

**AN ASSESSMENT OF CONSTRUCTED WETLANDS
FOR THE TREATMENT OF GREENHOUSE WASTEWATERS**

by

Ward A. Prystay

B.Sc., The University of British Columbia, 1989

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Bio-Resource Engineering Program

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

December 1997

© Ward A. Prystay, 1997

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of CHEMICAL & BIO-RESOURCE ENGINEERING

The University of British Columbia
Vancouver, Canada

Date January 21, 1998

ABSTRACT

The greenhouse vegetable industry in British Columbia is an expanding agricultural sector producing peppers, English cucumbers, tomatoes, and butter lettuce. Current production methods generate up to 4.5 litres of high nutrient runoff per square metre production area per day. The disposal of this wastewater untreated poses a significant environmental concern due to the potential for the high concentrations of nitrate and phosphate to induce eutrophication and alter the structure and dynamics of aquatic ecosystems.

Technical problems surrounding the sterilization and recycling of greenhouse overdrain has lead the greenhouse industry to investigate the use of constructed wetlands as a wastewater treatment option. In the spring of 1995 a pilot scale research project was initiated to assess the use of constructed wetlands for treatment of this low organic carbon, high nutrient wastewater. Five wetland designs, based on conventional surface flow (SF) and subsurface flow (SSF) design approaches, were assessed. These designs were: 15 cm water depth planted SF wetlands; 30 cm water depth planted SF wetlands; 30 cm water depth unplanted SF wetlands; 60 cm depth gravel bed planted SSF wetlands; and, 60 cm depth gravel bed unplanted SSF wetlands. Samples were collected every second week between April and December 1996 from three sites within each wetland and analyzed for: ammonia, nitrate, total Kjeldahl nitrogen, total phosphorus, ortho-phosphate, total solids, total organic carbon and biochemical oxygen demand.

Results of this study indicate that none of the individual designs assessed is capable of providing the highest treatment effect for all parameters concerned; however, the surface flow design emerged as the most appropriate design for the remediation of greenhouse wastewaters. No treatment effect was observed for either total Kjeldahl nitrogen or total solids in any of the designs assessed. The highest mean reductions of phosphorus was 65 % observed in one of the two unplanted SF wetlands. Peak nitrate reductions of 54% were observed in the 15 cm deep SF wetlands and ammonia removal of 74% were achieved in the unplanted SF wetlands. An increase in biochemical oxygen demand and total organic carbon was seen in all wetland designs. Based on available literature and the results of this research project, a multi-stage design, consisting of an unplanted pre-treatment basin followed by a 25 to 35 cm deep surface flow marsh with open water components, is recommended.

TABLE OF CONTENTS

ABSTRACT.....	ii
TABLE OF CONTENTS	iii
LIST OF FIGURES	vi
ACKNOWLEDGEMENTS	vii
1.0 INTRODUCTION.....	1
2.0 OBJECTIVES	4
3.0 LITERATURE REVIEW.....	5
3.1 WETLAND DESIGN AND TREATMENT PERFORMANCE	5
3.1.1 SURFACE FLOW WETLANDS.....	6
3.1.2 SUBSURFACE FLOW WETLANDS	10
3.1.3 VERTICAL FLOW WETLANDS.....	15
3.2 NUTRIENT REMOVAL PROCESSES.....	16
3.2.1 ORGANIC CARBON REDUCTION PROCESSES.....	17
3.2.2 NITROGEN REMOVAL MECHANISMS	19
3.2.3 PHOSPHORUS REMOVAL MECHANISMS	25
4.0 MATERIALS AND METHODS	30
4.1 MONITORING PROGRAM	34
4.2 STATISTICAL ANALYSES	38

5.0 RESULTS AND DISCUSSION	38
5.1 PHOSPHORUS	40
5.2 NITRATE	48
5.3 AMMONIA	53
5.5 COST ANALYSIS	56
6.0 CONCLUSIONS	57
7.0 BIBLIOGRAPHY	61
APPENDIX 1. RAW DATA	65
APPENDIX 2. CHARTS AND GRAPHS	76
APPENDIX 3. STATISTICAL ANALYSES	92

LIST OF TABLES

TABLE 1. MICROBIALY MEDIATED ORGANIC CARBON OXIDATION AND REDUCTION.....	18
TABLE 2. CALCIUM PHOSPHATES	26
TABLE 3. ANALYTICAL METHODS	36
TABLE 4. WATER QUALITY LABORATORY ANALYSES	37
TABLE 5. TOTAL PHOSPHORUS RESULTS (MG/L)	41
TABLE 6. ORTHO-PHOSPHORUS RESULTS (MG/L)	41
TABLE 7. NITRATE RESULTS (MG/L).....	50
TABLE 8. AMMONIA REMOVAL (MG/L)	54
TABLE 9. WETLAND CONSTRUCTION COSTS.....	57

LIST OF FIGURES

FIGURE 1. TYPICAL SF WETLAND DESIGN	7
FIGURE 2. TYPICAL SSF WETLAND DESIGN	12
FIGURE 3. TYPICAL VF WETLAND DESIGN.....	16
FIGURE 4. LOCATION MAP	33
FIGURE 5. PLAN VIEW OF TYPICAL WETLAND WITH SAMPLING SITE LOCATIONS.....	35
FIGURE 6. CHANGE IN O-PO ₄ CONCENTRATIONS IN CELLS 5 & 6 OVER TIME	43
FIGURE 7. WETLAND CELLS #5 & #6. CHANGES IN PH OVER TIME.....	44
FIGURE 8. TOTAL PHOSPHORUS AND ORTHO-PHOSPHATE VS. PH	45
FIGURE 9 RELATIONSHIP BETWEEN BOD ₅ AND TOC... ..	45
FIGURE 10. CHANGE IN TOTAL ORGANIC CARBON THROUGH EACH WETLAND DESIGN.....	51
FIGURE 11. CHANGE IN AMMONIUM AND PH OVER TIME.....	55

ACKNOWLEDGEMENTS

Support and funding of this research project was generously provided by ECL Envirowest Consultants Limited, Houweling Nurseries Ltd., the Science Council of British Columbia (Technology BC program), the BC Ministry of Agriculture, Fisheries and Food (Partners in Action program), Environment Canada (Green Plan) and the BC Vegetable Greenhouse Research Council. The time and effort of a number of very generous individuals was pivotal in putting this research project together. In particular I would like to thank: Ian Whyte and Mark Adams (ECL Envirowest Consultants Limited), Casey Houweling (Houweling Nurseries Ltd.), Bev Locken (BC Ministry of Environment, Lands and Parks), Jim Portree (BC Ministry of Agriculture, Fisheries and Foods) and Victor Lo (Bio-Resource Engineering Program, UBC). Laboratory and field work would not have been successful without the help and friendship of Chang-Six Ra and the "tolerance" of Neil Jackson and Jurgen Pelke. To Alison Ivan, I would like to say a very special "thank-you" for your unlimited support and patience over these past three years.

1.0 INTRODUCTION

The greenhouse vegetable industry in the Lower Mainland of British Columbia is a rapidly expanding agricultural sector generating more than fifty-five million Canadian dollars in annual revenues. Red, green and yellow peppers, English cucumbers, tomatoes, and butter lettuce are grown in an inert rockwool or yellow cedar medium with all nutrients provided via drip feed directly to the root zone. To ensure maximum nutrient and water uptake and to prevent salt accumulation in the root-zone, the plants are over watered by 25 to 45% generating up to 4.5 litres of high nutrient runoff per square metre production area per day at peak water use (BCMAFF 1993, Hardgrave and Hufton 1995). Most greenhouse operators are reluctant to recycle this effluent due to the potential of reduced crop production and disease and currently discharge the overdrain untreated to the environment. The term overdrain is industry nomenclature for the feed solution which is not consumed by plant uptake or evaporation and runs off from the production area. For the purposes of this document, the terms overdrain, effluent and wastewater all refer to this un-utilized high nutrient concentration solution and are used interchangeably.

Discharge of this untreated effluent to the environment may potentially result in degradation of ground- and surface water quality and fish and wildlife habitat. As a result, the regulatory agencies in British Columbia have been directing the greenhouse industry to control the quality of their wastewater discharge utilizing two pieces of legislation including the Federal *Fisheries Act* and the Code of Agricultural Practice for Waste Management under the Provincial *Waste Management Act*. Under section 36(3) of the *Fisheries Act*, it is an offence to deposit any deleterious substance into water frequented by fish, including water that may eventually enter water frequented by fish. Part 5, Section 11 and Section 13 of the Provincial Code of Agricultural Practice for Waste Management states that agricultural waste must not be directly or indirectly discharged into a watercourse or groundwater.

Greenhouse effluents are unique with respect to other well characterized and studied wastewaters due to their high nutrient and low organic carbon concentrations. Due to the high nutrient content, greenhouse effluent is considered as an agricultural waste and therefore cannot be discharged directly to the environment. Of particular environmental concern are the high nitrate and phosphate concentrations present in greenhouse overdrain and the potential for these nutrients to induce eutrophication of the receiving waters and alter the structure and dynamics of aquatic ecosystems. Algae blooms are one of the most common biological phenomena associated with eutrofication and can result in reduction of the dissolved oxygen (DO) in the water column and development of anaerobic sediments due to decay of the algal biomass. Reduction of the DO levels in receiving waters in the Greater Vancouver region is a concern as salmonids, most commonly coho salmon, rainbow trout and coastal cutthroat trout, often utilize agricultural ditches and/or the downstream creeks and rivers as year-round or over-wintering habitat (Ian Whyte, ECL Envirowest Consultants Limited, pers. comm.).

Research over the past 16 years has demonstrated constructed wetlands to be effective tools for nutrient management and suggests that they may be more cost-effective than other treatment alternatives (Haberl and Perfler 1990, Johnston 1991, Rogers *et al.* 1991, Reed and Brown 1992, 1995). The beneficial aspects of using wetlands for wastewater treatment include relatively low construction costs, low maintenance requirements, tolerance to variable hydrological and contaminant loading rates and reliable wastewater treatment. Further, periods of high wetland productivity roughly parallel the greenhouse vegetable production season with the winter dormancy period for wetlands coinciding with winter shut-down and periods of low wastewater production.

The alternative to treating the wastewater is to recycle it. By recirculating the effluent, the greenhouse operators would optimize fertilizer utilization and reduce the volume of water required for the operation

of the facility. The potential of spreading diseases by recycling the wastewater dictates sterilization of the overdrain water prior to reuse. Three methods are available for sterilization: ultraviolet radiation (UV), ozone (O_3) and heat. UV sterilization works by damaging the DNA and RNA of the bacteria, fungi and viruses within the wastewater. As the ultraviolet radiation must penetrate the prospective disease vector to be effective, the water must be relatively free of suspended solids. In contrast, ozone sterilization is a chemical process. Ozone is generated by applying a high voltage across a stream of air or pure oxygen producing 0.5 to 3 percent ozone in the air stream or 1 to 6 percent ozone in the pure oxygen stream. The ozone is then bubbled through the wastewater where it reacts with water molecules forming HO and HO_2 free radicals. The free radicals in turn react with the cellular membrane or cell wall of the vectors inducing lysis. Due to the nature of UV and ozone sterilization, both processes are inhibited by the presence of suspended solids. Vectors are encapsulated by suspended particles would be protected from both processes (Metcalf and Eddy, Inc. 1991).

Heat sterilization, which acts by denaturing cellular proteins and genetic material, is not affected by the presence of suspended particles and therefore is the most effective sterilization approach. For complete viral and fungal destruction by heat sterilization, the wastewater must be heated to $95^{\circ}C$ for a minimum of 30 seconds. The energy for sterilization is typically generated by natural gas or by electricity with the heat being transferred to the wastewater by titanium diffusion plates. This process can be negatively affected by the presence of soluble organic compounds in the overdrain which can damage the diffusion plates. Soluble organic materials, such as tannins and lignins, are present in overdrain due to the utilization of yellowcedar as a planting medium (BCMAFF, 1994).

These technical problems surrounding the sterilization of greenhouse overdrain has lead the greenhouse industry to look at alternative treatment options. One option is the use of constructed wetlands. In the spring of 1995, a partnership of three groups in the Greater Vancouver area, namely the Department of

Chemical and Bio-Resource Engineering (Bio-Resource Engineering Program) at the University of British Columbia, ECL Envirowest Consultants Limited and Houweling Nurseries Limited, initiated a pilot scale research project to assess the potential use of constructed wetlands technology for the treatment of the low organic carbon, high nutrient wastewaters generated by the B.C. vegetable greenhouse industry. The duration of the research program was two years ending March 31, 1997.

2.0 OBJECTIVES

The primary objective of this research project was to assess the capability of constructed wetland technology to reduce and remove the excess nutrients present in the overdrain generated by vegetable production in greenhouses. The primary constituents of concern in the effluent are nitrogen and phosphorus with secondary concern for biochemical oxygen demand (BOD), total solids, and organic carbon. The water quality criteria utilized to assess the efficacy of the wetland treatment are the provincial and federal water quality guidelines published in *Canadian Water Quality Guidelines* (CCME 1995) and *Water Quality Criteria: Approved and Working Criteria for Water Quality* (MELP 1994).

A secondary objective of this project was to identify water quality objectives specific to wetland treatment of greenhouse overdrain. This required the characterization of greenhouse wastewater with respect to nitrate, ammonia, total Kjeldahl nitrogen, ortho-phosphate, total phosphorus, total solids, total organic carbon, BOD₅ and pH. The analysis of water samples from specific points within each wetland design, to assess treatment efficacy relative to wetland size. The final project objective was to determine the most efficient and cost effective design and, if possible, publish a document which will offer greenhouse operators a design approach for a treatment wetland which will allow their operations to meet MELP discharge guidelines.

3.0 LITERATURE REVIEW

3.1 WETLAND DESIGN AND TREATMENT PERFORMANCE

The use of wetlands for the treatment of polluted waters has been under investigation since the early 1950's with interest in this "low-tech" approach to water quality improvement dramatically increasing since 1980 (Kadlec and Knight 1996). During this period, three major design approaches (surface flow, subsurface flow and vertical flow) have evolved and been used to remediate municipal sewage, stormwater, landfill leachate, acid mine drainage, industrial wastewaters and agricultural runoff (Hammer 1989, Moshiri 1993). By constructing artificial wetlands it is possible to maximize the treatment processes of natural wetlands and protect the fish and wildlife habitat values of natural wetland systems. The primary advantage of using constructed, or treatment, wetlands is their potential to provide low cost, low maintenance water treatment with ancillary aesthetic and wildlife benefits.

The constructed wetland approach to water treatment takes advantage of intrinsic processes occurring within natural wetlands. Water borne pollutants entering the wetland system are eliminated through a combination of physical, chemical and biological processes which include settling, flocculation, precipitation, adsorption to soil and organic compounds, volatilization, assimilation into plant tissues, microbial decomposition and microbial transformations. With the exception of plant assimilation and the various adsorptive processes, the contaminant processing mechanisms in wetlands are very similar to the removal processes that occur in package treatment plants, lagoons and other conventional wastewater treatment facilities. As these processes are naturally occurring in the wetland environment, treatment objectives similar to those established for traditional biological wastewater treatment facilities can theoretically be met at a relatively low developmental and operational cost. Compared to

conventional wastewater treatment technologies, wetlands have lower construction costs, lower maintenance costs, require less operational attention and rarely require the addition of chemical reagents. The chief drawback to the use of wetlands is related to the natural treatment processes which are inherently slower; as the biological removal mechanisms are operating under non-ideal conditions, enzymatic activity of the wetland micro-organisms is lower than that found in the microflora of traditional/conventional systems. Hence, longer residence times are required to meet treatment objectives and therefore constructed wetland facilities have large land requirements.

3.1.1 SURFACE FLOW WETLANDS

Of the three wetland designs that have developed, the surface flow (SF) wetlands are the simplest design and the most common in North America. SF wetlands have a number of “aliases” including free-water surface (FWS), artificial marshes and biofiltration marshes. These systems mimic natural marshes in that the water primarily flows above-ground in a sheet-like manner through emergent wetland plants. A simple SF wetland consists of an excavated basin with a 20 to 30 centimetre (cm) layer of a planting media overlying the bottom of the basin, 10 to 50 cm of water flowing over the soil and emergent vegetation covering greater than 50 percent of the surface area. Wastewater is directed into the system across the inlet end of the basin and is intended to move in a sheet-flow manner through the marsh to the outlet structure(s). Typically, the bottom of the wetland is level and, where infiltration of ground water into the system or seepage of the wastewater from the treatment wetland into the groundwater is a concern, the wetland is lined with an impermeable synthetic material or clay layer (USEPA 1988). Length to width ratios have traditionally been 3:1 or greater to prevent the water from short-circuiting; however, recent publications have suggested that ratios of 1:1 may be

sufficient. The use of berms and regions of open water, greater than one metre in depth, have also been suggested as tools to reduce the possibility of short circuiting (Knight *et al.* 1994).

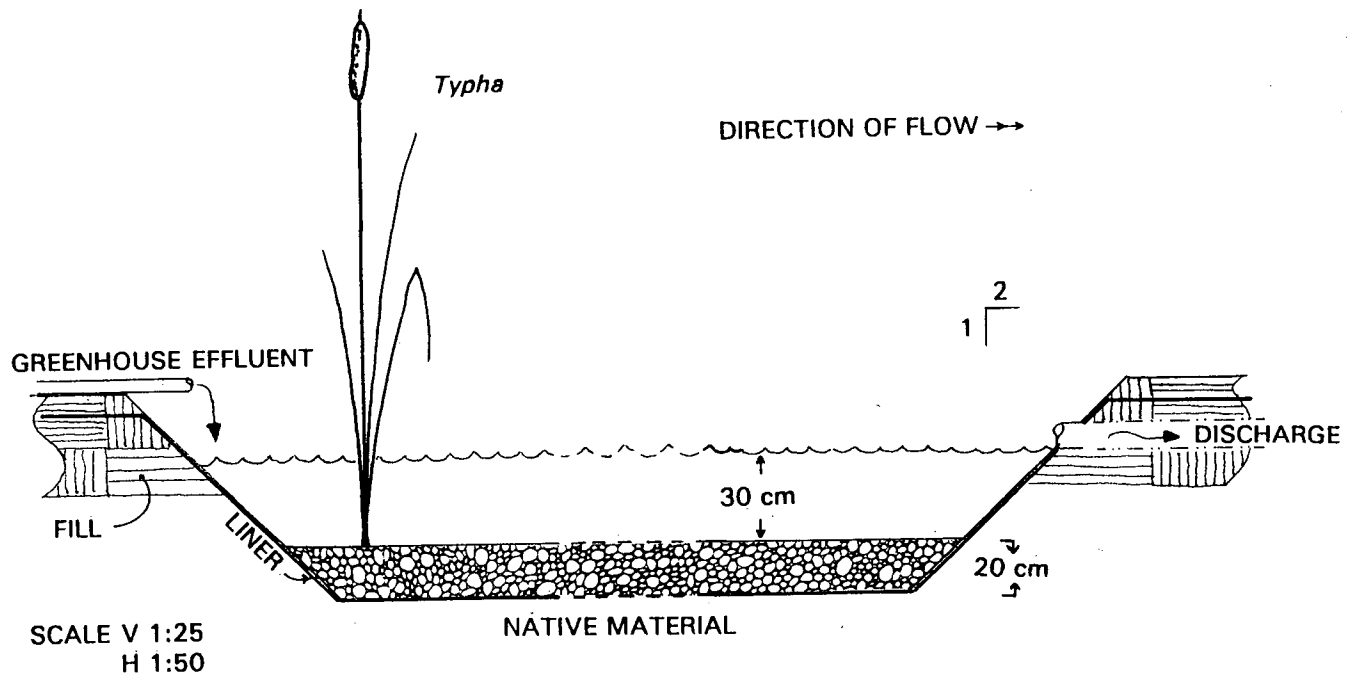


Figure 1. Typical SF Wetland Design

Wetland plants provide mineral cycling and the surface area required by the attached microbial populations which mediate the majority of the treatment processes. Choice of plant species is primarily limited by the hydroperiod and therefore by the design. As most SF wetland systems are flooded year-round, the plant choice is limited to emergent macrophytes. Wildlife habitat values and the option of planting more than one species are also features that should be considered. By planting more than one variety of wetland vegetation there is an increased habitat value and there is a reduced potential for a large scale die-off due to disease negatively impacting the system. Additionally, non-native species should be avoided as they have the potential invade surrounding wild wetlands and out-compete native species. Suitable species of wetland plants that are common in British Columbia include broadleaf cattail (*Typha latifolia*), rush (*Juncus* spp.), bulrush (*Scirpus* spp.), sedge (*Carex* spp.), mannagrass

(*Glyceria* spp.), bentgrass (*Agrostis* spp.), reedgrass (*Calamagrostis* spp.) and bluegrass (*Poa palustris* spp.).

A large body of literature on treatment wetlands exists addressing topics ranging from the role of the plants in constructed wetlands to design approaches to results of various research projects. Most of the design information is based on traditional wastewater treatment design approaches in combination with the results of academic and industry based wetland research. Research on SF treatment wetlands over the past two decades has primarily occurred in the United States (US). This is attributable, in large part, to the availability of larger parcels of land in the US, lower construction costs of SF designs with respect to SSF designs, and various federal and state environmental policies which promote the creation of wetland habitat. A database of North American constructed wetlands, released by the USEPA Risk Reduction Engineering Laboratory in 1994, compiled the data from 203 treatment wetland systems at 178 sites, five of which were in Canada. Of these treatment wetland systems, 151 were constructed (as opposed to natural wetlands) and 89 were SF. The majority all wetlands in the database were constructed for municipal wastewater treatment. Although there are a number of published papers on SF treatment wetlands, the majority of the readily available nutrient and organic carbon removal data for this design comes from the USEPA wetland database. The information in this database has been used extensively for the development of design criteria by Kadlec and Knight (1996).

Between August 1991 and July 1994, van Oostrom *et al.* (1994, 1995) assessed the potential of using SF wetlands planted with giant sweet grass (*Glyceria maxima*) for treating nitrified meat processing effluents in New Zealand. Bench-scale laboratory experiments conducted at 20 °C demonstrated a mean denitrification rate of 3.8 grams per square metre treatment area per day ($\text{g/m}^2/\text{d}$) under anoxic conditions. In these experiments 2.1 grams of plant biomass carbon was consumed per gram of

nitrate denitrified. In the two pilot-scale research projects, van Oostrom used 40 cm deep surface flow constructed wetland systems vegetated by a floating mat of giant sweet grass (*Glyceria maxima*). Mean nutrient characteristics of the wastewater being treated were reported as 197 mg/L total nitrogen (TN), 121 mg/L $\text{NO}_2 + \text{NO}_3$, 405 mg/L COD and 38 mg/L BOD_5 . The corresponding loading rates were 11.2 g/m²/d TN, 6.9 g/m²/d $\text{NO}_2 + \text{NO}_3$, 23.5 g/m²/d COD and 2.2 g/m²/d BOD_5 . Over the course of the first year (1992) the reported nitrogen removal rates varied between 0.5 g N/m²/d during the winter months to 3.0 g N/m²/d in the summer. Increased removal rates as high as 9.5 g N/m²/d during summer operation, with a year-round average of 5.3 g N/m²/d with an average nitrogen loading rate of 11.2 g N/m²/d, were reported (van Oostrom *et al.* 1995). Approximately 87 percent of the nitrogen removal realized was attributed to denitrification with 13 percent removal due to accumulation in the plant biomass and wetland sediments.

Martin and Johnson (1995) reported extremely high treatment efficiencies for a SF treatment wetland receiving landfill leachate in Escambia County, Florida. Leachate from a primary treatment pond was fed into a series of ten interconnected 11 m by 93 m wetlands comprising a system 1.1 hectares in area and close to one kilometre in length. Two hydraulic loading rates with resulting hydraulic retention times of 4.4 days and 7.2 days were assessed. Under both operating conditions, Martin and Johnson (1995) reported a 99% reduction in TN and the wetlands were able to attain 88% and 94% reductions in TP, during the 4.4 day HRT and 7.2 day HRT, respectively. Unlike van Oostrom (1994, 1995) who reported his data as loading rates, all data presented by Martin and Johnson (1995) was reported as influent and effluent concentrations in mg/L with ammonia the primary nitrogen component of the total nitrogen measurement. In the 4.4 day HRT assessment, the total phosphate concentrations in the lagoon effluent (wetland influent) averaged 3.4 mg/L and produced an average effluent concentration of 0.2 mg/L. Total nitrogen and ammonia nitrogen concentrations through this

phase of the data collection averaged 391 mg/L and 350 mg/L, respectively, while average wetland effluent concentrations were 2.2 mg/L and 0.1 mg/L, respectively.

Results from a two year pilot-scale SF constructed wetland treatment system installed at a pulp and paper mill in Florida were reported by Knight *et al.* (1994). The pilot wetlands were put into operation in July 1991 and monitored through to June 1993. In this study, the authors compared the effects of aspect (length to width) ratios, the effect of deeper open water areas and various hydraulic loading rates on the treatment efficiencies of SF systems. Mean influent concentrations were: 9.09 mg/L TN; 3.35 mg/L NH₃; 0.89 mg/L NO₃⁻; 0.97 mg/L TP; 21 mg/L BOD₅; and, 73 mg/L TOC. Of the design parameters assessed, HLR and the presence of unvegetated deep open water regions across the wetlands had the greatest impact on treatment efficiencies. The cell operating with the lowest HLR and containing the open water sections yielded the highest treatments with reductions of 67% BOD₅, 91% NH₄, 73% TN, 71% TP, and 88% NO₃⁻. An inverse relationship between TSS removals and HLR was also reported.

3.1.2 SUBSURFACE FLOW WETLANDS

Subsurface flow (SSF) treatment wetlands are known by a number of pseudonyms depending on what part of the world you are in. Vegetated submerged beds (VSB), reed beds, root-zone systems and gravel-bed wetlands are all commonly used terms for SSF treatment wetlands. Of the three treatment wetland design options, SF, SSF or VF, SSF wetlands are the most common world-wide. Simple SSF systems consist of an excavated bed 20 cm to 100 cm in depth with a gentle bottom slope between 0 and 0.5% and filled with a porous media ranging between sand to mixed gravel to cobbles (USEPA 1988, Kadlec and Knight 1996). As with the SF systems, if protection of the groundwater

is an issue, the cells are isolated with an impermeable synthetic or clay liner. The wastewater to be treated is distributed across the inlet end of the wetland and flows horizontally through the root zone of the plants, below the surface of the gravel, to the outlet(s).

The choice of bed material/media and plant species are critical factors in SSF design. It is important to choose a substrate material with sufficient void space available such that the wastewater can pass around/through the material without overland flow occurrence yet provide a high surface area for microbial biofilm development and thus treatment. For SSF wetlands with aspect ratios of 6:1 or greater, overland flow conditions often result if a coarse bed material is not used. In selecting a material that will provide an adequate void space to allow subsurface flow of the wastewater, it is important to realize that a heavy material may restrict the development of the plant root system and thus reduce the efficiency of the system (i.e. a large diameter rock material will provide high hydraulic conductivity but the weight will impede full root development). Microbial attachment sites are located on the surface of the media as well as on the root themselves. "Leakage" of oxygen and biochemically active organic molecules such as growth factors and vitamins from the root system allows aerobic microbial populations to develop within an otherwise anaerobic environment resulting both anaerobic and aerobic treatment microcosms. As a result, it is important to match the bed depth with a plant which has a dense root network of equal depth. If short-circuiting or overland flow does occur, the system ends up performing as a SF wetland with a short residence time. Subsequently, the treatment efficiency decreases. Other factors to consider in selecting a substrate include adsorptive capacity of the material, potential adsorbed or inherent contaminants and cost. As with the SF wetlands, emergent macrophytes are the plants of choice due to the permanently saturated root-zone; however, as there is no standing water in a properly designed SSF system, a larger selection of plant species, including grasses such as mannagrass, bluegrass, bentgrass and reedgrass, are available to choose from.

SSF wetlands are the predominant treatment wetland systems found around the world with their application being, almost exclusively, for single household or municipal wastewater treatment. The majority of published work on SSF designs originates from, in descending order, Europe, Australia and the United States of America (Hammer 1989, Moshiri 1993, Haberl *et al.* 1995). Although these systems have higher construction costs than SF designs on a per hectare basis, primarily due to the cost of the bed media, they have smaller land requirements than SF systems for treating BOD and TSS. Other significant advantages of the SSF system include a greater tolerance to low temperatures (because the treatment is occurring below the ground surface and therefore is insulated) and the greater adsorptive capacity due to the high surface area available (Maehlum *et al.* 1994, Wood 1995).

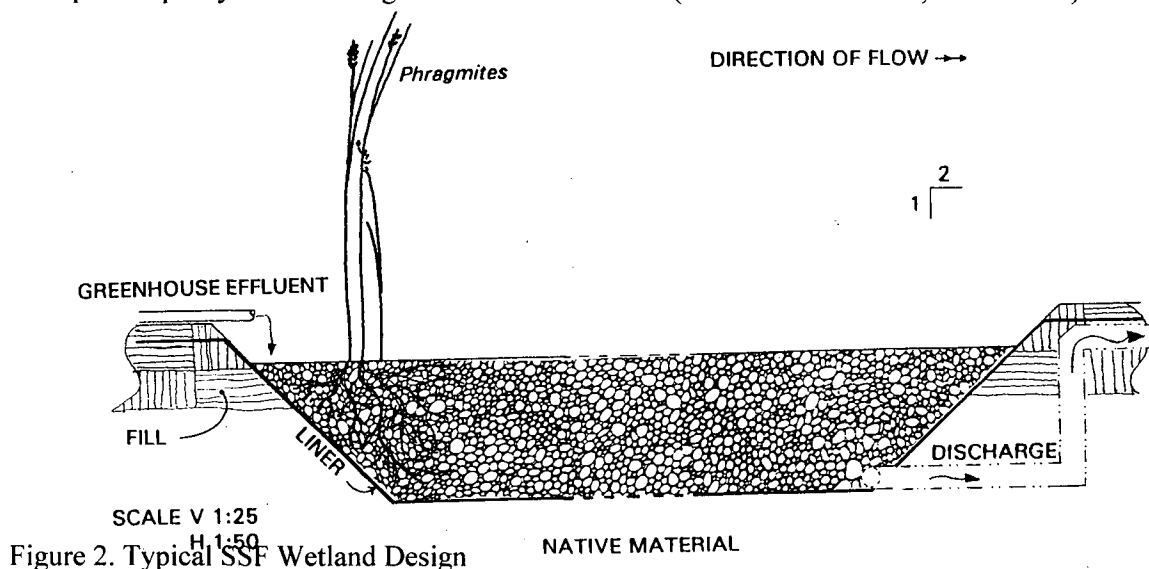


Figure 2. Typical SSF Wetland Design

A number of review articles have been written summarizing the design and performance of SSF wetlands. Cooper *et al.* (1990) provided a brief description of the principals underlying reed bed treatment systems and summarized the performance data from 26 operational municipal wastewater treatment systems in the United Kingdom (UK). The majority of the conclusions presented were related to choice of bed materials, design details and practical suggestions on bringing SSF systems into operation. Although the authors did not specifically address the removal efficiencies of the systems described, treatment reductions ranged from 68% to 89% for BOD₅, 70% to 93% SS, -9% to 68%

ammonia and 1% to 69% reductions for ortho-phosphate. Where data was available for more than one year, an improvement in treatment efficiency was observed over time for BOD, SS and $\text{NH}_4\text{-N}$ suggesting an evolution of the bacterial populations responsible for much of the wetland performance; however, in these systems O-PO_4 reductions decreased suggesting that phosphate removal in subsurface systems is via an adsorptive mechanism and may have a limiting removal capacity.

Green and Upton (1994) reported the details of Severn Trent Water Ltd.'s constructed wetland program for effluent polishing at 16 sites in England. The standard tertiary treatment reed beds at the various Severn Trent operations comprise 0.6 m deep gravel beds planted with common reed (*Phragmites australis*). While the primary goals of these systems are to produce an effluent with TSS and BOD_5 concentration less than 45 mg/L and 25 mg/L, respectively, nitrogen and phosphorus treatment was also monitored. Wetland data was provided for five of the described systems and were in use in communities with populations between 400 and 1,150. The wetland areas ranged between 0.78 m^2/person to 1.17 m^2/person although a standard 5 m^2 of wetland area per cubic metre wastewater to be treated per day was used for the designs. As described by Cooper *et al.* (1990), treatment performance for organic carbon, solids and nitrogen improved as the systems matured. Reductions in organic carbon and nutrients ranged from 77% to 88% for BOD_5 , 77% to 87% SS and -7% to 90% reductions in $\text{NH}_4\text{-N}$ for their second year of operation. Only the first year data was available for ortho-phosphate with an average 12% reduction observed over the five systems. In all five cases the authors reported that SS and BOD_5 objectives were exceeded; mean effluent concentrations for the combined data reported was 4.78 mg/L SS and 2.72 mg/L BOD_5 .

Using the finding of a USEPA sponsored evaluation of American SSF systems, Reed and Brown (1995) attempted to identify the relationship between hydraulic residence time and removal performance for BOD_5 , TSS, ammonia-nitrogen and phosphorus. Fourteen full-scale SSF systems were used in the

study. Of the SSF treatment wetland systems, one was treating industrial wastewater, one was treating domestic wastewater, one hospital wastewater and the remainder were municipal wastewater treatment systems. With one exception (for TSS) all of the systems analyzed were able to produce a final effluent with BOD₅ and TSS concentrations less than 20 mg/L. The authors also state that constructed wetland are incapable of producing an effluent BOD below the 2-7 mg/L range, regardless of design, due to decomposing plant matter and other natural organic materials inherently present in wetlands. By plotting BOD removal (%) vs. HRT (d) the authors demonstrated a minimum of 60% BOD removal occurring within the first day of retention within the SSF wetlands with up to 90% plus reduction achievable within a 8 day HRT. The initial high rate of BOD₅ and SS removal observed within the day of treatment is due to filtration and settling of the wastewater while further reductions observed are due to microbial processes. Ammonia removal in the assessed wetlands ranged between a net export of nitrogen, due to decomposing organic matter in the system, to greater than 90% ammonia removal. Effective nitrogen reduction required an extended HRT and was limited by the low concentration of available oxygen in the systems. Reed attributes the high level of ammonia removal in two of the wetlands investigated in his study to the density and depth of root-zone development within the gravel bed. In the two systems showing very high ammonia removal, both wetlands had highly developed root systems extending to the bottom of the treatment beds. As with the systems described above, phosphorus removal in the wetlands studied was somewhat limited with removal ranges between 0% to 60%. No relationship between HRT and treatment efficiency for phosphorus was suggested.

