THE EFFECTIVENESS OF CONSTRUCTED WETLANDS FOR TREATMENT OF WOODWASTE LEACHATE

by

ARASH MASBOUGH

B.Sc., The University of Tehran, 1995

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

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Department of Civil Engineering
Environmental Engineering Group
Pollution Control and Waste Management Program

We accept this thesis as conforming
to the required standard:

THE UNIVERSITY OF BRITISH COLUMBIA

April 2002

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 Civil Engineering

The University of British Columbia
Vancouver, Canada

Date: April 26, 2002

ABSTRACT

The forest industry is one of the most important contributors to the economy of the province of British Columbia. This industry supports many wood processing mills located throughout the province. Percolation of the rainfall through woodwaste piles and log storage areas leaches natural chemicals from the wood residuals.

A study was performed on a woodwaste storage site near Mission, B.C., where a number of wood processing mills are located adjacent to the Fraser River. The objective of this research was to evaluate the effectiveness of surface flow constructed wetlands for treatment of woodwaste leachate. The leachate was characterized over the period of the study. It had very low pH (~3.5), very high and aggressive oxygen demands (5,000-11,000 $mg.L^{-1}$ BOD_5, and 7,000-18,000 $mg.L^{-1}$ COD) , very high levels of tannin and lignin (2,800-6,500 $mg.L^{-1}$) and total VFAs (1,800-2,800 $mg.L^{-1}$), and low levels of nutrients (< 3 $mg.L^{-1}$ NH_3–N, < 0.2 $mg.L^{-1}$ NO_x-N, and < 4 $mg.L^{-1}$ PO_4-P). Diluted leachate was directed to six pilot-scale wetland cells, four planted with cattails (*Typha latifolia*) and two controls, during a total operational period of 34 weeks. As the leachate had a very low nutrient content and pH, nutrient addition and pH adjustments were made to improve contaminant removal. After physical modifications in the site, reductions in pollutants were consistently achieved. The average removals for BOD and COD were in the order of 60% and 50% respectively. On average, up to 69% of VFAs and 42% of tannin and lignin contents were removed. The ThOD comparisons with COD showed that VFAs and tannin and lignin accounted for over 60% of COD in effluent and influent.

"Planted and nutrient added" cells were more effective in BOD removal from leachate than the unplanted controls. In addition, the effluent pH values were higher for the planted cells. No significant differences were observed in removal efficiencies of other targeted pollutants between the six cells. Climatic conditions (i.e. precipitation, evaporation and temperature) had a great impact on the performance of the wetlands. In addition, acclimatization of the wetlands increased the treatment ratios.

Constructed wetlands proved effective in treatment of woodwaste leachate. Continuous operation of the system will help to elucidate the seasonal fluctuations. Microbiological studies can also shed light on the causes of performance variations.

TABLE OF CONTENTS

ABSTRACT ii

TABLE OF CONTENTS iii

List of Tables v

List of Figures vii

List of Abbreviations ix

ACKNOWLEDGEMENTS x

1) INTRODUCTION 1

1-1) B.C.'s Forest Industry 2

1-2) Research Objectives 6

1-3) Project Background 7

1-4) Research Site Description 8

2) BACKGROUND STUDIES 12

2-1) Constructed Wetlands 12

2-1-1) Different Layouts of Constructed Wetlands 14

2-1-1-1) Constructed Surface-Flow (SF) Wetlands 16

2-1-1-2) Constructed Subsurface-Flow (SSF) Wetlands 16

2-1-2) The Role of Plants in Constructed Wetlands 18

2-1-3) Hydraulic Characteristics of Constructed Wetlands 20

2-2) Leachate Control and Treatment 23

2-3) Woodwaste Leachate Characteristics 26

2-4) Using Constructed Wetlands as an Alternative for Leachate Treatment 31

3) WOODWASTE LEACHATE CHARACTERIZATION 35

3-1) Methods and Materials 35

3-1-1) Sampling Protocols 35

3-1-2) Analytical Protocols 37

3-2) Results and Discussion 40

3-2-1) pH, Temperature, Conductivity, and Solids 40

3-2-2) VFAs, Tannin and Lignin, COD, and BOD_5, and DO 42
3-2-3) Nutrients and Other Chemicals 48
3-3) Conclusions 51
4) PILOT SCALE TREATMENT EVALUATION 53
4-1) Methods and Materials 54
4-1-1) System Description 54
4-1-2) Nutrient Addition and pH Adjustment 61
4-1-3) Sampling and Analytical Protocols 62
4-2) Results and Discussion 62
4-2-1) Characterization of Dilution Water Sources 62
4-2-2) Treatment Performance 64
4-2-2-1) ThOD Comparisons with Measured COD 73
4-2-2-3) Seasonal Effects on Wetlands Performance 80
4-3) Conclusions 85
5) GENERAL CONCLUSIONS AND RECOMMENDATIONS 87
6) REFERENCES 90
APPENDICES 98
APPENDIX A Raw Data 99
APPENDIX B Theoretical Oxygen Demand Calculations 127
APPENDIX C Climatic Data 130
APPENDIX D Seasonal Changes in Wetlands Performance 132

