2Cs					29.3
HR2F	87.8	63.0	72.0	24.8	10.5
HR3A	90.8	55.5	39.8	19.8	6.0
HR3B	68.9	45.8	34.0	16.5	13.5
HR3Cd	45.0	33.0	30.0		40.5
HR3Cs					10.5
HR3F	111.0	51.0	24.0	21.8	9.0
HR4A	121.5	60.8	24.4	22.5	61.2
HR4B	121.5	63.0	21.0	19.5	17.3
HR4Cd	47.8	42.0	24.0		12.0
HR4Cs					5.3
HR4F	150.0	63.0	47.3	28.8	6.0

BOD_5 (cont.)

Field no.	7/28/93	8/25/93	9/14/93	10/13/93	11/9/93	2/8/94
STE	106.5	167.5			87	207
R1	87.8	114	66	122	165	
R2	114.3	118.8	28.5	94		
R3	77.3	93.0				
HR1Ad	122.3	126	131.3	137	45	126
HR1As	10.5	33.8	86.3	60.5	39.8	40
HR1Bd	125.3	126	125.1	98	36.8	63
HR1Bs	3.5	26.5	36	32.5	30.8	21.7
HR1Cd	45.0	90	63.8	48	28.5	63
HR1Cs	10	22.5	32.3	34	21.8	37.3

HR1F	94.5	109.5		114	57.0	68.6
HR2Ad	105	129.8	130.5	134	39.0	104.1
HR2As	39	46.5	114	56.5	32.3	58.4
HR2Bd	84	170.3	154.5	155	36.8	149.3
HR2Bs	11	44.3	65.3	31.5	27.8	32.7
HR2Cd	66	160.5	80.3	63	32.3	104.2
HR2Cs	51	21.8	55.5	37.5	23.3	7.2
HR2F	199.5	111		121	76.5	62.1
HR3Ad	106.5	147.8	114	137	48.8	82.5
HR3As	17	66	69.8	79.5	38.3	33.6
HR3Bd	142.5	130.5	207.8	112	36.8	52.9
HR3Bs	13.5	26.3	94.5	53	30.0	9
HR3Cd	102.0	120.0	91.5	83	33.8	12.7
HR3Cs	27.5	22.5	98.3	71	27.0	16.3
HR3F	101.3	108.8		131	53.5	51.0
HR4Ad	103.5	116.3	135.8	129	50.3	95.7
HR4As	20.5	29.3	63	67	34.5	16.3
HR4Bd	126.8	111.8	168	113	31.5	31.8
HR4Bs	26.5	70.5	63	42	21.0	58.4
HR4Cd	128.3	93.0	149.3	37	24.8	30.9
HR4Cs	24.5	30.8	57.0		21.8	9
HR4F	112.5	123.0			72.8	54.7

BOD$_5$ (cont.)

Field no.	3/16/94	4/20/94	6/14/94	9/7/94	1/11/95
STE	195.3	126	152	162.8	202
R1	142.5	87.8			
R2	163.5	102			
R3	129	85.5			

HR1Ad	193	87	127.5	83.3	114
HR1As	82.5	49.5	78		41.3
HR1Bd	138	124.5	129	88.5	81
HR1Bs	18	27	64.5		30.8
HR1Cd	36	12.8	49.5	30	33.8
HR1Cs	6	12	48		29.3
HR1F	182	63	90	113.3	128
HR2Ad	174	97.5	120	138.8	215
HR2As	105	75	91.5		78
HR2Bd	135	88.5	106.5	113.3	113
HR2Bs	28.5	30	148.5		198
HR2Cd	64.5	10.5	69	66	125
HR2Cs	27	6	70.5		90
HR2F	195	63	96	133.5	111
HR3Ad	171	55.5	112.5	103.5	104
HR3As	78	34.5	73		220
HR3Bd	165	51	78	72.0	88.5
HR3Bs	49.5	40.5	54		89
HR3Cd	157.5	25.5	75	81	88.5
HR3Cs	31.5	7.5	61.5		95
HR3F	165	60	75	132.8	83
HR4Ad	192	63	102	81	190
HR4As	73.5	40.5	70.5		76.5
HR4Bd	159	35.3	82.5	78	53
HR4Bs	36	15	46.5		92
HR4Cd	52.5	31.5	85.5	54	77
HR4Cs	37.5	6	45		84
HR4F	186	87	81	173.3	

3. Chemical oxygen demand (COD, mg/l)

Field no.	12/3/92	2/10/93	3/10/93	4/7/94	
STE	124	239	90	93	
R1	147	131			
R2	116	151			
R3	198	165			
HR1A	233	87	57		
HR1B	155	94	47	48	
HR1C	159	20			
HR1F	167	121	128		
HR2A	288	94	78		
HR2B	171	60	42	25	
HR2C	253	118			
HR2F	225	165	55		
HR3A	373	151	72		
HR3B	167	74	52	39	
HR3C	97	87			
HR3F	229	104	78		
HR4A	241	97	47		
HR4B	276	81	3	52	
HR4C	291	40			
HR4F	245	171	58		

4. Total K Nitrogen (TKN, mg /L)

Field no.	12/3/92	6/29/93	7/27/93	8/25/93	9/13/93	10/12/93	2/9/94
STE	57.0	62.2	50.6	54.5			72.7
R1	47.8		39.6	50.2	51.9	55.5	
R2	49.9		40.2	49.9	42.0	43.2	

R3	44.8		37.3	66.3			
HR1Ad	37.7		53.4	38.7	48.7	41.4	74.2
HR1As			16.7	9.1	24.3	21.8	22.8
HR1Bd	21.5		43.3	36.1	40.9	41.4	38.4
HR1Bs			13.0	6.5	9.4	15.6	13.5
HR1Cd	18.5		25.9	17	25	16.9	21.3
HR1Cs			12.1	3.8	7.6	10.7	9.9
HR1F	35.7		65.3	44		54.9	67.5
HR2Ad	28.6		54.3	49.2	67.5	52.4	49.3
HR2As			24.0	10.4	43.1	19.3	42.6
HR2Bd	9.4		67.2	41.3	49.1	47.5	53.5
HR2Bs			13.9	7.7	22.1	16.9	20.2
HR2Cd	16.5		42.4	24.9	43.4	25.4	23.4
HR2Cs			19.4	6.5	17.9	11.3	13.2
HR2F	42.8		77.2	44		49.3	46.7
HR3Ad	9.4		49.7	44.6	57.2	41.4	43.6
HR3As			21.3	20.3	39.9	22.4	29.1
HR3Bd	0.3		68.9	35.4	52.6	37.7	45.7
HR3Bs			15.8	9.7	31.4	29.7	24.4
HR3Cd	5.3		70.8	44.3	50.5	29.7	32.2
HR3Cs			9.4	6.5	30.6	10.7	19.7
HR3F	20.5		97.4	43.0		46.3	49.3
HR4Ad	23.6		48.8	41.0	56.2	19.3	45.7
HR4As			14.9	3.8	22.8	28.5	21.3
HR4Bd	18.5		47.0	32.7	42.0	40.8	33.7
HR4Bs			25.0	3.8	23.6	13.2	32.4
HR4Cd	8.4		41.5	34.7	38.4	11.3	24.9
HR4Cs			15.8	3.8	20.0	36.5	11.4
HR4F	10.4		49.7	48.6		51.2	52.9

TKN (cont.)