Research conducted in the UK by Horticulture Research International for the Horticultural Development Council (Hardgrave and Hufton 1995) investigated the potential of using reed-beds for removing nutrients from run-off generated from hydroponic tomato and pepper crops. This report was the only research project assessing the application of wetland technology to the vegetable greenhouse industry identified in this literature review. The wetland used for this study consisted of

a 8 m by 3 m bed, 0.6 m in depth, filled with 10 mm pea gravel and planted with common reed (*Phragmites australis*) and Wood small reedgrass (*Calamagrostis epigeios*). An average 8.5 m³ per week of run-off from 450 m² of production area was fed to the system in 50 L doses over the course of the study. Overdrain nutrient concentrations of 234 ppm nitrate, 0.8 ppm ammonia and 30 ppm phosphate reported are similar to target concentrations for BC growers (BCMAFF 1993). This study demonstrated nitrogen and phosphorus mass reductions of 28% for NO₃-N, 56.26% for NH₄-N and 40% for P. The reduction rates were lower than originally anticipated by the authors and have been attributed to the limited carbon source available to the microbial populations for denitrification and the limited absorptive capacity of the chosen wetland substrate for phosphorus removal, respectively. In their report the authors recommend composting of the plant biomass from the greenhouse operation and utilizing the product as a carbon supply for denitrification of the overdrain.

3.1.3 VERTICAL FLOW WETLANDS

Most recently investigations into vertical flow (VF) wetlands have been reported in the literature. These systems are very similar in design to SSF wetlands with the exception that the wastewater flows vertically rather than horizontally through the gravel bed, much like a trickling filter. Typically the wastewater is applied evenly over the surface of the wetland and is allowed to seep through the gravel bed and rhizosphere of the wetland to a collection grid installed at the bottom of the bed. If two beds are used there is the potential to alternate their use and allow one bed to drain and re-establish aerobic conditions to the system. The majority of the research to date assessing the application of VF wetlands has been conducted on a bench-scale level; however, there is some field testing being conducted in Europe (Perfler and Haberl 1993).

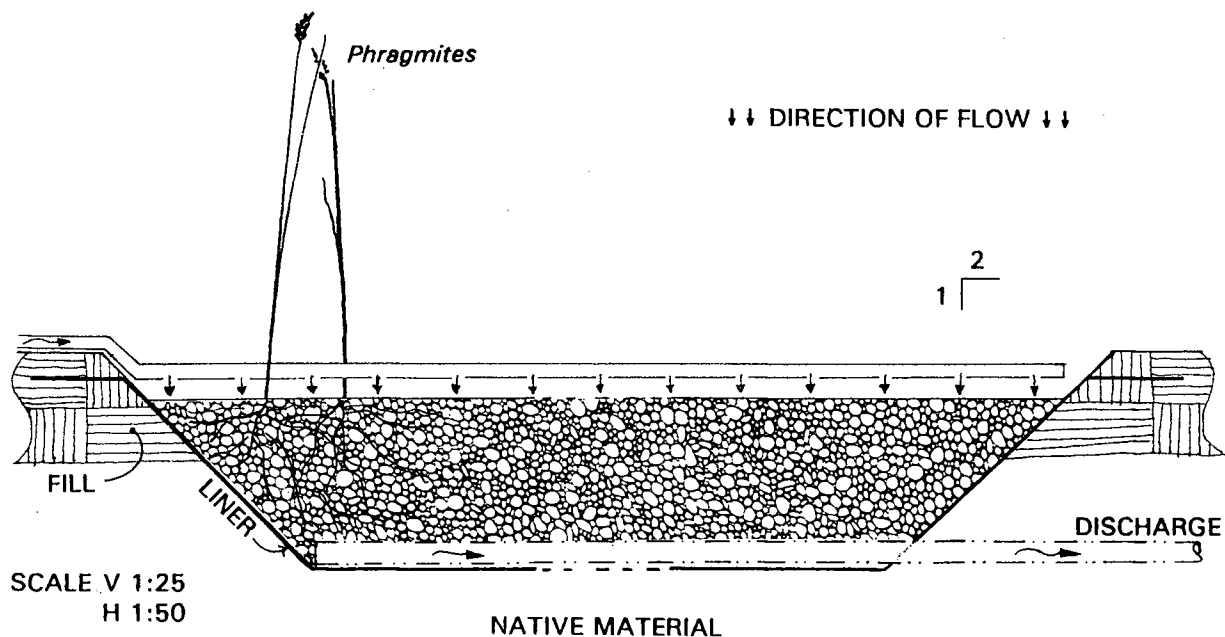


Figure 3. Typical VF Wetland Design

3.2 NUTRIENT REMOVAL PROCESSES

For any single element or natural compound, the combined natural mechanisms by which it is modified and eliminated from the wastewater stream comprise the biogeochemical cycle. These mechanisms include settling, flocculation, precipitation, adsorption to soil and organic compounds, volatilization, assimilation into plant tissues, microbial decomposition and microbial transformations. The biogeochemical cycles of most macro-nutrients have been extensively studied in wetlands and the natural environment as a whole. While these processes are common to all wetland systems, variability within the functional components of each system (i.e. water depth, substrates, plants, wastewater characteristics, temperature effects, etceteras) alter the biogeochemical cycling of the various wastewater constituents making it difficult to predict the response of any individual wetland system to different wastewater applications or to transfer results from one geographical area to another. As a

result, the effective design of a treatment wetland requires a strong understanding of the biogeochemical cycles of the individual wastewater constituents of concern and their impacts on the environment.

3.2.1 ORGANIC CARBON REDUCTION PROCESSES

Organic carbon in wetlands is derived from external inputs such as a wastewater stream and from internal inputs due to photosynthetic activity of algae and higher plants within the wetland. In solution, organic matter can be expressed as dissolved organic carbon (DOC), particulate organic carbon (POC) and total organic carbon (TOC), or in terms of chemical or biological oxygen demand (COD and BOD). The compounds which are measured by these collective parameters include a wide range of biochemically synthesised compounds such as carbohydrates, amino acids, sugars, fatty acids, alcohols, and proteins as well as humic and fluvic acids, a loose group of poorly defined high molecular weight compounds characterized by their aromatic character and phenolic and carboxylic acid functional groups. These latter compounds, collectively known as *gelbstoff*, are the by-products of fungal and bacterial degradation of plant tissues and are far more recalcitrant than the former organic compounds due to their aromatic nature. They are separated into the two groups by solubility due to molecular weight with the humic acid fraction being larger and less soluble than the fulvic acid fraction (Zehnder 1982).

Removal or reduction of organic carbon and suspended solids in a wetland environment occurs via physical settling, filtration and by microbially mediated processes. Physical settling and flocculation of suspended solids primarily occurs in the initial third of a constructed wetland system as flows entering the wetland slow down and spread out across the wetland (Wood 1995). Further resistance to water movement and removal of finer particles comes from the aboveground parts of the plants and organic litter which act like a filter to the wastewater.

Once in the wetland environment a number of different bacteria and fungi utilize DOC and POC as a substrate for building cellular compounds and energy production. The microbial process which result in the oxidation of organic matter to inorganic carbon dioxide is dependant on the oxidation-reduction state of the wetland environment and is often a sequential process involving more than one microbe species and/or purely chemical reactions. Table 1 summarizes the redox sequence of the biologically mediated oxidation of organic matter. The redox sequence changes from aerobic to anoxic to anaerobic from the top of the table to the bottom of the table. The denitrification and nitrate ammonification components of the redox sequence are important wetland processes and are discussed in the following section.

Table 1. Microbially Mediated Organic Carbon Oxidation and Reduction

Reaction	$-\Delta G^\circ$ per mol of e ⁻ exchanged (kJ/mol)	Redox potential E ^o _H (mV)
Aerobic respiration $[\text{CH}_2\text{O}] + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$	117.5	810
Denitrification $[\text{CH}_2\text{O}] + \frac{4}{5} \text{NO}_3^- + \frac{4}{5} \text{H}^+ \rightarrow \text{CO}_2 + \frac{2}{5} \text{N}_2 + \frac{7}{5} \text{H}_2\text{O}$	112.0	750
Manganese reduction $[\text{CH}_2\text{O}] + 2 \text{MnO}_2 + 2 \text{H}^+ \rightarrow \text{MnCO}_3 + \text{Mn}^{2+} + 2 \text{H}_2\text{O}$	94.5	500
Nitrate ammonification $[\text{CH}_2\text{O}] + \frac{1}{2} \text{NO}_3^- + \text{H}^+ \rightarrow \text{CO}_2 + \frac{1}{2} \text{NH}_4^+ + \frac{1}{2} \text{H}_2\text{O}$	74.0	360
Iron reduction $[\text{CH}_2\text{O}] + 4 \text{FeOOH}_{(\text{s})} + 6 \text{H}^+ \rightarrow \text{FeCO}_3 + 3 \text{Fe}^{2+} + 6 \text{H}_2\text{O}$	24.3	-100
Fermentation $[\text{CH}_2\text{O}] \rightarrow \frac{1}{3} \text{CO}_2 + \frac{1}{3} [\text{C}_2\text{H}_6\text{O}]$	23.4	-180
Sulphate reduction $[\text{CH}_2\text{O}] + \frac{1}{2} \text{SO}_4^{2-} + \frac{1}{2} \text{H}^+ \rightarrow \text{CO}_2 + \frac{1}{2} \text{HS}^- + \text{H}_2\text{O}$	18.0	-220
Methane formation $[\text{CH}_2\text{O}] + \frac{1}{2} \text{CO}_2 \rightarrow \text{CO}_2 + \frac{1}{2} \text{CH}_4$	16.3	-250

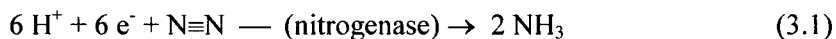
(Grant 1985)

3.2.2 NITROGEN REMOVAL MECHANISMS

Constructed wetlands have been utilized for the removal of nitrogen from wastewater streams with highly variable degrees of success. Understanding the behaviour of nitrogen in this climate is an important component in the design of functional treatment wetlands. In the wetland environment, nitrogen has a complex biogeochemical cycle comprising multiple transformations occurring under extremely different environmental conditions. Four of the seven possible oxidation states and corresponding inorganic forms of nitrogen are observed in aquatic solutions: ammonia (-III); molecular nitrogen (0); nitrite (III); and, nitrate (V). The conversion of nitrogen between these states occurs via the microbially mediated processes of fixation, ammonification (mineralization), nitrification and denitrification. A fifth process, ammonia volatilization, is an important component of the biogeochemical cycle of nitrogen in wetlands and is the only chemical/physical process involved in the removal of nitrogen from the aquatic environment (Bowden 1987).

Metabolically, all living organisms require nitrogen in the form of ammonia for its role in metabolic function (Boyd 1984, Vymazal 1995). Conversion of atmospheric nitrogen gas into ammonia is known as nitrogen fixation. This process is primarily mediated by a multitude of bacteria either as free organisms or in a symbiotic relationship with higher plants. Cyanobacteria, or blue-green algae, have species which are found in a free-living state and others living in a symbiotic relationship with fungi in lichens. The mechanism involved is an enzymatic catalysis of molecular nitrogen by nitrogenase which is only found in prokaryotes. The reduction of the triple bonds in N_2 is a high energy reaction requiring six electrons (equation 3.1) (Boyd 1984). Electrons required for nitrogen fixation are derived from photosynthetic reactions, such as in the cyanobacteria, or from the oxidation of organic carbon. The energy required for the reaction is supplied by ATP and the quantity of ATP necessary varies between one genus of bacteria to another. Once the nitrogen is in

the form of ammonia it is metabolized into glutamate and glutamine before its transamination to amino acids and eventual incorporation to protein (Boyd 1984).



Although nitrogenase activity is inhibited by oxygen, the environment conditions under which nitrogen fixation occurs range from aerobic to anaerobic. As a result, the overall rate of nitrogen fixation is determined by a number of environmental factors depending on the dominant nitrogen fixing micro-organism present. The most significant inhibiting factors are the availability of carbon substrate, low light intensities, high concentrations of oxygen and a high redox potential. In addition, nitrogen fixation is inhibited by high ambient concentrations of inorganic nitrogen and pH values greater than 8 and less than 5. Microorganisms which fix nitrogen under aerobic conditions have evolved systems that will maintain nitrogenase activity. For example, when *Azotobacter* have a readily available source of carbon its respiratory rate is high enough that oxygen is reduced to water before it can interact with the nitrogenase. When carbon becomes limited the respiration rate decreases and the oxygen is not reduced as rapidly thus potentially inhibiting the nitrogenase. Under these conditions the cell produces a protein which reversibly complexes with the enzyme providing protection during periods when oxygen is present (Boyd 1984).

Mineralization is the microbial conversion of an element from its organic state to its inorganic form. Although plants readily uptake nitrate to fulfil their nitrogen requirements it must be reduced to ammonia before it can be utilized metabolically. As ammonia is the required nitrogen form for incorporation into biomass, it is the preferred form for uptake by algae and higher plants. Thus the mineralization of nitrogen from a non-bioavailable organic form to ammonia or ammonium (NH_4^+)

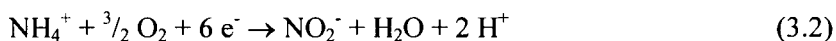
is an important process mediated by bacteria and fungi in nitrogen limited environments. The process occurs directly by enzymatic cleavage of nitrogen from various organic compounds or indirectly by carbon mineralization. Micro-organisms use a number of enzymes such as peptidases, proteases and deaminases to produce $\text{NH}_4^+\text{-N}$ from organic nitrogen compounds. During the mineralization of organic matter, bacteria and fungi obtain their energy from the oxidation of organic carbon to CO_2 . As the CO_2 is released by respiration, the organism accumulates an excess of nitrogen and eventually excretes the surplus to the surrounding environment where it is available to re-enter the nitrogen cycle. In wetlands treating municipal wastewater, which has a relatively high concentration of organic matter, nitrogen mineralization processes can drastically reduce the ammonia treatment efficiency of the system.

The sequential oxidation of ammonia to nitrite, and nitrite to nitrate, by bacteria is collectively known as nitrification. The group of bacteria which carry out these reactions are generally called nitrifying bacteria or nitrifiers. Nitrifying bacteria are strict aerobes yet can survive in conditions where oxygen is available in extremely low concentrations. In wetlands, nitrifiers can be found in the water column, at the sediment water interface and in sediments adjacent to the rhizosphere of the wetland plants. In this latter environment, the microorganisms are utilizing the microaerobic zone created by the radial oxygen loss from the root hairs of the emergent macrophytes.

Nitrification is a two step process. The first reaction, the oxidation of ammonia to nitrite (equation 3.2), occurs within obligate chemolithotrophic bacteria which are dependant on the oxidation of ammonia for their entire energy supply (USEPA 1993). While the overall reaction is relatively simple, it has been postulated that the reaction has a total of five steps: ammonia ($\text{NH}_3/\text{NH}_4^+$) \rightarrow hydroxylamine (NH_2OH) \rightarrow nitroxyl (NOH) \rightarrow nitrohydroxylamine ($\text{NO}_2\cdot\text{NH}_2\text{OH}$) \rightarrow nitrite (NO_2^-).

Various species within a number of prokaryotic genera have been identified as nitrifiers in soils but only one species, *Nitrosomonas europaea*, is capable of ammonia oxidation in freshwater habitats (Watson *et al.* 1981).

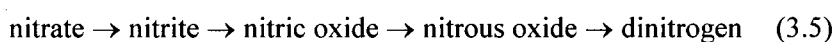
The second step in nitrification is the oxidation of nitrite to nitrate (equation 3.3). Unlike the oxidation of ammonia to nitrate which is catalyzed by a single bacterial species in fresh water aquatic environments and numerous species in soils, nitrite oxidation in both soils and fresh water is only carried out by a single species of bacteria (Watson *et al.* 1981, Grant and Long 1985). This micro-organism, *Nitrobacter winogradski*, is a chemoheterotroph obtaining its carbon for growth and replication from organic sources and its energy from nitrite.



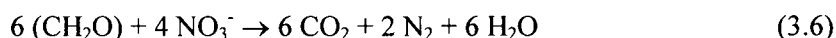
The rate of denitrification in wetlands is dependant on pH, temperature, alkalinity, inorganic carbon availability, organic carbon availability and ammonia concentration (Boyd 1984). In laboratory cultures, optimal growth of nitrifiers is between 25 and 35 °C (Watson *et al.* 1981).

Denitrification is loosely defined as the reduction of nitrate to a gaseous product, resulting in a loss of fixed nitrogen from the affected environment. More specifically, denitrification is the anaerobic bacterial process in which ionic and gaseous nitrogen oxides serve as terminal electron acceptors for respiratory electron transport. The oxidation of organic carbon substrates under anaerobic or

microaerobic conditions generates free electrons which pass through a cascade of electron carriers before reducing some form of oxidized nitrogen. In theory, denitrifying bacteria have five electron cascades resulting from organic carbon oxidation. This first cascade utilizes nitrate as the terminal electron acceptor reducing the nitrate to nitrite. The second cascade utilizes nitrite as the terminal electron acceptor reducing it to nitric oxide and so on with the sequential reduction occurring as shown in equation 3.5 (Jeter and Ingraham 1981, Vymazal 1995).



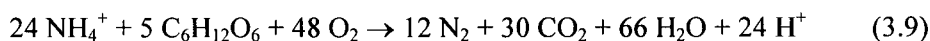
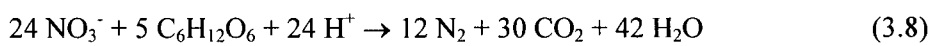
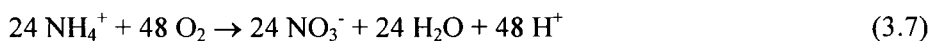
Energy generated by each cascade of the organic carbon oxidation is stored as ATP for use by the denitrifiers for other biochemical processes. The production of nitrogen gas by denitrification is depicted by equation 3.6 (Soderlund and Rosswall 1982, Boyd 1984).



On a global scale, denitrification is an extremely important ecological and geochemical process responsible for the formation of nearly all atmospheric nitrogen gas and it is the pathway of loss for most agricultural fertilizers. On a more regional scale, denitrification offers the most cost effective method for reducing fixed nitrogen concentrations in effluents, thereby reducing the impacts on the quality of receiving waters. In wetland soils denitrification occurs in anaerobic regions of the litter and below the aerobic sediments. The rate of denitrification is dependant on the supply of NO_3^- , temperature, pH, redox potential and available biodegradable organic carbon. While in natural systems nitrate is typically found in very low concentrations, many wastewaters have high nitrate

concentrations. In these instances temperature and available organic carbon are the limiting factors for denitrification. van Oostrom et al. (1994) reported sufficient carbon production in a *G. maxima* SF wetland to sustain a denitrification rate of 2.4 - 4.8 g N/m²/d. Further, it has been theorized that a *Typha* wetland could denitrify 1.1 metric tonnes of nitrate per hectare per year if favourable temperatures existed (Reed *et al.* 1995).

The combined nitrogen reduction of treatment wetlands is often assessed based on the combined nitrification and denitrification of the system. As these two processes are capable of occurring simultaneously in wetlands due to the presence of aerobic and anaerobic zones, it is possible to provide a combined equation for the removal of ammonia from their environment (Vymazal 1995).



The final mechanism for the removal of nitrogen from the wetland environment is the incorporation of nitrogen into plant tissues and eventually the sediments. As discussed above, ammonia is the required form of nitrogen for cellular metabolism. This does not limit cells to the uptake of ammonia or ammonium to meet cellular nitrogen requirements as all plants, fungi, yeast and many prokaryotes are able to reduce nitrate to ammonia for biosynthetic purposes. Biomass analysis of natural and constructed wetlands have shown wetlands to produce approximately one tonne of above-ground plant biomass annually (Vymazal 1995). Of this, up to 30% does not decompose over one year and slowly contributes to the development of the sediments (Godshalk and Barko 1985). Over long periods this accretion will result in the permanent loss of nitrogen from the biological cycle; however, on an annual

basis, the amount removed by this route is extremely small when compared to the nitrification/denitrification cycle.

3.2.3 PHOSPHORUS REMOVAL MECHANISMS

The inorganic and biological cycling of phosphorus in the environment has been extensively investigated due to the importance of phosphorus in cellular function and that phosphorus is the primary limiting nutrient in unpolluted freshwater lakes, streams and rivers. Unlike nitrogen, which has more than one stable oxidation state and is present in the environment in a number of chemical forms, phosphorus has only a single environmentally stable form, phosphate (PO_4^{3-}). To remove phosphate from the aquatic environment, it must be converted to a non-bioavailable form or permanently deposited into the sediments of the wetland.

A number of factors including pH, redox potential and concentration of Fe, Al and calcium Ca in the effluent and wetland soil contribute to the removal of phosphorus. Retention of phosphate in natural wetland systems has been demonstrated to be directly related to the content of iron (Fe) and aluminium (Al) in the sediments (Richardson, 1985 & 1986). Under acidic conditions PO_4 can be precipitated as insoluble Fe and Al-phosphates, while Ca-phosphate precipitate formation is the dominant removal transformation under neutral to alkaline conditions (Faulkner and Richardson 1989). Adsorption to oxides and hydroxides of Al and Fe are also potential removal mechanisms under acidic conditions (Huang 1980). By understanding these processes it is possible to design wastewater treatment approaches which incorporate these processes and therefore maximize phosphorus reductions.

In a geological context, phosphate-bearing minerals exist in sedimentary, metamorphic and igneous deposits with 85% of all phosphate rock mined from sedimentary sources (Emsley 1980). Phosphate rocks have been classified into three categories based on their mineral composition: Fe-Al phosphates, Ca-Fe-Al phosphates and Ca phosphates. Of these categories, calcium phosphates are the dominant phosphate mineral deposits in the Earth's crust with 95% of the solid phosphate world-wide present as fluoroapatite (Emsley 1980). Table 2 below presents a list of six common calcium phosphate minerals in order of decreasing solubility. With the exception of calcium dihydrogen phosphate hydrate, calcium phosphates are insoluble a neutral pH.

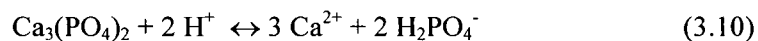
Table 2. Calcium Phosphates

Mineral	Formula
Calcium dihydrogen phosphate hydrate	$\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$
Calcium hydrogen phosphate dihydrate	$\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$
Octacalcium phosphate pentahydrate	$\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$
Calcium phosphate	$\text{Ca}_3(\text{PO}_4)_2$
Hydroxyapatite	$\text{Ca}_5(\text{PO}_4)_3\text{OH}$
Fluoroapatite	$\text{Ca}_5(\text{PO}_4)_3\text{F}$

(Emsley 1980)

Dissolution of phosphate rock/mineral in soils and sediments is dependant upon the mineral composition (i.e. solubility constant), pH of the surrounding water and the concentrations of calcium and dihydrogen phosphate in the immediate aqueous environment. The relationship between solubility and these four characteristics is fairly predictable when considering solubility products and acid-base chemistry and is illustrated by the equation below. The solubility of phosphate minerals increase with decreasing pH, calcium and/or dihydrogen phosphate concentration. Using calcium phosphate as an example, decreasing pH is equivalent to increasing hydrogen ion concentration

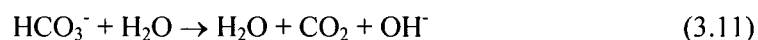
which drives the reaction to a dissociated state (equation 3.10). Conversely, high concentration of calcium or dihydrogen phosphate will drive the reaction to an associated state. In solution, the ionic form of phosphate is acid dependant with H_2PO_4^- the dominant ion at pH values less than neutral and HPO_4^{2-} is dominant at pH values greater than 7.5 (Kadlec and Knight 1996).



The solubility product of calcium phosphate, $\text{Ca}_3(\text{PO}_4)_2$, is 2×10^{-29} and decreases to 10^{-51} for hydroxyapatite and is even lower for fluoroapatite; however, the large difference in solubility does not directly influence the form of the precipitate. Environmental factors such as pH and the relative concentrations of the various metals or minerals present in solution have a greater influence the chemical composition of the precipitate. The mineralogical form of the precipitate is not relevant over long periods as it slowly converts to the more stable crystal structure of hydroxyapatite or fluoroapatite as isomorphous substitution of fluoride occurs (Khasawneh and Doll 1978, Emsley 1980).

One method of promoting phosphate precipitation in the presence of calcium, without the addition of a strong base to increase the pH, is to create an environment which will promote a dense algal population and subsequently a high rate of CO_2 uptake. Natural waters are buffered by dissolved inorganic carbon. The status of the $\text{CO}_2\text{-HCO}_3^-\text{-CO}_3^{2-}$ equilibrium, with respect to which species is dominant, is pH dependant. The equilibrium state of the buffering system depends on the concentration of hydrogen ion, amount of excess base, the partial pressure of carbon dioxide in the atmosphere and temperature. When algal biomass growth in a pond is rapid, the uptake of CO_2 from solution by the biomass outstrips the rate it can be replaced by atmospheric CO_2 diffusion,

respiration, fermentation or readjustment of the solid carbonate equilibrium. When this occurs, HCO_3^- is converted to CO_2 by reaction 3.11 and the pH of the water increases (Zehnder 1982, Kadlec and Knight 1996).



Similarly, when the source of HCO_3^- becomes limiting, CO_3^{2-} is converted to CO_2 by equation 3.12, further increasing the pH of the water above pH 10.



To promote optimal calcium phosphate precipitation, a pH between 7.5 and 9 is ideal as the solution will be sufficiently basic to ensure all phosphate is present as dihydrogen phosphate and able to combine with the calcium in solution but not basic enough to promote calcium carbonate precipitation (above pH 9) which may interfere with the availability of Ca^{2+} for further phosphate removal.

While calcium phosphate precipitation can play a significant role in the role of phosphate from solution under neutral or basic conditions, dissolved iron and aluminium and components of wetland sediments have a dominant role in the physical and chemical removal of phosphate under acidic conditions. Phosphate precipitation using aluminum or iron is commonly practised by traditional wastewater treatment plants (Metcalf and Eddy, Inc. 1991). At pH values of 5 and 6, respectively, phosphate precipitated by aluminium and iron is predominately in the form of pure metal phosphates (AlPO_4 and FePO_4), with the proportion of hydroxyl precipitates increasing as the pH increases

(Metcalf and Eddy, Inc. 1991). Most natural surface waters contain less than 1 mg/L aluminum and 0.5 mg/L iron, although these concentrations can increase in acidic waters (CCME 1995). Above a pH of 6.5, the dominant ionic form of aluminum is $\text{Al}(\text{OH})_4^-$ which no longer reacts with the phosphate anion. The permanent removal of phosphate from solution as ferric phosphate precipitates is doubtful as the precipitates will likely end up in the sediments. Under the reducing conditions found in the sediment layer, iron is reduced from its ferric form to its ferrous form and a soluble $\text{Fe}_3(\text{PO}_4)_2$ results.

The phosphorus retention capacity of natural wetlands can be predicted by the extractable aluminum and iron content of the soil (Richardson 1985). Sesquioxides are clays made up of oxides and hydroxides of aluminum and iron [Fe(III)] such as boehmite (AlOOH), gibbsite (Al_2O_3), goethite (FeOOH) and hematite (Fe_2O_3) and have the potential to remove phosphate from solution by adsorption. The adsorption mechanism at the surfaces of iron and aluminum oxides and hydrous oxides have been extensively studied in soil science. The mechanism of phosphate adsorption on iron sesquioxides is by the formation of a bi-nuclear bridge between the phosphate anion and two iron molecules (Parfitt 1978). This reaction is far more stable than the attachment of phosphate to aluminum sesquioxides where the phosphate is integrated into mineral crystals such as taranakite ($\text{K}_3\text{H}_6\text{Al}_5(\text{PO}_4)_8 \cdot 18\text{H}_2\text{O}$). A study of fen, bog and swamp wetland soils by Richardson (1985) demonstrated that the phosphorus retention capacity of a wetland can be predicted by the extractable aluminum content of the soil.

The final route of phosphorus removal from wetlands is by plant and animal uptake. Phosphate is a universal constituent of living cells and is an integral component of numerous biochemical compounds such as: nucleotides, the principal “building blocks” of DNA and RNA molecules and

energy storage/transport molecules in cells; phospholipids, which form the lipid bi-layer holding the cell together; inositol phosphates; NADP⁺/NADPH, a oxidation-reduction molecule; phosphorylated sugar molecules; various vitamins; and, co-factors. The phosphorus fraction of higher plant biomass ranges between 0.08% to 0.64% by mass (Boyd 1978). Comparatively, the phosphorus content of freshwater algae ranges between 0.04% to 7.98% (Vymazal 1995). Approximately 30% of emergent macrophyte biomass does not fully decompose in the course of one year (Godshalk and Barko 1985) resulting in an annual accumulation of nutrients in the sediment layer of the wetland. The permanent removal of phosphorus in *Typha* marshes which produce an average 1000 kg dry biomass per hectare per year is up to 6.4 kg of phosphorus per hectare annually. While this may not constitute a large component of the phosphorus loaded to a wetland system by a greenhouse operation, it does comprise 20% to 30% of the removal efficiencies observed in wetland systems utilized for treating municipal wastewaters.

4.0 MATERIALS AND METHODS

The intent of this research project was to assess the capability of treatment wetlands to remediate greenhouse overdrain at a pilot-scale level. Five wetland designs were assessed based on conventional surface flow and subsurface flow design approaches. All five designs were constructed in duplicate to ensure repeatability of the data. The wetland basins were constructed on the property of Houweling Nurseries Ltd., located at 2776 - 64th Street in Delta, BC, adjacent to the propagation greenhouse in March 1995. See Figure 4 for a location map of the site. The project was designed to utilize a total of 57,500 litres per day of the greenhouse wastewater flows originating from the propagation and pepper production areas. This is approximately 10% of total overdrain generated by the greenhouse operation. Overdrain flow from this production area was chosen due to the ebb and flood irrigation system in place which allowed collection of the overdrain from the entire production area at a single point.

The five wetland designs assessed were:

fifteen centimetre water depth surface flow wetland - planted;
thirty centimetre water depth surface flow wetland - planted;
thirty centimetre water depth surface flow wetland - unplanted;
sixty centimetre depth gravel bed subsurface flow wetland - planted; and,
sixty centimetre depth gravel bed subsurface flow wetland - unplanted.

All of the wetlands were designed with the same physical constraints: 7 metres wide by 35 metres long at mid water depth (5:1 aspect ratio); ten day hydraulic retention time (HRT); 20-25 mm nominal diameter gravel as the planting medium/treatment substrate; and, a 20 mil. thick PVC liner to prevent any infiltration of groundwater or exfiltration of wastewater. Broadleaf cattail (*Typha latifolia*), planted at a 0.5 metre spacing (four plants per square metre), was chosen for the wetland designs requiring plants. Wild stock from local donor sites was used. A 20 cm bed of gravel was placed in each of the SF wetland cells, including the unplanted systems, to anchor the wetland plants. Water depth was measured from the top of the substrate surface.

Overdrain flows from the greenhouse were initially pumped over an inclined fixed screen to remove any large pieces of plant debris, plastic clips and planting medium before being directed to a 45 cubic metre water silo. From the holding tank, flows were continuously pumped, 24 hours per day, through approximately 350 metres of 1.5 inch diameter black poly pipe to the wetlands. Two 1.25 inch ball valves were placed in-line between the pump and the wetlands to reduce the pressure and increase the flow rate in the main supply line immediately prior to the wetlands.

The flow into each wetland was controlled by a one-quarter inch brass needle valve. Based on the design HRT of ten days and water depth of each wetland the flow rates into each wetland was 2.55 L/min. for the 15 cm SF wetlands, 5.10 L/min. for the 30 cm SF wetlands and 3.57 L/min. for the SSF wetlands. During 1995, flows were supplied to the wetlands from the end of April through to October when the pipes froze. In March 1996 approximately 185 kg of wheat straw was added to each of the planted SF basins to enhance the litter layer and simulate a more mature wetland environment. Wheat straw was chosen for a number of reasons including expense, a C:N ratio near 120 (Haug 1993) and published studies indicating that straw has a capacity for adsorption of phosphate (Avnimelech 1993). Flows to the wetlands were re-established at the beginning of April 1996 and continued through to December 1996.

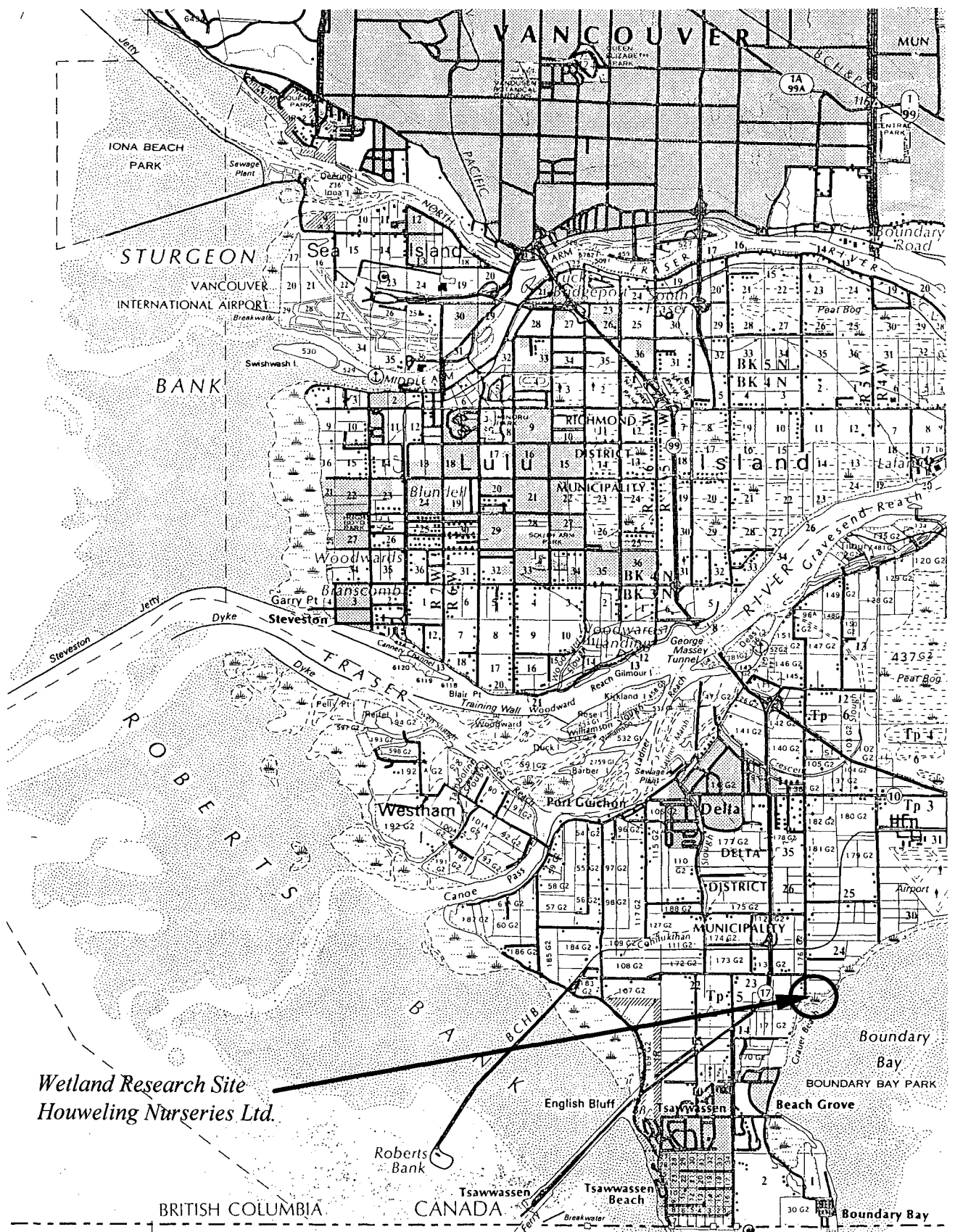


Figure 4. Location Map

4.1 MONITORING PROGRAM

Water samples were collected from the holding tank plus three sites within each wetland: $\frac{1}{3}$ of the length of the wetland; $\frac{2}{3}$ of the length of the wetland; and, at the outlet of the wetland (see Figure 5). These site locations allow the characterization of the wetland's remediation process and rates of treatment. Samples were collected every second week from each site of each wetland and analyzed for: ammonia-N ($\text{NH}_3\text{-N}$), nitrate-N ($\text{NO}_3\text{-N}$), total Kjeldahl nitrogen (TKN), total phosphorus (TP), orthophosphate (O-PO_4), pH, total solids (TS), total organic carbon (TOC) and biochemical oxygen demand (BOD_5). BOD_5 was only determined for samples collected between May and mid-September 1996. Dissolved metals (Al, Ag, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Si, Ti, Tl, V and Zn) were determined by ICP four times through the 1996 season. Metals and BOD_5 were not anticipated to be of concern and were not addressed in the study. Samples were only collected from the outlets of the unplanted SF wetlands (30 cm deep ponds) as these systems were well mixed by wind action and the collection of samples from within the basins could not give any indication of the rate of the treatment processes. All samples were collected in two litre opaque PET wide-mouthed screw-top containers and stored unpreserved at 4 °C. Ortho-phosphate and ammonia analyses were conducted within 36 hours of sampling and the remaining tests were conducted within 7 days. Samples for ICP analysis were stored at -20 °C in PET bottles prior to analysis. Methods and equipment utilized are presented in Table 3.