List of Tables

Page #

Table 2-1 Summary of the major roles of macrophytes in constructed treatment wetlands..... 20
Table 2-2 Chemical composition of leachate from municipal solid waste..... 25

Table 3-1 Sample collection, preservation and storage..... 36
Table 3-2 Methods and instruments used for analysis..... 38
Table 3-3 Frequently measured leachate characteristics (2000 and 2001)..... 41
Table 3-4 Concentrations of individual volatile fatty acids (2000)..... 43
Table 3-5 Oxygen demand ratio comparisons..... 47
Table 3-6 Summary of the measured nutrients in the leachate pool..... 48
Table 3-7 One-time measured components in the leachate..... 50

Table 4-1 Characterization of dilution water sources (slough in 2000 and well in 2001) 63
Table 4-2a Field data, pH, and conductivity measurements for influent and effluent, 2000..... 65
Table 4-2b Field data, pH, and conductivity measurements for influent and effluent, 2001..... 65
Table 4-3a Summary of removal performances for targeted parameters in the pilot-scale constructed wetlands (2000) 68
Table 4-3b Summary of removal performances for targeted parameters in the pilot-scale constructed wetlands (2001) 69
Table 4-4a Summary of removal performance for volatile fatty acids (C2-C6) in the pilot-scale constructed wetlands, 2000..... 71
Table 4-4b Summary of removal performance for volatile fatty acids (C2-C6) in the pilot-scale constructed wetlands, 2001..... 71
Table 4-5 Oxygen demand ratio comparisons..... 73
Table 4-6a Summary of performance for nutrients in pilot-scale constructed wetlands, 2000..... 76
Table 4-6b Summary of performance for nutrients in pilot-scale constructed wetlands, 2001..... 77

Table A1 Temperature, pH, DO, and conductivity in constructed Wetland Cells in 2000 99
Table A2 Solids Concentrations in Constructed Wetland Cells in 2000 101
Table A3 BOD, COD, and Tannin and Lignin Raw Data in Constructed Wetland Cells in 2000 110
Table A4 Total Volatile Fatty Acids Raw Data in Constructed Wetland Cells in 2000 113
Table A5 Nutrients Raw Data in Constructed Wetland Cells in 2000 116
Table A6 Temperature, pH, DO, and Conductivity Raw Data in Constructed Wetlands in 2001 117
Table A7 BOD, COD, and Tannin and Lignin Raw Data in Constructed Wetland Cells in 2001 120
Table A8 Total Volatile Fatty Acids Raw Data in Constructed wetland Cells in 2001 122
Table A9 Nutrients in Constructed wetland Cells in 2001 125
Table B1 Total ThOD for VFAs, 2000 128
Table B2 Total ThOD for Tannin and Lignin, 2000 128
Table B3 Total ThOD for VFAs, 2001 129
Table B4 Total ThOD for Tannin and Lignin, 2001 129
Table C1 Climate Normals, Abbotsford, BC, 1944-1990 131

List of Figures

Page #

Figure 1-1 B.C. exports by product groups, 1999..... 3
Figure 1-2 General plan of the research site..... 9
Figure 1-3 Wood-processing shake and shingle mills next to the Fraser River... 10
Figure 1-4 Woodwaste pile as seen from North-South direction..... 10
Figure 1-5 Leachate pool viewed from top of the pile..... 11

Figure 2-1 Contaminant removal processes in a constructed wetland..... 14
Figure 2-2 Types of constructed wetlands..... 15
Figure 2-3 The three wetland shapes with the best hydraulic efficiencies..... 22

Figure 3-1 BOD and COD changes in leachate..... 44

Figure 4-1 Wetland cell cross section..... 54
Figure 4-2 Influent inlet, the replaced spreader pipe, and the influent control valve..... 55
Figure 4-3 Pilot-scale system site diagram..... 56
Figure 4-4 General view of the pilot scale wetland cells..... 57
Figure 4-5 a) The stainless steel electric pump inside the wooden shelter, b) Flow control box: fuses, timers, and switches..... 58
Figure 4-6 Dosing tank cross-section and details..... 59
Figure 4-7 a) Drilling a well as the dilution water source replacement, b) Details of the well..... 60
Figure 4-8 Average pH improvement in pilot scale cells..... 66
Figure 4-9 pH neutralization measurements during three different time steps using 10g.L^{-1} limestone and pure leachate..... 67
Figure 4-10 COD comparisons with ThOD for VFAs and tannin and lignin..... 75
Figure 4-11 The effect of fertilizer addition on ortho-phosphate concentrations of the cells effluent..... 78
Figure 4-12 Wetlands seasonal variations for BOD_5 and VFAs removal in 2000..... 79
Figure 4-13 Wetland seasonal variations for COD and tannin and lignin removal in 2000..... 82
Figure 4-14 Climatic data for year 2000, top: temperature and bottom precipitation..... 83