Field no.	12/3/92	6/29/93	7/27/93	8/25/93	9/13/93	10/12/93	2/9/94
STE	57.0	62.2	50.6	54.5			72.7
R1	47.8		39.6	50.2	51.9	55.5	
R2	49.9		40.2	49.9	42.0	43.2	
R3	44.8		37.3	66.3			
HR1Ad	37.7		53.4	38.7	48.7	41.4	74.2
HR1As			16.7	9.1	24.3	21.8	22.8
HR1Bd	21.5		43.3	36.1	40.9	41.4	38.4
HR1Bs			13.0	6.5	9.4	15.6	13.5
HR1Cd	18.5		25.9	17	25	16.9	21.3
HR1Cs			12.1	3.8	7.6	10.7	9.9
HR1F	35.7		65.3	44		54.9	67.5
HR2Ad	28.6		54.3	49.2	67.5	52.4	49.3
HR2As			24.0	10.4	43.1	19.3	42.6
HR2Bd	9.4		67.2	41.3	49.1	47.5	53.5
HR2Bs			13.9	7.7	22.1	16.9	20.2
HR2Cd	16.5		42.4	24.9	43.4	25.4	23.4
HR2Cs			19.4	6.5	17.9	11.3	13.2
HR2F	42.8		77.2	44		49.3	46.7
HR3Ad	9.4		49.7	44.6	57.2	41.4	43.6
HR3As			21.3	20.3	39.9	22.4	29.1
HR3Bd	0.3		68.9	35.4	52.6	37.7	45.7
HR3Bs			15.8	9.7	31.4	29.7	24.4
HR3Cd	5.3		70.8	44.3	50.5	29.7	32.2
HR3Cs			9.4	6.5	30.6	10.7	19.7
HR3F	20.5		97.4	43.0		46.3	49.3
HR4Ad	23.6		48.8	41.0	56.2	19.3	45.7

HR4As			14.9	3.8	22.8	28.5	21.3
HR4Bd	18.5		47.0	32.7	42.0	40.8	33.7
HR4Bs			25.0	3.8	23.6	13.2	32.4
HR4Cd	8.4		41.5	34.7	38.4	11.3	24.9
HR4Cs			15.8	3.8	20.0	36.5	11.4
HR4F	10.4		49.7	48.6		51.2	52.9

TKN (cont.)

Field no.	3/15/93	4/21/94	6/15/94				
STE	58.7	47.2	53.6				
R1	34.0	35.5					
R2	34.7	45.2					
R3	34.8	35.4					
HR1Ad	29.6	33.0	19.2				
HR1As	13.5	14.8	11.5				
HR1Bd	22.2	23.7	20.8				
HR1Bs	3.6	5.8	19.2				
HR1Cd	3.1	4.6	13.1				
HR1Cs	2.5	2.3	3.8				
HR1F	30.2	32.1	35.6				
HR2Ad	34.3	37.4	37.8				
HR2As	15.1	14.3	17.5				
HR2Bd	23.6	26.1	27.9				
HR2Bs	15.1	4.4	13.1				
HR2Cd	24.0	9.0	26.8				
HR2Cs	2.5	1.7	9.9				
HR2F	29.5	32.3	36.1				
HR3Ad	29.2	30.7	25.2				
HR3As	14.2	12.8	19.7				

HR3Bd	21.9	18.1	33.9				
HR3Bs	8.8	6.22	21.3				
HR3Cd	10.7	8.5	27.9				
HR3Cs	1.7	1.7	10.9				
HR3F	24.8	27.4	44.9				
HR4Ad	28.8	27.8	35.6				
HR4As	6.4	12.9	11.5				
HR4Bd	6.6	14.8	43.8				
HR4Bs	6.2	4.7	12.6				
HR4Cd	15.6	15.5	35.6				
HR4Cs	3.1	2.0	9.9				
HR4F	28.8	40.8	42.7				

5. Ammium (NH_4-N, mg/l)

Field no.	2/19/92	3/17/92	4/27/92	6/23/92	7/30/92	9/2/92	12/3/92
STE	35.9	49.7	51.1	43.8	50.6	47.1	
R1	50.5	42.9	49.2	38.9	26.8	48.9	47.6
R2	50.5	39.5	60.7	51.2	22.1	22.6	46.8
R3	47.6	37.8	66.5	58.5	38.7	47.1	46.4
HR1Ad	31.4	36.1	55.0	26.6	41.1	46.5	41.2
HR1Bd	35.9	27.5	45.4		26.8	27.3	26.7
HR1Cd							21.9
HR1F	40.3	30.9	53.1	31.5	48.2	36.9	37.2
HR2Ad	32.9	32.6	49.2	24.1	48.2	36.9	47.6
HR2Bd	28.5	25.8	35.8	9.4	45.8		24.3
HR2Cd							32.3
HR2F	30.0	24.1	37.7	27.8	48.2	18.6	39.6
HR3Ad	27.0	27.5	45.4	16.7	41.1	8.1	38.8
HR3Bd	9.4	15.5	24.2		24.5	23.8	26.7

HR3Cd							12.2
HR3F	32.9	25.8	39.6	9.4	48.2	36.0	40.4
HR4Ad	31.5	30.9	53.1		45.8	33.4	40.4
HR4Bd	21.1	25.8	45.4	19.2	38.7	55.2	36.3
HR4Cd							16.2
HR4F	35.8	29.2	51.1	38.8	50.6	36.9	40.4

NH$_4$-N (cont.)

Field no.	1/13/93	2/10/93	7/27/93	8/25/93	9/13/93	10/12/93	11/11/93
STE	39	42.7	40.8	40.2			53.5
R1	39	34.6	33.7	40.1	47.3		43.6
R2	37	39	8.2	44	39.2	31.2	
R3		37.8	7.5	47			
HR1Ad	32	18.8	33.7	35.2	39.2	22.5	32.0
HR1As			17.1	7.8	25.6	8.8	20.5
HR1Bd	22	20.8	36.7	29.5	30.2	23.3	23.5
HR1Bs			9.1	5.9	8.2	3.4	5.1
HR1Cd	2.3	7.5	19.7	7.8	17.8	5.2	4.7
HR1Cs			9.1	2.1	5.6	0	2.0
HR1F	24	33.6	56	42.1		38.1	34.6
HR2Ad	38	21.5	44.3	43.2	39.2	35.2	36.3
HR2As			18.5	9.7	34.1	4.8	23.1
HR2Bd	18	10.2	59.5	36	34.8	27.6	27.6
HR2Bs			10.9	6.7	19.7	0.1	9.2
HR2Cd	12	23.3	36.1	21.9	30	16.4	14.5
HR2Cs			10.3	5.2	18.2	1.7	4.7
HR2F	26	33.9	71.2	42.8		40.4	36.3
HR3Ad	22	22	36.7	43.2	43.2	31.4	32.6
HR3As			9.1	19.6	35.8	17.5	24.5

HR3Bd	17	15.1	30.2	31.4	35.8	28.9	22.3
HR3Bs			9.1	9.3	26.1	16	16.2
HR3Cd	7.2	12.6	65.4	24.2	30.2	19.3	14.1
HR3Cs			8	6.3	24.6	4.1	6.9
HR3F	23	31.2	90.7	40.9		40.2	34.6
HR4Ad	28	19.1	36.1	36	34.4	27.9	36.3
HR4As			41.9	2.9	19.2	10.9	16.6
HR4Bd	26	17.6	37.3	29.9	34.1	29.1	27.2
HR4Bs			17.9	2.5	17.5	4.3	7.1
HR4Cd	18	3.5	39	30.3	29.7	0	18.2
HR4Cs			10.3	2.1	15.1	18.4	6.7
HR4F	27	38.6	46.6	48.1		38.1	35.4

NH_4-N (cont.)

Field no.	2/9/94	3/15/94	4/21/94	6/15/94	9/7/94	1/11/95
STE	51.2	49.9	43.3	35.4	67.9	52.3
R1	39.9	34.0	35.5			44.7
R2	41.0	34.3	39.2			48.7
R3	40.3	34.9	38.5		50.5	46.9
HR1Ad	32.7	25.1	33.3	26.1	31.1	29.6
HR1As	12.5	10.7	14.5	17.2		11.3
HR1Bd	29.5	18.7	25.5	27.3	31.6	19.9
HR1Bs	4.5	2.1	5.2	14.4		4.3
HR1Cd	6.0	1.0	3.1	10.1	10.5	3.6
HR1Cs	2.0	0.2	0.8	4.1		3.0
HR1F	41.0	30.8	34.8	40.0	47.6	37.1
HR2Ad	37.4	30.8	38.1	34.4	51.1	42.2
HR2As	24.4	15.9	16.6	25.3		25.0
HR2Bd	34.5	23.4	28.1	38.0	45.3	9.1

HR2Bs	15.0	3.9	3.8	18.2		7.6
HR2Cd	15.4	9.5	10.1	33.4	19.5	5.2
HR2Cs	4.2	0.5	0.3	12.2		42.2
HR2F	39.2	30.3	34.6	52.7	51.1	16.9
HR3Ad	36.5	28.0	33.3	29.2	40.9	12.8
HR3As	19.0	14.1	12.9	19.2		10.4
HR3Bd	29.5	19.9	20.8	33.9	22.5	6.1
HR3Bs	13.6	6.05	6.3	17.7		8.9
HR3Cd	11.8	8.93	8.4	35.9	22.3	5.9
HR3Cs	2.9	0.2	0.8	13.7		26.4
HR3F	35.2	24.5	32.9	46.1	40.6	26.4
HR4Ad	36.3	28.5	31.8	27.8	32.3	13.8
HR4As	14.3	5.5	11.7	15.7		12.5
HR4Bd	21.5	19.9	14.8	38.0	23.5	9.8
HR4Bs	3.1	3.7	4.5	12.7		3.2
HR4Cd	14.3	13.0	14.5	30.4	16.4	6.9
HR4Cs	3.1	0.22	0.7	14.7		2.7
HR4F	34.5	28.5	35.7	31.1	44.7	17.9