In the 1995 field season, some water samples were collected between July and October 1995; however, the absence of any decaying plant biomass or soluble BOD in the wastewater did not allow development of significant bacterial populations within the wetland basins and therefore little treatment was realized in this period. Water quality monitoring continued through to late October

1995 when temperatures at the research site dropped below freezing and the pipes conveying effluent to the experimental wetland froze. As it was not financially practical to bury the pipes to prevent periodic freezing, the pipes were drained for the winter. The intent of the 1995 season was not to obtain data on the treatment capacity of the wetlands but to allow the vegetation and bacterial population to become established. All analysis of the water samples was conducted in the Bio-Resource Engineering laboratory at UBC.

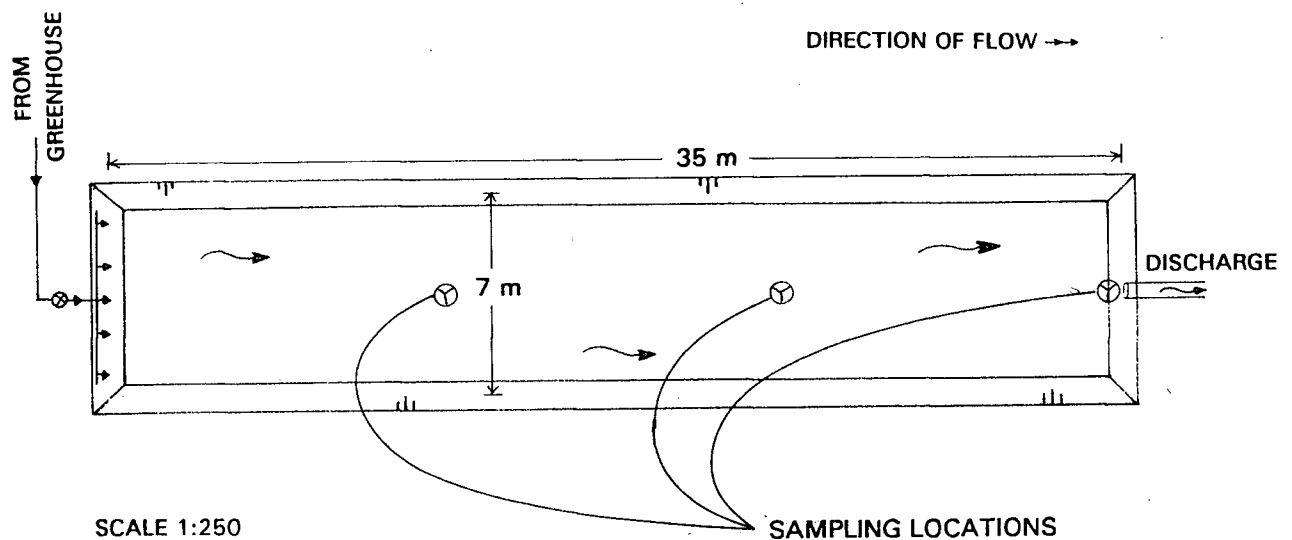


Figure 5. Plan view of typical wetland with sampling site locations

Biomass harvesting from all six planted wetland cells was conducted between November 6 and 9, 1995 with the assistance from Envirowest. Ten one square metre areas were completely harvested. The harvested biomass was dried and weighed at the UBC Department of Plant Science plant drying facilities. The information from this analysis is used to estimate the available carbon for denitrification. Table 4 shows sampling dates and analyses conducted. The raw data collected over the entire research project is presented in Appendix 1.

Table 3. Analytical Methods

Parameter	Method	Equipment	Detection Limit	Chemistry
NO ₃ -N	I.M. ¹ 33-96W	Technicon AutoAnalyzer II	0.1 µg/L	Diazo method
NH ₃	I.M. 98-70W	Technicon AutoAnalyzer II	0.2 µg/L	Berthelot Reaction
TKN	I.M. 30-69W	Technicon AutoAnalyzer II	0.2 µg/L	Sulphuric acid digestion followed by Berthelot Reaction
TP	I.M. 327-74W	Technicon AutoAnalyzer II	0.008 mg/L	Sulphuric acid digestion followed by ammonium molybdate reduction using ascorbic acid
O-PO ₄	I.M. 94-70W	Technicon AutoAnalyzer II	0.2 mg/L	Ammonium molybdate reduction using ascorbic acid
TOC	Std Mtds ² 5310B	Shimadzu TOC-5050	0.001 mg/L	Combustion-infrared
TS	Std Mtds 2540B		0.0001 mg/L	Dried at 103-105 °C
BOD ₅	Std Mtds 5201B		5 mg/L	
pH		Hanna Instruments Model HI 9214	±0.01 pH unit	

1. Technicon Industrial Method.

2. Standard Methods for the Analysis of Water and Wastewater (AWWA 1995)

Table 4. Water Quality Laboratory Analyses

Sampling Date	Analyses Conducted								
	NO ₃	NH ₄	TKN	TP	O-PO ₄	TOC	TS	BOD ₅	Metals
1995									
Aug. 8						√	√		
Aug. 21							√		
Sept. 28	√	√	√	√	√	√	√		
Oct. 10	√	√	√	√	√	√	√		
Oct. 23		√			√	√			
1996									
April 12	√	√	√	x	√	√	√		
April 25	√	√	√	√	√	√	√		
May 2	√	√	√	√	√	√	√	√	
May 16	√	√	√	√	√	√	√	√	
May 30	√	√	√	√	√	√	√	√	√
June 13	√	√	√	√	√	√	√	√	
June 27	√	√	√	√	√	√	√	x	
July 11	x	x	x	x	x	x	x	x	
July 25	√	√	√	√	√	√	x	√	√
Aug. 8	√	√	√	√	√	√	√	√	
Aug. 22	√	√	√	√	√	√	√	√	
Sept. 5	√	√	√	√	√	√	√	√	
Sept. 19	√	√	x	√	√	√	√		
Oct. 3	√	√	√	x	√	√	√		√
Oct. 17	√	√	√	x	√	√	√		
Oct. 31	√	√	√	√	√	√	√		
Nov. 14	√	√	√	√	√	√	√		
Nov. 28	√	√	√	√	√	√	√		
Dec. 12	√	√	√	√	√	√	√		√

x = sample collection was scheduled but not collected. Valves to the 15 cm SF basins were plugged on June 13. Due low water levels no samples were collected from these wetlands.

4.2 STATISTICAL ANALYSES

Statistical analyses conducted with the data consisted of:

- developing correlation matrices for each of O-PO₄, TP, NH₄, NO₃-N, TKN, TOC and TS to establish independence of the sampling;
- developing a randomized block design for the entire data-set and conducting a simple factorial analysis of variance (ANOVA) to identify the relative influence of design, replicate and sampling date on treatment effect;
- conducting paired t-tests using the influent and effluent data from each of the ten wetland basins for each of the water quality parameters listed above to determine if a real treatment effect was observed; and,
- conducting Scheffe tests for each of the parameters identified above, using the mean square error from the ANOVA, to determine if the treatment effects observed between the five wetland designs were different.

SPSS 6.0 for Windows was used to conduct the correlation matrices, randomized block ANOVA and the paired t-tests. The Scheffe tests were calculated manually using a Quattro Pro spreadsheet. The results of all statistical analyses are presented in Appendix 3.

5.0 RESULTS AND DISCUSSION

Published literature show a highly variable ability of constructed wetland to remove nutrients from wastewaters. Similarly, the results of water quality analyses conducted on samples collected during the 1996 field season show a wide range of treatment effects. For TP, O-PO₄, NO₃-N, NH₄, and TOC, a statistically supportable treatment effect was observed in the majority of the wetlands but not

all. TKN and TS data show no reductions in concentration for any of the five wetland designs assessed.

Three aspect of the design of this research project have somewhat challenged the analysis of the results. These aspects are: the greenhouse production area supplying the overdrain to the wetlands was not consistently utilized for production of a single crop; the design HRT was 10 days yet the sampling period was 14 days; and, the root system of broadleaf cattails did not penetrate to the bottom of the SSF wetlands. The impact of these factors are further elaborated below.

Overdrain flows used for this research project were collected from a production area used for a number of crops. Approximately half of the area was permanently utilized for green pepper production while the other half was used for propagation of tomato and pepper starter plants, bedding plants and poinsettias. Each of these crops require different fertilizer regimes resulting in significant variations in the concentration of individual nutrients in the overdrain being fed to the experimental wetlands. It was not possible to directly monitor these fluctuations as the nutrients pass through the wetland due to the unsynchronized sampling period and HRT.

The incomplete root penetration in the planted SSF wetlands resulted in the development of two distinct 'layers', and therefore two distinct flow paths, within the substrate bed. The maximum penetration of the *Typha* roots system is approximately 35 cm. As the root system developed in the upper portion of the wetland bed, it filled void spaces between the gravel leading to a higher resistance to water flow with respect to the regions of substrate with no roots present. In contrast, void spaces within the bottom portion of the substrate bed remained unaltered and two different flow paths, based on resistance, developed within the planted SSF basins. This difference in resistance to flow can be seen in the charts of nutrient concentration versus distance though the wetland for the

planted SSF basins (Appendix 2). For most of the parameters monitored in the SSF wetlands, water samples from 11.67 m and 23.33 m along the basin were collected from the middle of the bed via vertical sampling ports and show a trend of decreasing nutrient concentration; however, the outlet sample was taken from the outlet structure which collected flows from at the bottom of the gravel bed. Nutrient concentrations in samples collected from this point show a marked increase to concentrations near that of the raw greenhouse effluent/wetland influent.

An additional problem was encountered due to equipment failure. Between May 21 and July 13, 1996 the sump pump providing overdrain to the wetlands was rebuilt. During this period a smaller sump was used to pump the overdrain flows to the wetlands; however, this pump was unable to handle the plastic and organic debris in the raw overdrain and became plugged on a regular basis. As a result flows to the wetlands were intermittent over this seven week period.

5.1 PHOSPHORUS

The maximum allowable total phosphorus concentration for drinking water in British Columbia, established in *Water Quality Criteria: Approved and Working Criteria for Water Quality* (MELP 1994), is 10 µg/L. Acceptable total phosphorus levels for the protection of freshwater aquatic life in provincial lakes with salmonids as the predominant fish species are between 5-15 µg/L, site specific, with no standards established for lakes where salmonids are not the dominant fish species or for watercourses. As most waterbodies in British Columbia are oligotrophic or at the low end of the mesotrophic range, these standards ensure that the natural phosphorus-limited status of provincial lakes is not degraded and algae populations are held constant. To achieve a phosphorus concentration of 15 µg/L or less in vegetable greenhouse overdrain, a removal efficiency greater than

99.98% is required. The *Canadian Water Quality Guidelines* (CCME 1995) does not provide any phosphorus guidelines for drinking water or aquatic life protection. Tables 5 and 6 below shows the average ortho-phosphate and total phosphorus outlet concentrations and treatment efficiencies for the ten wetlands between April and December 1996.

The total phosphorus results presented below are not considered highly accurate due to the analysis method utilized. Samples were acid digested and analyzed according to Technicon's Industrial Method 327-74W. Although all standards were subjected to the same digestion process and R^2 values for the standard curves were 98.5% or greater, it is suspected that the acid concentrations in the analyzed samples suppressed the intensity or formation of the molybdenum blue complex in samples with lower phosphorus concentrations. As a result, the calculated reductions presented in Table 5 are thought to be higher than the true removal efficiency with ortho-phosphorus results reflecting the accurate treatment effect.

Table 5. Total Phosphorus Results (mg/L)

Cell #	Design	Average	StdDev	Max	Min	% Reduction
	Greenhouse Effluent	99.31	81.92	305.79	8.14	N/A
1	15 cm SF #1	45.75	38.37	141.58	7.80	53.93%
2	15 cm SF #2	46.21	34.52	113.20	6.40	53.47%
3	30 cm SF #1	71.78	59.99	193.22	11.52	27.72%
4	30 cm SF #2	73.98	64.18	206.71	10.38	25.50%
5	Unplanted SF #1	57.94	55.57	152.09	0.75	41.66%
6	Unplanted SF #2	39.31	43.31	108.20	1.26	60.42%
7	Unplanted SSF #1	46.20	27.98	89.36	10.77	53.48%
8	Unplanted SSF #2	38.86	25.92	89.40	9.76	60.87%
9	SSF #1	44.74	26.74	90.86	11.89	54.95%
10	SSF #2	53.22	31.60	95.54	16.02	46.41%

Table 6. Ortho-Phosphorus Results (mg/L)

Cell #	Wetland Design	Average	StdDev	Max	Min	% Reduction
	Greenhouse Effluent	98.87	39.67	155.26	19.69	N/A
1	15 cm SF #1	64.69	32.14	125.82	22.88	34.57%
2	15 cm SF #2	56.27	26.79	100.82	0.93	43.09%
3	30 cm SF #1	79.14	32.24	148.94	29.82	19.96%
4	30 cm SF #2	79.04	36.15	151.33	28.86	20.06%
5	Unplanted SF #1	76.32	43.14	148.02	17.42	22.81%
6	Unplanted SF #2	36.11	40.85	118.52	1.90	63.48%
7	Unplanted SSF #1	67.17	28.81	111.89	18.94	32.07%
8	Unplanted SSF #2	53.69	24.44	106.73	3.08	45.70%
9	SSF #1	65.19	27.71	120.76	21.42	34.07%
10	SSF #2	68.95	35.06	134.54	5.24	30.26%

Paired t-tests comparing the mean of influent concentrations and outlet concentrations of TP and O-PO₄ (Appendix 3) show a TP treatment effect for all of the wetlands except Cell #4 (the second planted 30 cm SF basin) and a O-PO₄ treatment effect for all wetlands except cells #3 (the first planted 30 cm SF basin) and #5 (the first unplanted 30 cm SF basin). Taking both total phosphorus and ortho-phosphate into account, the largest reduction of phosphorus was observed in Cell #6, the second unplanted SF wetland. The mean reduction in O-PO₄ for this wetland over the entire field season was 66.21%. It is important to note that most of this treatment effect was observed in the latter half of the year (Figure 6) and coincided with a significant increase in pH within the unplanted SF basins (Figure 7).

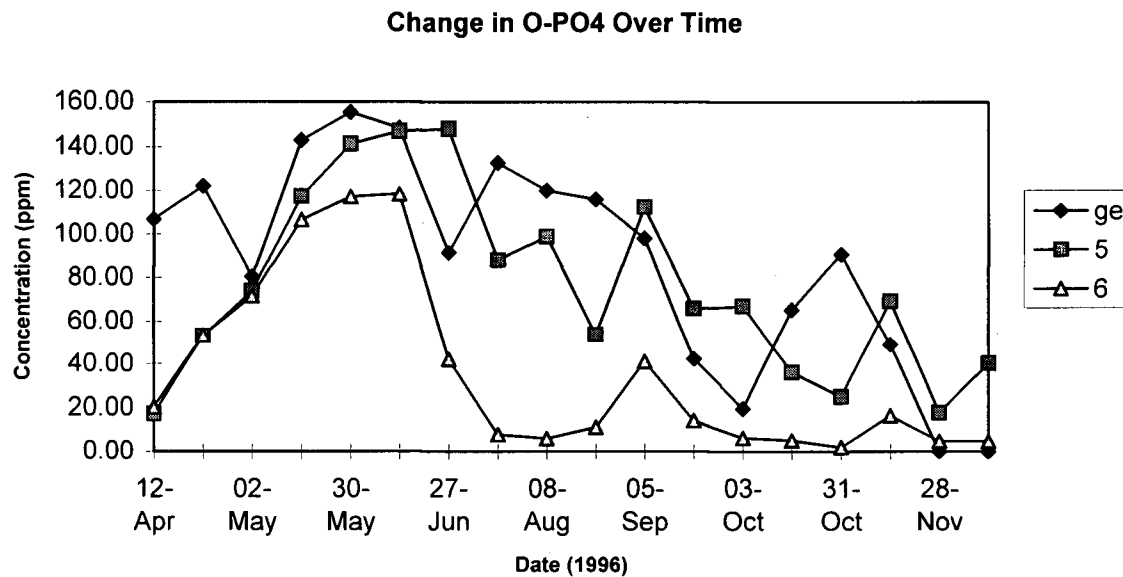


Figure 6. Change in O-PO₄ Concentrations in Cells 5 & 6 Over Time

As discussed in Section 3.2.3, the three predominant modes of phosphate removal in wetlands are plant uptake, adsorptive processes and chemical precipitation. The high treatment effect documented in the unplanted SF wetland is attributed to chemical precipitation reactions under alkaline conditions. In their review article of design and performance of SSF treatment wetlands, Cooper *et al.* (1990) suggested that phosphate reduction observed in SSF wetlands occurs primarily via an absorptive mechanism and therefore may wetlands have an ultimate phosphorus retention capacity. Plant uptake is also limited by the storage capacity of phosphorous within the plant tissues. Given that the peak permanent removal of phosphorus in *Typha* marshes producing an average 1,000 kg dry biomass per year is 6.4 kg per hectare annually, a maximum of 0.157 kg of phosphorus removal observed in the planted wetland can be attributed to plant uptake. Figure 7 shows the change of pH in Cells 5 and 6 (in which the most significant reduction of PO₄⁻ was observed) over the course of the 1996 field season. The pH increase observed in the wetland cells is thought to be due to CO₂ uptake by algae as observed in natural marl lakes and described in Section 3.2.3. As the algal population in

the unplanted wetland basins increase they begin to uptake CO_2 from solution faster than it can diffuse from the atmosphere into solution resulting in an imbalance of the $\text{CO}_2\text{-HCO}_3^-\text{-CO}_3^{2-}$ equilibrium. As these species attempt to return to an equilibrium status, OH^- is generated, as shown in equations 3.11 and 3.12, and the pH in the basin increases. With the resulting increase in pH the proportion of phosphate in solution in the form of HPO_4^{2-} increases creating suitable conditions for the formation of calcium phosphate which then precipitates from solution. Figure 8 clearly shows the strong relationship between pH and phosphorus (TP and O- PO_4) concentrations for the combined data from both unplanted SF wetlands.

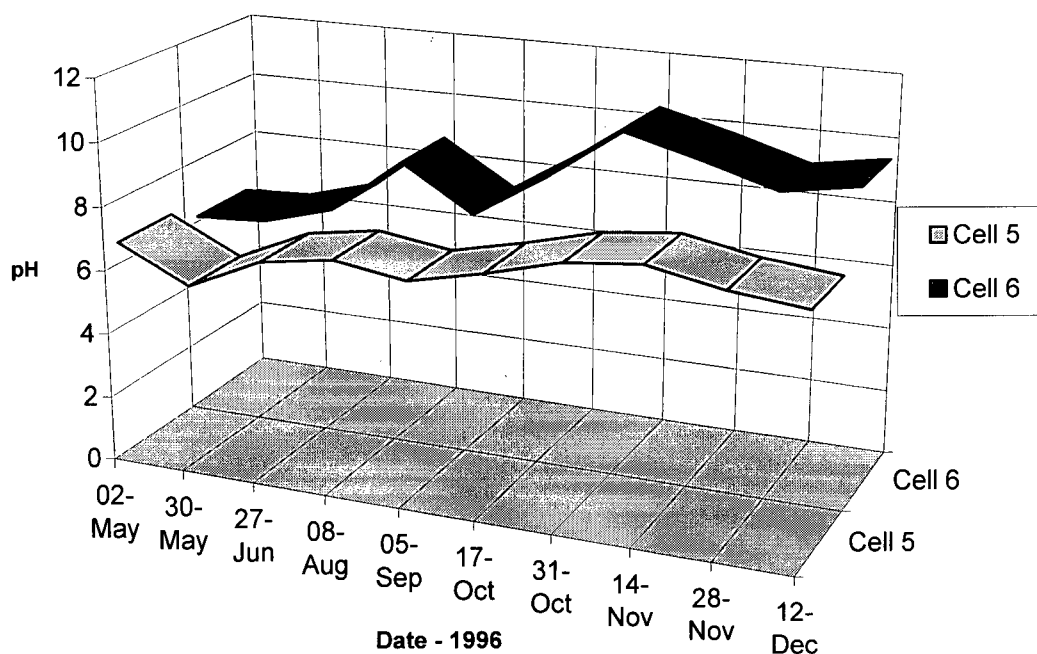


Figure 7. Wetland Cells #5 & #6. Changes in pH Over Time

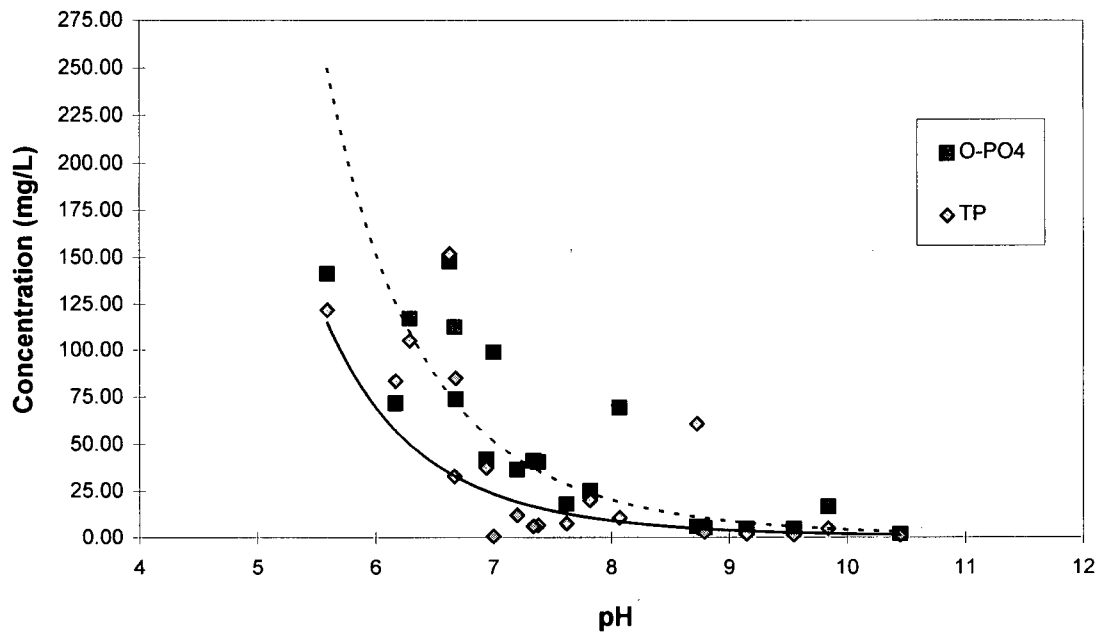


Figure 8. Total Phosphorus and Ortho-Phosphate vs. pH

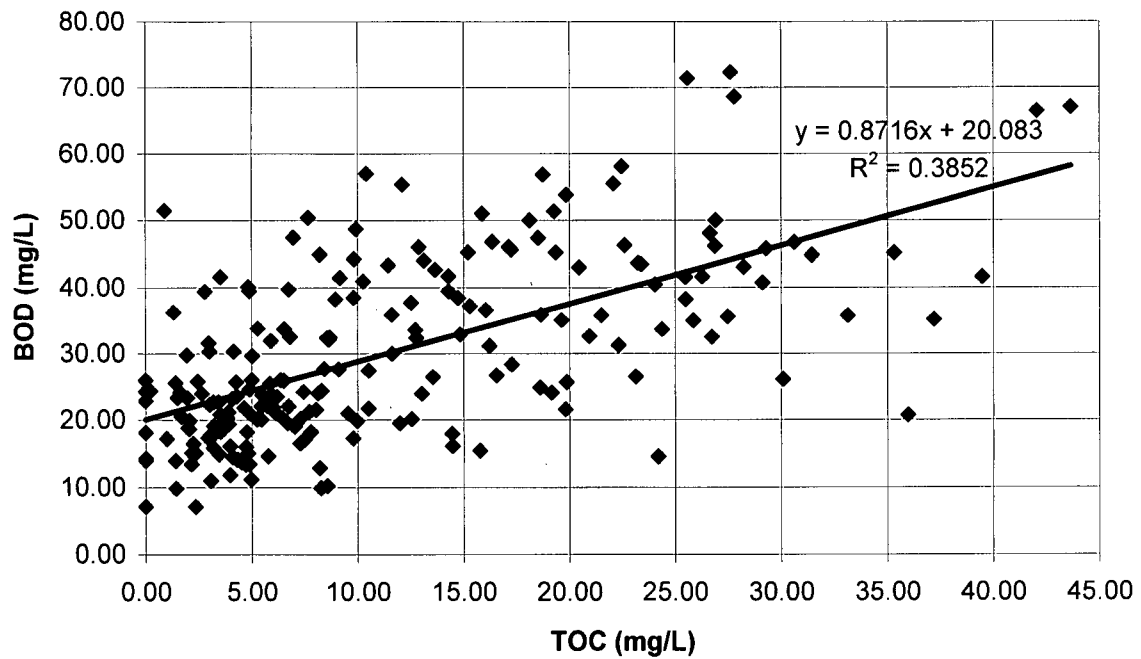


Figure 9. Relationship Between BOD₅ and TOC Using Combined Data From All Wetlands

Over the course of the field season, when comparing the two unplanted surface flow wetlands, a higher concentration of algae was visually observed in Cell #6 with respect to Cell #5. The pH values measured in Cell #6 in the latter portion of the sampling season were also higher than in Cell #5. In an attempt to identify the cause of the chemical variations between these two basins, water samples from both cells were analyzed under a microscope to see if there was any difference in the algal populations between the two wetlands which may explain the observed differences. *Scenedesmus* sp. was the dominant species of algae identified in both basins although Cell #5 had a distinctly lower concentration of algae present with a significant protist component to the algal community. In contrast, Cell #6 had almost no protists present. The relationship between pH, algae population levels and the presence or absence of protists was not investigated; however, one hypothesis to explain the observation is that the high pH present in Cell #6 was outside the protists' environmental range of tolerance thereby inhibiting the establishment of a protist community. If this hypothesis is correct, the lack of any significant predator population would allow an algal population to develop to a density that would result in a depletion of free CO₂ in solution. It then follows that the grazing pressure exerted on the algal community of Cell #5 by the protists is the cause of the lower algal concentrations observed thereby inhibiting the development of a high pH environment.

Based on the data presented in tables 6 and 7, the treatment order of the wetland designs for phosphorus removal can be arranged, from most efficient to least efficient, as:

unplanted 30 cm SF > unplanted SSF > 15 cm SF > planted SSF > planted 30 cm SF.

This design progression suggests that, for the high phosphorus concentrations studied in this research project, the non-biological factors of phosphorus removal are not only more influential on the treatment efficiency but that phosphorus removal capacity is decreased by interactions of the

biological components. Unlike the unplanted 30 cm deep SF wetland, the unplanted SSF basins did not have a high pH and phosphorus reductions observed in these basins are likely due to adsorption processes to limestone, aluminum or iron mineral components of the rock used as substrate material. If this is the case then it is possible that SSF designs may have a limited capacity for phosphorus removal as suggested by Cooper *et al.* (1990).

More moderate removal efficiencies, between 19.96% and 43.09% for ortho-phosphate, were observed for the planted wetlands. This lower treatment capacity is in part attributed to the ability of the plants (*Typha*) to release phosphorus back into solution in the fall. A higher removal capacity was observed in the spring and early summer for all three planted wetland designs followed by no net phosphorus removal or a net export observed in the fall (see charts in Appendix 2). This follows the life cycle of the wetland vegetation of nutrient uptake during the high growth stage in the spring, the more static stage during summer development of flowers into seeds and the release of nutrients from the above-ground biomass during the late fall senescence. The long-term biological removal of ortho-phosphate from wastewaters by wetlands occurs by the incorporation of recalcitrant portions of the biomass becoming buried in the sediments. This process is limited due to the relatively low composition of phosphorus in plant tissues (0.02 - 1.15%) (Boyd 1978; Vymazal 1995).

The calculated loading rates for total phosphorus were 1.49 g TP/m²/d for the 15 cm deep SF wetlands, 2.98 g TP/m²/d for the 30 cm deep SF wetlands and 2.08 g TP/m²/d for the SSF wetlands. By comparing the mass loading rates of phosphate to each planted wetland it is possible to demonstrate that the mass loading order (the 30 cm SF wetlands received a higher mass loading than the SSF wetlands which in turn received a higher mass loading than the 15 cm SF wetlands) is the inverse of the treatment efficiency sequence (53.70% average reduction for the 15 cm SF wetlands, 50.68% average reduction for the planted SSF wetlands and 26.61% average reduction for the

planted 30 cm SF wetlands). This suggests that for the removal of phosphorus, design is not as important as the mass loading rate for vegetated wetland systems. As SSF wetlands are significantly more expensive to construct than SF wetlands due to the cost of the bed material, it would be preferable to utilize a SF design and reduce the mass loading via a high pH pre-treatment pond where possible.

As the provincial water quality guidelines provide a total phosphorus criteria of 10 µg/L it is unlikely that a constructed wetland system could meet this target concentration; however, conventional wastewater treatment plants are unable to meet a 10 µg/L criteria without the addition of tertiary biological nutrient removal technology. The ability of wetland systems to produce an effluent with phosphate concentrations less than 0.5 mg/L has been effectively demonstrated by Martin and Johnson (1995). To provide treatment of greenhouse effluents that would yield a effluent phosphate concentration in the 0.1 mg/L total phosphorus range a two stage wetland system would be required. Using an unvegetated wetland basin to promote optimal precipitation reactions followed by a vegetated wetland incorporating a mass loading design strategy, a TP concentration of 0.1 mg/L is achievable.

5.2 NITRATE

The maximum allowable concentration of nitrate in drinking water has been set at 10 mg/L as NO₃-N, or 45 mg/L, as NO₃ in both *Water Quality Criteria: Approved and Working Criteria for Water Quality* (MELP, 1994) and in *Canadian Water Quality Guidelines* (CCME, 1995). In cases where nitrite is also present, the combined concentration of nitrate plus nitrite cannot exceed the 10 mg/L guideline. Where concentrations of nitrate in drinking water is greater than 10 mg/L as nitrate as

nitrogen, there is an unacceptable risk of methemaglobin formation in infants¹. For the protection of freshwater aquatic life, an average concentration of 40 mg/L nitrate (as nitrogen) with a maximum of 200 mg/L is allowable (MELP 1994).

In wetland systems, the removal of nitrate from wastewaters can occur via two mechanisms, uptake by the algae and emergent macrophytes present in the wetland or by denitrification. Of these two process it is the latter which is the most important. Plant uptake of nitrogen is limited by the annual biomass production the wetland is capable of generating. Biomass analysis of *Typha latifolia* has shown the plants to contain between 0.51% and 2.94% nitrogen by mass (Vymazal 1995). Using an annual average dry weight biomass production of 1,000 kg per hectare, a maximum of 294 kg of nitrogen per hectare could be accounted for by plant uptake. As Houweling Nurseries Ltd. has reported an average overdrain production of 3 L/m²/day with an average nitrate concentration of 250 mg/L, the maximum vegetation nitrogen storage of 294 kg would be exceeded by a one hectare vegetable production greenhouse in 40 days. Based on the rate of nitrate discharge from the greenhouse and that nitrogen uptake by macrophytes occurs primarily in high plant growth periods (i.e. the spring), denitrification is the more significant mechanism for nitrate removal for the majority of the greenhouse production season. Table 7 below shows the results of nitrate analyses for the 1996 field season.

¹ Methemoglobin or "blue baby disease" occurs when nitrate, absorbed by the infant through drinking water, is reduced to nitrite in the blood-stream. The nitrite binds with haemoglobin in the red blood cells and forms methemoglobin which is unable to bind O₂. As it is the O₂-haemoglobin complex that gives blood its red colour, the lower concentration of haemoglobin, and therefore reduced oxygen carrying capacity by the blood, results in the infant's skin gaining a bluish colour. Brain damage and/or death of infants are both a risk in areas with high nitrate concentrations in the drinking water.