Figure C1 Temperature Data of Abbotsford, B.C. for 2001 118
Figure C2 Precipitation Data of Abbotsford, B.C. for 2001 118
Figure D1 Seasonal Variability in BOD_5 in Constructed Wetlands Cells in 2001 120
Figure D2 Seasonal Variability in COD in Constructed Wetlands Cells in 2001 121
Figure D3 Seasonal Variability in Tannin and Lignin in Constructed Wetlands Cells in 2001 122
Figure D4 Seasonal Variability in Volatile fatty Acids in Constructed Wetlands Cells in 2001 123
Figure D5 Seasonal variability in Ammonia in Constructed Wetland Cells in 2000 124
Figure D6 Seasonal variability in Ammonia in Constructed Wetland Cells in 2001 124
Figure D7 Seasonal variability in Nitrate+Nitrite in Constructed Wetland Cells in 2000 125
Figure D8 Seasonal variability in Nitrate+Nitrite in Constructed Wetland Cells in 2001 125
Figure D9 Seasonal Variability in ortho-Phosphate in Constructed Wetland Cells in 2000 126
Figure D9 Seasonal Variability in ortho-Phosphate in Constructed Wetland Cells in 2000 126

List of Abbreviations

AAS	Atomic Absorption Spectrophotometer(y)
APHA	American Public Health Association
BC	British Columbia
BOD	Biochemical Oxygen Demand
BOD_5	5-Day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
FSS	Fixed Suspended Solids
GC	Gas Chromatograph(y)
HDPE	High Density Polyethylene
HRT	Hydraulic Retention (Residence) Time
LC_{50}	Lethal Concentration: 50%
NDIR	Non-Depressive Infrared Analyzer
PPE	Personal Protection Equipments
PVC	Poly Vinyl Chloride
ReCip	Reciprocating Bed Wetlands
SF	Surface Flow Wetlands
SSF	Sub-surface Flow Wetlands
T&L	Tannin and Lignin
TDS	Total Dissolved Solids
ThOD	Theoretical Oxygen Demand
TOC	Total Organic Carbon
TSS	Total Suspended Solids
VFAs	Volatile Fatty Acids
VF	Vertical Flow Wetlands
VOA	Volatile Organic Acids
VSS	Volatile Suspended Solids

ACKNOWLEDGEMENTS

I have to thank my research advisor, Dr. Ken Hall. He was extremely supportive, patient, and helpful from the first moment that I started in this program. I don't remember a single day going to his office with the most complicated problems, and not leaving without a smile on my face. His knowledge and wisdom were infinitely valuable during the course of this research.

I would like to thank Dr. Noboro Yonemitsu in the Environmental Hydraulics Group at UBC. He was always willing to help. It was impossible for me to get to this point without his support.

Any student who has been involved in research in Environmental Engineering Group in UBC knows that experiments are not possible without the support of Susan Harper and Paula Parkinson. My research was not an exception. All the instruments and equipment in the Environmental Engineering Laboratory would have been useless without their insight.

I am also thankful to the Department of Civil Engineering in UBC for giving me the opportunity. Apart from intensive coarse load, they taught me how to be persistent, examining my knowledge, as well as my endurance.

During the period of this research I benefited from the support of a lot of friends. In particular Jody Addah, my friend and officemate. Not only for the fact that he helped me with filed work, but also for his support in the moments that nothing was working. I am also thankful to Wendong Tao. He helped me with the fieldwork and analyses

I want to offer my endless thanks to my parents. Their supports during my studies, and life have been unbelievable. And of course it is difficult to say about all of that within these lines.

Finally, I should thank my life partner. Parisa always gave me the hope and reason to proceed. She also gave me all the confidence and motivation that I needed.

1) INTRODUCTION

In addition to sunlight and air, water is an indispensable element for most animal and plant life. A casual observation of the world map would suggest that the supply of water is endless, since it covers over 80% of the Earth's surface. Unfortunately, we cannot use it directly; over 95% is in the salty oceans, 2% is tied up in the polar ice caps, and most of the remainder is beneath the Earth's surface. Therefore, there is only a small fraction of the water available for human use, and it is up to humans to maintain access to sustainable sources of clean water.

The chemicals present in water affect its quality for the end users. Most industrial activities produce considerable amount of wastewater. Treatment and disposal of industrial wastewater is one of the most challenging fields in environmental engineering practice. Because of the great variety of wastes produced from established industries, and the introduction of wastes from new processes, it is difficult to select a single treatment method for industrial wastewater.

Many of the industrial waste problems faced by environmental engineers can be solved by minimizing the quantities of these materials produced and used through product substitution, waste recovery, and recycling. The next step is the introduction of efficient and cost effective treatment processes that are suitable for treating a variety of waste problems.

Control and disposal of solid waste are other challenges for environmental engineers. Leachate control and treatment is by far one of the most important aspects in this area. Solid waste composition varies substantially with sources, socio-economic conditions, location, and season. Leachate formation is the result of the removal of soluble compounds by the non-uniform and intermittent percolation of water through the refuse mass. Soluble compounds are generally encountered in the refuse at emplacement or are formed by chemical and biological processes. The sources of percolating water are primarily precipitation, irrigation, runoff, and ground water intrusion and to a lesser extent, initial refuse moisture content. Refuse decomposition due to microbial activity contributes to leachate characteristics and its potential environmental impacts (El-Fadel *et al.*, 1997).