6. Nitrate (NO_3-N, mg/l)

Field no.	2/19/92	3/17/92	4/27/92	6/23/92	7/30/92	9/2/92
STE	0.5	0.49	0.26	0.32	0.77	0.14
R1	0.4	0.05	0.05	0.06	0	0.22
R2	0.5	0.05	0.45	0	0.39	0.17
R3	0.5	0.11	0	0.12	0	0.28
HR1A	0.8	0.24	0	0.25	0.47	0.13
HR1B	0.2	0.24	0.41	0.10	0.92	0.13
HR1F	0	0.18	1.15	0.12	0.62	0.13
HR2A	0	0.11	0.81	0.10	0.47	0.13

HR2B	0	0.18	0.41	0.10	0.39	0.22
HR2F	0	0.18	0.76	0.10	0.47	0.17
HR3A	0.2	0.11	0.41	0	0.58	0.14
HR3B	0	0.18	0.06	0.20	0.24	0.14
HR3F	0	0.30	0.81	0.10	0.39	0.17
HR4A	0	0.11	0.36	0	0.62	0.17
HR4B		0.10	0.51	0	0.62	0.14
HR4F		0.05	1.50	0.10	0.47	0.22

NO_3-N (cont.)

Field no.	12/3/92	1/12/93	2/10/93	3/10/93	4/7/93	
STE		0	0.1	0.1	0.3	
R1	0.2	0.65	0.1			
R2	0.15	0.92	0.1			
R3	0.66	0.30	0.1			
HR1A	0.16	0.39	0.1	0.1		
HR1B	0.33	1.1	0.1	0.1	0.4	
HR1C	0.33	2.2	0.1			
HR1F	0.09	1.1	0	0		
HR2A	0.20	1.3	0.1	0		
HR2B	0.27	1.1	0	0	0.7	
HR2C	0	0.30	0			
HR2F	0.03	0.21	0.1	0		
HR3A	0	1.3	0.1	0.1		
HR3B	0	2.8	0.1	005	1.0	
HR3C	0.08	2.2	0			
HR3F	0.11	7.5	0	0		
HR4A	0.01	0.39	0	0.1		
HR4B	0.01	0.03	0	0.1	0.4	

HR4C	0.04	0	0			
HR4F	0.15	0.03	0	0		

NO_3-N(cont.)

Field no.	7/27/93	8/25/93	9/13/93	10/12/93	11/11/93	2/9/94
STE	0.12	1.42			0.07	0.38
R1	0.09	0.22		0.02	0.09	0.10
R2	0.15	0.34	0.63	0.01		0.03
R3	0.12	0.09	0.24			0.05
HR1Ad	0.30	0.78	0.50	0.31	0.3	0.13
HR1As	1.11	0.75	1.28	0.27	0.43	0.02
HR1Bd	0.37	0.43	0.37	0.28	0.28	0.10
HR1Bs	0.66	0.41	0.63	0.46	0.48	0.11
HR1Cd	0.13	0.43	0.44	0.22	0.43	0
HR1Cs	0.27	0.24	0.44	0.23	0.58	0.02
HR1F	0.13	0.40		0.27	0.03	0.24
HR2Ad	0.24	0.17	0.47	0.28	0.21	0.12
HR2As	0.12	0.40	0.57	0.06	0.20	0.16
HR2Bd	0.11	0.17	0.37	0.14	0.16	0.12
HR2Bs	0.59	0.29	0.24	0.05	0.20	0.05
HR2Cd	0.16	0.30	0.24	0.03	0.04	0
HR2Cs	0.08	0.11	0.37	0.02	0.04	0.01
HR2F	0.10	0.21		0.17	0.28	0.22
HR3Ad	0.09	0.12	0.63	0.16	0.19	0.03
HR3As	0.17	0.33	0.31	0.08	0.30	0.09
HR3Bd	0.10	0.08	0.50	0.12	0.41	0.07
HR3Bs	0.14	0.19	0.57	0.01	0.71	0.02
HR3Cd	0.18	0.28	0.24	0.02	0.05	0
HR3Cs	0.07	0.07	0.24	0.01	0.11	0.06

HR3F	0.16	0.08		0.02	030	0.05
HR4Ad	0.08	0.09	0.66	0.17	0.04	0.05
HR4As	0.10	0.30	0.18	0.01	0.02	0
HR4Bd	0.07	0.08	0.63	0.14	0.07	0
HR4Bs	0.19	0.25	0.70	0.01	0.01	0.07
HR4Cd	0.09	0.33	0.57	0.01	0.13	0
HR4Cs	0.45	0.21	0.50	0.09	0.16	0
HR4F	0.05	0.13		0.17	0.35	0.16

NO_3-N (cont.)

Field no.	3/15/94	4/21/94	6/15/94	9/7/94	1/11/95	
STE	0.28	0.56	0.42	1.15	3.00	
R1	0.22	0.67			1.25	
R2	0.17	0.10			0.08	
R3	0.24	0.16		0.29	2.70	
HR1Ad	0.11	0.42	0.04	0.82	1.49	
HR1As	0.29	0.72	0.10		0.28	
HR1Bd	0.25	0.39	0.01	0.51	0.28	
HR1Bs	0.20	0.34	0.03		0.28	
HR1Cd	0.31	0.25	0	0.35	0.42	
HR1Cs	0.28	0.23	0.01		0.47	
HR1F	0.42	0.34	0.04	0.35	3.72	
HR2Ad	0.31	0.35	021	0.23	3.38	
HR2As	0.25	0.45	0.04		1.10	
HR2Bd	0.22	0.31	0.04	0.29	1.59	
HR2Bs	0.28	0.23	0		0.23	
HR2Cd	0.14	0.22	0.02	0.30	1.78	
HR2Cs	0.26	0.23	0		2.80	
HR2F	0.23	0.32	0.13	0.28	4.93	

HR3Ad	0.18	0.35	0.03	0.13	1.05	
HR3As	0.19	0.50	0.16		1.01	
HR3Bd	0.25	0.18	0.10	0.16	0.47	
HR3Bs	0.21	0.56	0		0.57	
HR3Cd	0.18	0.14	0.08	0.17	2.56	
HR3Cs	0.22	0.37	0		4.45	
HR3F	0.31	0.23	0.01	0.28	2.61	
HR4Ad	0.17	0.13	0	0.30	0.28	
HR4As	0.16	0.14	0.16		0.91	
HR4Bd	0.13	0.22	0	0.19	0.47	
HR4Bs	0.13	0.29	0.06		0.97	
HR4Cd	0.14	0.15	0.1	0.19	0.23	
HR4Cs	0.21	0.20	0.04		0.47	
HR4F	0.31	0.31	0.16	0.30	1.15	

7. Phosphorus (PO_4-P, mg/l)

Field no.	2/19/92	3/20/92	4/27/92	6/23/92	7/3092	9/2/93
STE	5.20	5.47	5.14	4.14	5.74	5.40
R1	5.9	3.21	5.51	3.55	1.31	2.6
R2	5.9	4.33	6.40	4.36	1.88	2.8
R3	6.7	3.87	6.79	4.29	3.17	5.4
HR1A		3.25	5.09	2.53	3.91	4.3
HR1B	3.16	2.67	4.30	1.65	1.67	3.9
HR1F	3.64	3.01	5.11	2.24	4.06	3.6
HR2A	2.72	4.09	4.87	2.11	4.19	3.2
HR2B	2.28	2.66	3.71	0.62	3.57	3.7
HR2F	2.04	2.35	3.66	1.97	3.80	2.9
HR3A	2.76	2.80	4.42	1.04	3.26	1.4
HR3B	0.76	1.60	2.64	0.35	1.82	2.1

HR3F	3.60	2.79	4.40	0.52	4.10	3.5
HR4A	3.08	2.96	5.12	1.30	3.28	4.5
HR4B	1.84	2.96	4.88	1.36	3.44	2.1
HR4F	3.72	3.48	5.34	3.18	4.86	3.7

PO_4-P (cont.)