Table 7. Nitrate Results (mg/L)

Cell #	Design	Average	StdDev	Max	Min	% Reduction
	Greenhouse Effluent	223.22	92.60	362.25	28.96	N/A
1	15 cm SF #1	105.20	93.31	328.29	6.55	52.87%
2	15 cm SF #2	81.94	54.74	224.15	17.36	63.29%
3	30 cm SF #1	111.57	67.50	235.68	12.23	50.02%
4	30 cm SF #2	115.80	70.76	246.88	21.63	48.12%
5	Unplanted SF #1	204.47	113.36	445.42	42.51	8.40%
6	Unplanted SF #2	171.55	87.50	295.05	37.38	23.15%
7	Unplanted SSF #1	175.67	74.37	297.70	44.70	21.30%
8	Unplanted SSF #2	162.22	76.86	239.61	22.52	27.33%
9	SSF #1	167.05	85.46	307.57	23.39	25.17%
10	SSF #2	193.37	124.75	428.80	16.21	13.37%

As seen in the results presented, a relatively low reduction in nitrate concentrations was observed in all of the SSF design wetlands and in the unplanted SF wetlands. Results of paired t-tests for these basins indicates that there is insufficient evidence to conclude that any real treatment effect was observed in either the unplanted SF wetlands or the planted SSF wetlands. These results are consistent with nitrate removal reported by Hardgrave and Hufton (1995) and is not unexpected as the rate of denitrification is primarily dependant on temperature, pH, redox potential and available biodegradable organic carbon. Of these, low levels of available biodegradable organic carbon and high dissolved oxygen levels, respectively, were the limiting factors for denitrification of the greenhouse wastewaters by the SSF and unplanted SF designs. While no dissolved oxygen data was collected from the unplanted SF basins, the low organic content of the greenhouse effluent, high photosynthetic activity of the algae, the shallow unprotected nature of the basins and the constants winds originating from the Strait of Georgia and Boundary Bay all imply an oxygen saturated or supersaturated state in the unplanted basins. The TOC concentration of the greenhouse overdrain was consistently in the 20 mg/L range compared to the year mean nitrate concentration of 217.75

mg/L. Additionally, there was minimal input of organic carbon to the water column from the broadleaf cattail or algae biomass in any of the SSF or unplanted SF systems. Narkis *et al.* (1979) have reported that 2.3 mg BOD₅ is required to completely denitrify 1 mg NO₃ in bench-scale activated sludge systems. Using this 2.3:1 ratio and the relationship between TOC and BOD₅, derived from the scatter plot of TOC concentration versus BOD₅ concentration (Figure 9) obtained from 1996 field data, 621.5 mg of TOC is required to completely denitrify each litre of overdrain (assuming 300 mg/L nitrate). Figure 10 shows the change in TOC in as flow passed through each of the five wetland designs assessed in this study. No increase in TOC was observed in either of the unplanted basins and a minimal increase was observed in the planted SSF wetland design. Additionally, there was a high level of wind mixing of the unplanted 30 cm deep SF basins. The shallow nature of these basins in conjunction with the regular wind blowing off Boundary Bay ensured that these wetlands were well aerated. This in itself is sufficient to suppress any potential denitrification.

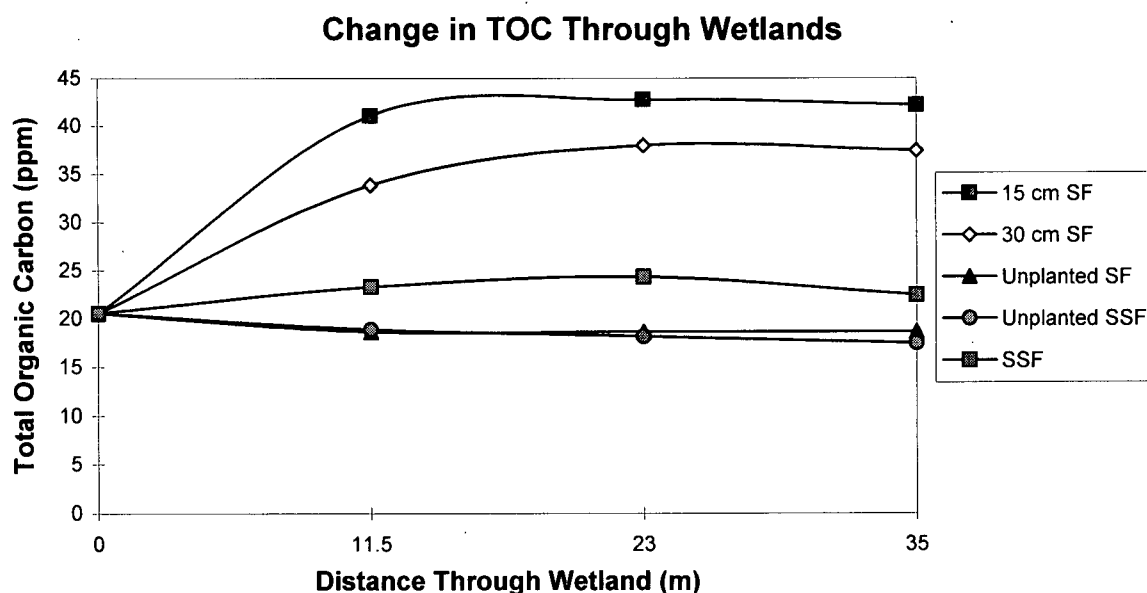


Figure 10. Change in Total Organic Carbon Through Each Wetland Design

In contrast, the planted 15 cm and 30 cm SF wetlands showed fairly good levels of nitrate removal and had supplemental sources of carbon available to the denitrifying bacteria. Carbon sources in each of these basins consisted of decaying cattail, algae and duckweed biomass as well as the 225 kg of wheat straw added in the spring of 1996 to supplement the existing carbon sources and simulate a more mature marsh litter layer. Combined, these carbon sources effectively doubled the TOC concentration in the wetland effluent for both the 15 cm and 30 cm deep designs, with respect to the greenhouse overdrain, yielding average TOC outlet concentrations of 42.19 mg/L and 37.40 mg/L for each design, respectively (Figure 9). This observed increase is statistically supported by paired-sample t-tests. As the 30 cm deep wetlands have twice the volume of the 15 cm deep basins, there was twice the TOC available for denitrification.

Based on the 10 day HRT, no real difference in between the outlet nitrate concentrations of two planted SF designs was observed. However, if the data is analyzed from a mass loading perspective, the 15 cm SF wetlands had an average 3.26 grams of $\text{NO}_3\text{-N}$ applied per square metre surface area per day ($\text{g/m}^2/\text{d}$) with removal rates of 1.55 $\text{g/m}^2/\text{d}$ and 1.94 $\text{g/m}^2/\text{d}$ for each of the two replicates. In contrast, the 30 cm deep SF wetlands had nitrate application rates of 6.53 $\text{g/m}^2/\text{d}$ with mean removal rates of 3.02 $\text{g/m}^2/\text{d}$ and 2.89 $\text{g/m}^2/\text{d}$ for each of the replicates. This higher rate of denitrification may be attributed to the combination of a number of factors such as: higher levels of available organic carbon for denitrification; deeper waters resulting in more anaerobic environments for denitrification to occur; and, the submergence of more plant biomass in a deeper marsh results in a higher surface area available for biofilm development.

These nitrate removal rates are significantly less than the mean removal rate of 5.3 $\text{g N/m}^2/\text{d}$ reported by van Oostrom *et al.* (1995). Two significant design differences existed between the wetlands

studied by van Oostrom and the wetlands studied here. In van Oostrom's study *Glyceria maxima* was the wetland vegetation chosen and the water depth was 40 cm. Additionally, the concentration of organic matter was significantly higher in the meat processing effluent than in the greenhouse effluent. Given the deeper water depth there is greater opportunity for development of anaerobic zones which are required for denitrification. The additional organic carbon provided by the *Glyceria* biomass and the BOD present in the effluent would also promote a higher rate of denitrification.

Nitrate application rates used in this study did not allow either drinking water standards or protection of aquatic life criteria to be met. However, using the results presented above and the implication from van Oostrom's study that a higher rate of denitrification is possible with a deeper water depth, it is postulated that a nitrate application rate of 3.0 g N/m²/day and a design wetland depth between 30 cm and 40 cm in depth would produce an effluent that meets provincial water quality criteria.

5.3 AMMONIA

The toxicity of ammonia to freshwater aquatic life is dependant on concentration, pH and temperature with the latter two parameters affecting the concentration of the toxic un-ionized ammonia. Acceptable 30 day average ammonia levels range between 2.08 mg/L at pH 6.5 and 0 °C to 0.102 mg/L at pH 9.0 and 20 °C. In any given sampling period, not more than one in five of the collected samples can be more than 1.5 times the criteria for that temperature and pH (MELP 1994). No guidelines, either federal or provincial, are proposed to limit the concentration of ammonia in drinking water. Tables 8 and 9 below shows the average ammonia and nitrate outlet concentrations and treatment efficiencies for the ten wetlands between April and December 1996.

Table 8. Ammonia Results (mg/L)

Cell #	Design	Average	StdDev	Max	Min	% Reduction
	Greenhouse Effluent	17.88	17.44	46.38	0.90	N/A
1	15 cm SF #1	5.43	5.89	22.10	0.00	69.66%
2	15 cm SF #2	5.13	5.34	17.45	0.00	71.32%
3	30 cm SF #1	8.16	7.40	24.40	0.65	54.34%
4	30 cm SF #2	8.35	7.76	24.40	0.72	53.28%
5	Unplanted SF #1	5.78	6.96	20.73	0.00	67.68%
6	Unplanted SF #2	4.38	6.86	20.98	0.00	75.50%
7	Unplanted SSF #1	11.00	8.66	25.85	0.00	38.46%
8	Unplanted SSF #2	9.33	9.09	27.49	0.00	47.83%
9	SSF #1	9.16	8.72	31.37	0.72	48.79%
10	SSF #2	9.05	8.66	27.15	0.85	49.41%

With the exception of Cell #7, the first unplanted SSF wetland, the reductions in ammonia observed in all of the wetland basins can be statistically defended with the paired-sample t-test. Based on the data presented in Table 8, the treatment order of the wetland designs for ammonia removal can be arranged, from most efficient to least efficient, as:

unplanted 30 cm SF > 15 cm SF > planted 30 cm SF > planted SSF = unplanted SSF.

This order closely follows the relative potential for diffusion of oxygen from the atmosphere into solution.

The 67.68% and 75.50% average reductions in ammonia observed in the two unplanted 30 cm SF wetlands represent the highest ammonia treatment effects observed over the course of the 1996 field season. These reductions are attributed to a combination of nitrification, uptake by algae and volatilisation. As the water in both basins was well aerated by wind mixing and had significant algal

growth present, the conditions for the conversion of ammonia to nitrate and volatilisation of the ammonia were ideal. Of the two wetlands, a higher reduction was observed in Cell #6. This higher level of treatment can be explained by the higher pH and algae population observed in this wetland. As discussed in Section 3.2.2, most plants, including algae, preferentially uptake ammonia over other forms of inorganic nitrogen form for metabolic purposes. Additionally, ammonia stripping is enhanced at pH values greater than 10, which was observed in the late summer and fall in Cell #6.

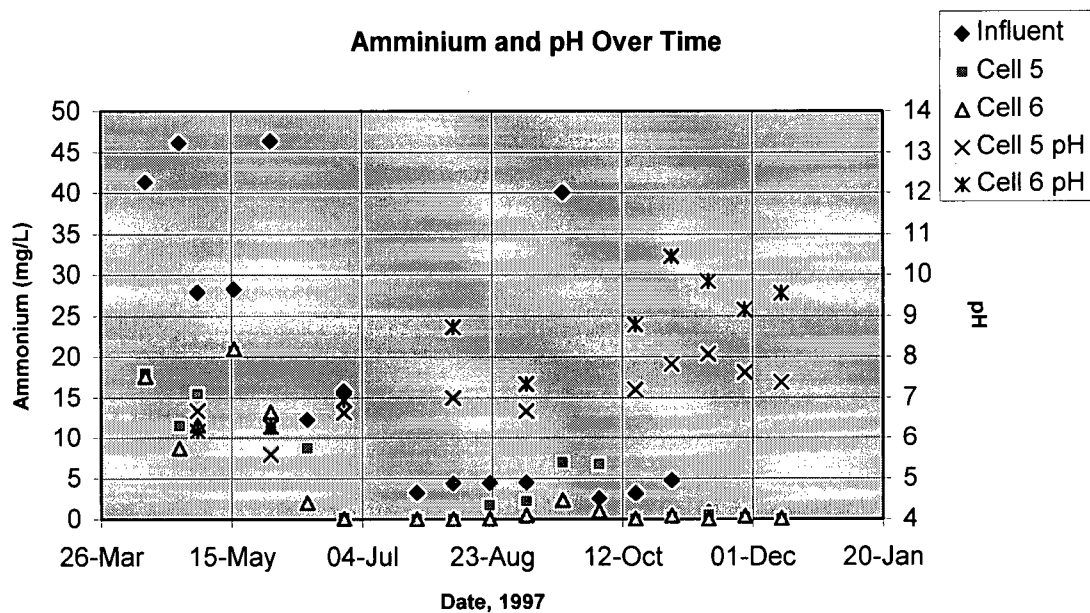


Figure 11. Change in Ammonium and pH Over Time.

The difference in ammonia treatment observed between the two planted surface flow wetland designs cannot be totally explained by the difference in loading rates. While the 30 cm SF wetlands did receive twice the ammonia loading as the 15 cm deep designs, the treatment effect observed through the 30 cm deep wetland is primarily observed in the first third of the wetland. A continuing decrease in ammonia concentration was observed through both of the shallower systems. This difference may

be explained by a higher concentration of available oxygen in the shallower system. As there is less water to oxygenate, diffusion of oxygen from the atmosphere and from the roots of the cattails provide a greater opportunity for nitrification in the shallow water environment.

The poor treatment of the SSF wetlands is likely due to the short circuiting of the greenhouse effluent under the root zone of the cattails. Traditionally, SSF wetlands with well developed root systems are very efficient in reducing the concentration of ammonia in the wastewater. One significant advantage these systems have is that they contribute less ammonia to the wastewater while it is passing through the wetland as the majority of the decaying biomass is located above the water level.

5.5 COST ANALYSIS

The construction cost analysis is based on the cost of materials as determined in the construction phase of this project. To provide a base for the comparison of system expenses, the analysis has been standardized for a 1,000 square metre wetland. Construction costs and infrastructure costs are presented separately as the latter would not change between designs. The value of in-kind and volunteer contributions to this project (i.e. design, construction supervision and manual labour) has been estimated based on estimates from suppliers and professional consulting fees.

Infrastructure costs are constant for both designs and assume that there are no complications with the location of the wetland and that there are no significant barriers to laying the pipe conveying the wastewater from the greenhouse to the wetland. Basic requirements for a treatment wetland include: one pump (horsepower and voltage requirements are site specific) (\$ 1,000), one 20,000 L surge/storage tank (\$ 2,250); 250 metres of 3 inch Ø poly pipe (\$ 600); 60 metres of 150 mm Ø PVC

pipe (\$ 700); and, miscellaneous poly and PVC elbows, couplings and t-joints (\$ 250). The total infrastructure cost is \$ 4,800. It should be noted that this is a fixed cost, regardless of wetland size, and would only increase if the wetland was located more than 200 metres away from the greenhouse. General labour associated with installing the infrastructure is represented in the construction costs.

Table 9. Wetland Construction Costs

Item	Surface Flow Wetland	Subsurface Flow Wetland
Design and construction supervision @ \$75/hour	\$ 3,900	\$ 3,900
Excavator @ \$90/hour including \$175 haul-in fee	\$ 1,150	\$ 1,350
Bulldozer @ \$75/hour including \$125.00 haul-in fee	\$ 935	\$ 1,100
Labourers @ \$ 16/hour	\$ 705	\$ 705
20-25 mm nominal diameter gravel	\$ 5,300*	\$ 16,000
20 mil. PVC liner	\$ 3,400	\$ 3,400
Wetland plants @ \$1.25 each (4 per m ² with 80% survival guarantee)	\$ 5,000	\$ 5,000
Infrastructure	\$ 4,800	\$ 4,800
TOTAL	\$24,995	\$ 36,060

Note that gravel was used as the planting medium for this research project to reduce the number of variables potentially influencing the comparison of results; however, native top soil from the wetland site can be used thereby reducing the total construction costs for a 1,000 m² SF wetland to \$ 19,695.

6.0 CONCLUSIONS

The results presented in Section 5 indicate that no one specific design is “the most efficient” for all parameters concerned. Of the five designs tested, the surface flow design emerged as the most

appropriate design for the remediation of greenhouse wastewaters. The treatment capacity of all wetland designs tested were significantly exceeded for all nutrients analyzed. This does provide information on the maximum treatment capacity of the various designs. Reductions of 74% ammonia and 65% phosphate were achieved in the second unplanted SF wetland. Reductions of 54% and 45% nitrate-nitrogen were realized in the 15 cm planted SF and 30 cm planted SF wetlands, respectively. Based on the results of the research and data obtained from the literature, a multi-stage design, consisting of an unplanted pre-treatment basin followed by a 30 cm surface flow marsh with open water, is recommended for the combined removal of phosphate, nitrate and ammonium from greenhouse overdrain.

For the removal of phosphorus as either total phosphorus or phosphate, pre-treatment of the greenhouse overdrain will be required to reduce the concentration of phosphorus entering the treatment wetland to a level than can be realistically treated. Due to the high concentration of calcium in the greenhouse effluents, this can be accomplished by raising the pH in a settling basin and precipitating the phosphorus from solution as hydroxyapatite. If a pH of 8.5 to 9.0 is maintained within the basin, more than 90% of the phosphate can realistically be removed from solution before the overdrain enters the marsh component of the treatment wetland. The pH can be raised to this level naturally by promoting algal growth or artificially by raising the pH using caustic soda (NaOH) or another inexpensive base. Artificially raising the pH of the pre-treatment basin would create an environment that permits the establishment of the desired algal communities. As high pH conditions are commonly found in municipal wastewater treatment lagoons, it is not unlikely that an algal community which promotes a high pH environment will develop.

Nitrate removal is accomplished in the marsh component of the wetland utilizing the decaying plant and algal biomass as the carbon source for denitrification. Based on the results from the 15 cm SF

and 30 cm SF experimental wetlands from this study, nitrate concentration in the greenhouse overdrain can be reduced to acceptable levels for the protection of freshwater aquatic life (less than 40 ppm) using a loading rate of 1.65 g $\text{NO}_3\text{-N}/\text{m}^2/\text{day}$ and a design water depth of 30 cm or greater. As the pH of raw greenhouse wastewaters is at the low end of the pH range for denitrifying bacteria, an ancillary benefit to having a pre-treatment basin for lowering the phosphate concentration is the alkaline wastewaters entering the marsh portion of a treatment wetland provides a more favourable pH for denitrification.

The primary objective of this research project was assess the capability of constructed wetlands to reduce and remove the excess nutrients present in the overdrain generated by vegetable production greenhouses. It was also an objective to use the results of this assessment to identify the most efficient constructed wetland design for the treatment of vegetable greenhouse wastewaters. Based on the findings of this research, a treatment wetland could effectively remediate the wastewaters generated from vegetable production greenhouses. However, given the extremely high concentrations of nitrate and very low concentrations of organic carbon in the overdrain, a very large area of land, in the order of 0.5 hectare of wetland per hectare of greenhouse, would be required for the wetland itself to generate sufficient carbon to denitrify all of the nitrate. If producers can achieve greater control over water and nutrient wastes, appropriately designed natural treatment options, such as constructed wetlands, can provide the necessary level of remediation.

Recommendations for further research in this field include conducting an assessment of a multi-stage design and more detailed assessments of denitrification rates in the wetland. Collection of dissolved oxygen and oxidation-reduction potential data would allow for a more accurate estimate of denitrification rates and the development of more specific design criteria. The identification of a higher supply of organic carbon for denitrification is also a necessity. One potential source of carbon

for use as a supplement to improve denitrification is the plant biomass which is removed from the production areas at the end of each growing season. Composting this plant matter and using the end product may provide the necessary mass of carbon for complete denitrification without the area requirements suggested by the results of this research project.

7.0 BIBLIOGRAPHY

1. American Waste Water Association. Standard Methods for the Analysis of Water and Wastewater. 1995.
2. Avnimelech, Y., S. Diab and M. Kochba. Development and evaluation of a biofilter for turbid and nitrogen rich irrigation water. *Water Research*. 1993; 27(5):785-790.
3. Bowden, W. B. The biogeochemistry of nitrogen in freshwater wetlands. *Biogeochemistry*. 1987; 4:313-348.
4. Boyd, C. E. Chemical Composition of Wetland Plants. In. *Freshwater Wetlands: Ecological Processes and Management Potential*. New York: Academic Press; 1978; pp. 155-167.
5. Boyd, R. F. General Microbiology. Toronto: Times Mirror/Mosby College Publishing; 1984; ISBN: 0-8016-0900-3.
6. British Columbia Ministry of Agriculture, Fisheries and Food. Greenhouse Vegetable Production Guide for Commercial Growers. Victoria: BCMAFF; 1993.
7. British Columbia Ministry of Agriculture, Fisheries and Food. Environmental Guidelines for Greenhouse Growers. Victoria, B.C.: BCMAFF; 1994; ISBN: 0-7726-2005-9.
8. British Columbia Ministry of Environment Lands and Parks. Water Quality Criteria. Victoria: MELP; 1994.
9. Canadian Council of Ministers of the Environment. Canadian Water Quality Guidelines. Ottawa; 1995.
10. Cooper, P. F., J. A. Hobson and C. Findlater. The use of reed bed treatment systems in the UK. *Water Science and Technology*. 1990; 22(3/4):57-64.
11. Emsley, J. The Phosphorus Cycle. In. *The Handbook of Environmental Chemistry*, Vol. 1 Part A. New York: Springer-Verlag Berlin Heidelberg; 1980; pp. 147-167.
12. Faulkner, S. P. and C. J. Richardson. Physical and Chemical Characteristics of Freshwater Wetland Soils. In. *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural*. Boca Raton, Florida: Lewis Publishers; 1989; pp. 41-72.
13. Frevert, T. Chemical Limnology. In. *The Handbook of Environmental Chemistry*, Vol. 1, Part D. Berlin: Springer-Verlag; 1985; pp. 83-124.
14. Godshalk, G. L. and J. W. Barko. Vegetative succession and decomposition in reservoirs. In. *Microbial Processes in Reservoirs*. Boston: Dr. W. Junk Publishers; 1985; pp. 59-77.
15. Grant, W. D. and P. E. Long. Environmental Microbiology. In. *The Handbook of Environmental Chemistry*, Vol. 1, Part D. Berlin: Springer-Verlag; 1985; pp. 125-237.

16. Green, M. B. and J. Upton. Constructed reed beds: A cost-effective way to polish wastewater effluents for small communities. *Water Environment Research*. 1994 May; 66(3):188-192.
17. Haberl, R. and R. Perfler. Nutrient removal in a reed bed system. *Water Science and Technology*. 1990; 23(4):729-737.
18. Haberl, R., R. Perfler and H. Mayer. Constructed wetlands in Europe. *Water Science and Technology*. 1995; 32(3):305-315.
19. Hammer, D. A. (ed.) *Constructed Wetlands for Wastewater Treatment*. Chelsea, Michigan: Lewis Publishers; 1989; ISBN: 0-87371-184-X.
20. Hardgrave, M. and C. Hufton. Reed-beds for treatment of hydroponic run-off. 1995 Mar:22. Note: Horticultural Development Council Project PC67.
21. Huag, R. T. *The Practical Handbook of Compost Engineering*. Lewis Publishers; 1993.
22. Huang, P. M. Adsorption Processes in Soil. In. *The Handbook of Environmental Chemistry*. Berlin: Springer-Verlag; 1980; pp. 47-61.
23. Jeter, R. M. and J. L. Ingraham. The Denitrifying Prokaryotes. In. *The Prokaryotes: A Handbook of Habits, Isolation and Identification of Bacteria*. Volume I. Berlin: Springer-Verlag; 1981.
24. Johnston, Carol A. Sediment and Nutrient Retention by Freshwater Wetlands: Effects on Surface Water Quality. *Critical Reviews in Environmental Control*. 1991; 21(5,6):491-565.
25. Kadlec, R. H. and R. L. Knight. *Treatment Wetlands*. Boca Raton, FL: Lewis Publishers; 1996; ISBN: 0-87371-930-1.
26. Khasawneh, F. E. and E. C. Doll. The Use of Phosphate Rock for Direct Application to Soils. *Advances in Agronomy*. 1978; 30:159-206.
27. Knight, R., J. Hilleke and S. Grayson. Design and performance of the Champion pilot-constructed wetland treatment system. *Tappi*. 1994 May; 77(5):240-245.
28. Maehlum, T. Treatment of landfill leachate in on-site lagoons and constructed wetlands. *Water Science and Technology*. 1994; 32(3):129-136.
29. Martin, C. D. and K. D. Johnson. The use of extended aeration and in-series surface-flow wetlands for treatment of landfill leachate. *Water Science and Technology*. 1995; 32(3):119-128.
30. Metcalf and Eddy, Inc. *Wastewater Engineering: Treatment, Disposal and Reuse*. - 3rd Edition. Revised by G. Tchobanoglous and F.L. Burton. New York: McGraw-Hill, Inc.; 1991; ISBN: 0-07-041690-7.

31. Mosheri, G. A. ed. *Constructed Wetlands for Water Quality Improvement*. Boca Raton, Florida: Lewis Publishers; 1993; ISBN: 0-87371-550-0.
32. Narkis, N., Rebhun, M. and Sheindorf, C.H. Denitrification at Various Carbon to Nitrogen Ratios. *Water Research* 1979, 13(1):93-98.
33. Parfitt, R. L. Anion Adsorption by Soils and Soil Materials. *Advances in Agronomy*. 1978; 30:1-49.
34. Perfler, R. and R. Haberl. Actual experiences with the use of reed bed systems for wastewater treatment in single households. *Water Science and Technology*. 1993; 28(10):141-148.
35. Reed, S. C. and D.S. Brown. Subsurface flow wetlands - A performance evaluation. *Water Environment Research*. 1995; 67(2):244-248.
36. Reed, S. C. and D. S. Brown. Constructed wetland design - the first generation. *Water Environment Research*. 1992; 64(6):776-781.
37. Reed, S. C., R. W. Crites and E. J. Middlebrooks. *Natural Systems for Waste Management and Treatment*, Second Edition. New York: McGraw-Hill, Inc.; 1995; ISBN: 0-07-060982-9.
38. Richardson, C. J. Mechanisms Controlling Phosphorus Retention Capacity in Freshwater Wetlands. *Science*. 1985 Jun; 228:1424-1427.
39. Richardson, C. J. and P. E. Marshall. Processes Controlling Movement, Storage and Export of Phosphorus in a Fen Peatland. *Ecological Monographs*. 1986; 56(4):279-302.
40. Rogers, K. H., P. F. Breen and A. J. Chick. Nitrogen removal in experimental wetland treatment systems: evidence for the role of aquatic plants. *Research Journal of the Water Pollution Control Federation*. 1991; 63(7):934-941.
41. Soderlund, R. and T. Rosswall. The Nitrogen Cycles. In: *The Handbook of Environmental Chemistry*, Vol. 1, Part B. Berlin: Springer-Verlag; 1982; pp. 61-81.
42. USEPA. *Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment*. Cincinnati, OH: USEPA; 1988.
43. USEPA. *Manual: Nitrogen Control*. Cincinnati, OH: USEPA; 1993.
44. van Oostrom, A. J. Nitrogen removal in constructed wetlands treating nitrified meat processing effluent. *Water Science and Technology*. 1995; 32(3):137-148.
45. van Oostrom, A. J. and J. M. Russel. Denitrification in constructed wastewater wetlands receiving high concentrations of nitrite. *Water Science and Technology*. 1994; 29(4):7-14.
46. Vymazal, J. *Algae and Element Cycling in Wetlands*. Boca Raton, FL: Lewis Publishers; 1995; ISBN: 0-87371-899-2.

47. Watson, W. W., F. W. Valois and J. B. Waterbury. The Family Nitrobacteraceae. In. The Prokaryotes: A Handbook of Habits, Isolation and Identification of Bacteria. Volume I. New York: Springer-Verlag; 1981; pp. 925-1022.
48. Wood, A. Constructed wetlands in water pollution control: Fundamentals to their understanding. Water Science and Technology. 1995; 32(3):21-30.
49. Zehnder, A. J. B. The Carbon Cycle. In. The Handbook of Environmental Chemistry, Vol. 1, Part B. Berlin: Springer-Verlag; 1982; pp. 83-110.

APPENDIX 1. RAW DATA

Total phosphorus (mg/L)

	25-Apr	02-May	16-May	30-May	13-Jun	27-Jun	08-Aug	22-Aug	05-Sep	19-Sep	17-Oct	31-Oct	14-Nov	28-Nov	12-Dec
ge	141.57	83.16	153.49	153.93	305.79	99.00	x	61.68	67.37	17.76	28.24	71.62	8.14	x	x
1a	80.01	79.54	76.91	129.05	x	x	112.05	63.40	54.89	31.76	14.23	39.21	14.06	10.70	10.32
1b	69.66	58.98	67.29	141.06	x	x	116.71	71.01	51.89	20.56	15.26	30.87	11.80	6.32	9.35
1c	62.92	56.14	53.21	141.58	x	x	88.66	61.90	36.92	19.40	12.89	31.35	13.13	8.85	7.80
2a	88.08	84.35	140.12	72.78	x	x	131.11	73.84	40.85	15.34	11.45	28.86	8.89	5.27	5.24
2b	88.72	86.81	115.88	72.73	x	x	115.33	78.75	49.23	17.14	12.46	29.42	10.32	5.75	5.48
2c	72.47	77.84	89.51	50.01	x	x	113.20	62.18	40.32	10.96	21.81	31.18	14.19	10.62	6.40
3a	81.00	96.28	122.20	241.72	263.89	99.98	109.13	48.54	39.08	29.98	13.71	33.54	11.81	6.20	8.00
3b	65.37	87.03	115.34	237.30	249.30	101.92	65.94	62.34	44.25	30.52	15.64	28.42	13.79	6.67	9.94
3c	74.95	88.22	125.36	193.22	190.60	98.57	59.12	82.07	45.54	26.06	17.83	37.08	14.92	11.64	11.52
4a	78.69	102.86	126.61	241.04	237.13	91.01	116.23	60.85	38.10	15.60	13.68	19.05	11.43	8.81	7.58
4b	45.17	80.60	124.40	220.08	234.45	100.31	104.17	62.01	39.32	15.06	14.79	34.87	12.02	9.08	8.69
4c	87.99	89.34	125.17	202.40	206.71	88.57	74.28	84.71	40.39	18.04	16.73	37.56	16.47	10.38	11.03
5c	60.34	85.04	138.82	121.91	139.96	152.09	0.75	60.10	32.81	20.11	12.03	20.02	10.79	7.69	6.60
6c	62.17	83.61	102.72	105.21	108.20	37.38	61.00	6.57	6.06	4.35	2.83	1.26	5.00	1.85	1.38
7a	53.97	82.59	111.13	123.33	76.11	77.36	103.98	60.25	26.97	33.48	14.94	30.91	12.14	12.05	9.37
7b	54.53	72.67	81.20	91.16	51.03	49.27	28.47	46.78	40.12	26.77	25.55	32.84	14.69	9.29	8.55
7c	53.21	65.58	76.11	89.36	85.74	66.28	36.41	66.82	26.77	17.82	20.61	50.82	15.57	10.77	11.03
8a	60.29	84.12	114.67	77.25	52.72	66.21	20.03	45.66	25.92	24.34	15.67	19.22	13.21	5.92	6.10
8b	35.45	58.76	111.51	68.84	36.14	37.17	17.45	18.47	26.27	13.35	15.93	23.11	11.15	10.20	7.20
8c	67.48	72.88	89.40	69.61	45.95	50.05	38.40	26.88	28.44	10.20	18.67	28.31	16.31	9.76	10.49
9a	42.84	72.73	64.63	15.94	21.95	26.22	87.57	49.37	30.70	30.06	14.73	30.42	11.72	11.07	9.37
9b	16.33	51.69	43.86	23.16	1.96	21.79	15.27	33.04	31.66	17.76	18.34	35.41	11.60	11.76	9.28
9c	83.77	90.86	78.01	52.40	49.37	55.03	34.92	67.22	44.54	17.39	19.36	39.49	14.30	12.55	11.89
10a	47.14	76.89	73.35	74.04	x	101.99	103.30	59.34	32.01	17.80	16.23	35.68	15.12	14.33	10.32
10b	8.33	37.73	40.73	35.30	24.64	54.58	19.86	49.65	34.82	21.41	16.94	32.10	12.41	9.93	6.89
10c	80.37	87.34	95.54	94.03	73.28	79.53	30.49	63.46	68.35	16.86	16.86	40.11	17.47	18.63	16.02

Ammonia (mg/L)

	12-Apr	25-Apr	02-May	16-May	30-May	13-Jun	27-Jun	25-Jul	08-Aug	22-Aug	05-Sep	19-Sep	03-Oct	17-Oct	31-Oct	14-Nov	28-Nov	12-Dec
ge	41.33	46.15	27.87	28.26	46.38	12.28	15.79	3.27	4.38	4.45	4.51	40.04	2.59	3.14	4.74	0.90 x	x	
1a	23.78	15.42	14.21	3.43	21.46	x	x	3.51	2.52	1.88	2.75	17.22	20.20	5.07	4.67	3.94	5.12	3.86
1b	16.53	16.00	6.92	2.76	26.81	x	x	2.52	1.95	0.78	1.44	11.45	10.38	4.36	3.14	2.08	2.93	4.31
1c	8.92	14.09	6.83	0.74	22.10	x	x	1.66	0.52	0.00	0.76	8.00	6.86	5.31	1.24	3.11	3.95	2.71
2a	14.39	18.35	15.70	20.31	1.82	x	x	3.01	2.74	2.11	1.61	7.11	15.23	1.44	2.61	1.07	2.48	2.64
2b	17.25	21.14	17.55	16.34	2.17	x	x	2.49	1.09	0.45	1.25	4.51	3.43	3.99	2.59	2.13	2.71	2.43
2c	10.77	17.45	15.18	9.53	0.87	x	x	1.95	1.54	0.00	0.75	3.52	1.21	6.04	1.91	3.71	5.03	2.60
3a	10.95	19.67	20.61	24.40	16.10	14.83	2.86	1.86	2.67	2.96	4.05	17.09	21.16	7.30	4.43	3.63	3.25	2.36
3b	13.23	16.37	19.09	24.40	13.73	14.69	2.44	0.84	2.44	2.00	2.91	9.96	6.23	1.73	1.78	3.30	2.94	2.00
3c	12.75	19.82	22.09	24.40	12.03	1.83	1.55	0.65	2.09	2.12	2.52	9.21	9.93	6.12	2.95	6.05	6.32	4.55
4a	11.78	18.81	20.52	22.04	9.92	11.87	1.93	1.80	1.80	1.90	1.05	10.15	6.09	3.26	4.96	2.89	4.94	2.57
4b	16.53	10.42	16.54	24.40	8.49	7.67	1.86	1.33	2.15	1.56	0.87	4.85	4.33	4.29	2.49	4.63	4.60	2.93
4c	12.93	19.82	24.08	24.40	12.31	3.62	0.72	0.73	1.62	0.72	2.25	11.27	2.82	9.77	4.58	7.51	6.20	5.01
5c	17.98	11.53	15.49	20.73	11.03	8.66	0.12	0.00	0.00	1.69	2.22	6.91	6.74	0.00	0.23	0.49	0.19	0.00
6c	17.57	8.69	11.60	20.98	13.23	2.01	0.06	0.00	0.00	0.03	0.48	2.34	0.95	0.04	0.42	0.00	0.39	0.06
7a	14.42	9.24	13.93	24.40	27.09	24.37	27.32	2.09	0.00	2.66	2.52	16.89	12.95	8.81	1.11	3.19	4.37	0.03
7b	14.27	7.47	11.84	22.93	20.95	12.53	11.14	1.66	0.00	1.18	2.20	11.19	14.50	17.08	2.50	1.53	3.37	0.57
7c	25.85	9.01	10.76	20.95	19.72	21.57	24.44	2.96	0.00	1.10	2.25	13.40	14.03	13.00	9.63	2.70	6.25	0.44
8a	19.29	9.55	18.04	19.67	15.12	x	16.50	1.27	0.00	2.40	2.22	15.71	16.03	3.37	0.52	0.88	0.77	6.02
8b	9.95	4.05	10.71	19.81	13.28	x	14.93	1.12	0.00	1.72	1.71	11.34	8.91	1.71	0.46	0.08	0.04	0.05
8c	27.49	15.90	17.78	19.61	18.12	x	21.70	3.39	0.00	1.10	1.23	9.20	11.41	7.66	1.64	1.24	0.09	1.02
9a	13.62	5.64	9.34	3.38	2.28	4.75	5.70	2.19	0.00	2.66	3.28	17.76	17.57	3.16	1.90	1.90	2.02	1.74
9b	8.73	0.57	6.34	2.20	0.90	2.04	21.33	2.61	0.53	1.43	2.93	15.19	11.82	5.37	2.03	1.46	2.24	1.25
9c	31.37	21.42	21.06	15.52	4.83	8.46	10.26	2.03	0.72	2.27	2.12	12.81	14.33	8.09	3.45	2.10	2.34	1.62
10a	13.99	7.33	10.31	7.70	8.78	10.66	15.51	2.10	1.19	3.04	3.14	14.33	11.84	3.98	2.56	1.60	3.75	1.91
10b	8.72	0.29	6.48	1.29	2.01	2.25	11.92	3.14	1.46	2.01	1.13	11.10	6.12	5.75	2.54	0.83	3.06	1.31
10c	27.15	20.54	19.81	16.46	18.14	12.12	18.66	0.85	1.23	2.24	3.01	2.16	2.90	5.73	4.07	3.16	3.29	1.30