The quantity of leachate generated is site-specific. It depends on water availability and weather conditions as well as the characteristics of the solid waste, the landfill surface, and the underlying soil. The quality of leachate is highly dependent upon the stage of fermentation in the solid waste, the composition of the waste, operational procedures, and co-disposal of the wastes (Pohland *et al.*, 1983).

1-1) B.C.'s Forest Industry

British Columbia's forest industry is a dominant contributor to the provincial economy. In 1999, it made up over 50.3 percent or $18.6 billion of total manufactured shipments inside the province. Wood products accounted for 33 percent and pulp and paper products

for 17.3 percent. B.C. has only 17 percent of Canada's total forestland, but grows almost 40 percent of the nations merchantable timber. In general, B.C. harvests less area annually than Ontario and Quebec, yet plants two to three times more area per year. Almost 50 percent of all silviculture expenditures in Canada occur in B.C. (COFI, 2000).

Among the goods-producing industries, the forest industry (a combination of the wood products, paper allied industries and logging) is one of the largest contributors to B.C.'s gross domestic product. The total value of forest products exported from B.C. in 1999 was $15.3 billion. Forest products were counted for 58 percent of the total province's exports (Figure 1-1), (Statistics Canada, 2000).

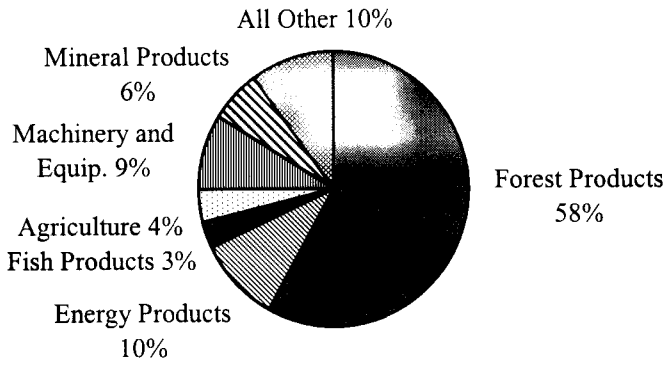


Figure 1-1 B.C.'s exports by product groups, 1999
(Source: B.C. Stats; B.C. Origin Exports, Economics and Trade Branch, Ministry of Forests)

The B.C. forest industry accounted for 90,600 direct jobs and a further 181,200 indirect and induced jobs in 1999. The forest industry is a source of livelihood for 271,800 British

Columbians and represented 14 percent of total provincial workforce in 1999. (COFI, 2000).

B.C. produces 48.8 percent of the total lumber production in Canada. The province's contribution in pulp, paper and plywood are 28.6, 13.7, and 83.0 percent of total production in Canada, respectively. There are close to 500 primary mills located in BC, processing almost all of the wood harvested in the province (65 million m^3 in 1998). Considering the size of the industry, it is obvious that the related environmental management measures play a very important role in the province (COFI, 2000).

Given the dimensions and importance of the industry, it is necessary to consider a management strategy and appropriate regulations to deal with the waste produced. Woodwaste as defined in British Columbia's Waste Management Act includes hog fuel, mill ends, wood chips, bark, and sawdust. It does not include demolition waste, construction wastes, tree stumps, branches, logs or log ends (Government of B.C., 1996). Collection and disposal of this waste is an immense task. There are about 50 sawmills located in British Columbia (Bailey *et al.*, 1999). The woodwaste from sawmills alone has been estimated at about 2.8 million bone-dry tonnes per year (McCloy, 1997). The woodwaste generated from other sectors of the industry such as chipping, panel, and other type of mills, as well as the pulp and paper mills, must be added to this total. Moreover, a large number of wood product storage locations including log yards and chip piles at barge loading facilities require waste management measures, particularly in connection with leachate runoff control and treatment.

Woodwaste is a natural product. However, if rainwater seeps into woodwaste it can pollute the environment. Provincial and Federal guidelines provide information on woodwaste use, storage and the woodwaste leachate control. For example, management practices that are specific to woodwaste use and storage include, but are not limited to, the following (Government of B.C., 1996):

- Only woodwaste uses that minimize the leachate and prevent water contamination are permitted.
- Environmental requirements common to all woodwaste uses include:

    - Woodwaste must not be used as landfill unless a permit or approval has been obtained from B.C. Environment.
    - Woodwaste deposits must not exceed a total of 30 cm, which should be achieved by applying layers that do not exceed 15 cm per year.
    - A buffer zone of 30 m is required between woodwaste deposit and domestic water supplies, and other sensitive water bodies.
    - Woodwaste and woodwaste leachate must not be allowed to contaminate surface or ground water.
    - Stored woodwaste should be covered to prevent leachate from forming and polluting the environment.

A quick look at the existing acts, regulations, and bylaws shows that the environmental hazards of woodwaste and its leachate are more or less addressed. The growth of woodwaste piles demonstrates that the amount of woodwaste production in the province is much more than the demand for its use. Conversely, having a look at the active wood processing mills in the province suggests that not all of the regulations are practically applied. There are numerous woodwaste piles along the lower Fraser River and in the interior of the province without any control of leachate production or discharge.