Field no.	12/3/92	1/12/93	2/10/93	3/10/93	7/27/93	8/25/93
STE	4.38	4.0	3.10	0.2	5.48	4.52
R1	3.64	2.3	2.2		5.66	4.91
R2	4.40	3.0	2.4		6.83	5.46
R3	5.26	2.7	2.6		6.76	5.89
HR1Ad	4.11	2.9	1.2	0.5	10.1	5.23
HR1As					2.26	2.42
HR1Bd	2.97	2.0	1.3	0.3	10.2	5.36
HR1Bs					0.59	2.07
HR1Cd	2.69	0	0.3		3.45	2.31
HR1Cs					0.3	1.70
HR1F	4.65	2.0	2.1	1.6	15.02	8.40
HR2Ad	4.52	2.7	1.2	0.6	10.6	11.0
HR2As					3.51	9.18
HR2Bd	2.06	1.3	0.7	0.2	12.8	6.42
HR2Bs					1.53	2.57
HR2Cd	3.51	0.9	1.3		7.94	4.10
HR2Cs					1.02	1.96
HR2F	4.65	1.9	2.0	1.3	12.8	7.35
HR3Ad	3.39	1.4	1.4	0.4	9.26	6.28
HR3As					0.67	4.46
HR3Bd	2.81	1.2	0.7	0.1	11.4	4.95
HR3Bs					0.83	2.46

HR3Cd	0.90	0.4	0.5		13.01	8.05
HR3Cs					0.1	2.91
HR3F	4.62	1.9	1.8	1.3	17.2	7.59
HR4Ad	4.02	2.4	1.1	0.4	9.23	3.48
HR4As					8.26	1.68
HR4Bd	3.96	2.1	0.7	0.1	8.21	11.9
HR4Bs					4.46	
HR4Cd	1.21	1.1	0.4		8.08	9.90
HR4Cs					1.21	4.97
HR4F	4.72	0.3	2.2	1.6	8.42	9.22

PO_4-P (cont.)

Field no.	9/13/93	10/12/93	11/11/93	2/9/94	3/15/95	4/21/94
STE			9.62	9.20	5.15	4.87
R1	4.61	7.88		2.00	2.96	3.31
R2	4.37	8.38		2.20	3.60	4.78
R3				2.26	3.67	3.96
HR1Ad	4.96	8.97	3.15	3.60	2.86	3.24
HR1As	3.88	2.81	2.78	1.50	1.27	1.48
HR1Bd	5.40	7.05	2.88	2.67	1.98	2.15
HR1Bs	1.81	1.25	0.70	0.66	0.26	0.71
HR1Cd	2.89	1.54	0.53	0.41	0.15	0.33
HR1Cs	1.07	0.36	0.30	0.13	0.07	0.20
HR1F		9.63	4.40	4.24	4.17	3.92
HR2Ad	5.70	9.53	4.06	3.91	3.30	3.83
HR2As	4.79	3.20	2.39	2.44	1.71	1.89
HR2Bd	6.64	6.67	3.08	3.24	2.63	3.06
HR2Bs	3.58	6.90	1.11	1.38	0.48	0.54
HR2Cd	5.93	4.37	1.66	1.36	1.07	1.13

HR2Cs	3.54	1.21	0.75	0.35	0.12	0.32
HR2F		10.0	5.02	4.04	3.80	3.89
HR3Ad	4.99	9.40	3.42	3.79	2.96	3.54
HR3As	4.27	6.34	3.01	2.03	1.56	1.24
HR3Bd	5.51	7.46	2.47	2.66	2.17	2.00
HR3Bs	4.42	4.45	1.98	1.17	0.77	0.74
HR3Cd	5.50	5.50	2.49	1.16	0.98	0.93
HR3Cs	4.48	1.91	1.12	2.92	0.12	0.21
HR3F		9.52	4.69	5.70	3.56	3.85
HR4Ad	4.39	7.78	3.86	3.76	3.14	3.02
HR4As	2.59	3.31	1.68	1.64	0.74	1.31
HR4Bd	5.81	6.86	2.90	2.23	2.45	1.61
HR4Bs	3.21	1.81	1.07	0.35	0.54	0.57
HR4Cd	5.32	0.43	1.99	1.73	1.41	1.53
HR4Cs	2.90	4.80	1.01	0.26	0.12	0.71
HR4F		9.46	4.94	4.61	3.52	4.05

PO_4-P (cont.)

Field no.	6/15/94	9/7/94	1/11/95	9/6/95		
STE	3.91	5.99	5.27	4.97		
R1			5.04			
R2			4.58			
R3		5.54	4.95			
HR1Ad	2.50	3.36	3.36	3.96		
HR1As	1.64		1.11	3.34		
HR1Bd	2.23	3.05	2.14	2.18		
HR1Bs	1.26		0.46	0.67		
HR1Cd	0.84	0.9	0.21	1.24		
HR1Cs	0.42		0.16	0.55		

HR1F	2.80	4.05	4.71	3.68		
HR2Ad	3.04	4.68	4.42	4.26		
HR2As	0.05		2.37	3.95		
HR2Bd	1.44	3.56	2.95	2.75		
HR2Bs	1.46		0.76	1.97		
HR2Cd	2.40	1.84	0.60	2.02		
HR2Cs	0.98		0.27	1.11		
HR2F	3.67	4.10	4.74	4.16		
HR3Ad	2.13	4.16	1.68	5.36		
HR3As	2.86		1.02	4.24		
HR3Bd	2.49	2.09	0.97	3.45		
HR3Bs	1.38		0.51	2.23		
HR3Cd	2.36	2.09	0.60	2.02		
HR3Cs	1.08		0.32	1.18		
HR3F	3.11	3.97	3.03	4.20		
HR4Ad	2.66	2.64	1.0	3.06		
HR4As	1.51		0.46	2.56		
HR4Bd	2.35	2.14	0.73	2.99		
HR4Bs	0.77		0.26	2.85		
HR4Cd	2.12	3.73	0.60	1.73		
HR4Cs	0.68		0.28	0.92		
HR4F	3.28	5.54	2.64	2.77		

8. Chloride (Cl, mg /L)

Field no.	2/19/92	3/17/92	4/27/92	6/23/93	7/12/92	9/2/92	11/3/92	1/2/93
STE	104	191	58.1	52.5	129	92	119	77.1
R1	105	157	64.8	52.3	24	92	54	73.3
R2	93	129	71.6	59.1	30	42	48	70.7
R3	79	114	105.4	61.5	39	38	71	61.6

HR1A	44.1	131	92.6	51.9	99	76		61.6
HR1B	43.1	94	64.8	44.8	60	64		34.5
HR1C								68.1
HR1F	45.2	105	71.9	48.8	124	73		42.3
HR2A	46.9	111	85.8	36.9	115	72		60.4
HR2B	34.6	90	73.3	12.6	103	87		22.9
HR2C								16.5
HR2F	39.6	86	84.4	43.3	107	40		39.7
HR3A	52.6	100	80.1	19.6	103	23		34.5
HR3B	16.6	61	77.2	7.5	64	72		26.8
HR3C								7.4
HR3F	42.4	93	91.8	8.9	125	79		44.9
HR4A	51.6	123	73.4	22.9	83	92		41.0
HR4B	28.9	111	79.8	27.9	93	29		51.3
HR4C								22.9
HR4F	45.2	112	95.8	71.3	128	75		60.4

Chloride (cont.)