Nitrate-nitrogen (mg/L)

	12-Apr	25-Apr	02-May	16-May	30-May	13-Jun	27-Jun	25-Jul	08-Aug	22-Aug	19-Sep	03-Oct	17-Oct	31-Oct	14-Nov	28-Nov	12-Dec
ge	206.66	219.10	194.19	314.71	268.64	333.80	178.52	315.71	230.12	362.25	251.33	66.45	209.74	168.07	28.96	x	x
1a	118.91	121.16	106.54	38.23	340.83	x	x	262.84	287.42	251.61	188.15	179.06	76.31	65.78	66.87	30.61	7.48
1b	82.65	80.66	63.58	30.57	290.12	x	x	237.00	191.82	219.79	122.02	172.32	86.16	26.67	20.49	9.14	0.32
1c	44.61	69.44	50.64	29.10	328.29	x	x	240.50	197.74	188.55	105.66	119.74	86.91	35.91	48.77	25.60	6.55
2a	71.97	142.56	164.72	175.74	63.97	x	x	239.99	229.55	327.88	94.00	186.47	55.23	46.87	10.11	5.45	16.54
2b	86.24	122.78	141.21	130.42	53.13	x	x	248.15	165.37	185.63	59.65	80.34	60.18	40.33	24.62	6.84	9.20
2c	53.86	89.95	114.89	95.96	33.46	x	x	224.15	145.89	134.84	50.19	35.43	81.20	49.85	56.72	45.35	17.36
3a	54.73	111.63	164.12	253.36	229.26	175.06	198.09	220.97	186.03	301.51	134.99	181.27	93.66	46.42	38.77	4.16	10.06
3b	66.17	75.74	131.54	229.86	163.26	137.94	135.80	162.06	143.51	249.77	172.08	98.06	34.98	7.26	22.03	6.56	15.16
3c	63.76	96.35	142.35	235.68	135.29	108.96	121.06	145.78	192.00	232.53	103.96	124.38	79.73	12.23	71.22	17.55	13.93
4a	58.92	96.99	184.72	279.77	209.40	143.60	156.37	229.23	182.16	324.51	163.48	109.98	83.45	63.53	31.98	25.25	9.15
4b	82.67	51.99	114.55	245.98	153.60	113.64	144.60	219.49	176.01	254.00	113.62	160.63	45.66	7.66	40.49	9.86	13.32
4c	64.63	113.61	152.42	240.24	154.64	115.73	115.74	171.94	200.72	246.88	86.10	67.33	57.32	25.33	107.03	27.32	21.63
5c	89.90	112.13	169.53	264.21	271.71	306.19	297.70	327.07	278.68	445.42	232.72	243.35	144.12	106.13	82.97	61.61	42.51
6c	87.86	111.73	164.29	252.32	253.62	252.36	280.67	241.08	231.56	295.05	182.83	214.00	109.43	75.31	66.97	59.83	37.38
7a	72.08	105.64	209.67	237.87	236.95	189.53	279.95	249.68	138.00	368.79	175.31	179.10	103.16	14.16	37.25	75.59	25.40
7b	71.33	102.53	178.30	258.90	210.97	77.35	150.80	229.13	173.56	289.88	114.02	178.55	145.81	15.67	17.73	63.38	27.73
7c	129.24	126.63	167.34	254.15	210.54	246.92	297.70	205.97	271.62	240.79	169.52	204.36	123.40	97.42	44.70	138.26	57.78
8a	96.45	72.06	170.79	255.66	114.15	111.07	226.00	261.76	137.72	294.50	179.97	201.58	109.71	24.98	22.98	34.18	14.20
8b	49.73	77.53	140.33	238.17	124.53	132.09	186.59	206.16	152.13	344.17	151.74	135.37	62.39	34.12	7.04	32.56	13.09
8c	137.43	170.80	191.60	222.17	216.50	187.52	222.41	239.61	235.49	236.93	193.34	223.03	101.08	73.84	56.74	22.52	26.72
9a	68.12	30.30	127.81	101.70	78.72	116.22	207.28	244.30	172.79	292.98	176.50	219.08	101.24	35.43	26.52	13.31	1.16
9b	43.65	27.62	82.52	56.22	35.66	53.97	109.54	285.37	146.45	195.45	179.80	191.19	104.44	45.84	36.48	18.29	1.49
9c	156.84	117.84	223.36	207.07	153.06	163.77	193.88	244.36	299.36	307.57	200.18	243.80	110.09	112.01	45.30	37.91	23.39
10a	69.96	27.62	121.90	96.62	137.13	178.95	297.70	255.26	184.13	280.83	257.60	238.40	101.58	33.23	2.54	2.17	0.29
10b	43.62	27.62	59.23	30.22	44.66	79.98	211.62	313.90	186.93	194.29	315.89	186.89	89.73	23.00	1.92	1.37	0.02
10c	135.77	38.09	180.74	192.16	304.89	204.84	273.18	428.80	350.19	398.11	239.15	164.38	114.87	105.43	101.69	38.76	16.21

Total Organic Carbon (mg/L)

	12-Apr	25-Apr	02-May	16-May	30-May	13-Jun	27-Jun	25-Jul	08-Aug	22-Aug	05-Sep	19-Sep	03-Oct	17-Oct	31-Oct	14-Nov	28-Nov	12-Dec
dH2O	0.58	0.78	1.69	1.46	1.80	1.16	1.07	2.08	1.85	1.59	2.256	2.602	6.22	x	3.165	3.298	3.786	3.502
ge	32.24	13.83	15.06	26.05	15.07	27.60	13.77	20.13	9.84	10.21	18.24	19.79	32.14	42.48	18.75	8.39	x	x
1a	67.27	46.11	47.41	67.05	21.27	x	x	35.59	35.75	35.15	38.25	36.16	56.36	21.55	34.83	23.52	34.90	35.26
1b	60.33	36.06	51.37	68.63	21.58	x	x	32.90	44.87	41.65	51.00	49.04	36.56	22.83	44.87	35.23	25.18	50.72
1c	73.38	37.85	49.99	66.43	23.52	x	x	46.05	44.95	51.45	38.46	46.50	29.05	27.20	31.07	25.05	25.14	28.82
2a	67.82	43.97	37.72	43.05	50.40	x	x	37.19	40.77	32.61	46.30	62.24	30.00	36.82	37.41	44.75	23.79	27.85
2b	67.62	39.37	39.46	43.00	53.83	x	x	45.66	40.45	46.18	55.50	56.95	37.40	38.80	28.30	35.92	23.23	26.45
2c	65.77	37.66	38.44	45.83	57.01	x	x	58.13	43.49	48.73	55.35	57.50	38.15	29.34	29.05	26.32	19.80	25.98
3a	55.79	36.04	38.23	35.08	40.95	46.72	43.81	31.15	35.01	20.74	24.11	30.92	21.92	20.36	28.13	25.61	16.77	18.26
3b	57.19	39.48	44.27	36.27	45.25	48.07	45.71	42.66	43.67	23.60	24.41	30.60	32.64	31.56	33.78	38.19	18.76	18.90
3c	54.56	37.77	27.66	39.41	40.13	45.35	47.43	46.05	33.68	24.66	31.23	37.22	26.03	22.84	40.20	21.95	24.77	25.11
4a	57.42	39.84	46.81	41.63	43.38	71.41	45.87	26.53	32.50	17.93	45.20	41.20	40.45	28.70	44.95	19.91	16.35	19.83
4b	56.87	36.32	41.71	41.63	56.83	72.33	52.13	32.37	50.00	26.16	41.55	41.55	34.65	49.05	38.88	27.34	17.56	18.57
4c	53.12	38.85	41.47	39.76	47.43	55.21	50.63	44.05	32.34	25.68	45.30	51.05	42.90	46.25	56.85	17.50	23.15	22.95
5c	27.21	25.41	32.46	23.91	23.19	30.01	30.41	19.53	17.28	14.67	11.18	19.16	21.40	15.90	10.92	11.47	9.79	9.27
6c	36.24	21.86	22.73	22.11	19.50	28.37	19.88	9.87	15.44	7.07	7.11	20.81	15.42	24.73	28.27	21.47	8.20	11.86
7a	26.29	15.08	27.69	24.87	19.57	24.03	31.23	20.33	27.45	10.98	12.90	22.07	15.21	11.26	7.07	11.42	5.43	5.42
7b	21.98	14.39	20.15	26.49	23.78	33.54	36.06	35.77	26.72	16.10	14.55	17.52	16.28	12.24	9.92	11.77	9.35	7.53
7c	18.70	17.85	16.56	21.20	22.33	24.16	24.25	31.94	20.85	24.30	13.47	12.82	12.81	10.62	10.15	9.99	5.90	5.20
8a	25.44	26.12	25.69	21.04	22.07	21.73	24.58	32.12	20.35	14.26	14.92	16.84	15.99	5.79	24.48	21.80	23.34	13.98
8b	9.46	12.63	21.60	21.84	20.21	19.00	18.80	32.48	33.80	17.20	16.09	14.34	15.97	7.72	6.84	13.24	9.99	6.43
8c	18.54	24.49	21.04	23.95	19.40	19.68	24.46	26.04	30.34	24.35	18.66	13.40	13.14	10.12	9.19	12.64	7.37	7.00
9a	18.06	18.43	22.13	19.31	18.21	17.37	19.23	25.95	24.27	11.83	13.45	20.52	14.74	13.34	31.24	19.52	24.58	28.84
9b	15.11	14.70	19.87	16.03	17.14	15.11	33.53	36.62	35.90	22.88	13.42	18.77	20.52	14.01	22.93	20.19	25.14	28.36
9c	20.80	27.40	31.58	25.58	15.85	20.10	24.15	29.68	25.82	18.09	13.93	17.05	16.60	19.16	10.43	12.23	15.07	16.28
10a	17.46	17.68	21.94	18.24	17.75	16.49	20.04	23.98	25.47	13.99	19.08	29.48	22.14	16.60	38.72	60.03	60.45	33.76
10b	14.03	11.84	13.74	14.50	21.03	14.14	20.52	35.88	33.71	23.34	29.74	35.62	34.88	22.83	33.70	38.88	38.14	26.46
10c	21.55	27.77	19.92	20.56	23.35	18.79	26.27	39.51	30.33	26.01	22.70	31.37	19.66	21.20	12.73	13.88	28.95	38.94

BOD5 (mg/L)

	03-May	17-May	30-May	13-Jun	25-Jul	08-Aug	22-Aug	05-Sep
ge	4.82	6.37	2.17	x	5.25	1.43	8.56	7.79
1a	18.53	43.66	7.72	x	27.48	33.14	37.19	25.50
1b	19.28	27.80	8.04	x	14.84	31.44	26.28	15.88
1c	18.12	42.06	6.20	x	17.14	8.22	0.90	9.81
2a	12.53	28.24	7.68	x	15.30	29.12	20.94	22.62
2b	14.29	20.46	19.86	x	17.24	24.04	26.88	22.08
2c	14.75	29.29	10.42	x	22.48	23.40	9.92	12.11
3a	8.95	19.63	10.27	30.62	16.23	25.85	35.97	19.16
3b	9.83	1.32	19.35	26.64	13.66	23.25	4.30	8.31
3c	9.11	2.81	4.86	x	12.89	24.37	4.90	22.32
4a	16.35	39.46	11.44	25.59	23.13	26.73	14.46	35.32
4b	14.29	3.55	18.76	27.62	12.77	26.91	30.09	25.48
4c	9.16	6.75	6.96	x	13.13	8.55	4.26	15.21
5c	8.68	5.92	4.09	11.62	11.98	9.79	5.78	4.97
6c	3.44	6.74	3.57	17.28	8.26	15.77	0.00	2.35
7a	8.43	18.62	6.68	8.14	6.45	10.53	3.08	8.20
7b	12.54	13.56	5.50	12.73	21.51	16.56	14.47	24.20
7c	7.28	3.90	3.02	1.63	5.91	3.52	0.00	2.16
8a	19.87	6.15	5.46	10.51	8.64	3.84	0.00	3.46
8b	19.81	4.65	7.30	7.03	6.81	5.29	0.99	3.98
8c	4.91	2.65	3.92	3.62	5.01	4.16	0.22	2.05
9a	5.75	3.74	4.78	2.94	6.53	7.44	3.98	4.88
9b	9.96	4.74	7.50	2.36	16.06	11.61	0.00	4.72
9c	2.98	1.41	3.20	5.46	5.04	2.46	0.00	1.42
10a	6.00	3.53	3.16	2.24	13.02	5.86	0.00	3.20
10b	4.55	4.10	9.55	4.33	18.66	6.55	1.52	1.95
10c	2.07	1.70	1.96	2.01	4.90	3.01	0.00	3.20

Total Solids (g/L)

	25-Apr	03-May	17-May	30-May	13-Jun	27-Jun	08-Aug	22-Aug	05-Sep	19-Sep	03-Oct	17-Oct	31-Oct	14-Nov	28-Nov	12-Dec
1a	1.42	1.08	1.12	1.34	x	x	2.44	3.96	4.02	2.96	2.38	1.542	1.042	0.752	0.692	0.41
1b	1.02	0.52	0.88	1.2	x	x	2.86	3.4	3.87	2.48	2.3	1.424	0.824	0.628	0.408	0.438
1c	1	0.78	-0.16	0	x	x	2.82	3.54	2.6	2.74	2.2	2.1	1.16	0.838	0.706	0.542
2a	1.64	0.94	2.26	1	x	x	3.14	3.12	4.4	2.2	2.4	0.81	0.822	0.522	0.502	0.426
2b	1.48	1.2	1.96	0.74	x	x	2.58	2.56	4.71	1.78	1.82	0.942	0.636	0.58	0.37	0.374
2c	1.16	1.38	1.54	0.6	x	x	2.1	2.48	2.67	1.64	1.6	1.65	0.876	0.866	0.786	0.588
3a	1.16	1.24	1.74	1.68	2.4	1.94	2.98	3.28	3.24	2.52	2.28	1.322	0.812	0.64	0.338	0.336
3b	1.02	0.94	1.64	1.32	2.82	1.88	3.46	2.44	3.4	3.18	1.38	0.712	0.412	0.71	0.308	0.422
3c	2.2	0.88	1.54	1.4	1.84	1.36	3	2.82	2.84	1.94	2	1.35	0.6	0.858	0.534	0.62
4a	1.86	2.04	1.58	2.06	3.38	1.66	3.1	2.9	4.33	3.2	2.2	1.762	1.62	0.864	0.598	0.31
4b	0.72	1.36	2.1	2.06	2.68	2.04	3.64	3.16	3.67	2.68	2.74	1.438	0.582	0.762	0.374	0.428
4c	1.34	1.3	1.02	1.6	1.38	1.84	1.58	2.84	3.38	2.56	2.1	1.32	0.932	1.138	0.596	0.64
5c	1.26	68.12	1.68	1.78	2.42	2.74	3	2.66	3.18	3.08	2.48	1.96	0.996	0.776	0.586	0.45
6c	1.26	1.44	1.94	1.34	1.76	2.38	2.56	2.44	2.93	2.88	2.12	1.44	0.798	0.616	0.57	0.41
7a	1.08	1.5	1.86	1.68	1.84	2.8	1.86	2.86	3.09	2.46	1.88	1.078	0.3	0.624	0.958	0.292
7b	1.08	1.52	2.1	1.52	0.7	1.68	3.42	3.22	3.02	1.9	2.32	2.374	0.646	0.632	1.272	0.432
7c	1.22	1.44	1.4	7.26	1.74	2.6	3.06	2.16	1.96	2.44	2.2	1.07	0.954	0.52	1.214	1.06
8a	0.9	1.5	1.96	1.4	1.18	2.9	1.94	3.14	2.49	2.46	1.92	1.022	0.494	0.468	0.524	0.282
8b	0.84	1.28	1.72	1.1	1.02	2.02	-10.7	3.04	2.93	2.26	1.68	0.702	0.44	0.326	0.46	0.216
8c	1.58	1.44	1.8	1.66	1.48	2.12	2.9	3.12	3.64	2.66	2.08	1.32	0.658	0.65	0.314	0.68
9a	0.4	1.44	0.94	0.96	1.08	1.84	1.96	2.88	2.8	2.32	2	1.046	0.512	0.448	0.332	0.224
9b	0.3	1.7	1.3	0.14	0.76	1.2	2.3	2.48	2.93	2.52	2.48	1.142	0.624	0.514	0.574	0.234
9c	1.58	1.86	1.02	1.54	1.28	1.7	3.3	3.08	2.98	2.72	2.24	1.03	1.028	0.536	0.506	0.41
10a	0.5	1.38	1.16	1.3	1.8	2.64	2.3	3.04	3.49	3.36	1.86	1.104	0.538	0.414	0.422	0.23
10b	0.18	0.98	0.52	0.44	1.38	2.12	1.72	2.54	4.02	4.46	3.7	1.072	0.488	0.386	0.324	0.196
10c	1.58	1.18	1.42	2.22	1.46	2.52	3.7	3.66	3.64	3.4	11.64	1.22	0.986	0.992	0.644	0.47
GE	1.44	1.42	2.56	1.3	2.72	1.42	2.44	3.86	2.67	2.36	1.46	1.27	1.422	0.236	x	x

Total Kjeldahl Nitrogen (TKN) (mg/L)

	12-Apr	25-Apr	16-May	30-May	13-Jun	08-Aug	22-Aug	05-Sep	19-Sep	31-Oct	14-Nov	28-Nov	12-Dec
ge	66.863	4.06075	3.50763	4.6305	1.8935	7.76	11.505	23.49	9.911	2.316	3.433	x	x
1a	30.283	12.8509	14.1098	6.499	x	7.28	5.404	3.38	4.934	52.2035	5.4105	8.3485	9.9025
1b	42.167	8.17063	7.35088	2.527	x	11.57	5.496	1.912	1.076	12.197	10.871	4.185	16.1735
1c	43.5335	9.89925	9.39413	3.8855	x	1.73	x	1.638	0.896	13.621	5.003	4.944	4.8375
2a	41.5265	4.71813	1.37588	32.689	x	0.13	6.72	6.956	3.474	8.0565	8.755	6.596	6.2945
2b	46.215	11.5971	1.81788	17.541	x	6.79	5.196	x	8.542	12.6145	7.562	4.5015	6.765
2c	43.0825	11.6564	1.52788	13.989	x	11.67	5.414	1.186	4.688	4.7945	4.12	4.127	4.37
3a	41.3085	5.94938	2.34013	17.3275	1.8335	3.53	7.162	8.546	3.884	8.5165	9.17	4.5825	6.394
3b	41.3275	16.3835	4.91425	8.3495	2.077	0.00	9.832	1.362	2.258	7.7565	12.158	3.8095	11.051
3c	34.5455	8.36138	2.05325	9.237	2.0105	4.70	1.056	7.014	1.356	9.057	5.603	6.2425	7.3135
4a	47.9615	6.04713	1.39975	12.8845	1.8375	4.56	5.4	3.59	15.6	7.9215	10.5135	5.4445	6.2485
4b	38.6455	10.8065	3.12713	16.3805	1.95	0.00	9.018	1.428	1.684	9.3445	8.8325	5.2515	5.0305
4c	33.497	4.875	1.79713	9.0635	2.1325	3.69	2.086	8.814	0.934	8.6755	3.7995	5.488	7.0405
5c	40.3115	8.885	2.32163	17.433	1.9365	0.00	x	1.496	3.348	1.828	2.0325	0.306	0.266
6c	29.256	6.53925	0.68925	7.9415	1.791	0.00	x	x	0.906	11.232	4.259	0.348	2.1365
7a	46.717	4.47038	0.68925	14.075	1.8965	2.21	5.228	9.16	4.156	5.7275	6.1115	1.7255	2.16
7b	45.3465	13.282	6.25875	7.4745	1.861	7.72	0.436	0.476	3.404	6.2075	5.3475	1.476	0.2755
7c	35.995	5.62088	0.68925	11.932	1.732	10.56	4.254	7.808	1.928	7.7825	4.6045	2.1105	x
8a	31.3715	10.7573	1.16688	5.197	1.7645	0.00	0.426	5.206	3.212	7.032	5.1105	1.7275	0.929
8b	28.6025	4.50913	0.98225	5.9475	1.793	0.00	2.65	2.484	2.72	5.244	3.9675	1.8745	x
8c	33.035	9.14013	1.05963	6.0345	1.749	6.00	0.716	5.096	0.972	6.3075	2.602	0.5665	x
9a	25.479	7.21975	1.86713	3.654	1.9745	13.04	7.37	8.016	5.592	6.492	4.7685	4.252	2.311
9b	28.535	3.93225	1.70688	13.1625	1.84	16.70	9.51	6.394	6.424	5.464	4.275	4.355	1.852
9c	31.7065	4.49475	2.283	15.527	1.896	3.69	0.894	4.358	1.472	2.304	3.711	1.7845	3.5875
10a	35.8905	3.859	1.49688	7.8965	x	1.66	9.802	9.358	2.44	6.215	7.05	6.1595	3.254
10b	32.48	3.859	1.4415	22.8535	1.9075	2.40	11.718	2.45	0.938	6.739	5.523	4.353	2.182
10c	34.64	3.859	2.11463	16.254	0.866	0.00	3.138	x	2.588	2.6925	2.862	3.94	4.561

Ortho-phosphate (mg/L)

	12-Apr	25-Apr	02-May	16-May	30-May	13-Jun	27-Jun	25-Jul	08-Aug	22-Aug	05-Sep	19-Sep	03-Oct	17-Oct	31-Oct	14-Nov	28-Nov	12-Dec
ge	106.68	122.16	80.33	142.97	155.26	148.38	91.39	132.91	120.16	116.05	98.31	42.43	19.69	65.35	90.76	49.16	x	x
1a	45.44	68.49	65.09	48.39	135.54	x	x	151.57	94.52	71.55	159.49	78.63	91.31	37.55	43.66	83.72	26.20	59.74
1b	67.70	58.41	50.61	42.54	124.67	x	x	123.24	109.02	70.24	112.41	67.69	78.26	37.16	34.39	59.45	16.76	57.34
1c	23.56	52.03	48.19	33.04	115.65	x	x	125.82	95.27	56.32	105.82	67.82	68.36	45.36	35.24	81.48	22.88	58.30
2a	32.60	74.14	74.16	106.71	40.00	x	x	153.79	118.87	63.19	76.40	50.79	85.20	28.53	32.33	45.46	12.31	37.42
2b	40.44	73.73	75.43	88.50	28.80	x	x	155.98	121.97	72.92	103.32	52.11	48.27	37.01	33.92	62.95	14.03	37.98
2c	27.77	60.22	65.96	75.04	0.93	x	x	100.82	96.30	61.19	62.03	48.18	45.95	55.14	35.77	91.54	27.14	46.34
3a	29.14	68.07	81.17	120.12	59.86	133.35	92.74	142.76	77.59	63.04	156.24	68.69	82.97	40.60	38.63	70.94	15.70	48.67
3b	55.40	55.64	71.50	120.90	67.61	127.05	95.25	93.87	98.12	71.08	169.23	80.29	59.71	29.64	32.10	80.65	17.18	62.18
3c	39.55	64.56	73.31	121.68	68.15	98.75	94.03	86.62	128.07	72.14	148.94	68.65	66.86	41.27	41.74	99.62	29.82	80.71
4a	30.48	67.70	86.64	119.83	93.95	123.41	86.52	156.60	94.71	57.86	84.23	50.05	42.85	35.92	49.62	63.50	23.37	48.69
4b	43.73	38.07	66.16	122.60	86.73	125.18	96.82	143.18	100.72	60.63	81.84	44.25	50.46	38.52	42.48	77.81	23.34	58.17
4c	39.79	73.80	76.53	122.31	94.34	109.71	85.93	151.33	131.48	61.20	91.92	47.58	35.17	42.94	42.48	110.76	28.86	76.65
5c	17.42	53.33	73.81	117.32	141.27	146.85	148.02	88.04	98.93	53.85	112.53	65.98	67.07	36.27	25.05	69.50	17.99	40.47
6c	20.49	53.36	71.75	106.54	117.25	118.52	41.98	7.94	5.93	11.20	41.14	14.33	6.29	5.10	1.90	16.67	4.75	4.81
7a	25.44	48.74	71.57	96.20	121.53	87.27	78.84	133.40	92.07	40.61	187.45	72.92	68.03	47.89	33.64	72.57	31.11	61.81
7b	17.62	45.54	61.02	76.33	93.30	64.14	54.38	38.26	69.61	56.92	162.37	75.91	66.11	65.07	29.29	94.26	24.03	57.50
7c	18.94	45.34	56.73	70.35	93.77	101.25	81.05	47.85	106.30	43.38	111.89	74.49	72.11	54.78	25.36	100.10	28.46	76.88
8a	22.69	48.37	72.61	106.62	79.53	68.83	72.30	36.31	71.71	42.08	147.49	76.25	74.58	42.19	6.31	81.68	15.48	42.54
8b	7.11	29.90	50.54	103.80	68.92	52.41	45.50	13.81	28.27	41.73	84.60	65.53	59.35	31.38	6.54	75.74	23.40	47.29
8c	15.98	57.60	63.34	83.43	75.70	63.88	57.27	39.04	42.33	44.74	61.77	50.46	56.47	44.50	3.08	106.73	26.16	74.00
9a	10.49	37.43	63.79	45.07	33.98	39.40	34.19	98.08	77.58	48.46	177.46	77.22	76.16	36.22	7.36	76.24	29.42	59.12
9b	12.11	13.01	44.17	29.06	18.30	18.56	29.77	3.53	50.81	49.40	123.89	72.53	64.80	45.43	44.29	72.09	31.00	61.86
9c	32.89	70.60	80.22	66.62	55.00	67.38	60.73	21.42	120.76	69.19	115.74	67.44	66.22	47.46	24.22	94.31	33.57	79.60
10a	12.00	40.02	65.56	63.02	76.45	90.41	105.94	109.75	92.94	49.28	117.19	53.16	47.01	40.44	22.83	90.82	37.34	66.68
10b	11.12	7.37	30.88	16.87	30.71	42.70	66.39	3.44	74.17	55.34	144.03	50.68	31.95	42.20	31.56	70.36	25.52	40.66
10c	29.36	67.16	73.42	79.76	98.43	46.92	86.75	5.24	93.75	102.69	134.54	47.73	47.72	41.08	21.32	110.45	49.21	105.62

To: Ward Prystay Bio-Resource Engineering
Room 76A-2357 Main Hall Van, B.C. V6Z 1T5
Phone:264-9793 822-6642 Fax:

1650 Pandora Street
Vancouver, B.C. V5L 1L6
Ph:(604)251-4456 Fax:258-9497

Project: Ward
Certificate: 9703191
Samples: 75

CAVENDISH LABORATORY LTD.
CERTIFICATE OF ANALYSIS

Date In: 3/19/97

Date Out: 3/27/97

Type of Analysis: WICP30-DIS

Sample	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPB	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM
--------	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----

To: Ward Prystay Bio-Resource Engineering
Room 76A-2357 Main Hall Van, B.C. V6Z 1T5
Phone:264-9793 822-6642 Fax:

1650 Pandora Street
Vancouver, B.C. V5L 1L6
Ph:(604)251-4456 Fax:258-9497

Project: Ward

CAVENDISH LABORATORY LTD.