1-2) Research Objectives

The objective of this research was to evaluate the effectiveness of surface flow constructed wetlands for treatment of woodwaste leachate. The research was conducted on six constructed wetland cells located near the city of Mission, B.C., Canada, adjacent to the Fraser River. A leachate pool was formed at the site because of runoff from an active woodwaste pile. Leachate was directed to wetland cells, after dilution. The fieldwork began with hydraulic and mixing improvements. The performance of wetlands on the removal of targeted pollutants was monitored for a total of 34 weeks (from May to September, 2000 and from July to October, 2001).

This thesis provides with a brief review of the project background and research site description. In the next section (Chapter 2), a background literature review introduces and assesses the types and performances of constructed wetlands as systems of treatment for diverse wastewaters. The characteristics of woodwaste leachate and a review of the

leachate control and treatment measures are presented. There are few literature sources on woodwaste leachate treatment. As a result, the production and treatment mechanisms of landfill leachate, as the most similar wastewater to woodwaste leachate, are discussed. In the following section (Chapter 3), the results on long-term characteristics of woodwaste leachate on the study site are presented. Next is a description of the pilot scale site and the different components of the system. This is followed by presentation and discussion on the results of the removal efficiency for targeted pollutants (Chapter 4). In the last section (Chapter 5), this thesis finishes with the conclusions based on the presented results and recommendations for further possible research.

1-3) Project Background

The research site was selected on October 1997 and permission was secured from the landowners and B.C. Shake and Shingle Association to conduct research on the wood-processing site. The agreements were collected from the B.C. Ministry of Environment, Lands and Parks and various other stakeholders. A particular agreement required that the bottom of the experimental wetland cells should be protected with impermeable liners and all of the produced effluent should be collected and pumped back to the woodwaste pile (i.e. generation point) (Frankowski, 2000).

Characterization studies were started on the site and nine sampling trials were conducted. In the mean time, bench scale studies were carried out to evaluate the feasibility of constructed wetlands in treatment of the woodwaste leachate. Eight small wetlands were

constructed using broad-leaved cattails (*Typha latifolia*) planted in fish tanks. The microcosm wetlands were placed in a controlled environment room.

The results from the bench scale wetlands were promising. The system with 29 days HRT, achieved 93% removal in toxicity and 80% removal in COD. The BOD removal was as high as 94% with a HRT of 25 days.

After the successful bench scale trials, the construction of the pilot scale wetlands started in May 1998 at the research site. Six wetland cells were constructed on the site and four of them were randomly selected and planted with cattails (*Typha latifolia*). Due to necessary adaptation time, Fraser River flooding event, and financial constraints, the field trials were limited to a six-week period (October-December 1999). However, in this period, the wetland system proved to be capable of treating this leachate. There was a need for more research to optimize the performance of the wetlands (Frankowski, 2000).

The project was taken over in May 2000. New research activities were started with physical improvement of the treatment system.

1-4) Research Site Description

The research site was situated on the west side of the city of Mission, approximately 75 kilometres east of Vancouver, B.C. It was located in the coastal climate region with relatively high mean annual precipitation (1563 mm per year). Daily mean temperatures

varied between 2 °C in January to 17 °C in August. Daily minimum and maximum temperatures were reported as low as –1 °C and as high as 24 °C, respectively (Environment Canada, 1999).

The west side of Mission is a rural setting with a few agricultural farms (mostly corn farms) and a few wood processing mills. The study site was adjacent to one of the wood-processing mills on the north bank of the Fraser River (Figures1-2 and 1-3).