Field no.	2/10/93	3/10/93	6/29/93	7/27/93	8/25/93	9/13/93	10/12/93	11/13/93
STE	50.2	33.0	87.4	62.0	108.8			105.7
R1	57.8		91.6	69.8	64.2		44.5	121
R2	82.3		98.6	64.6	83.9	60.0	48.4	122.3
R3	104.2		92.4	44.6	82.6	54.9		128.4
HR1Ad	109.4	24.3	83.5	51.5	57.7	68.9	56.2	
HR1As				11.1	6.55	57.4	35.4	83.5
HR1Bd	56.5	21.4	79.9	48.6	60.3	67.6	66.6	93.7
HR1Bs				5.85	0	31.9	38.0	32.8
HR1Cd	32.0		53.9	25.4	5.24	51.1	17.3	30.3
HR1Cs			33.6	5.85	0	19.2	9.5	21.6

HR1F	78.4	48.8	70.3	59.4	94.4		60.1	112.6
HR2Ad	61.6	37.3	90.8	65.9	76.0	74.0	56.2	132
HR2As				38.5	22.3	68.9	23.8	85.5
HR2Bd	39.7	21.4	76.0	47.6	83.9	85.5	49.7	108.4
HR2Bs				11.1	5.24	65.1	13.4	33.7
HR2Cd	53.9		62.5	47.6	73.4	88.0	43.2	
HR2Cs			31.2	9.8	0	65.1	23.8	
HR2F	91.3	113.6	60.6	64.4	112.7		64.0	106.2
HR3Ad	86.2	80.5	94.2	62.0	80.0	66.9	54.9	107.1
HR3As				3.24	44.6	68.9	45.8	
HR3Bd	41.0	57.4	75.2	55.4	69.5	85.5	60.1	94.6
HR3Bs				4.54	21.0	71.5	45.8	76.6
HR3Cd	50.0		53.1	52.8	64.2	95.7	60.1	40.6
HR3Cs			39.3	0	2.62	68.9	27.7	2.7
HR3F	70.7	69.0	61.9	63.3	108.8		69.2	107.1
HR4Ad	69.4	48.8	101.2	65.9	65.5	66.4	53.6	120.9
HR4As				58.1	0	53.6	47.3	71.1
HR4Bd	52.6	155.3	74.2	68.5	64.2	76.6	54.9	96.0
HR4Bs				37.2	0	21.5	29.0	31.0
HR4Cd	24.2		63.0	59.4	2.9	47.2	9.3	73.8
R4Cs			46.6	7.15	62.9	71.5	43.2	33.7
HR4F	81.0	69.0	74.7	68.5	97.0		66.6	112.6

Chloride (cont.)

Field no.	2/9/94	3/15/94	4/21/94	6/15/94	9/7/94	1/15/95
STE	83.0	69.7	51.6	62.4	115	171
R1	67.6	49.2	43.9			155
R2	73.2	67.0	56.3			145
R3	74.6	67.0	58.3		99.1	157

HR1Ad	63.4	60.1	47.0	3639	92	102
HR1As	41.1	23.7	24.4	28.4		27.9
HR1Bd	56.4	41.0	29.9	23.3	81	58.9
HR1Bs	11.7	8.8	8.7	24.0		13.1
HR1Cd	21.5	5.9	6.3	4.6	55	5
HR1Cs	10.3	5.9	3.0	11.4		231
HR1F	69	71.1	47.0	28.4	115	135.6
HR2Ad	70.4	56.0	48.5	35.2	172	131.6
HR2As	49.4	29.6	27.7	33.7		87.8
HR2Bd	64.8	49.2	43.9	36.9	215	102
HR2Bs	35.5	11.2	11.1	28.1		38.3
HR2Cd	31.3	21.4	12.2	33.5	61	25.2
HR2Cs	14.5	4.4	2.9	22.1		19.8
HR2F	58.5	72.4	51.6	40.3	115	146
HR3Ad	70.4	57.4	50.0	26.7	98	54.8
HR3As	38.3	29.9	19.9	42.8		37.3
HR3Bd	62.0	39.7	25.2	31.8	87	33.3
HR3Bs	46.6	15.6	13.8	28.1		23.9
HR3Cd	24.3	21.1	10.5	35.2	70	23.9
HR3Cs	11.7	5.9	3.2	23.4		13.1
HR3F	62.0	61.5	51.6	35.2	138	73.7
HR4Ad	67.6	54.7	36.1	43.7	66.8	15.8
HR4As	42.5	20.4	13.4	29.0		10.4
HR4Bd	42.5	43.8	14.3	26.7	49.7	14.2
HR4Bs	13.1	12.1	8.9	18.0		7.7
HR4Cd	31.3	25.1	26.2	23.3	35.4	14.4
HR4Cs	8.9	4.3	2.9	17.4		10.4
HR4F	49.4	65.6	53.2	38.6	78.2	31.9

9. Electrical conductivity (EC, uS/cm)

Field no.	2/19/92	3/17/92	4/27/92	6/23/92	7/30/92	9/2/92	12/3/92
STE	2253	2448		1947	1606	1935	
R1	2183	2142		1789	605	1853	2010
R2	2113	1907		1362	699	941	1928
R3	2078	1801		1493	959	1679	1881
HR1Ad	1693	1789		1501	1272	1638	1588
HR1Bd	1821	1448	1678	1057	937	1484	1261
HR1Cd							1286
HR1F	2184	1565	1965	915	1439	1515	1718
HR2Ad	1751	1671	1832	1057	1637	1494	1840
HR2Bd	1529	1389	1633	588	1562	1617	1140
HR2Cd							1607
HR2F	1892	1424	1700	926	1637	675	2070
HR3Ad	1599	1567	1722	708	1585	337	1580
HR3Bd	724	1000	1313	479	1137	1310	1438
HR3Cd							891
HR3F	1892	1389	1799	523	1661	1597	2000
HR4Ad	1775	1507	1799	828	1356	1689	1670
HR4Bd	1366	1507	1578	850	1377	778	1781
HR4Cd							1120
HR4F	2032	1624	1578	1144	1575	1689	2000

EC (cont.)

Field no.	1/13/93	2/10/93	3/10/93	6/29/93	7/27/93	8/25/93	9/13/93
STE	1540	1963	780	2278	2325	2193	
R1	1454	950		2180	2077	2003	
R2	1364	1055		2111	2292	2291	

R3	1339	1390		2160	2281	2325	
HR1Ad	1113	720	488	2180	1875	1673	2036
HR1As					725	614	1625
HR1Bd	878	929	340	1915	1675	1465	1837
HR1Bs					544	510	955
HR1Cd	338	607		1041	1148	668	1325
HR1Cs				580	523	353	867
HR1F	811	1332	915	2337	2150	1993	
HR2Ad	1227	1092	533	2003	2149	1995	2233
HR2As					1141	800	2063
HR2Bd	679	741	359	1974	1980	1842	2069
HR2Bs					623	651	1591
HR2Cd	602	1056		2867	1552	1259	1901
HR2Cs				969	632	607	1565
HR2F	872	1281	959	3525	2281	2025	
HR3Ad	875	1170	504	2887	2050	1918	2321
HR3As					724	1115	2144
HR3Bd	812	908	299	2318	2004	1565	2112
HR3Bs					710	777	1832
HR3Cd	546	788		1701	2074	1427	1973
HR3Cs				964	465	655	1836
HR3F	971	1145	906	2936	2459	2101	
HR4Ad	1093	870	485	2023	2066	1864	2060
HR4As					1245	608	1646
HR4Bd	963	739	320	1609	1950	1646	1994
HR4Bs					1177	492	1561
HR4Cd	721	548		2092	1781	1630	1874
HR4Cs					515	428	1359
HR4F	953	1000	974	1228	2215	2155	

EC (cont.)

Field no.	10/12/93	11/11/93	2/9/94	3/15/94	4/21/94	6/15/94	9/7/94	1/11/95
STE		2340	1454	1423	1384	2370	2600	2840
R1	1984	2310	1459	1421	1369			2570
R2	2010	2270	1475	1423	1360			2490
R3		1123	1456	1427	1353		2560	2560
HR1Ad	1871	1900	1445	1311	1395	1637	1663	1810
HR1As	869	1435	878	766	1161	1090		689
HR1Bd	1617	1498	1344	1125	1447	1517	1613	1289
HR1Bs	611	595	456	293	576	906		346
HR1Cd	721	647	529	313	427	638	830	216
HR1Cs	440	473	333	252	309	417		185
HR1F	1935	2040	1441	1432	1384	1776	1982	2500
HR2Ad	1986	2030	1453	1414	1392	1892	2150	2220
HR2As	868	1469	1307	1062	878	1603		1338
HR2Bd	1626	1686	1414	1331	1375	1757	1898	1641
HR2Bs	721	918	878	461	585	1135		559
HR2Cd	1279		892	763	857	1534	1191	500
HR2Cs	826	730	483	300	393	922		290
HR2F	2010	2040	1443	1423	1384	2070	1986	2520
HR3Ad	1902	1858	150	1409	1379	1833	2010	1052
HR3As	1420	1555	1129	1024	875	1355		710
HR3Bd	1692	1498	1318	1191	1302	1674	1397	676
HR3Bs	1283	1264	748	545	672	1138		447
HR3Cd	1479	1130	763	772	818	1496	1262	570
HR3Cs	920	794	408	267	352	883		381
HR3F	2020	2040	1400	1413	1379	1914	2020	1686
HR4Ad	1800	2020	1420	1414	1375	1746	1372	1351