Date In: 3/19/97

Certificate: 9703191

CERTIFICATE OF ANALYSIS

Date Out: 3/27/97

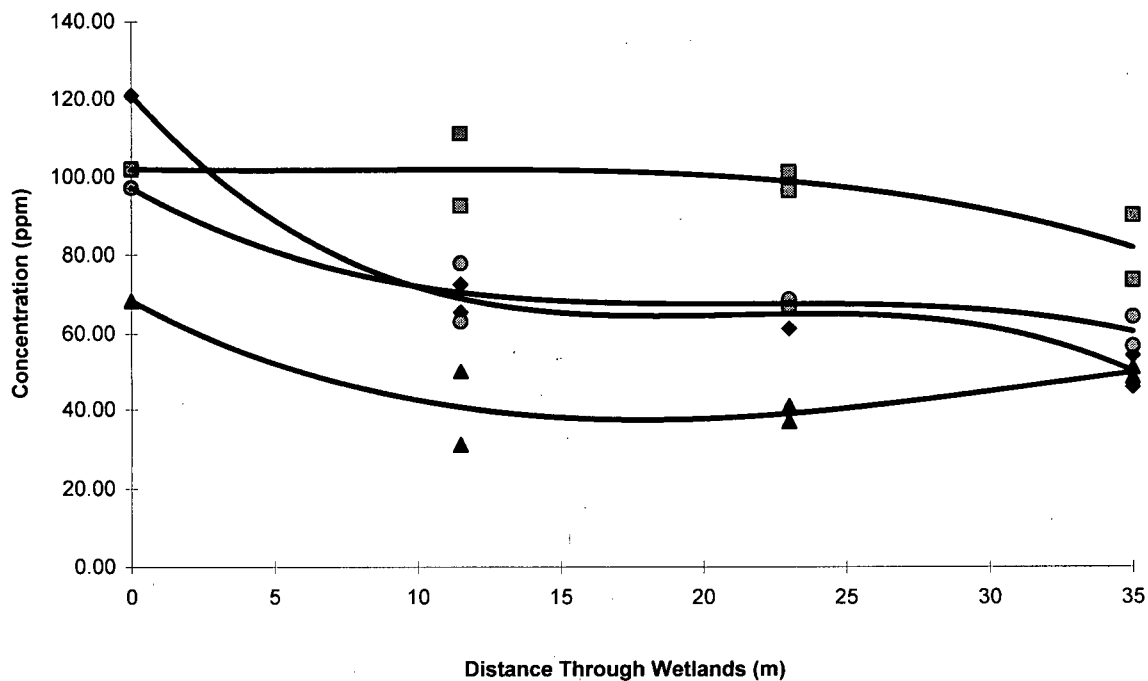
Samples: 75

Type of Analysis: WICP30-DIS

Sample Name	Ag	Al	As	B	Ba	Be	Bi	Ca	Cd	Co	Cr	Cu	Fe	Hg	K	La	Mg	Mn	Mo	Na	Ni	P	Pb	S	Sb	Se	Si	Sn	Sr	Ti	V	W	Zn
OCT 3 8A	.003	.81	.03	.23	.016	.003	<.04	104.6	<.002	<.005	.007	.077	.29	<.02	146.2	.022	32.5	.15	.072	14	.008	10.23	.04	42	.05	<.005	.1	<.01	1.400	<.005	<.005	<.03	.20
OCT 3 8B	<.003	.20	<.02	.07	.010	<.001	<.04	34.9	<.002	<.005	<.005	.038	.06	<.02	74.4	.025	14.5	.08	.014	8	<.005	4.77	<.02	17	<.03	<.005	<.01	<.01	.502	<.005	<.005	<.03	.09
OCT 3 8C	<.003	.60	.03	.14	.028	.002	<.04	82.7	<.002	<.005	<.005	.058	.12	<.02	118.9	.014	24.0	.20	.044	7	<.005	4.57	<.02	39	<.03	<.005	1.9	<.01	.995	<.005	<.005	<.03	.16
OCT 3 9A	<.003	.61	<.02	.15	.024	.002	<.04	81.8	<.002	<.005	<.005	.061	.41	<.02	111.5	.028	21.0	.28	.054	5	<.005	13.92	<.02	32	<.03	<.005	.1	<.01	1.065	<.005	<.005	<.03	.16
OCT 3 9B	<.003	.28	<.02	<.05	.018	<.001	<.04	43.6	<.002	<.005	<.005	.039	.09	<.02	64.5	.020	10.7	.02	.026	3	<.005	9.54	<.02	17	<.03	<.005	<.01	<.01	.598	<.005	<.005	<.03	.11
OCT 3 9C	<.003	.41	<.02	.08	.030	.001	<.04	58.5	<.002	<.005	<.005	.045	.24	<.02	76.8	.010	15.3	.09	.029	4	<.005	8.45	<.02	22	<.03	<.005	.2	<.01	.722	<.005	<.005	<.03	.12
OCT 3 10A	.004	.67	<.02	.30	.026	.002	<.04	86.8	<.002	<.005	<.005	.069	.19	<.02	134.3	.028	23.9	.02	.064	13	.009	8.69	.04	38	<.03	<.005	1.0	<.01	1.136	<.005	<.005	<.03	.21
OCT 3 10B	<.003	.46	<.02	.15	.027	.001	<.04	64.2	<.002	<.005	<.005	.077	.06	<.02	146.5	<.005	20.2	.01	.049	18	.013	5.16	<.02	30	<.03	<.005	.1	<.01	.817	<.005	.006	<.03	.15
OCT 3 10C	.014	1.42	.11	.33	.135	.006	.06	192.8	.003	.022	.008	.171	.55	<.02	220.6	.015	55.6	.43	.039	34	.028	10.88	.06	>.50	.12	<.005	2.2	.07	2.237	<.005	.008	.09	.16
DEC 12 1A	<.003	.05	<.02	.06	.005	<.001	<.04	11.7	<.002	<.005	<.005	.023	.03	<.02	56.0	<.005	4.3	<.01	.004	8	<.005	5.50	<.02	5	<.03	.009	<.01	<.01	.148	<.005	<.005	.17	<.01
DEC 12 1B	<.003	.05	<.02	<.05	.006	<.001	<.04	9.7	<.002	<.005	<.005	.031	.04	<.02	42.0	.017	3.3	<.01	<.002	10	<.005	4.67	<.02	5	<.03	<.005	<.01	<.01	.118	<.005	<.005	<.03	<.01
DEC 12 1C	<.003	.07	<.02	.06	.010	<.001	<.04	21.2	<.002	<.005	<.005	.031	.07	<.02	52.6	.040	10.2	<.01	.003	29	.017	4.38	<.02	14	<.03	<.005	<.01	<.01	.267	<.005	<.005	<.03	.05
DEC 12 2A	<.003	.05	<.02	<.05	.006	<.001	<.04	13.3	<.002	<.005	<.005	.025	.03	<.02	38.1	.026	6.3	<.01	<.002	21	.013	3.14	<.02	9	<.03	<.005	.2	<.01	.176	<.005	<.005	<.03	.02
DEC 12 2B	<.003	.05	<.02	<.05	.006	<.001	<.04	9.7	<.002	<.005	<.005	.018	<.01	<.02	26.3	.022	3.4	<.01	<.002	11	.008	2.68	<.02	5	<.03	<.005	<.01	<.01	.121	<.005	<.005	<.03	.06
DEC 12 2C	<.003	.05	<.02	<.05	.008	<.001	<.04	16.4	<.002	<.005	<.005	.034	.02	<.02	49.9	.022	10.2	<.01	.002	28	.012	2.83	<.02	17	<.03	<.005	.4	<.01	.239	<.005	<.005	<.03	.05
DEC 12 3A	<.003	.09	<.02	<.05	.010	<.001	<.04	22.9	<.002	<.005	<.005	.033	.07	<.02	59.9	<.005	8.1	<.01	.012	11	<.005	6.49	<.02	11	<.03	<.005	<.01	<.01	.300	<.005	<.005	<.03	.04
DEC 12 3B	<.003	.08	<.02	<.05	.008	<.001	<.04	22.7	<.002	<.005	<.005	.047	.06	<.02	61.0	<.005	7.6	<.01	.007	12	<.005	5.93	<.02	12	<.03	<.005	<.01	<.01	.297	<.005	<.005	<.03	.06
DEC 12 3C	<.003	.05	<.02	<.05	.008	<.001	<.04	16.7	<.002	<.005	<.005	.045	.06	<.02	94.0	<.005	12.7	<.01	.007	22	<.005	4.37	<.02	22	<.03	<.005	.4	<.01	.236	<.005	<.005	<.03	.08
DEC 12 4A	<.003	.05	<.02	<.05	.006	<.001	<.04	19.0	<.002	<.005	<.005	.030	.06	<.02	58.6	<.005	6.3	<.01	.003	9	<.005	5.85	<.02	8	<.03	<.005	<.01	<.01	.263	<.005	<.005	<.03	.08
DEC 12 4B	<.003	.05	<.02	<.05	.007	<.001	<.04	17.5	<.002	<.005	<.005	.032	.07	<.02	67.9	<.005	8.6	<.01	.005	14	<.005	3.82	<.02	13	<.03	<.005	<.01	<.01	.257	<.005	<.005	<.03	.11
DEC 12 4C	<.003	.10	<.02	.08	.012	<.001	<.04	23.0	<.002	<.005	<.005	.036	.06	<.02	85.3	.031	12.7	<.01	.011	20	<.005	4.42	<.02	18	<.03	<.005	.5	<.01	.368	<.005	<.005	<.03	.07
DEC 12 5C	<.003	.06	<.02	<.05	.008	<.001	<.04	21.1	<.002	<.005	<.005	.032	<.01	<.02	57.2	.021	8.2	<.01	.007	15	<.005	2.79	<.02	12	<.03	<.005	<.01	<.01	.284	<.005	<.005	<.03	.07
DEC 12 6C	<.003	.05	<.02	.06	.008	<.001	<.04	15.4	<.002	<.005	<.005	.037	<.01	<.02	59.6	.017	7.8	<.01	.015	9	<.005	.80	<.02	11	<.03	<.005	.1	<.01	.243	<.005	<.005	<.03	.10
DEC 12 7A	<.003	.05	<.02	<.05	.006	<.001	<.04	13.6	<.002	<.005	<.005	.040	<.01	<.02	46.1	.017	4.8	<.01	.008	7	<.005	5.08	<.02	7	<.03	<.005	<.01	<.01	.193	<.005	<.005	<.03	.06
DEC 12 7B	<.003	.05	<.02	.06	.007	<.001	<.04	12.1	<.002	<.005	<.005	.045	<.01	<.02	38.6	.022	4.1	<.01	.004	9	<.005	3.46	<.02	5	<.03	<.005	<.01	<.01	.153	<.005	<.005	<.03	.10
DEC 12 7C	<.003	.11	<.02	<.05	.013	<.001	<.04	25.1	<.002	<.005	<.005	.041	<.01	<.02	60.1	.026	8.4	<.01	.003	10	<.005	2.32	<.02	8	<.03	<.005	<.01	<.01	.369	<.005	.006	<.03	.07
DEC 12 8A	<.003	.05	<.02	.14	.003	<.001	<.04	12.7	<.002	<.005	<.005	.041	<.01	<.02	32.1	.022	6.3	<.01	.007	25	.009	4.60	<.02	7	<.03	<.005	.6	<.01	.149	<.005	.006	<.03	.04
DEC 12 8B	<.003	.05	<.02	.08	<.002	<.001	<.04	12.2	<.002	<.005	<.005	.034	<.01	<.02	30.5	<.005	4.2	<.01	.002	8	<.005	4.79	<.02	5	<.03	<.005	<.01	<.01	.153	<.005	.008	<.03	.07
DEC 12 8C	<.003	.05	<.02	.05	.008	<.001	<.04	19.1	<.002	<.005	<.005	.042	<.01	<.02	56.4	.017	8.0	<.01	.007	12	<.005	2.95	<.02	7	<.03	<.005	<.01	<.01	.269	<.005	.008	<.03	.03
DEC 12 9A	<.003	.05	<.02	<.05	<.002	<.001	<.04	7.9	<.002	<.005	<.005	.033	<.01	<.02	56.6	.017	3.6	.02	<.002	5	<.005	7.43	<.02	3	<.03	<.005	<.01	<.01	.092	<.005	.010	<.03	.04
DEC 12 9B	<.003	.05	<.02	<.05	.004	<.001	<.04	5.7	<.002	<.005	<.005	.081	.04	<.02	54.7	<.005	2.2	<.01	.011	6	<.005	6.12	<.02	3	<.03	<.005	<.01	<.01	.074	<.005	<.005	<.03	.05
DEC 12 9C	<.003	.05	<.02	<.05	.006	<.001	<.04	13.9	<.002	<.005	<.005	.076	.04	<.02	75.2	.012	5.8	<.01	.027	15	<.005	6.82	<.02	10	<.03	<.005	<.01	<.01	.184	<.005	<.005	<.03	.02
DEC 12 10A	.004	.05	<.02	<.05	.005	<.001	.07	4.9	<.002	<.005	.007	.051	.08	<.02	63.3	.008	1.9	<.01	.010	4	.014	6.93	.03	3	<.03	<.005	<.01	<.01	.061	<.005	.019	<.03	.04
DEC 12 10B	<.003	.05	<.02	<.05	.007	<.001	.10	7.0	<.002	<.005	.013	.050	.16	<.02	56.2	<.005	2.4	<.01	.009	5	.006	6.28	.03	2	<.03	<.005	<.01	<.01	.079	<.005	.023	<.03	.11
DEC 12 10C	.003	.07	<.02	.09	.012	<.001	<.04	16.8	<.002	<.005	.005	.110	.10	<.02	96.7	.017	7.1	.01	.046	14	.015	8.82	.04	13	<.03	<.005	.4	<.01	.186	<.005	.022	<.03	.03

APPENDIX 2. CHARTS AND GRAPHS

15 cm SF Wetlands; O-PO4



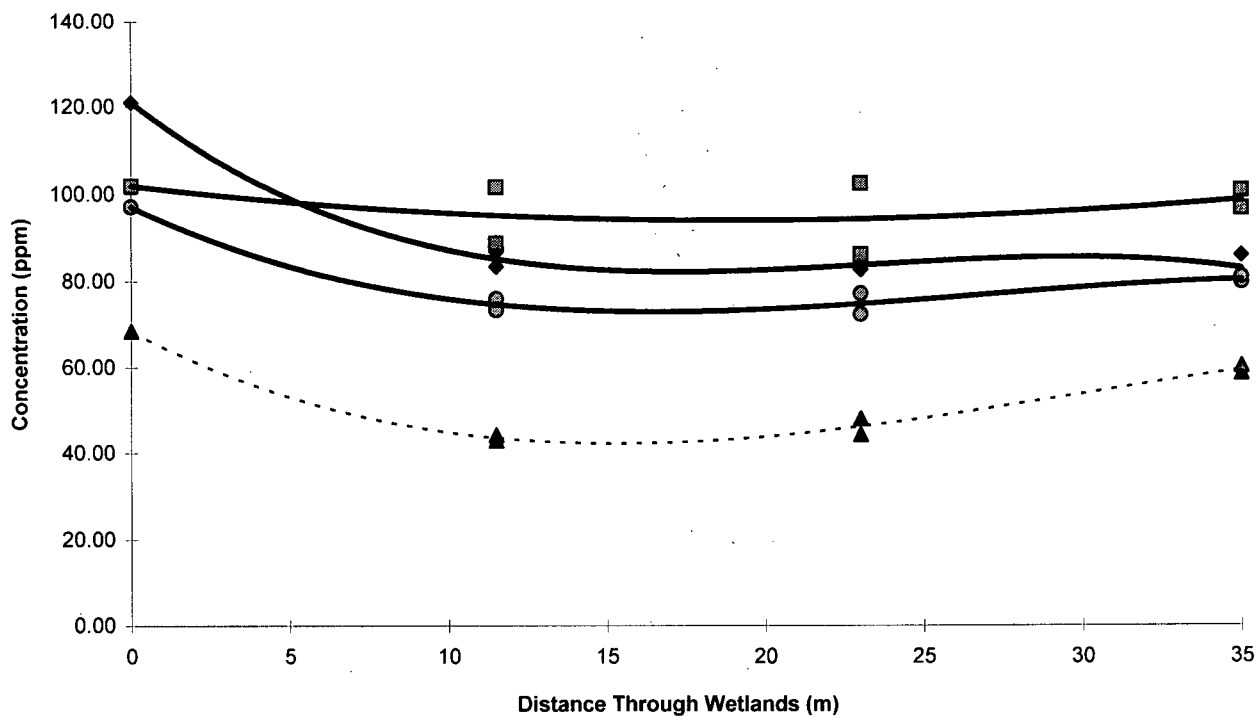
◆ April-June

■ July-Sept.

▲ Oct.-Dec.

● Year

30 cm SF Wetlands; O-PO4



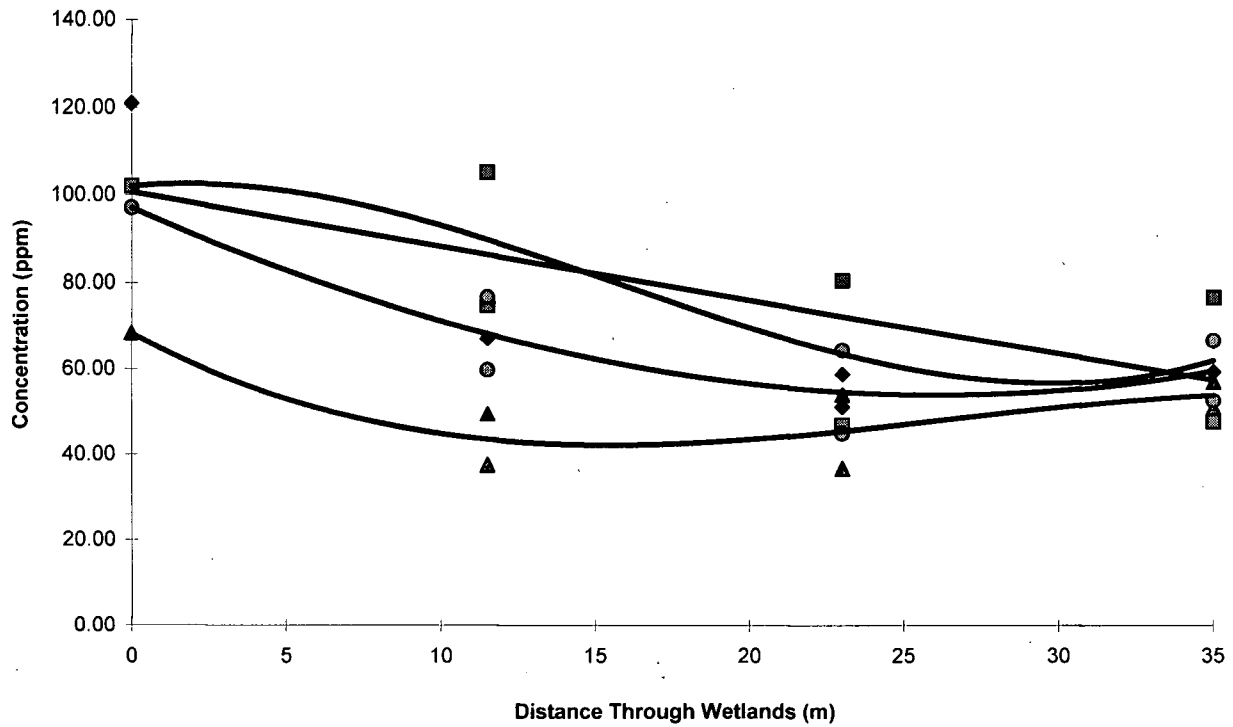
◆ April-June

■ July-Sept.

▲ Oct.-Dec.

● Year

Unplanted SSF Wetlands; O-PO4



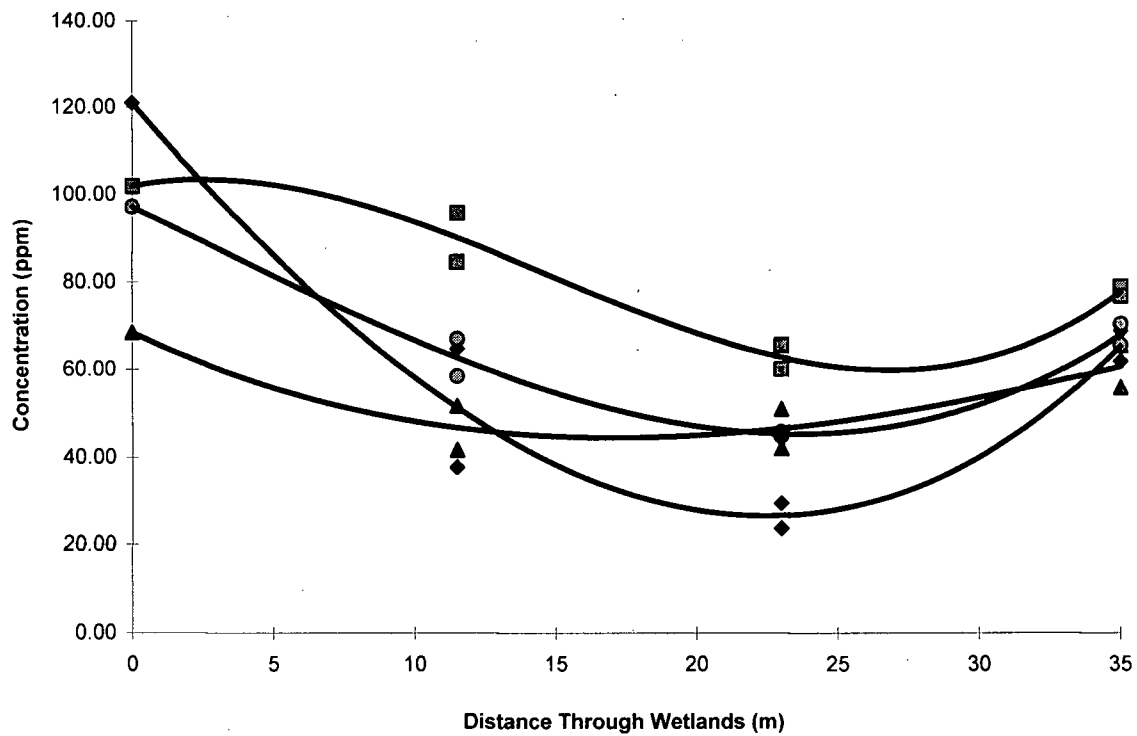
◆ April-June

■ July-Sept.

▲ Oct.-Dec.

● Year

Planted SSF Wetlands; O-PO4



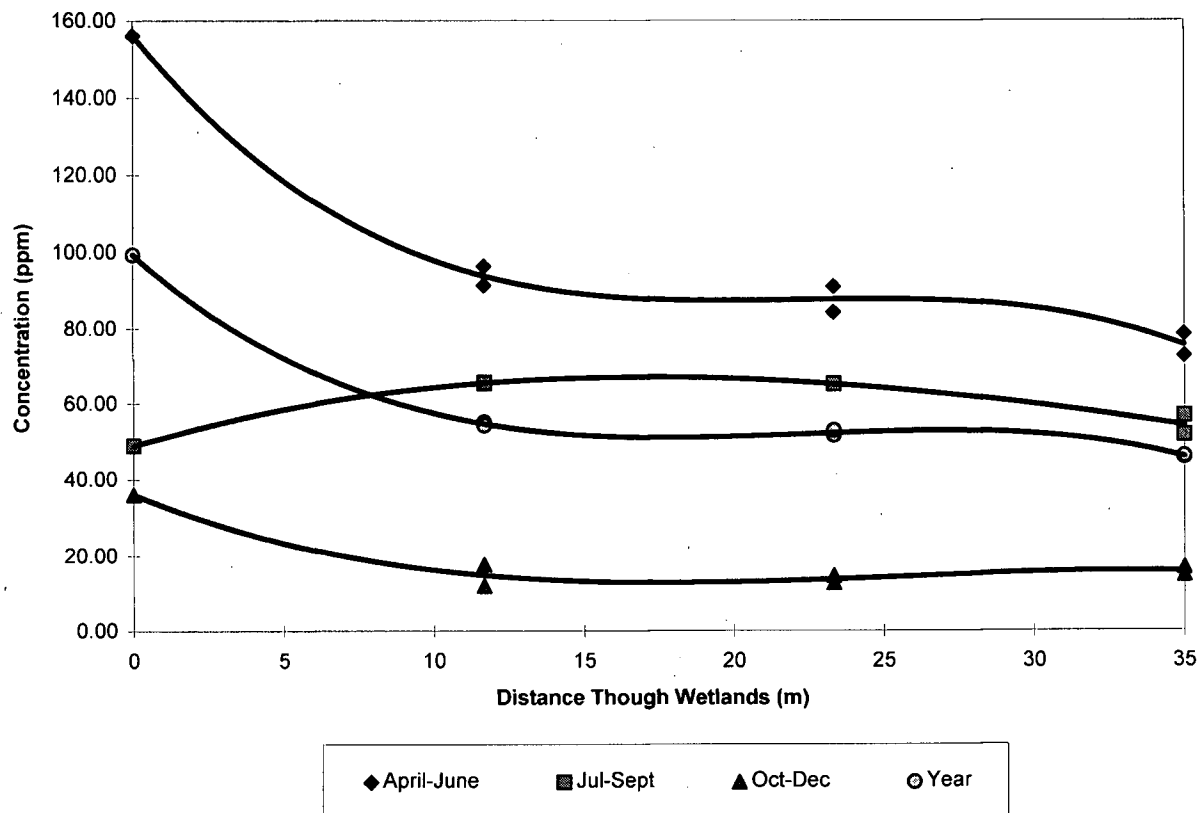
◆ April-June

■ July-Sept.

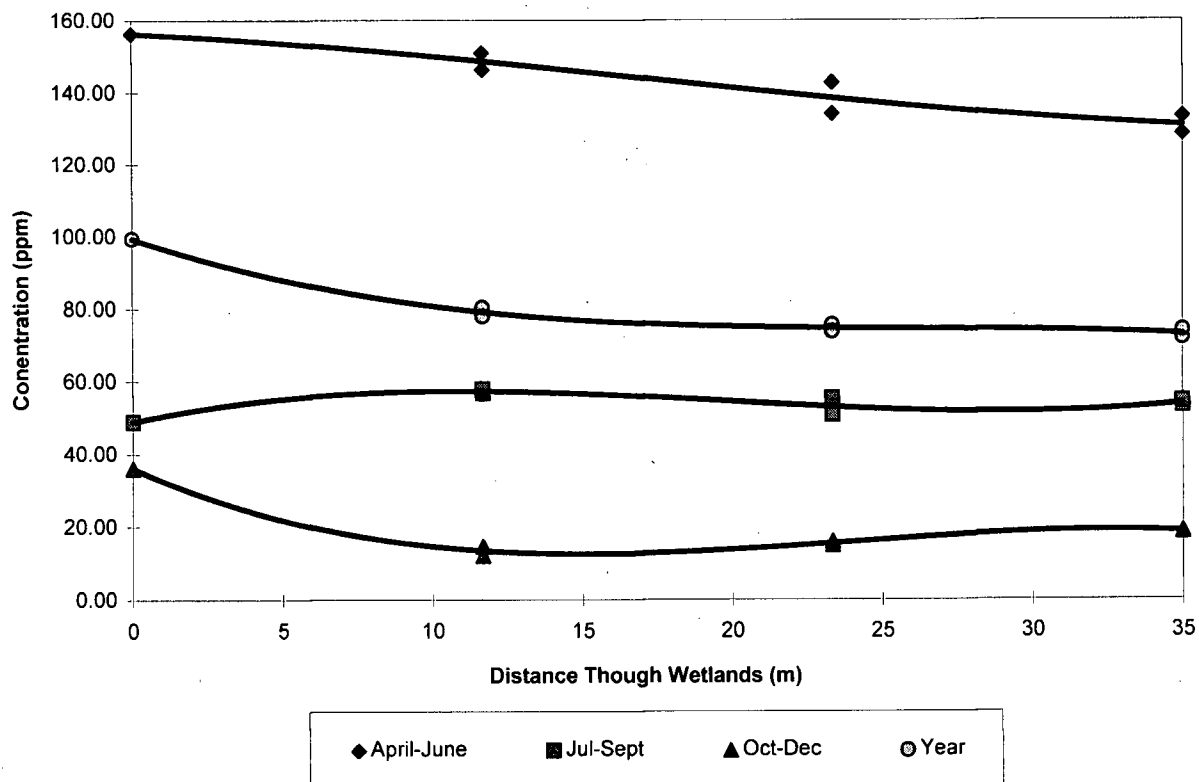
▲ Oct.-Dec.

● Year

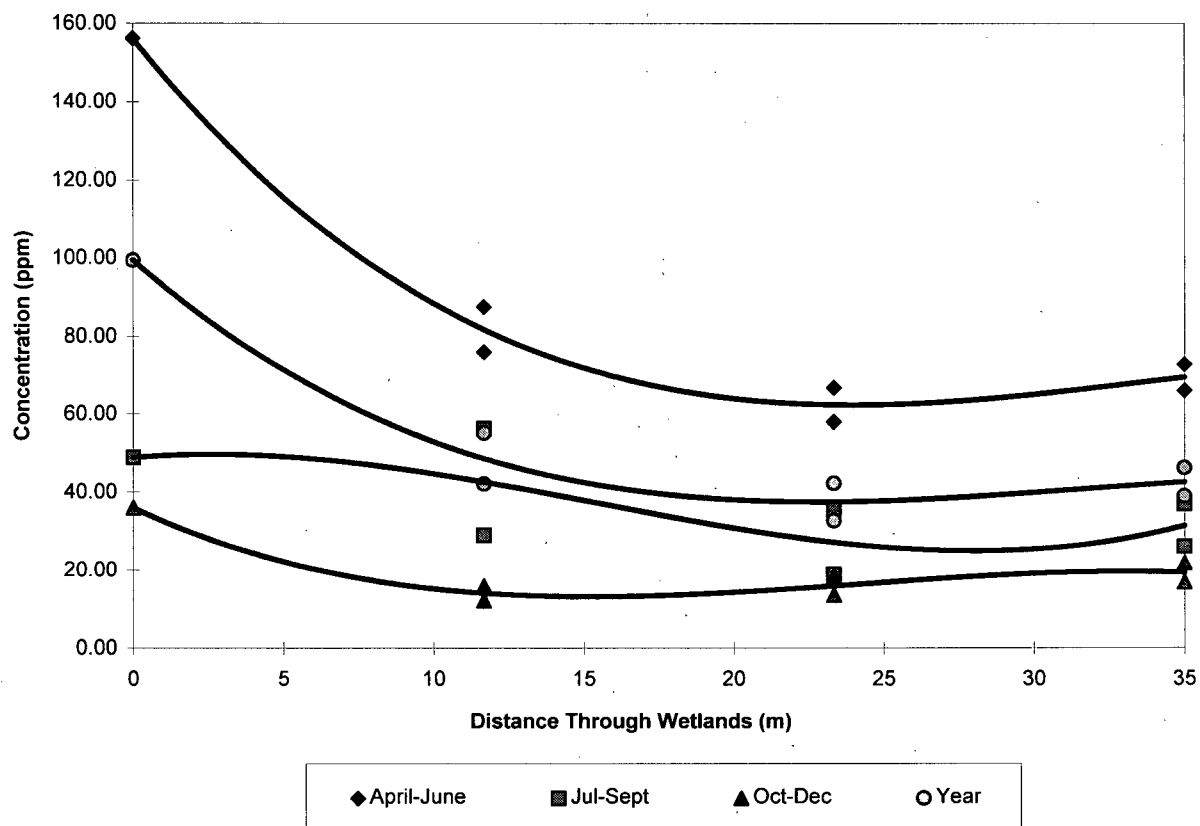
15 cm SF Wetlands; Total Phosphorus



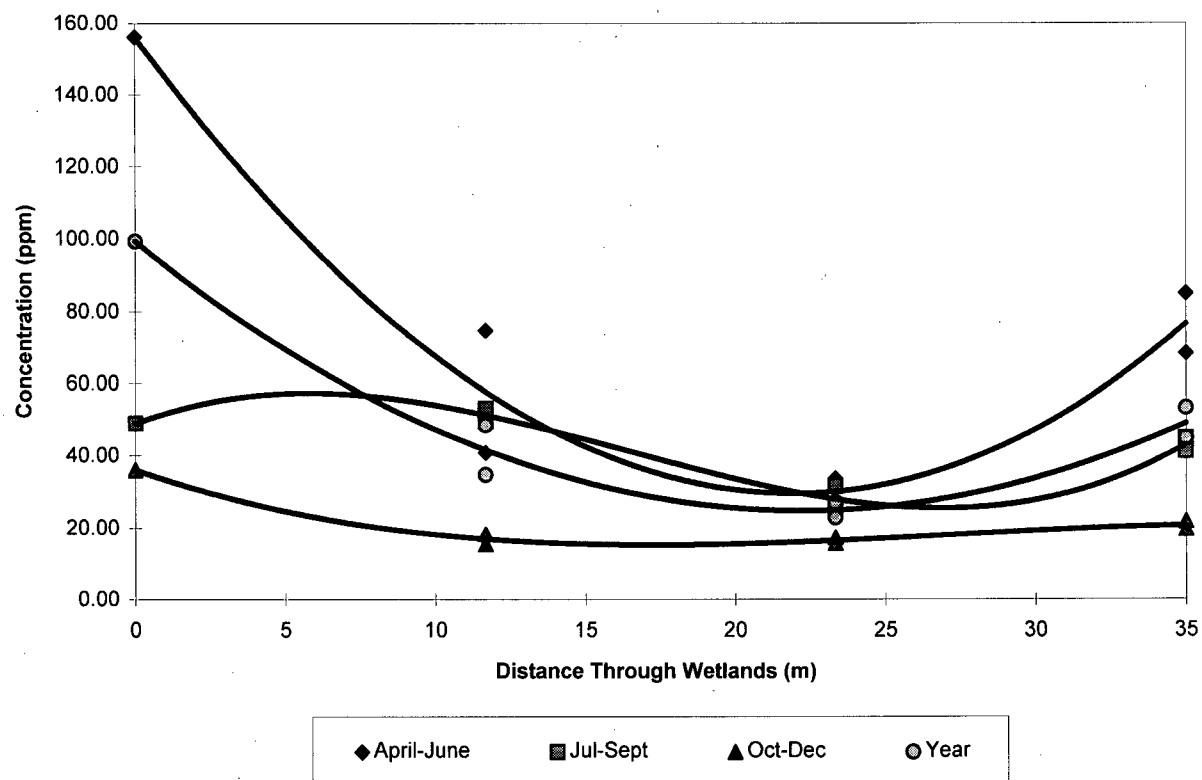
30 cm SF Wetlands; Total Phosphorus



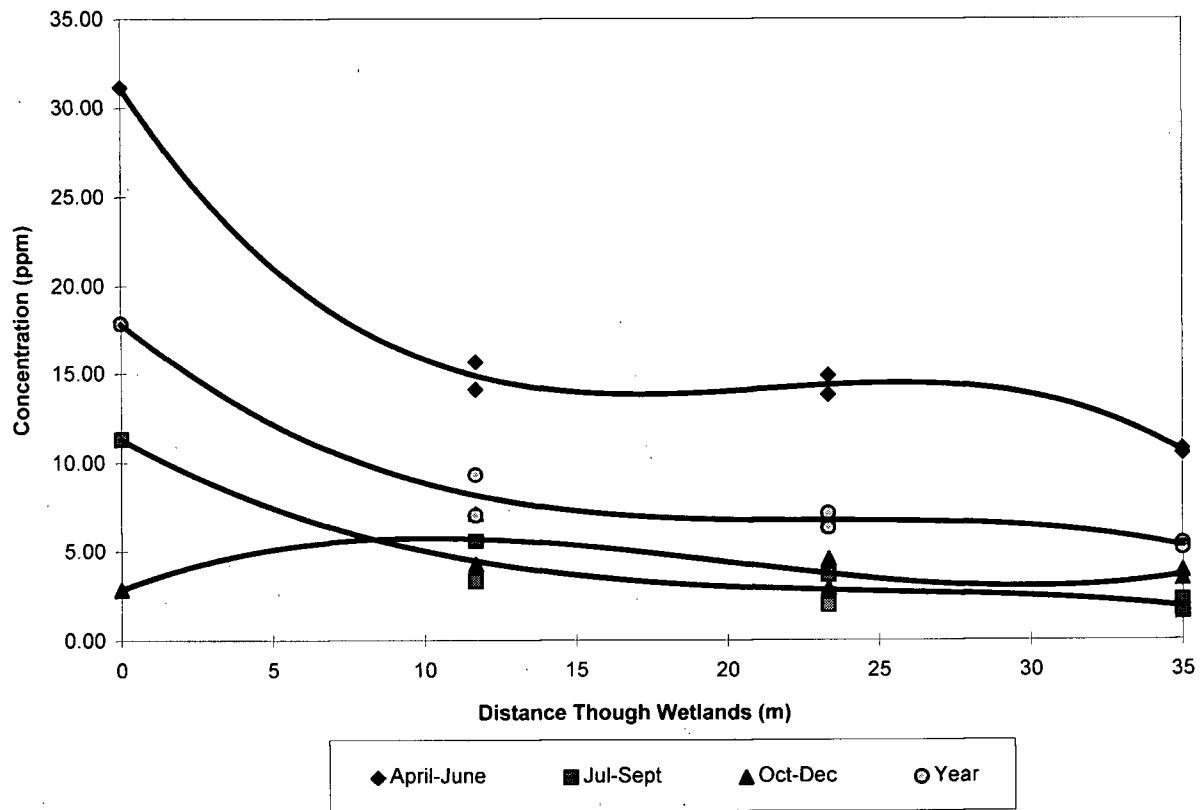
Unplanted SSF Wetlands; Total Phosphorus