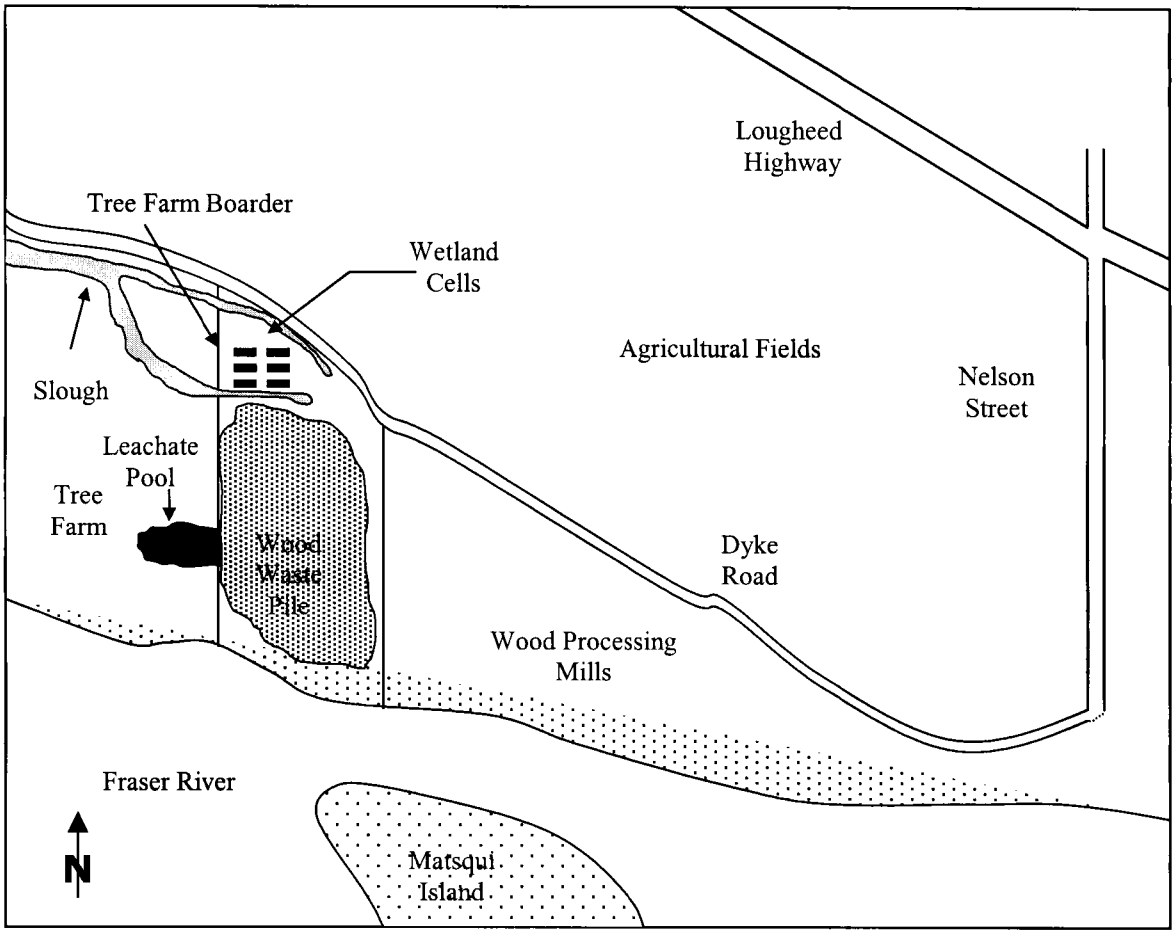


Figure 1-2 General plan of the research site
(not on scale)

Figure 1-3 Wood-processing shake and shingle mills next to the Fraser River

On the east side of the series of processing mills, there was a pile of miscellaneous woodwaste generated. The pile had a diameter of approximately 200 m and was over 20 m high. Taking into account the significant precipitation and the permeable character of the woodwaste, a considerable amount of leachate was potentially produced (Figure 1-4).

Figure 1-4 Woodwaste pile as seen from North-South direction

Due to leachate flowing to the adjacent tree farm, a pool was formed on the west side of the pile. The pool was approximately 20 m wide and 70 m long. The leachate had a very dark colour, strong sour smell, and fine bubbles were noticeable on its surface. A number of dead trees were still standing throughout in the pool and the nearby trees were clearly weakened (Figure 1-5).

Figure 1-5 Leachate pool viewed from top of the pile

Because of the closeness of the pile to the Fraser River (<60 m), there was a concern about the effects of leachate discharge to the river. The Fraser River and its tributaries comprise the world's most productive salmon river system and they have a great environmental, economic and social value in the province of British Columbia (CHRS, 2001).

2) BACKGROUND STUDIES

2-1) Constructed Wetlands

Natural wetlands have been used as convenient wastewater discharge sites for as long as sewage has been collected (at least 100 years in some locations) (Kadlec and Knight, 1996). Constructed wetlands have been recognized for several years as low cost, minimal maintenance systems that could lower the impact of wastewater drainage on natural water bodies (Mitsch and Wise, 1998).

The first scientific research studies and pilot-scale constructed wetland wastewater treatment facilities originated in Germany at the Max Planck Institute, where Kathe Seidel undertook detailed testing of many aquatic plants to determine their ability to absorb and breakdown chemical pollutants. Her research first presented in 1953, proved that particular plant species had the ability to remove some pollutants. In addition, plants grown in wastewater exhibited surprisingly varied physiological and morphological changes that aided their performance (Campbell and Ogden, 1999).

In a very general sense, understanding the function of constructed wetlands requires us to step back in time to achieve a more basic understanding that every farmer had: plants require water and fertilizer for their growth. Wastewater essentially consists of water, fertilizer, and organic chemicals. Wetland plants, unlike dryland plants, can grow in

saturated soils and standing water, and consume several times the nutrients used by dryland crops (Campbell and Ogden, 1999).

Constructed wetlands are a designed and man-made complex of saturated substrates, emergent and submergent vegetation, animal life, and water that simulate natural wetlands for human use and benefits (Hammer and Bastian, 1989). Natural or artificial wetlands such as marshes or swamps, with their vegetation (primarily cattails, reeds, and rushes), provide an ideal microenvironment for the sedimentation, filtration, adsorption, and bacterial decomposition of wastewater constituents. Since natural wetlands are usually considered as receiving waters, discharges must meet applicable regulatory requirements and thus are limited to treatment of secondary or tertiary effluents. Constructed wetlands, however, have a much broader application, having been employed to treat primary effluent, industrial wastewaters, acid mine drainage, landfill leachate, and urban runoff. In a typical design, continuously applied wastewater flows freely through parallel basins or channels with relatively impermeable bottom soil, emergent vegetation, and water depths of 0.1 to 0.6 m (Henry and Heinke, 1996). A combination of biological, physical, and chemical reactions are involved in contaminant removal processes in constructed wetlands (Figure 2-1) (USGS 1996).