HR4As	1248	1276	912	638	1048	1262		400
HR4Bd	1702	1650	1144	1298	1111	1622	1185	571
HR4Bs	899	798	449	466	562	798		288
HR4Cd	1332	1268	893	952	1105	1485	916	509
HR4Cs	569	763	412	259	314	760		283
HR4F	1980	2010	1440	1417	1387	1927	1713	1034

10. pH values

Field no.	2/19/92	3/17/92	4/27/92	6/23/92	7/30/92	9/2/92	12/3/92
STE	7.4	7.6		7.2	7.55	7.48	
R1	8.2	8.1		7.4	7.90	8.10	8.0
R2	8.3	8.1		7.1	7.45	8.15	8.10
R3	8.2	8.2		7.2	7.35	7.90	8.20
HR1Ad	7.8	7.9		8.1	8.20	7.95	8.30
HR1Bd	7.9	8.1	8.2	8.0	7.90	8.05	8.10
HR1Cd							8.0
HR1F	7.9	8.15	8.2	8.0	7.85	7.75	7.60
HR2Ad	7.9	8.1	8.3	8.1	8.10	7.65	8.30
HR2Bd	7.9	8.1	8.3	7.7	7.90	7.75	7.90
HR2Cd							8.20
HR2F	7.7	8.1	8.3	7.9	7.85	8.00	7.50
HR3Ad	7.7	8.1	8.3	8.1	8.10	8.00	8.30
HR3Bd	7.8	8.1	7.9	8.2	7.80	7.60	8.10
HR3Cd							7.80
HR3F	7.9	8.0	8.2	7.8	7.90	7.65	7.60
HR4Ad	7.8	8.0	8.3	8.3	7.85	8.00	8.20
HR4Bd	7.9	8.1	8.2	8.0	7.75	7.75	8.20
HR4Cd							7.70
HR4F	7.9	8.2	8.2	7.9	8.00	7.45	7.50

pH (cont.)

Field no.	1/13/93	2/10/93	3/10/93	6/29/93	7/27/93	8/25/93	9/13/93
STE	7.20	7.30	6.47	7.57	7.85	7.72	
R1	7.80	7.60			8.39	8.43	8.29
R2	7.70	7.40			8.21	8.53	8.13
R3	7.80	7.70			8.24	8.40	
HR1Ad	7.70	7.70	7.79	8.09	8.16	8.27	8.30
HR1As					7.46	7.90	8.13
HR1Bd	7.80	7.70	7.85	8.23	8.23	8.27	7.97
HR1Bs					7.47	7.84	7.84
HR1Cd	7.80	7.80		7.75	7.62	8.24	7.78
HR1Cs				7.55	7.96	7.86	7.40
HR1F	7.60	7.70	7.63	8.21	7.70	8.25	
HR2Ad	7.60	7.60	7.62	7.92	8.06	8.33	8.34
HR2As					7.92	7.69	8.40
HR2Bd	7.60	7.50	7.81	7.68	8.11	8.33	7.89
HR2Bs				8.13	7.53	7.78	8.35
HR2Cd	7.50	7.60		7.41	7.77	7.90	7.93
HR2Cs					7.38	7.80	7.96
HR2F	7.60	7.80	7.52	8.15	7.69	8.39	
HR3Ad	7.60	7.70	7.85	8.13	7.82	8.44	8.40
HR3As					7.37	8.12	8.33
HR3Bd	7.60	7.60	7.94	8.03	8.07	8.17	8.02
HR3Bs					7.63	7.96	8.06
HR3Cd	7.50	7.50		7.36	8.20	8.18	7.84
HR3Cs				7.35	8.87	8.07	7.88
HR3F	7.50	7.70	7.45	8.18	7.51	8.27	
HR4Ad	7.60	7.50	7.75	8.04	7.75	8.40	7.97

HR4As					8.02	7.91	7.88
HR4Bd	7.70	7.50	7.90	7.56	7.58	7.93	7.99
HR4Bs					8.02	7.30	7.70
HR4Cd	7.60	7.60		7.87	8.01	8.12	8.04
HR4Cs				7.64	7.60	8.07	7.81
HR4F	7.70	7.90	7.55	7.99	7.61	8.44	

pH (cont.)

Field no.	10/12/9	11/11/93	2/9/94	3/15/94	4/21/94	6/15/94	9/7/94	1/11/95
STE		7.84	7.03	7.52	7.71	7.22	7.65	7.52
R1	8.20	8.03	6.68	7.72	8.48			7.83
R2	8.16	6.03	7.60	8.40	8.43			8.09
R3		7.95	7.52	8.45	8.51		7.65	7.93
HR1Ad	7.74	7.94	7.76	8.53	8.60	8.10	7.46	8.26
HR1As	7.61	7.71	7.66	8.23	8.50	7.64		8.10
HR1Bd	7.79	7.86	7.93	8.42	8.63	7.80	7.43	8.23
HR1Bs	7.37	7.64	7.90	8.16	8.26	7.51		7.91
HR1Cd	7.34	7.63	7.84	7.98	7.78	7.36	7.30	7.96
HR1Cs	7.28	7.62	7.88	8.04	7.33	7.54		7.99
HR1F	7.48	7.86	7.59	8.23	9.68	7.61	7.15	7.78
HR2Ad	7.70	7.99	7.79	8.45	8.63	7.63	7.37	8.11
HR2As	7.40	7.81	7.79	8.34	8.68	7.70		8.16
HR2Bd	7.64	7.85	7.82	8.48	8.62	7.49	7.22	8.13
HR2Bs	7.09	7.59	7.79	8.02	8.52	7.30		7.93
HR2Cd	7.31	7.65	7.88	8.07	8.38	7.30	7.09	7.99
HR2Cs	7.10	7.66	7.22	8.23	8.27	7.10		7.87
HR2F	7.56	7.90	7.65	8.09	8.64	7.65	7.30	7.72
HR3Ad	7.74	8.05	8.02	8.59	8.46	7.61	7.56	8.23
HR3As	7.75	7.96	7.83	8.41	8.32	7.99		7.92

HR3Bd	7.65	7.76	7.83	8.54	8.60	7.36	7.36	7.82
HR3Bs	7.63	7.83	7.82	8.32	8.25	7.31		7.79
HR3Cd	7.38	7.59	7.70	8.01	8.15	7.11	7.34	7.63
HR3Cs	7.13	7.55	7.69	8.03	8.27	6.99		7.70
HR3F	7.45	7.83	8.03	8.52	8.66	7.19	7.32	7.87
HR4Ad	7.60	8.06	8.14	8.49	8.71	7.83	7.24	7.59
HR4As	7.37	7.63	7.89	8.18	8.48	7.38		7.64
HR4Bd	7.54	7.88	7.93	8.51	8.57	7.42	7.29	7.73
HR4Bs	7.16	7.73	7.80	8.29	8.40	7.12		8.04
HR4Cd	7.53	7.77	7.77	8.42	8.41	7.23	7.10	7.68
HR4Cs	7.17	7.66	7.86	8.29	8.30	7.25		7.67
HR4F	7.55	7.71	7.89	8.55	8.39	7.44	7.10	8.00

11. Total dissolved solids (TDS, mg/L)

Field no.	6/29/93	9/13/93	10/12/93	11/11/93	2/9/94	3/15/94	4/21/94	6/15/94
STE	1563			1182	1454	1260	1093	2370
R1	1495	1198	936	1146	1042	882	1164	
R2	1444		994		1018	1034	1164	
R3	1479				1079	1031	1152	
HR1Ad	1492	1004	925	939	855	666	981	815
HR1As		803	434	708	434	379	572	546
HR1Bd	1308	909	800	739	677	552	788	750
HR1Bs		472	303	294	225	145	283	451
HR1Cd	713	681	354	320	261	155	212	316
HR1Cs	397	422	217	234	164	124	152	208
HR1F	1601		958	1013	840	837	1051	884
HR2Ad	1976	1696	982	1007	916	828	1100	944
HR2As		1012	430	726	653	523	464	794
HR2Bd	1590	1023	808	834	758	698	871	874

HR2Bs		785	357	454	432	228	287	563
HR2Cd	1164	937	364		441	378	425	765
HR2Cs	591	773	408	359	240	152	193	458
HR2F	1950		1002	1010	838	830	1078	1024
HR3Ad	1387	1148	935	918	890	820	1021	915
HR3As		1062	696	770	560	508	436	674
HR3Bd	1100	1045	835	742	662	590	702	832
HR3Bs	1445	905	634	624	369	270	335	566
HR3Cd	841	976	735	559	377	382	404	743
HR3Cs		877	454	394	202	133	173	439
HR3F	1933		995	1012	739	816	1030	952
HR4Ad	1374	1020	890	1003	773	818	943	868
HR4As		809	617	634	450	316	519	627
HR4Bd	1351	1014	842	817	565	666	553	808
HR4Bs		774	444	396	223	230	280	397
HR4Cd	1965	927	280	628	439	471	547	738
HR4Cs		672	657	377	203	128	155	377
HR4F	2443		976	999	830	819	1089	954

TDS (cont.)