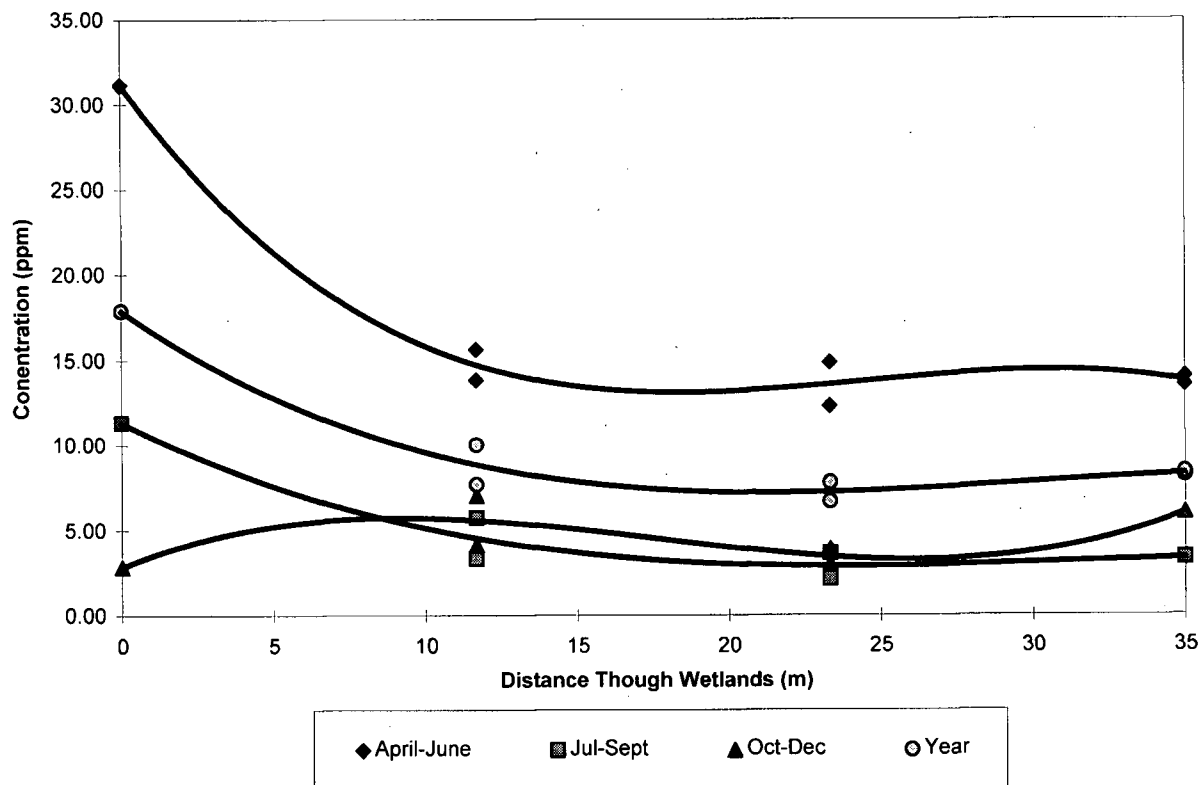
Planted SSF Wetlands; Total Phosphorus



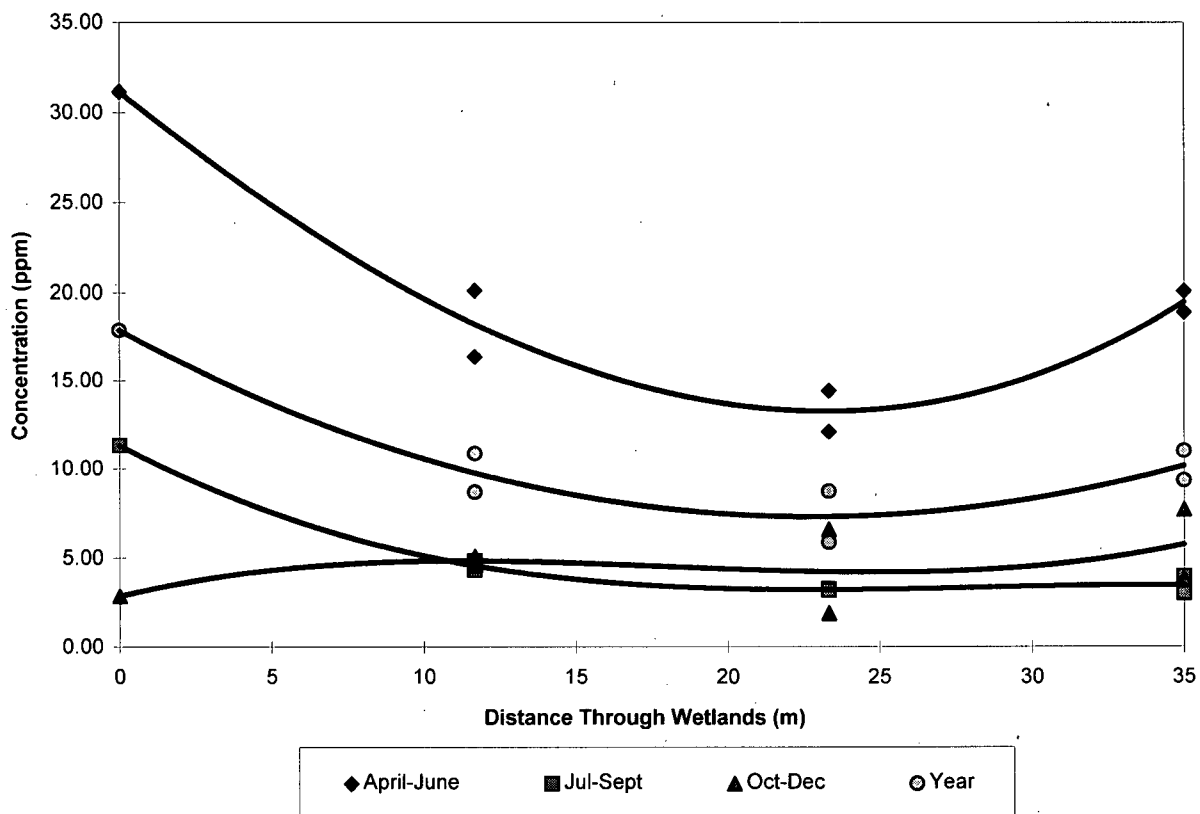
15 cm SF Wetlands; Ammonia



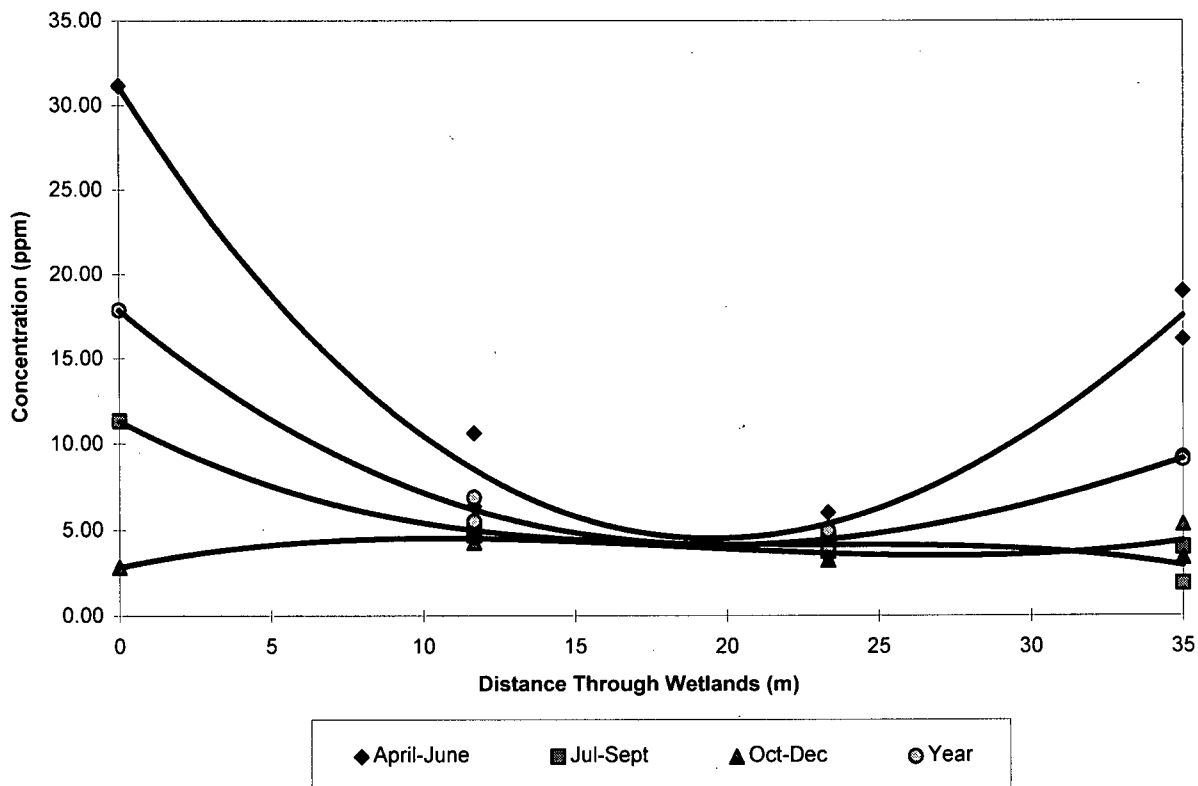
30 cm SF Wetlands; Ammonia



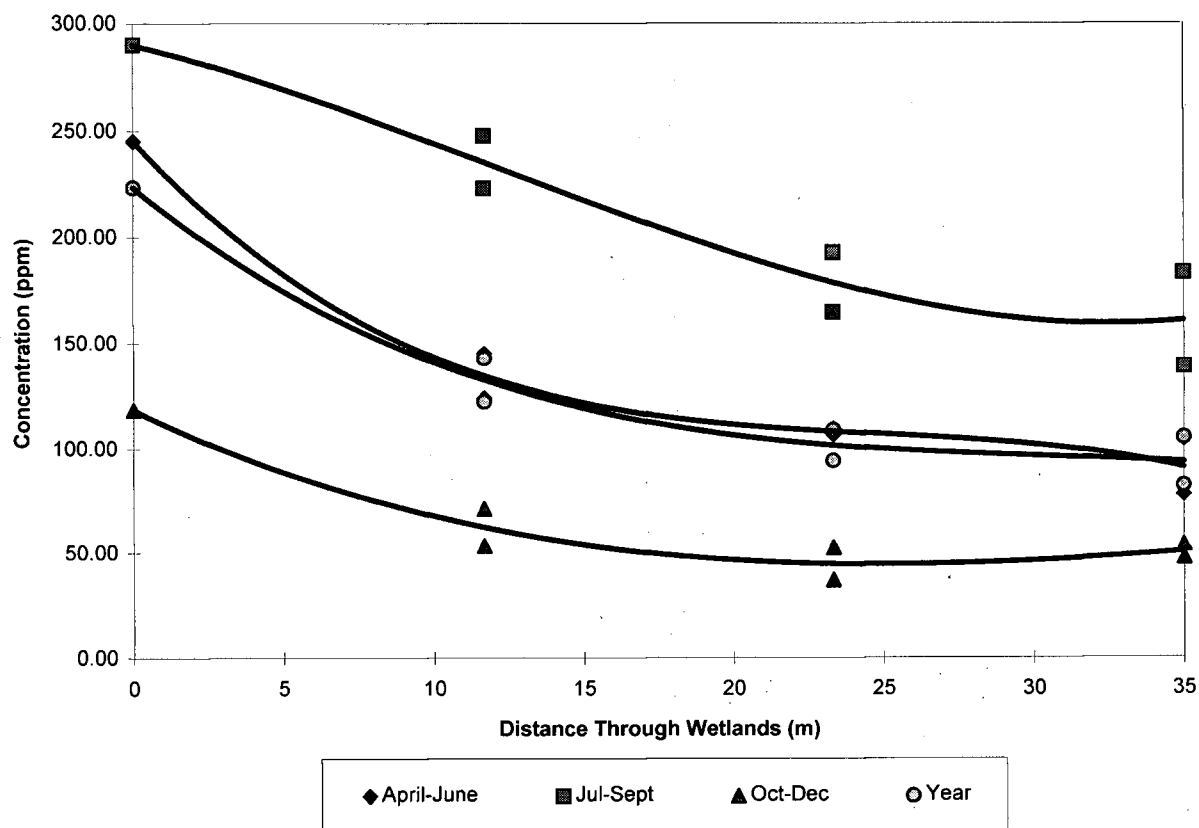
Unplanted SSF Wetlands; Ammonia



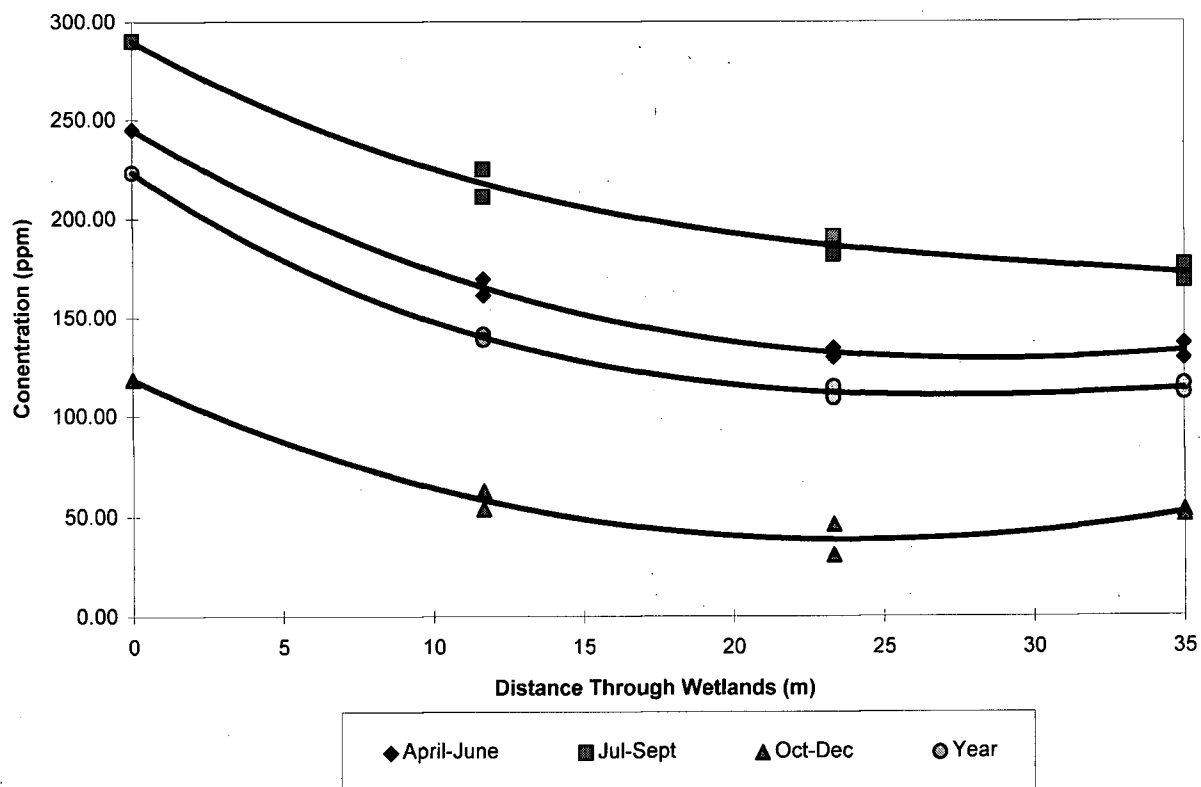
Planted SSF Wetlands; Ammonia



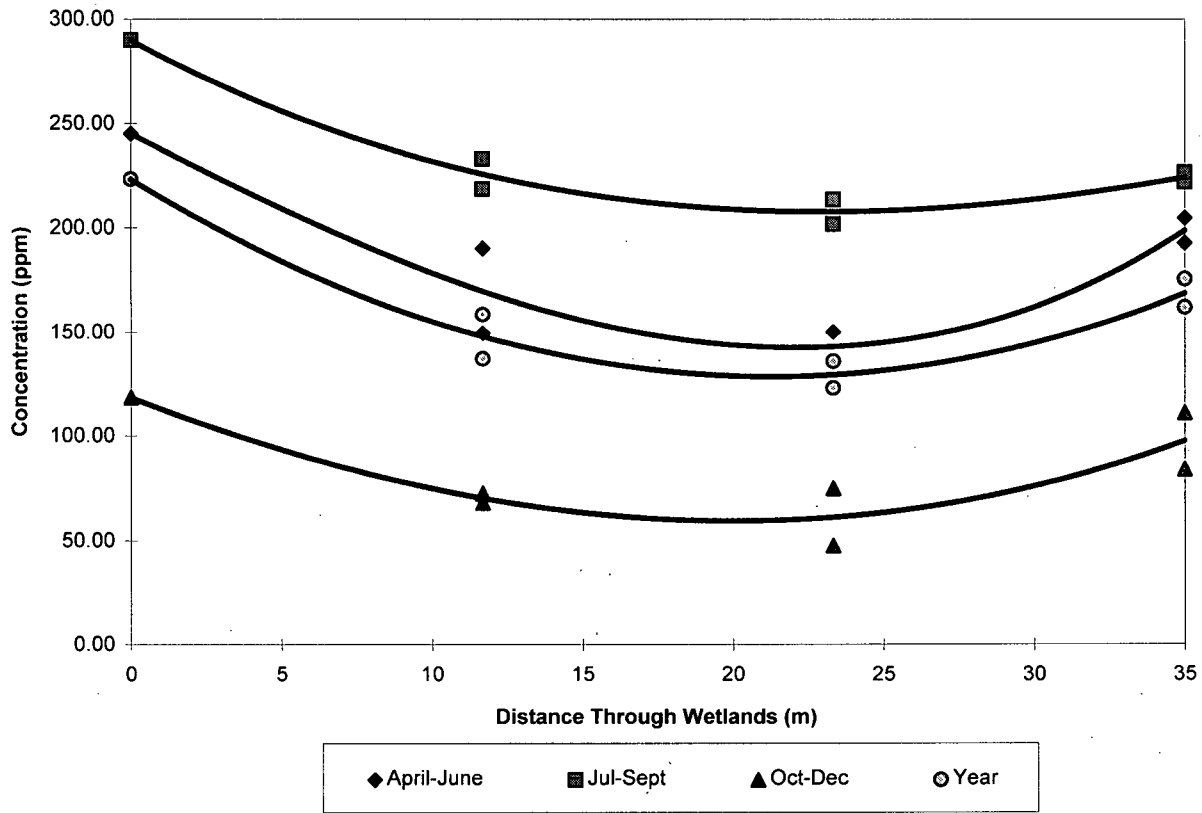
15 cm SF Wetlands; Nitrate



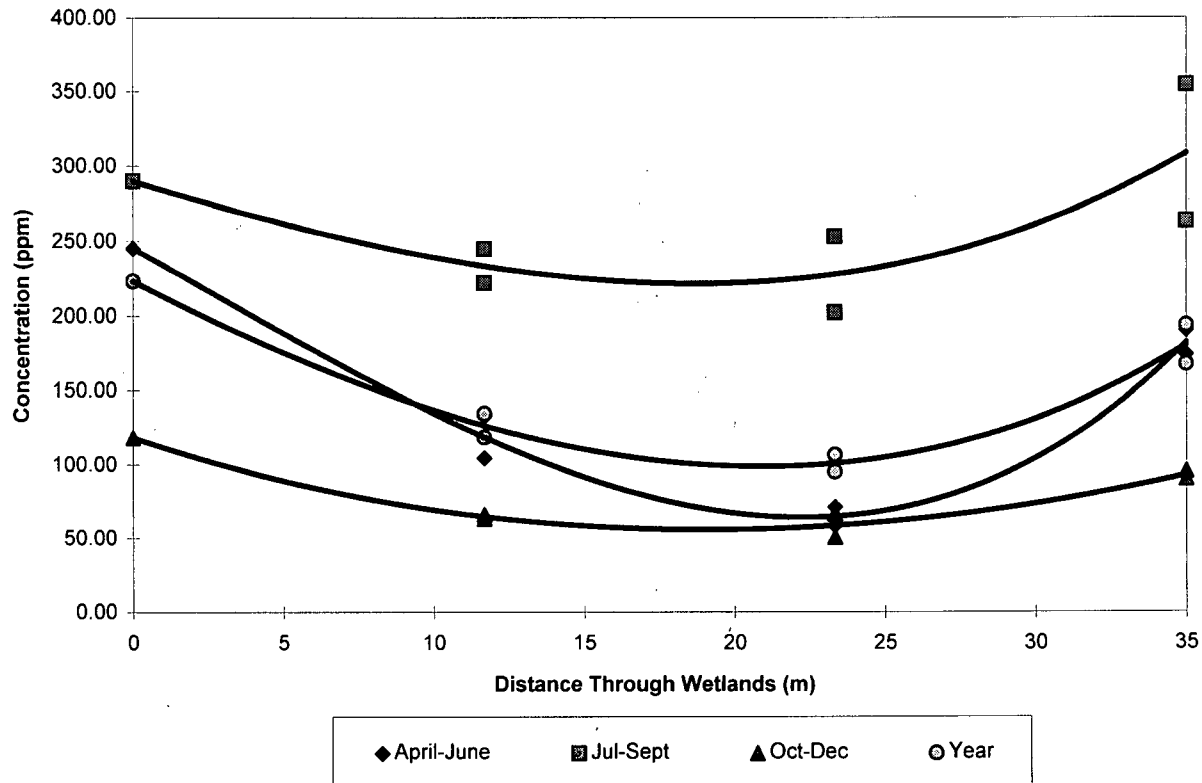
30 cm SF Wetlands; Nitrate



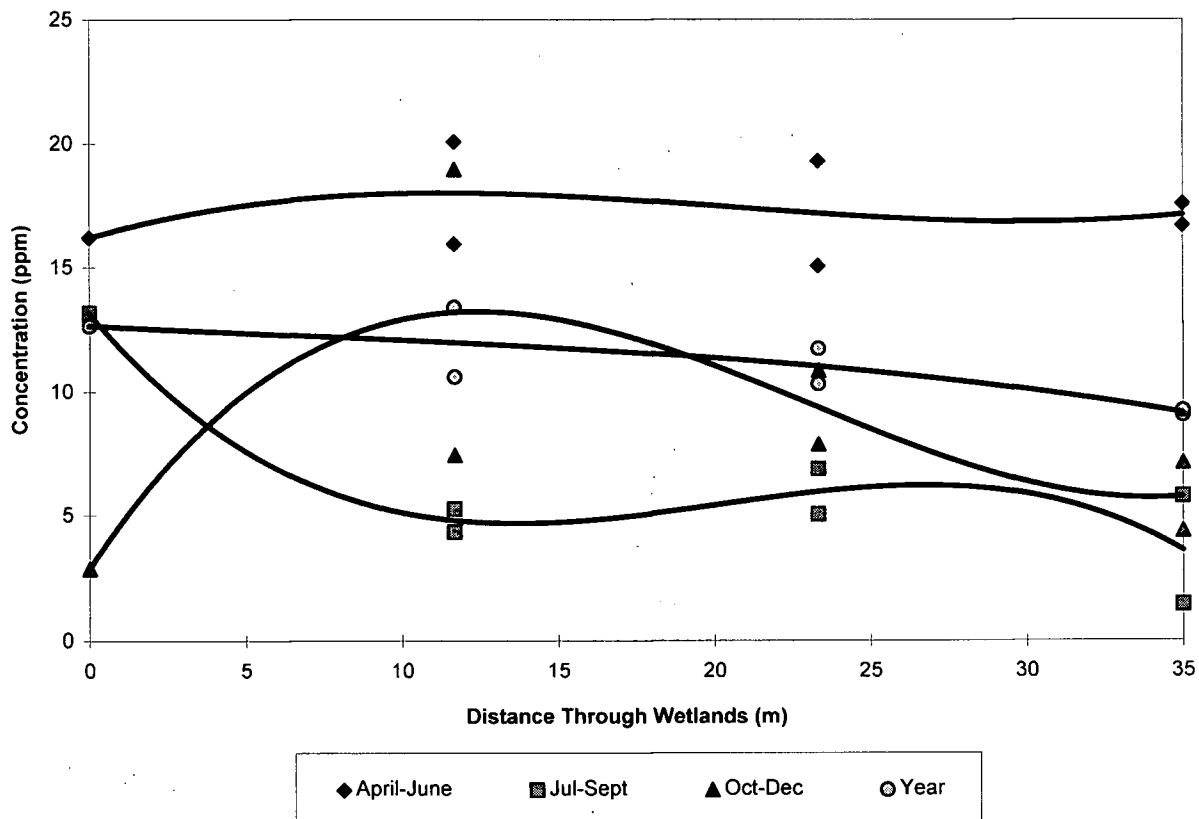
Unplanted SSF Wetlands; Nitrate



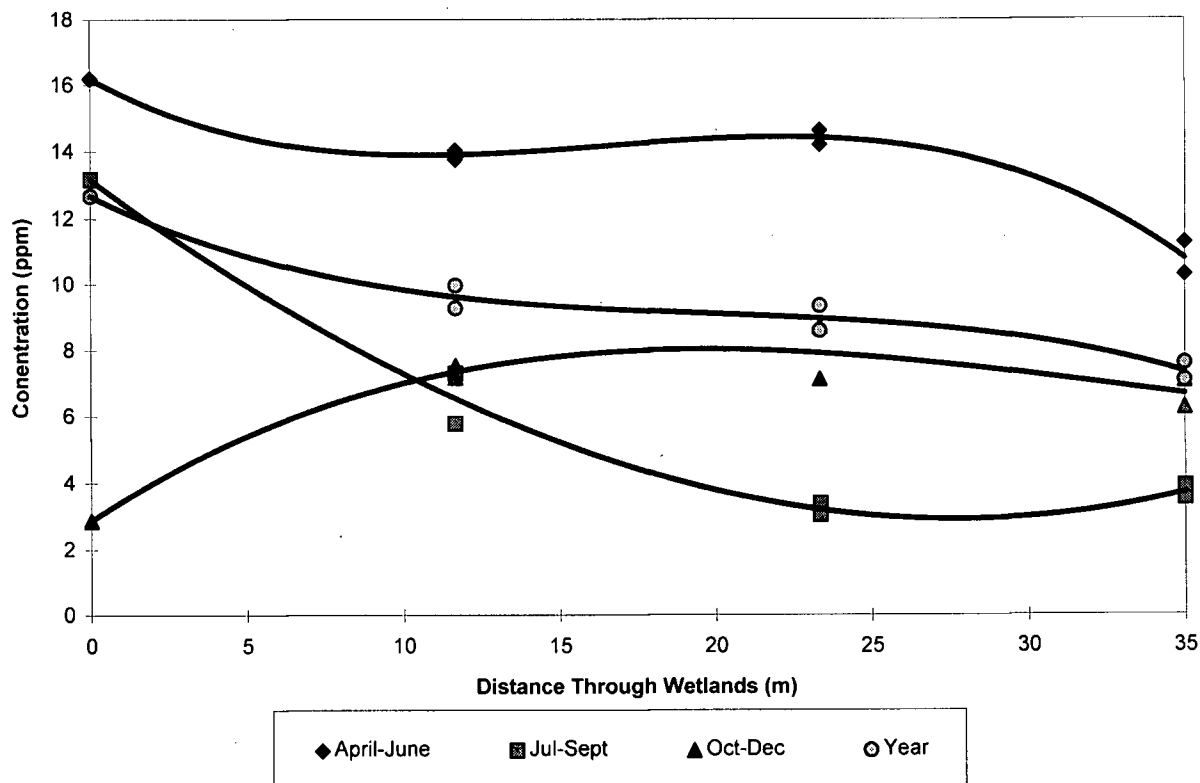
Planted SSF Wetlands; Nitrate



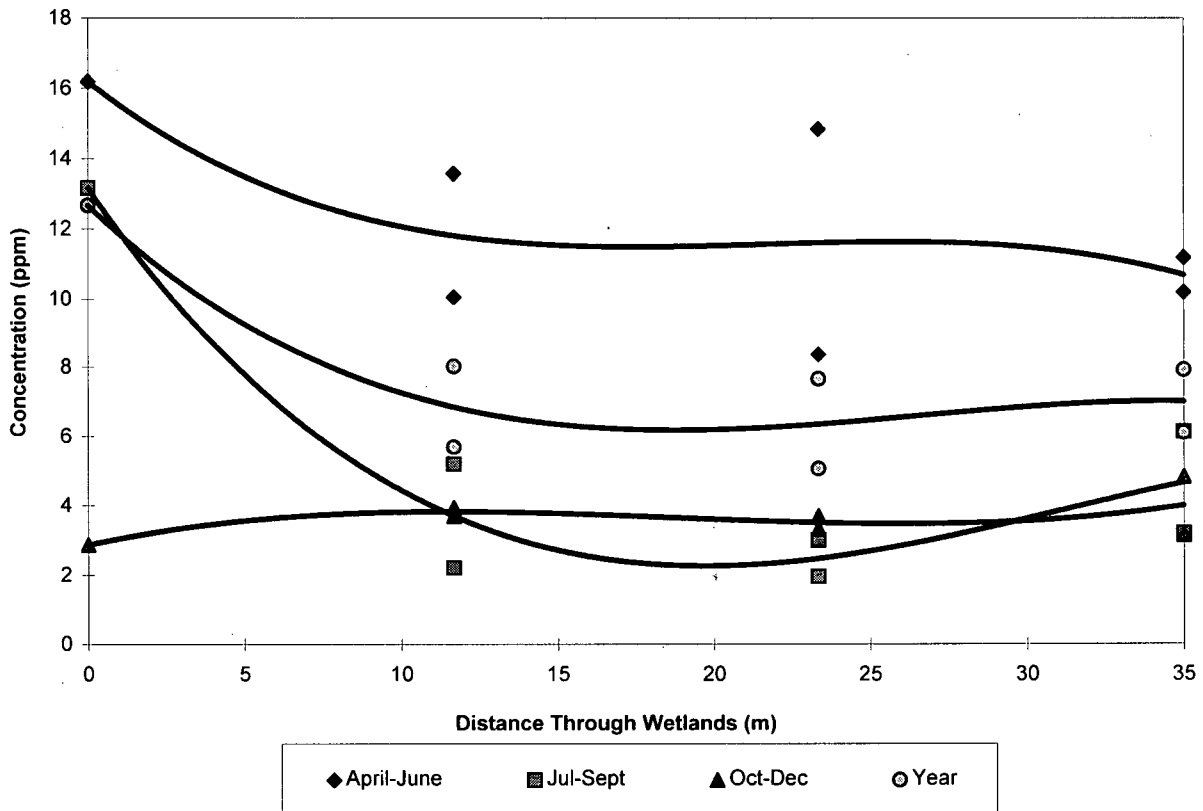
15 cm SF Wetlands; Total Kjeldahl Nitrogen



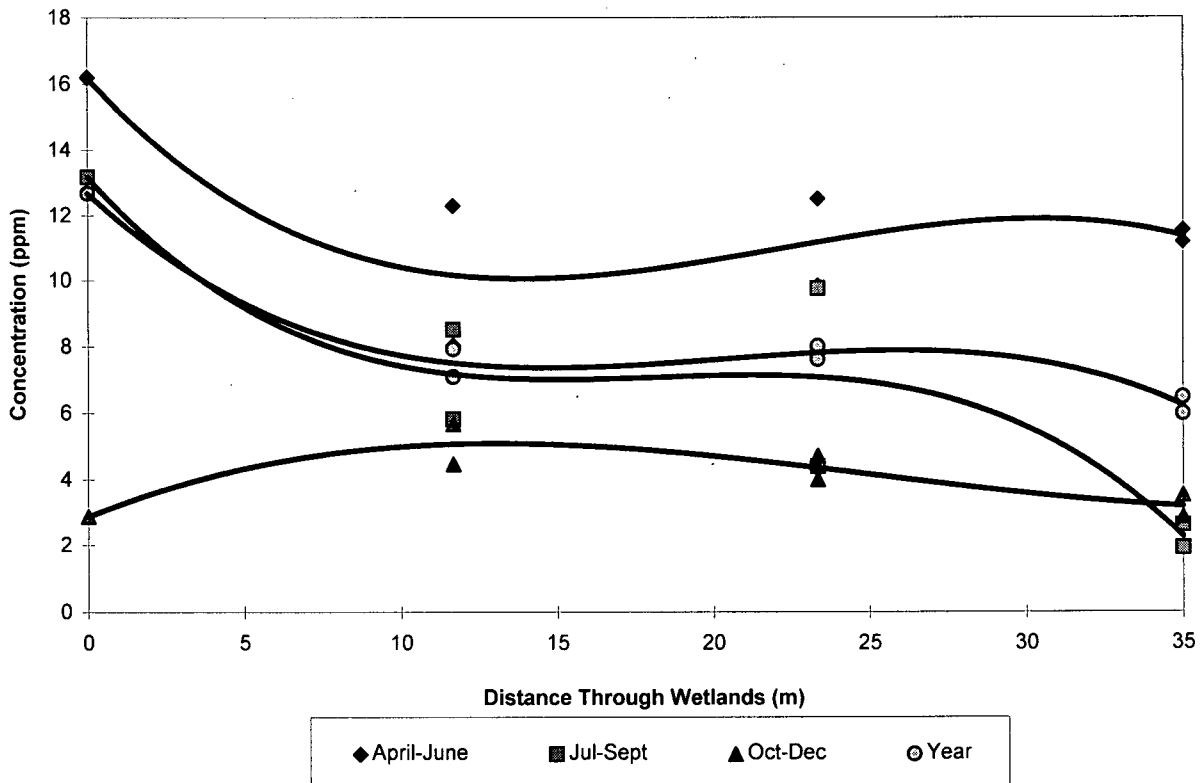
30 cm SF Wetlands; Total Kjeldahl Nitrogen



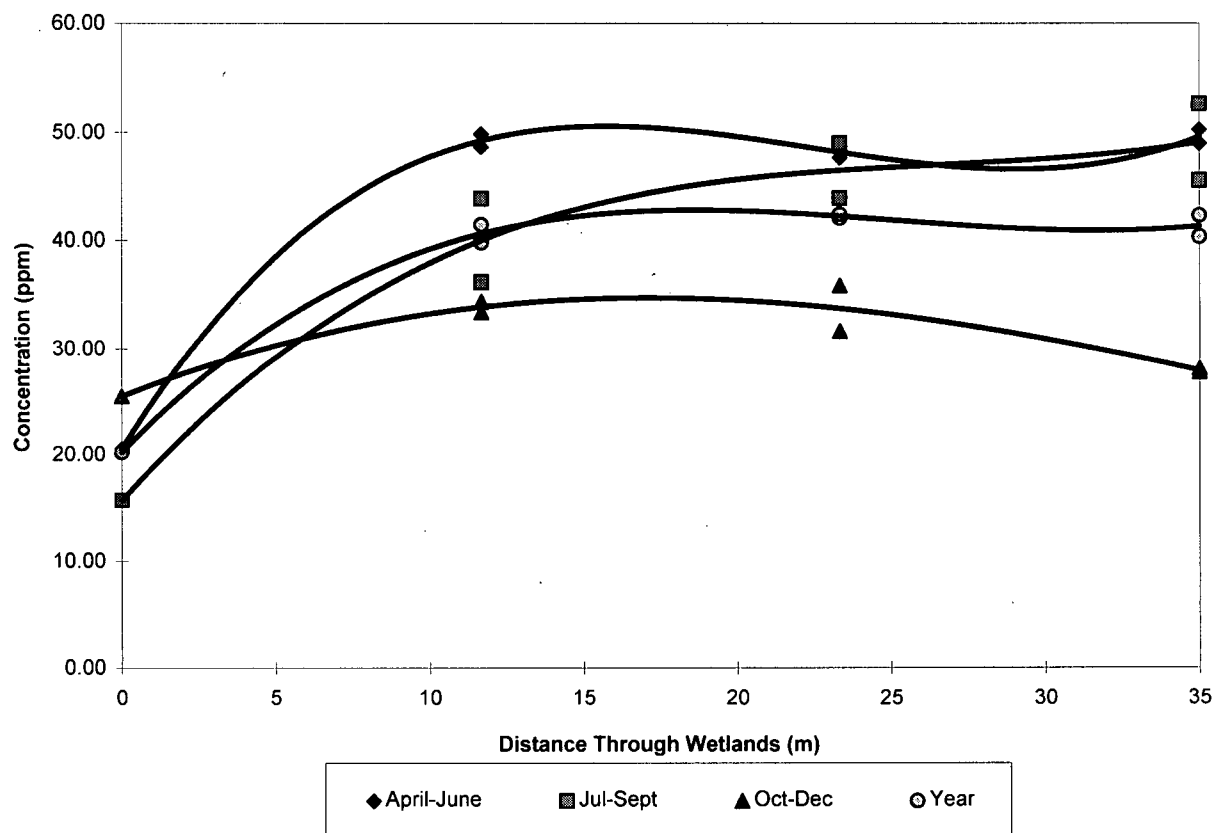
Unplanted SSF Wetlands; Total Kjeldahl Nitrogen



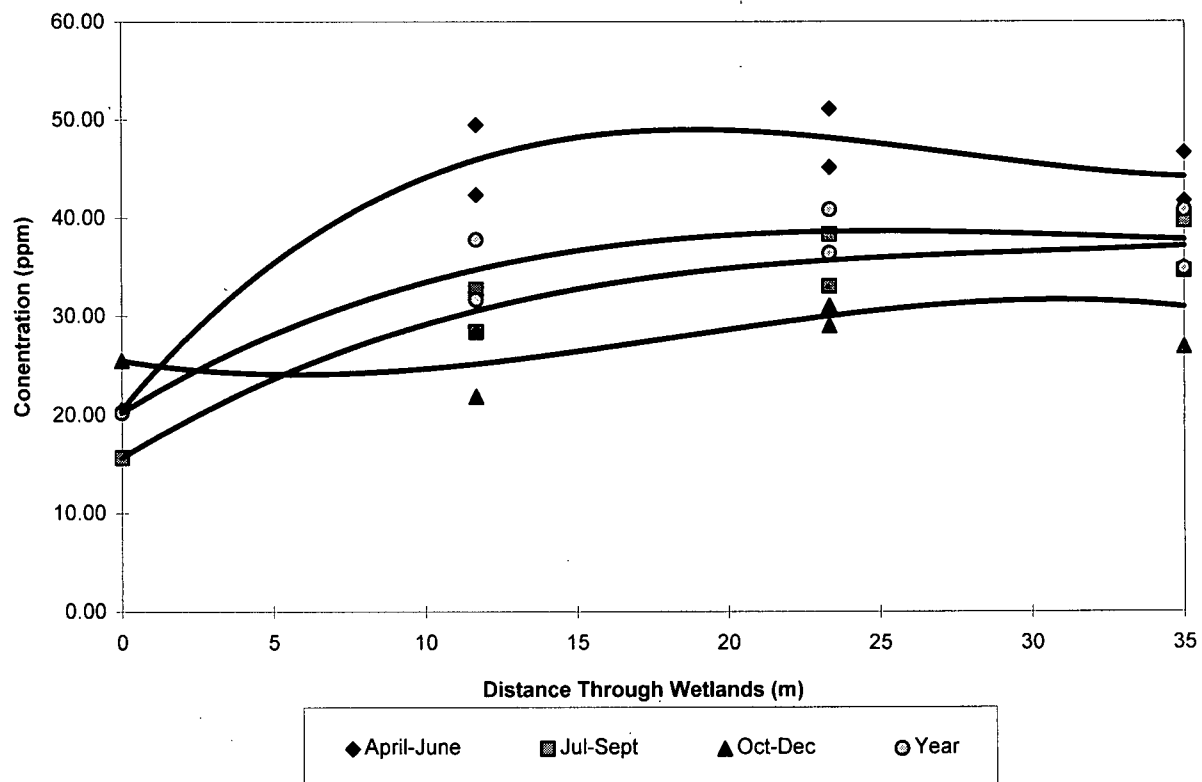
Planted SSF Wetlands; Total Kjeldahl Nitrogen