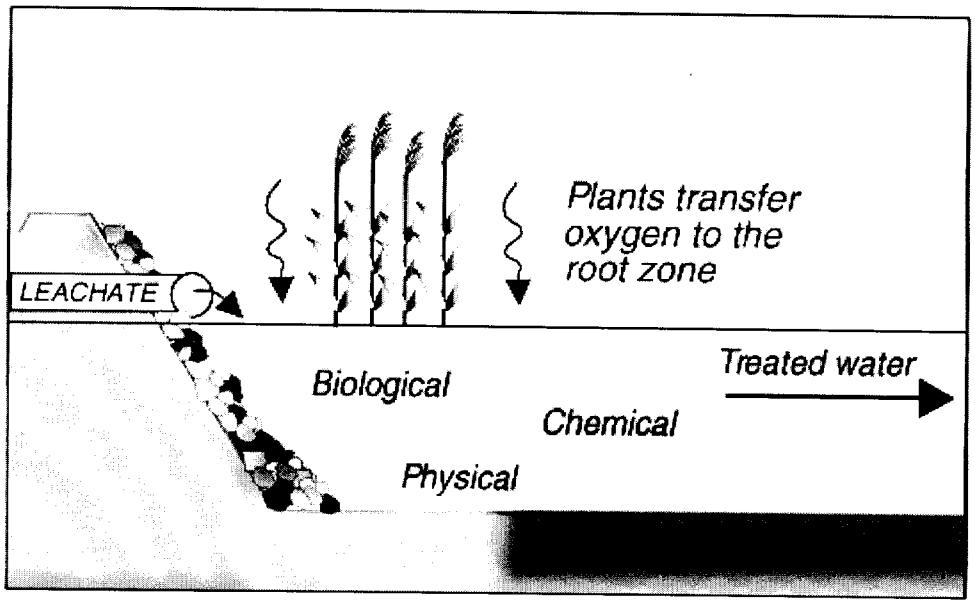


Figure 2-1 Contaminant removal processes in a constructed wetland
(Source: USGS, 1996)

The use of constructed wetlands provides a relatively simple and inexpensive solution for treatment of pollution from small communities, industries, storm water, and agricultural runoff. Experience shows that constructed wetlands provide an effective treatment alteration to conventional treatment systems especially for small communities (Vymazal, 1999).

2-1-1) Different Layouts of Constructed Wetlands

Constructed wetland technology has advanced dramatically in the last ten years. New wetland designs have the capability of treating high-strength wastes and functioning even in subfreezing environments. Constructed wetlands usually comprise reeds (*Phragmites australis*) and/or bulrushes (*Schoenoplectus*) planted in gravel or sand. Constructed wetlands may use horizontal or vertical flow (see Figure 2-2). Horizontal-flow wetlands

may be of two types: surface flow (SF) or subsurface flow (SSF). In the former, the effluent flows freely above the sand/gravel bed in which the reeds etc. are planted, and there may be patches of open water. In the latter type, effluent passes through the sand/gravel bed (Wallace, 2001). A wide selection of design variations exists for each of these alternatives. In addition, these two types of wetlands can be combined with each other or with other conventional, and natural technologies to create hybrid systems that meet specific needs. Each type has advantages and disadvantages for different applications.

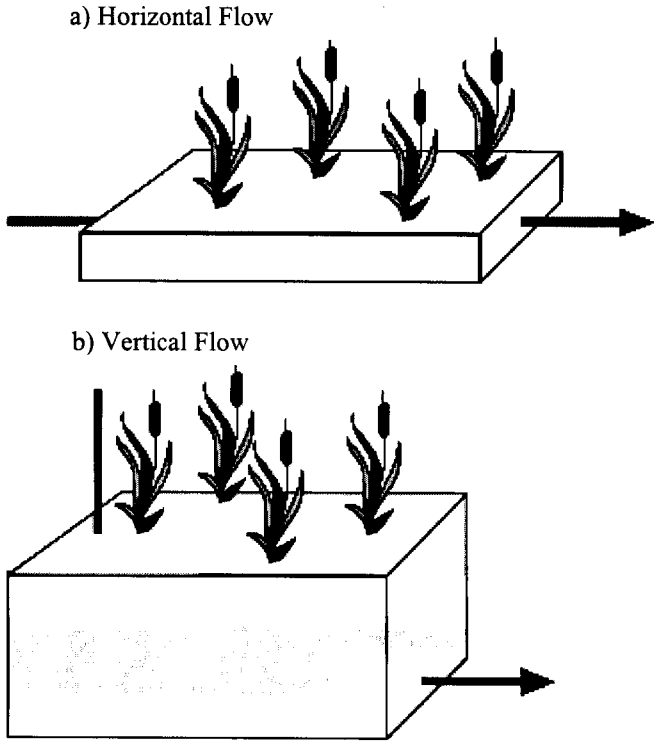


Figure 2-2 Types of constructed wetlands: a) Vertical flow b) Horizontal flow (Source: Fujita, 1998)

2-1-1-1) Constructed Surface-Flow (SF) Wetlands

Surface-flow constructed wetlands mimic natural wetlands in that water flows principally above the ground surface, as shallow sheet flow, through a more or less dense growth of emergent wetland plants. Four features are common to all constructed SF wetlands: an inlet device, the wetland basin, the wetland plants, and an outlet device (Kadlec and Knight, 1996).