Field no.	9/7/94	1/11/95	6/9/95			
STE	1294	1412	1251			
R1		1280				
R2		1240				
R3	1276	1278				
HR1Ad	827	904	1048			
HR1As		369	894			
HR1Bd	802	642	721			
HR1Bs		172	448			

HR1Cd	412	107	586			
HR1Cs		91	373			
HR1F	986	1243	1015			
HR2Ad	1074	1104	1064			
HR2As		668	1016			
HR2Bd	944	815	970			
HR2Bs		278	821			
HR2Cd	595	248	855			
HR2Cs		144	675			
HR2F	988	1252	1038			
HR3Ad	999	524	1115			
HR3As		352	1019			
HR3Bd	695	336	962			
HR3Bs		222	794			
HR3Cd	628	284	778			
HR3Cs		189	660			
HR3F	1005	838	1062			
HR4Ad	682	706	899			
HR4As		199	825			
HR4Bd	582	283	992			
HR4Bs		143	820			
HR4Cd	455	252	844			
HR4Cs		141	649			
HR4F	853	514	999			

12. Dissolved oxygen in SVBs (DO, mg/L)

Field no.	6/23/92	7/29/92	9/2/92	9/23/92	6/29/93	7/27/93	9/14/93
Temperature	18.0°C	21.0 °C	21.0 °C	21.0 °C	23.0 °C	24.0 °C	21.0 °C
HR1Ad	0.80	0.3	0.5	0.75	1.7	2.7	0.9

HR1Bd	0.35	0.3	0.4	0.60	1.9	1.8	0.8
HR1Cd	0.40	0.5	0.5	0.55	1.2	1.2	0.7
HR2Ad	0.20	0.25	0.4		1.4	1.9	0.4
HR2Bd	0.35	0.30	0.5		0.9	1.1	0.4
HR2Cd	0.40	0.75	0.5		1.5	1.1	0.8
HR3Ad	0.25	0.5	0.25	0.55	1.1	0.9	0.4
HR3Bd	0.30	0.3	0.25	0.55	1.0	1.1	0.5
HR3Cd	0.40	0.4	0.30	0.60	1.1	0.8	0.4
HR4Ad	0.20	0.25	0.25		1.6	0.8	0.4
HR4Bd	0.10	0.20	0.30		0.8	0.9	0.3
HR4Cd	0.20	0.25	0.30		1.5	1.1	0.5

DO (cont.)

Field no.	10/12/94	11/11/93	2/7/94	3/8/94	3/15/94	4/19/94	5/24/94
Temperature	16.0 °C	7.5 °C	3.0 °C	8.0 °C	6.0 °C		17.5 °C
HR1Ad	0.8	3.7	1.48				1.2
HR1As				4.4	2.6	2.5	
HR1Bd	1.4	2.1	1.55				1.3
HR1Bs				4.2	2.8	2.7	
HR1Cd	0.8	1.6	1.60				1.6
HR1Cs				3.5	3.6	3.3	
HR2Ad	0.8	1.0	1.25				1.2
HR2As				4.4	4.2	2.8	
HR2Bd	0.7	1.4	1.35				0.8
HR2Bs				5.5	4.4	3.8	
HR2Cd	0.9	1.0	1.40				1.2
HR2Cs				4.2	3.0	3.3	
HR3Ad	1.5	0.6	1.40				0.5
HR3As				2.8	2.5	1.9	

HR3Bd	1.0	0.4	2.2				1.3
HR3Bs				6.5	3.0	3.9	
HR3Cd	1.1	0.7	1.6				1.4
HR3Cs				4.5	3.1	3.5	
HR4Ad	1.2	1.1	1.50				0.8
HR4As				4.0	2.5	1.9	
HR4Bd	1.1	1.4	1.50				0.9
HR4Bs				3.7	2.9	2.2	
HR4Cd	0.7	0.8	1.60				1.4
HR4Cs				4.3	4.8	3.9	

DO (cont.)

Field no.	6/13/94	9/7/94	1/10/95	9/6/95		
HR1Ad	0.7	0.3	1.5	0.5		
HR1As		0.75	2.2			
HR1Bd	0.6	0.3	1.5	0.4		
HR1Bs		0.8	2.3			
HR1Cd	1.1	0.25	1.9	0.35		
HR1Cs		0.3	2.4			
HR2Ad	0.8	0.2	1.4	0.4		
HR2As		0.3	2.0			
HR2Bd	0.8	0.2	1.4	0.4		
HR2Bs		0.2	2.0			
HR2Cd	1.0	0.2	1.4	0.4		
HR2Cs		0.2	1.8			
HR3Ad	0.6	0.15	1.4	0.3		
HR3As		0.25	1.6			
HR3Bd	1.4	0.1	1.5	0.35		
HR3Bs		0.3	1.7			

HR3Cd	1.2	0.15	1.6	0.45		
HR3Cs		0.3	1.7			
HR4Ad	0.5	0.15	1.2	0.3		
HR4As		0.25	1.4			
HR4Bd	0.9	0.2	1.1	0.3		
HR4Bs		0.75	1.5			
HR4Cd	0.8	0.15	1.2	0.5		
HR4Cs		0.3	1.5			

13. Metals in the SVBE (mg/L, 9/7/92)

Field no.	Lab no.	K	Ca	Mg	Mn	Zn
STE	13	20	171	76.8	1.96	0.03
HR1Ad	1	18.0	132.7	59.0	0.46	0.02
HR1Bd	2	16.3	125.2	55.7	0.23	0.02
HR1F	3	15.7	129.6	59.2	0.13	0.02
HR2Ad	4	13.8	138.3	59.1	0.13	0.02
HR2Bd	5	15.7	141.5	66.0	0.09	0.03
HR2F	6	9.37	71.5	34.5	0.21	0.02
HR3Ad	7				0.16	0.02
HR3Bd	8	10.6	139.4	51.0	0.10	0.02
HR3F	9	14.0	143.2	36.9	0.09	0.03
HR4Ad	10	19.0	150.0	64.0	0.56	0.02
HR4Bd	11	4.92	71.9	30.1	0.11	0.03
HR4F	12	14.3	153.2	64.6	0.17	0.03

14. Redox potential (Eh=Ehs, Ehm, or Ehd+243, mvolts)

Field no.	Lab no.	7/29/92			9/2/92		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs

HR1A	1	-510	-510	-450	-530	-520	-480
HR1B	2	-600	-480	-390	-630	-470	-410
HR1C	3	-470	-480	-110	-470	-360	-250
HR2A	4	-600	-510	-470	-500	-450	-410
HR2B	5	-480	-540	-390	-470	-580	-400
HR2C	6	-500	-350	-340	-500	-390	-380
HR3A	7	-610	-480	-340	-610	-410	-380
HR3B	8	-560	-510	-420	-540	-390	-430
HR3C	9	-640	-410	-430	-660	-440	-440
HR4A	10	-580	-570	-490	-470	-630	-450
HR4B	11	-530	-470	-460	-530	-470	-400
HR4C	12	-490	-490	-440	-440	-430	-330

Eh (cont.)

Field no.	Lab no.	9/22/92			11/3/92		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-570	-500	-425	-476	-461	-530
HR1B	2	-620	-430	-470	-456	-455	-399
HR1C	3	-480	-490	-460	-435	-464	-99
HR2A	4	-590	-480	-430	-628	-471	-453
HR2B	5	-550	-450	-410	-476	-480	-441
HR2C	6	-490	-460	-360	-468	-468	+254
HR3A	7	-590	-425	-390	-642	-426	-288
HR3B	8	-500	-410	-390	-535	+14	+294
HR3C	9	-670	-460	-420	-658	-429	+301
HR4A	10	-590	-615	-460	-480	-626	-499
HR4B	11	-440	-460	-450	-493	-556	-443
HR4C	12	-440	-470	-420			

Eh (cont.)