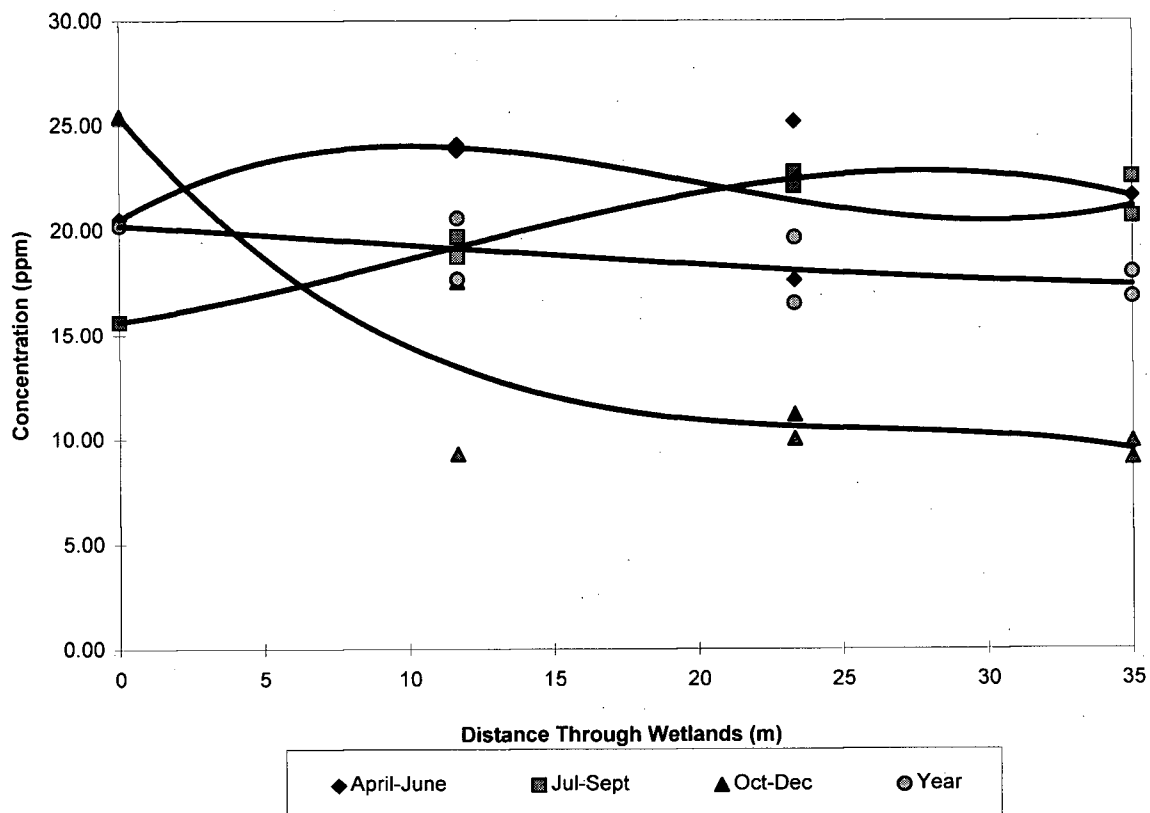
15 cm SF Wetlands; Total Organic Carbon



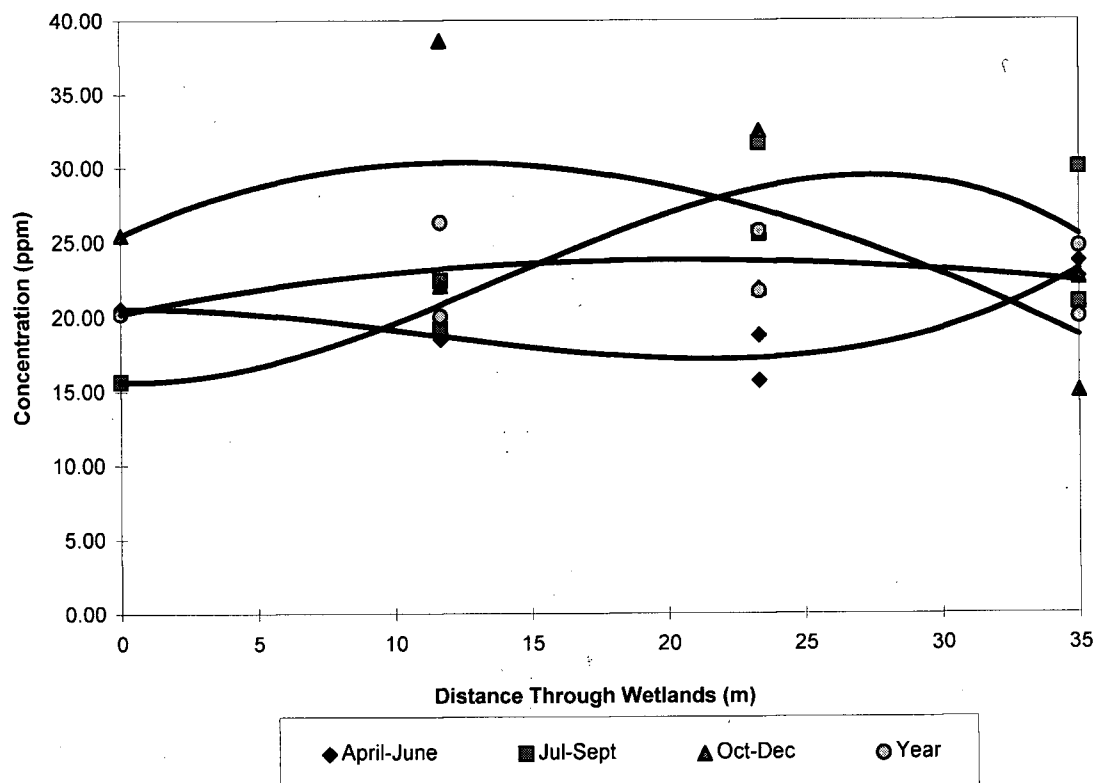
30 cm SF Wetlands; Total Organic Carbon



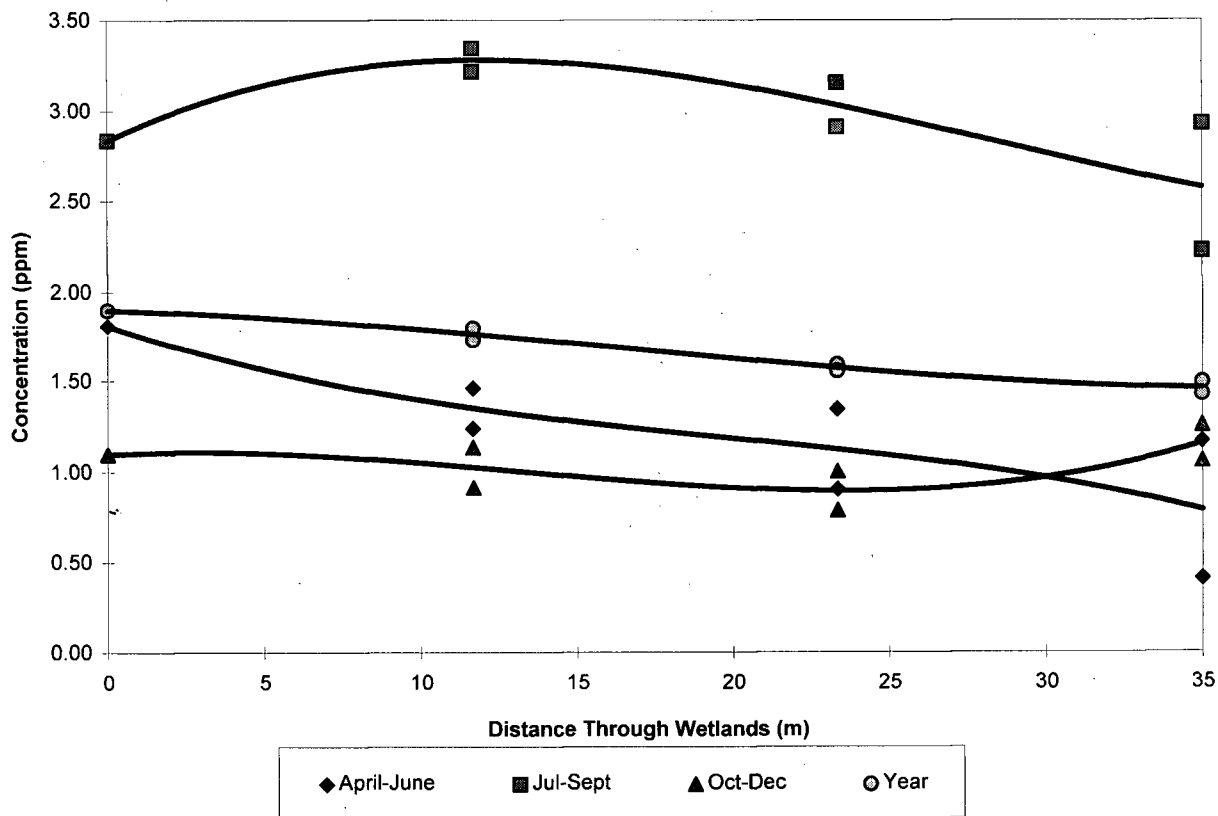
Unplanted SSF Wetlands; Total Organic Carbon



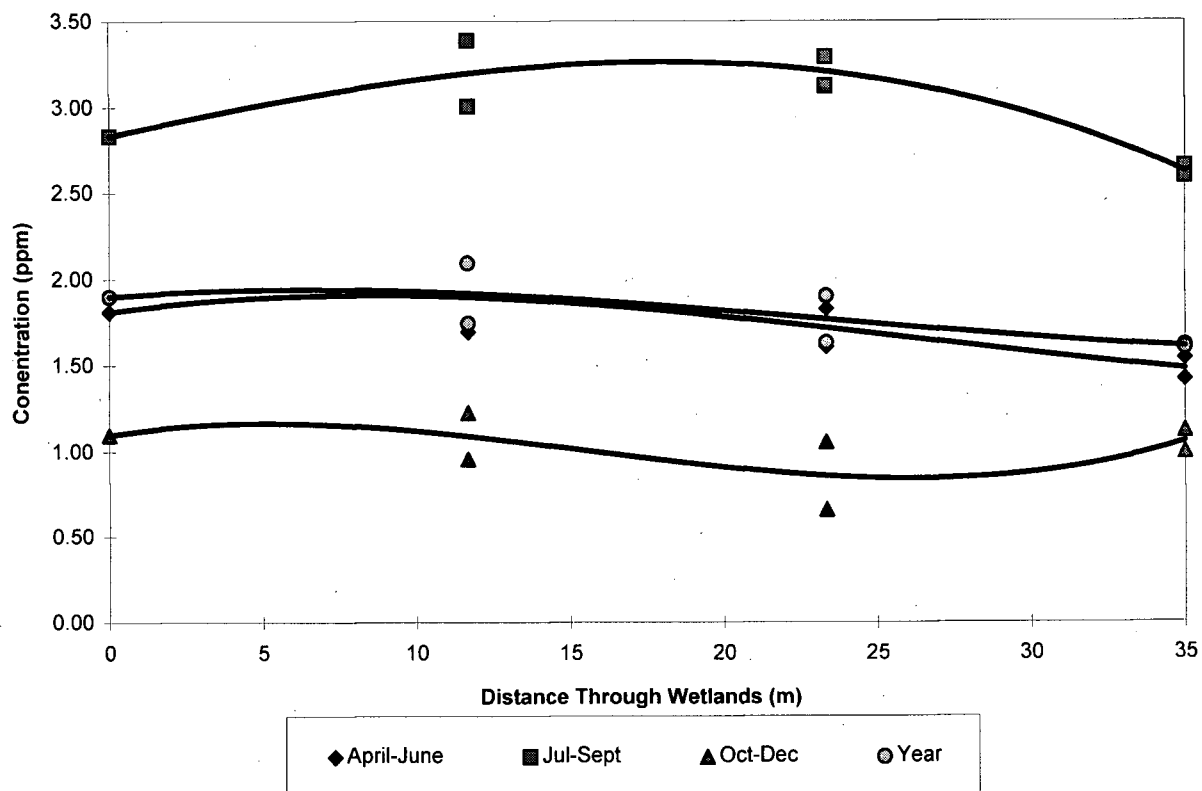
Planted SSF Wetlands; Total Organic Carbon



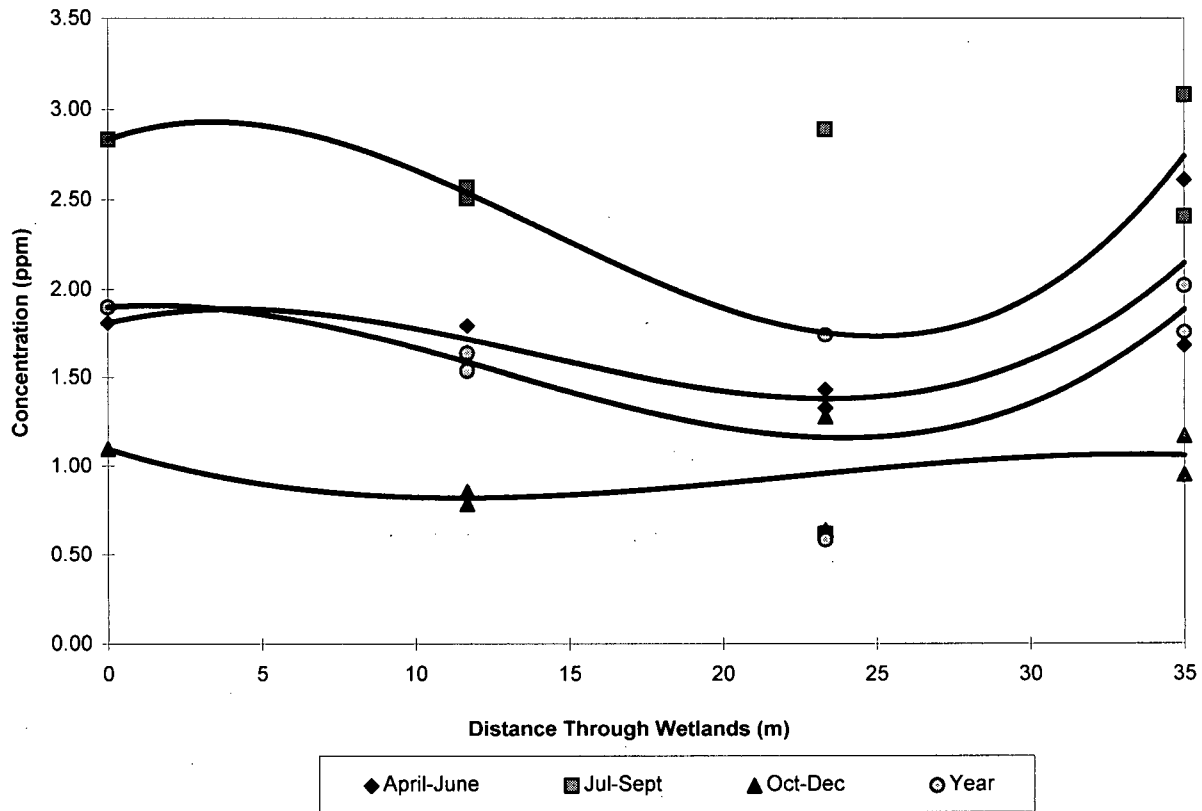
15 cm SF Wetlands; Total Solids



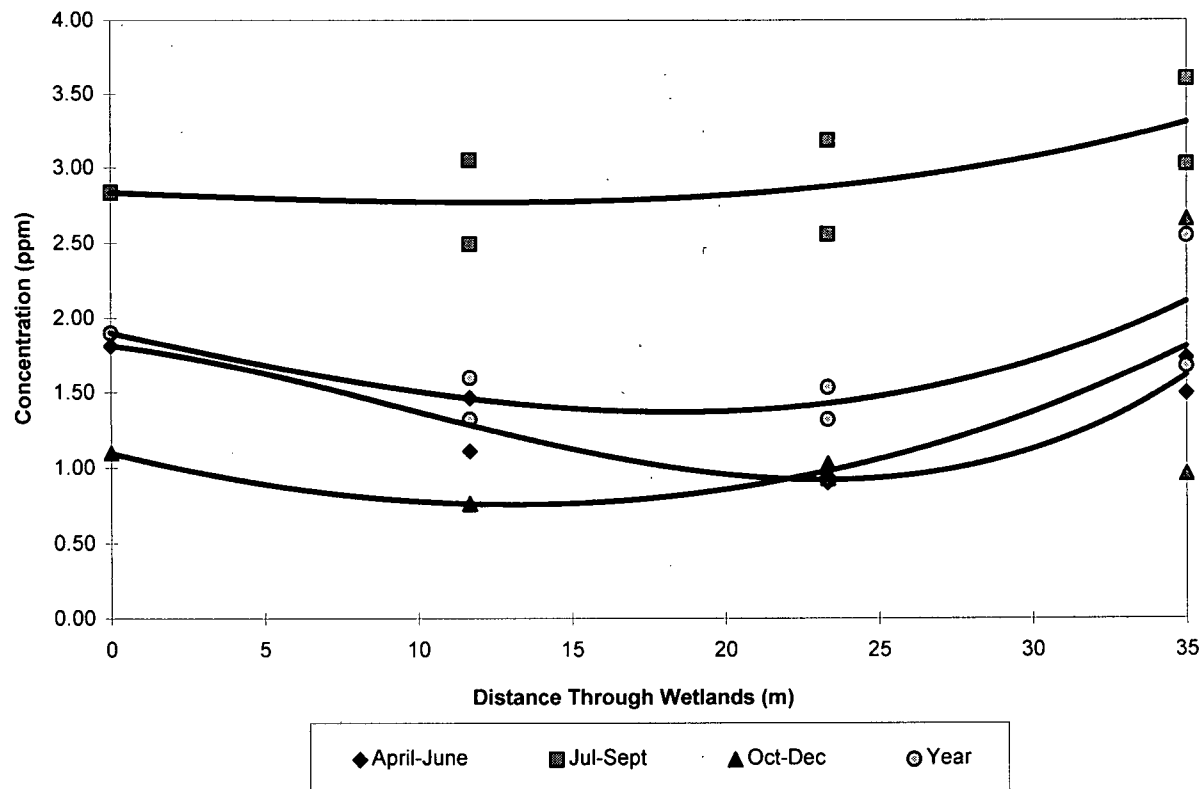
30 cm SF Wetlands; Total Solids



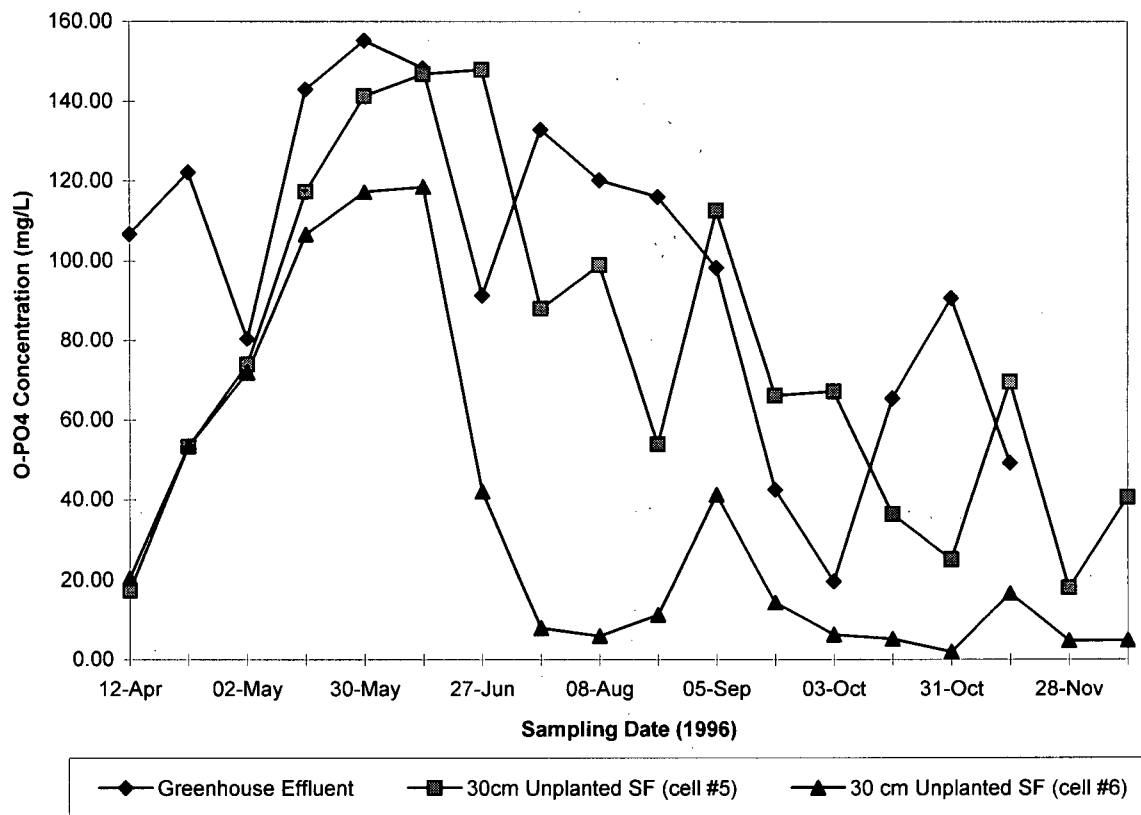
Unplanted SSF Wetlands; Total Solids



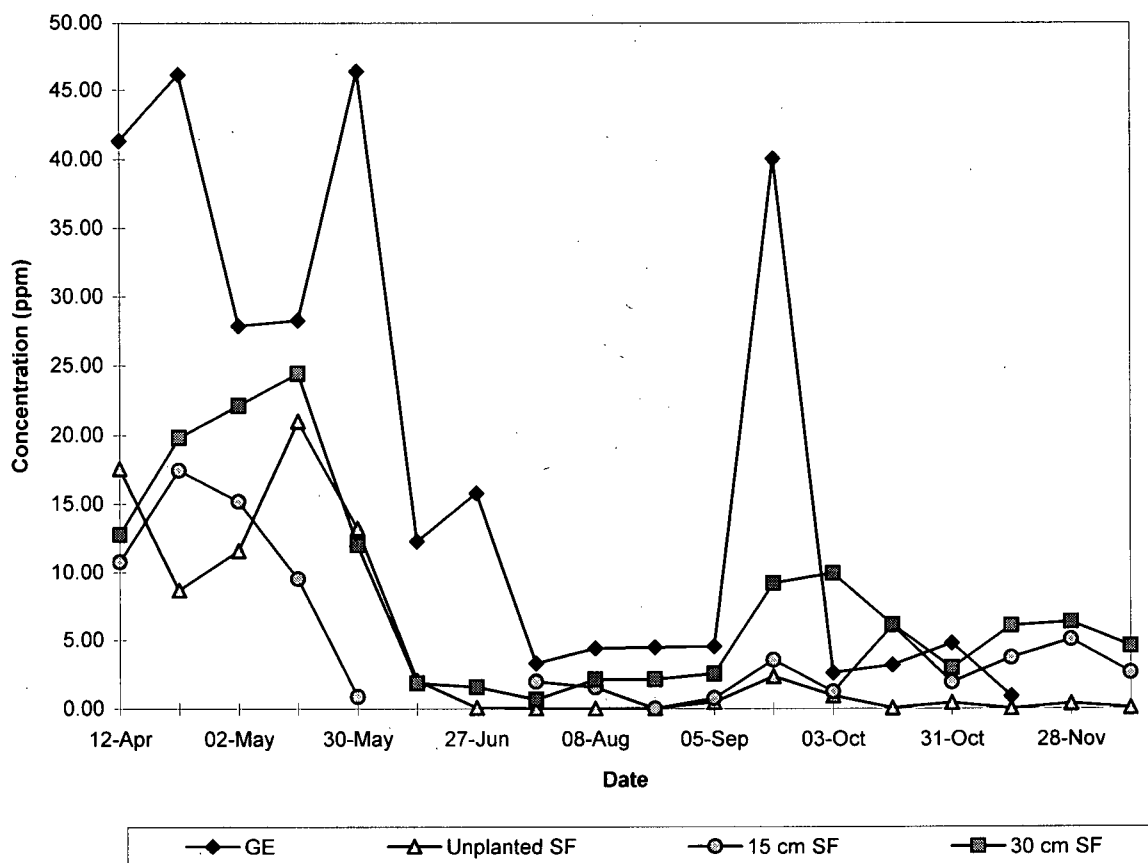
Planted SSF Wetlands; Total Solids



Ortho-phosphate Concentrations; Unplanted SF Wetlands



Ammonia Concentrations in Surface Flow Wetlands



APPENDIX 3. STATISTICAL ANALYSES

Analysis of Variance Results

by **NO3-N**
DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	1123583.667	21	53503.984	23.794	0.000
DATE	888590.326	16	55536.895	24.698	.000
REPLICATE	2299.705	1	2299.705	1.023	.314
TYPE	209239.564	4	52309.891	23.263	.000
Explained	1123583.667	21	53503.984	23.794	.000
Residual	323799.078	144	2248.605		
Total	1447382.746	165	8772.017		

180 cases were processed.

14 cases (7.8 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

by **O_PO4**
DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	113238.957	22	5147.225	7.916	.000
DATE	95676.978	17	5628.058	8.655	.000
REPLICATE	6086.859	1	6086.859	9.361	.003
TYPE	10912.540	4	2728.135	4.196	.003
Explained	113238.957	22	5147.225	7.916	.000
Residual	99485.501	153	650.232		
Total	212724.459	175	1215.568		

180 cases were processed.

4 cases (2.2 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

by TKN
DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	998.886	18	55.494	6.606	.000
DATE	855.350	13	65.796	7.833	.000
REPLICATE	10.679	1	10.679	1.271	.262
TYPE	112.923	4	28.231	3.361	.012
Explained	998.886	18	55.494	6.606	.000
Residual	982.839	117	8.400		
Total	1981.726	135	14.679		

180 cases were processed.

44 cases (24.4 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

by TOC
DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	23876.399	22	1085.291	17.840	.000
DATE	6609.883	17	388.817	6.391	.000
REPLICATE	306.478	1	306.478	5.038	.026
TYPE	17503.349	4	4375.837	71.929	.000
Explained	23876.399	22	1085.291	17.840	.000
Residual	9307.825	153	60.835		
Total	33184.224	175	189.624		

180 cases were processed.

4 cases (2.2 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

NH4

by DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	7537.499	22	342.614	18.178	.000
DATE	6757.611	17	397.507	21.091	.000
REPLICATE	16.055	1	16.055	1.852	.375
TYPE	723.532	4	180.883	9.597	.000
Explained	7537.499	22	342.614	18.178	.000
Residual	2864.832	152	18.848		
Total	10402.331	174	59.784		

180 cases were processed.

5 cases (2.8 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

T_SOLIDS

by DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	120.144	20	6.007	5.222	.000
DATE	111.417	15	7.428	6.457	.000
REPLICATE	.000	1	.000	.000	.985
TYPE	8.541	4	2.135	1.856	.122
Explained	120.144	20	6.007	5.222	.000
Residual	155.304	135	1.150		
Total	275.447	155	1.777		

170 cases were processed.

14 cases (8.2 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

by **TOTAL_P**
DATE
REPLICATE
TYPE

UNIQUE sums of squares All effects entered simultaneously

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	201845.026	19	10623.422	18.354	.000
DATE	184169.500	14	13154.964	22.728	.000
REPLICATE	341.496	1	341.496	.590	.444
TYPE	16216.028	4	4054.007	7.004	.000
Explained	201845.026	19	10623.422	18.354	.000
Residual	72929.111	126	578.802		
Total	274774.137	145	1894.994		

170 cases were processed.

24 cases (14.1 pct) were missing.

Due to empty cells or a singular matrix, higher order interactions have been suppressed.

Paired-Sample T-Test Results

Mean influent concentration and mean effluent concentration for each water quality parameter analyzed for each of the ten wetlands were used. Wetland cell numbering follows the numbering in Section 5 of the report body. Highlighted t-values indicate that there was no statistically defensible treatment effect observed.

Paired-Sample T-tests to Determine Presence of Treatment Effect ($\alpha = 0.05$)

Cell#	TP			O-PO ₄			TOC		
	d.f.	t-value	t-crit.	d.f.	t-value	t-crit.	d.f.	t-value	t-crit.
1	10	-3.06	-1.812	13	-2.25	-1.771	13	4.84	1.771
2	10	-2.70	-1.812	13	-2.81	-1.771	13	5.93	1.771
3	12	-1.85	-1.782	15	-1.52	-1.753	15	4.91	1.753
4	12	-1.77	-1.782	15	-1.88	-1.753	15	9.15	1.753
5	12	-2.32	-1.782	15	-1.56	-1.753	15	0.24	1.753
6	12	-4.03	-1.782	15	-6.54	-1.753	15	-0.07	1.753
7	12	-3.00	-1.782	15	-2.48	-1.753	15	-0.63	1.753
8	12	-3.13	-1.782	15	-3.81	-1.753	15	-0.26	1.753
9	12	-2.66	-1.782	15	-2.56	-1.753	15	0.10	1.753
10	12	-2.44	-1.782	15	-2.41	-1.753	15	1.03	1.753
Cell#	NH ₄ -N			NO ₃ -N			TKN		
	d.f.	t-value	t-crit.	d.f.	t-value	t-crit.	d.f.	t-value	t-crit.
1	13	-3.28	-1.771	12	-3.57	-1.782	8	-0.02	-1.860
2	13	-3.06	-1.771	12	-5.86	-1.782	8	0.11	-1.860
3	15	-2.79	-1.753	14	-4.92	-1.761	10	-0.55	-1.812
4	15	-2.79	-1.753	14	-4.91	-1.761	10	-0.91	-1.812
5	15	-3.48	-1.753	14	0.07	-1.761	10	-0.47	-1.812
6	15	-3.97	-1.753	14	-1.75	-1.761	10	-1.11	-1.812
7	15	-1.60	-1.753	14	-1.79	-1.761	10	-0.04	-1.812
8	14	-2.34	-1.761	14	-2.12	-1.761	10	-1.40	-1.812
9	15	-2.36	-1.753	14	-1.69	-1.761	10	-1.05	-1.812
10	15	-2.57	-1.753	14	-0.30	-1.761	10	-1.02	-1.812
Cell#	TS								
	d.f.	t-value	t-crit.						
1	11	-1.25	-1.796						
2	11	-2.62	-1.796						
3	13	-1.14	-1.771						
4	13	-0.84	-1.771						
5	13	1.16	-1.771						
6	13	-0.71	-1.771						
7	13	0.42	-1.771						
8	13	-0.22	-1.771						
9	13	-0.45	-1.771						
10	13	1.16	-1.771						

Scheffe Test Results

Scheffe Tests to Determine if Treatment Effects Observed Are Different ($\alpha=0.05$)

O-PO₄	Basin #	2	3	4	5	6	7	8	9	10
	1	0.764	2.395	2.364	1.551	9.384	0.070	1.390	0.003	0.208
	2		6.004	5.956	4.615	4.668	1.364	0.076	0.913	1.847
	3			0.000	0.091	21.261	1.644	7.434	2.235	1.191
	4				0.085	21.170	1.619	7.380	2.205	1.169
	5					18.566	0.961	5.877	1.423	0.623
	6						1.080	3.551	9.710	12.388
	7							2.086	0.045	0.036
	8								1.517	2.674
	9									0.163

Total P	Basin #	2	3	4	5	6	7	8	9	10
	1	0.002	6.975	8.207	1.529	0.427	0.002	0.489	0.011	0.575
	2		6.732	7.943	1.416	0.490	0.000	0.556	0.022	0.507
	3			0.050	1.973	10.856	6.738	11.158	7.527	3.545
	4				2.651	12.380	7.950	12.703	8.805	4.438
	5					3.573	1.419	3.748	1.793	0.229
	6						0.489	0.002	0.304	1.994
	7							0.554	0.022	0.508
	8								0.356	2.124
	9									0.741

NH₄	Basin #	2	3	4	5	6	7	8	9	10
	1	0.737	1.243	1.362	0.080	1.079	13.236	2.627	1.121	1.542
	2		4.007	4.218	0.366	0.023	20.476	6.288	3.785	4.531
	3			0.003	1.952	4.640	6.366	0.256	0.003	0.016
	4				2.100	4.866	6.106	0.206	0.012	0.006
	5					0.573	15.369	3.621	1.798	2.322
	6						21.876	7.074	4.400	5.202
	7							4.070	6.654	5.743
	8								0.316	0.144
	9									0.034

NO₃-N	Basin #	2	3	4	5	6	7	8	9	10
	1	2.453	0.031	0.141	34.569	14.533	14.925	7.958	10.561	27.920
	2		3.230	3.986	56.259	29.520	30.078	19.731	23.725	47.679
	3			0.040	32.530	13.221	13.595	6.995	9.448	26.090
	4				30.296	11.812	12.165	5.980	8.262	24.094
	5					4.274	4.065	9.355	6.916	0.355
	6						0.003	0.983	0.316	2.166
	7							1.087	0.376	2.018
	8								0.184	6.067
	9									4.138

TOC	Basin #	2	3	4	5	6	7	8	9	10
	1	1.769	1.479	1.006	45.885	48.442	51.792	48.571	42.187	18.442
	2		6.706	0.137	66.383	69.452	73.452	69.606	61.919	32.127
	3			4.924	30.890	32.994	35.769	33.101	27.870	9.477
	4				60.480	63.411	67.236	63.559	56.224	28.063
	5					0.035	0.179	0.038	0.078	6.148
	6						0.056	0.000	0.216	7.106
	7							0.052	0.492	8.423
	8								0.225	7.155
	9									4.843

$F_{\text{critical}} = 17.1$

Highlighted F-values indicate that there was a statistically defensible difference in the treatment effect observed.