Field no.	Lab no.	12/1/92			1/13/93		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-615	-479	-534	-611	-437	-582
HR1B	2	-496	-442	-436	-499	-510	-406
HR1C	3	-482	-429	-17	-419	-238	-158
HR2A	4	-644	-517	-458	-617	-494	-410
HR2B	5	-498	-438	-429	-473	-422	-430
HR2C	6	-479	-451	+324	-438	-408	+294
HR3A	7	-629	-448	-353	-581	-427	-327
HR3B	8	-523	-20	+310	-480	+16	+236
HR3C	9	-681	-502	+312	-426	-341	+314
HR4A	10	-492	-623	-487	-561	-438	-496
HR4B	11	-461	-567	-426	-419	-425	-411
HR4C	12	-479	-462	-379	-424	-416	-415

Eh (cont.)

Field no.	Lab no.	2/9/93			3/9/93		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-529.5	-475.6	-596.7	-563	-491	-542
HR1B	2	-598.9	-543.7	-452.4	-566	-536	-381
HR1C	3	-440.0	-449.5	-176.4	-391	-142	+282
HR2A	4	-633.2	-499.8	-506.6	-569	-514	-494
HR2B	5	-569.7	-549.9	-446.2	-563	-550	-409
HR2C	6	-505.1	-423.0	+330.3	-471	-65	+305
HR3A	7	-601.6	-462.9	-264.5	-520	-405	+56
HR3B	8	-444.4	-84.7	+310.5	-447	+31	+292
HR3C	9	-644.1	-413.1	+306.0	-393	+241	+283
HR4A	10	-577.6	-582.2	-522.5	-587	-504	-510

HR4B	11	-539.3	-436.4	-499.0	-537	-408	-476
HR4C	12	-452.1	-425.3	+272.1	-438	-394	+285

Eh (cont.)

Field no.	Lab no.	6/29/93			7/27/93		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-245	-472	-513	-465	-476	-605
HR1B	2	-511	-478	-476	-463	-453	-410
HR1C	3	-483	-491	-497	-505	-433	-457
HR2A	4	-259	-486	-480	-494	-493	-462
HR2B	5	-230	-528	-591	-461	-505	-494
HR2C	6	-392	-477	-478	-457	-492	-497
HR3A	7	-619	-310	-481	-550	-484	-440
HR3B	8	-192	-514	-478	-480	-534	-510
HR3C	9	-192	-473	-465	-594	-498	-498
HR4A	10	-491	-463	-484	-562	-481	-475
HR4B	11	-485	-499	-400	-542	-466	-422
HR4C	12	-486	-476	-485	-468	-230	-407

Eh (cont.)

Field no.	Lab no.	9/14/93			2/7/94		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-459	-484	-570	-551	-539	-520
HR1B	2	-453	-479	-434	-539	-509	-501
HR1C	3	-458	-419	-419	-498	-439	-44
HR2A	4	-623	-468	-479	-661	-452	-435
HR2B	5	-453	-539	-453	-488	-472	-441
HR2C	6	-451	-441	-484	-497	-206	+300
HR3A	7	-500	-537	-434	-579	-498	-440

HR3B	8	-509	-462	-456	-766	-256	-660
HR3C	9	-488	-447	-454	-495	-35	-303
HR4A	10	-565	-456	-447	-496	-556	-500
HR4B	11	-524	+31	-453	-500	-559	-439
HR4C	12	-522	-453	-502	-506	-379	-260

Eh (cont.)

Field no.	Lab no.	3/8/94			3/15/94		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-559	-473	-509	-573	-532	-556
HR1B	2	-587	-440	-25	-595	-515	-60
HR1C	3	-274	+199	+269	-405	-1	+269
HR2A	4	-642	-425	-328	-667	-497	-450
HR2B	5	-432	-440	+230	-496	-489	+243
HR2C	6	-441	-89	+280	-496	-15	+294
HR3A	7	-356	-419	-295	-538	-491	-437
HR3B	8	-457	-2	+271	-510	-27	-32
HR3C	9	-274	+263	+171	-473	-439	+285
HR4A	10	-498	-425	-486	-492	-497	-485
HR4B	11	-497	-569	-242	-510	-476	-459
HR4C	12	-446	+230	-34	-503	-567	-145

Eh (cont.)

Field no.	Lab no.	4/19/94			5/24/94		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-538	-509	-589	-605	-566	-600
HR1B	2	-577	-502	-409	-636	-472	-475
HR1C	3	-488	-15	+253	-507	-398	+277
HR2A	4	-681	-457	-464	-685	-475	-475

HR2B	5	-510	-458	+265	-528	-504	-485
HR2C	6	-512	-314	+22	-514	-493	-436
HR3A	7	-651	-495	-468	-669	-493	-455
HR3B	8	-461	-449	-473	-490	-454	-470
HR3C	9	-464	-351	+277	-594	-502	+177
HR4A	10	-501	-517	-484	-544	-546	-513
HR4B	11	-495	-513	-520	-583	-517	-501
HR4C	12	-512	-440	-463	-575	-504	-490

Eh (cont.)

Field no.	Lab no.	6/13/94			9/7/94		
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-593	-516	-573	-421	-379	-689
HR1B	2	-588	-441	-471	-416	-368	-382
HR1C	3	-508	-515	-184	-366	-337	+30
HR2A	4	-660	-479	-447	-426	-411	-364
HR2B	5	-477	-505	-499	-385	-392	-339
HR2C	6	-499	-495	-430	-255	-399	-358
HR3A	7	-642	-484	-450	-427	-380	-378
HR3B	8	-477	-492	-493	-360	-438	-312
HR3C	9	-672	-491	-478	-581	-335	-157
HR4A	10	-499	-553	-449	-397	-441	-389
HR4B	11	-491	-474	-490	-394	-448	-371
HR4C	12	-568	-428	-496	-410	-367	-410

Eh (cont.)

Field no.	Lab no.	1/10/95					
		Ehd	Ehm	Ehs	Ehd	Ehm	Ehs
HR1A	1	-520	-440	-441			

HR1B	2	-509	-491	-461			
HR1C	3	-425	-429	-202			
HR2A	4	-621	-422	-337			
HR2B	5	-392	-402	-383			
HR2C	6	-381	-326	-262			
HR3A	7	-451	-305	-244			
HR3B	8	-420	-393	-371			
HR3C	9	-409	-417	-377			
HR4A	10	-482	-434	-427			
HR4B	11	-492	-476	-432			
HR4C	12	-465	-425	-318			

*HR1A and HR4A-Subsurface vegetated bed has 4 days detention time with cattail;
HR2A and HR3A-Subsurface vegetated bed has 4 days detention time with woolgrass;
HR1B and HR4B-Subsurface vegetated bed has 8 days detention time with cattails;
HR2B and HR4B-Subsurface vegetated bed has 8 days detention time with woolgrass;
HR1C and HR4C-Subsurface vegetated bed has 12 days detention time with cattails;
HR2C and HR3C-Subsurface vegetated bed has 12 days detention time with woolgrass;
d-deep samples, collected from 10 cm from the bottom of the SVBs;
s-shallow samples, collected from 10 cm below the water surface;
Ehs, Ehm, and Ehd-Eh values measured at 25, 15, and 3 cm from the bottom of the SVBs;

VITA

Jie Huang was born in Zixi, Zhejiang on June 19, 1958. She was raised in the countryside of southeastern China. Since she grew up during "the cultural revolution" periods, she changed schools several time before graduating from Longshen High School in 1975 (She attended four elementary schools, two middle schools and one high school within 10 years). She taught Math and Chemistry as a substitute teacher in a middle school for a year, then she was sent to a government-owned farm to learn how to culture crops (cotton and rice). After the end of "cultural revolution", she was admitted to the Zhejiang Agricultural University in 1978, and earned her B. S. in Soil and Agrochemistry in 1982. After working for one year worked as a research specialist in the Department of Agriculture of Zhaoxin, Ms. Huang enrolled in Graduate School of the Zhejinag Agricultural University and got M.S. degree in Plant Nutrition in 1986. After graduation, she taught "Introduction of Biochemistry", "Agrochemistry" and "Analytical chemistry" at the undergraduate level in the Zhejiang TV University for four years. She also directed laboratories in "Inorganic Chemistry", "General Chemistry", "Analytical Chemistry", and "Basic Computer Language". Ms. Huang came to the United Sates in 1991 to study for her Ph.D. degree. She enrolled in graduate school at Virginia Tech in August 1991. Since January 1992, Ms. Huang has been working as a research assistant in the Environmental Quality Lab under Dr. R. B. Reneau's guidance.

Jie Huang