A typical constructed SF wetland is a sequence of sealed shallow basins containing 20-30 cm of rooting soil with water depth of 20-40 cm. Dense emergent vegetation covers a significant fraction of the surface, usually more than 50%. Commonly used plants are *Typha* spp. and *Scirpus* spp., but natural assemblages of volunteer regrowth from native seed banks are also used. Deep, open areas are added for wildlife, or to function as sedimentation basins. Flow is directed into a cell along a line comprising the inlet, upstream embankment, and is intended to proceed across all portions of the marsh to one or more outlet structures (Kadlec, 1995). Surface flow wetlands are well established, but their use is limited in severely cold-climate applications when year-round treatment is required (Wallace, 2001).

2-1-1-2) Constructed Subsurface-Flow (SSF) Wetlands

Constructed, SSF wetland systems treat wastewater by passing it horizontally or vertically through a permeable media planted with wetland plants. Microbial attachment

sites are located on the surface of media and on the roots of the wetland plants. Although SSF wetlands have many features in common with SF wetlands, they also have a number of differences that are important during planning. The principal components of a SSF constructed wetland are the inlet distribution system, the basin configuration, the bed media, the plants, and the outlet control system (Kadlec and Knight, 1996).

SSF beds are commonly vegetated with *Phragmites* spp. Submerged beds, populated by plants such as *Elodea canadensis* or *Mariophyllum aquaticum*, are seen less frequently. Channels with floating leaved plants, either *Eichhornia crassipes* or *Lemna spp.*, are also used. The former is used in frost-free climates (Kadlec, 1995).

Freezing of the gravel bed could occur in winter if the weather is cold enough. The extent and severity of freezing is strongly influenced by the amount of snow or other insulation present. With cold temperature and no snow resulting in the worst freezing. The year-round use of SSF constructed wetlands has proved feasible in the permafrost zone. Vertical Flow (VF) and Reciprocating Bed (ReCip) wetlands, which are two sub-groups of SSF wetlands, are being successfully used to treat waste previously considered "too strong". In VF wetlands, as the name implies, water flows vertically within the gravel bed. ReCip wetland was originally developed to deal with high-strength agricultural waste. The basic process uses two gravel-filed wetland cells. Wastewater is pumped back and forth between the two cells. The alternative filling and draining of the wetland draws atmospheric oxygen into the gravel pore spaces, enhancing oxygen transfer. Technical

developments in constructed wetlands allow for lower treatment costs in a variety of previously unexplored applications (Wallace, 2001).

2-1-2) The Role of Plants in Constructed Wetlands

Plants are an integral part of the effluent treatment processes in constructed wetlands (Wetzel, 1993). The presence or absence of wetland plants is one of the characteristics often used to define the boundary of wetlands. In Clean Water Act of the US Government, wetlands are defined as "areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions" (Mitsch and Gosselink, 1993). Thus, it is an inherent property of wetlands, including constructed wetlands, that they are vegetated by wetland plants.

The most important functions of the macrophytes in relation to the treatment of wastewater are physical effects due to the presence of the plants. The macrophytes stabilize the surface of the beds, provide good conditions for physical filtration, prevent vertical flow system from clogging, insulate the surface against frost during winter, and provide a huge surface area for attached microbial growth (Brix, 1997). Research has shown that the plant canopy captures the contaminants by creating still regions that allow particulate material to accumulate around stems and leaves. Another effect of plant/flow interaction is the creation of small wakes behind plant stems. This bit of turbulence may

improve the plants' uptake of elements, or it may accelerate the uptake of chemicals by microbial communities living on the plants' surfaces (Nepf and Koch, 1999).

It is well documented that aquatic macrophytes release oxygen from roots into the rhizosphere and that this release influences the biogeochemical cycles in the sediments through the effects on the redox status of the sediments (Sorrel and Boon, 1992). The roots of the wetland plants supply habitat for microorganisms, which are responsible for degradation of many polluting constituents of wastewater. For this reason, recent studies have considered maximizing the contact between wastewater and the rhizosphere (the root zone). Indeed, it is often considered the primary objective in designing these systems, especially in SSF constructed wetlands (Rash and Liehr, 1999). The metabolism of macrophytes affects the treatment process to a different extent depending on the types of the constructed wetland. Plant uptake of nutrients is only of quantitative importance in SF systems. The macrophytes have additional site-specific values by providing habitat for wildlife and making wastewater treatment systems aesthetically pleasing (Brix, 1997).

Constructed wetlands can be planted with a number of adapted, emergent wetland plant species. Wetlands created as part of compensatory mitigation, or for wild life habitat, typically include a large number of planted species. Wetland plant species selection should consider the following: expected water quality, normal and extreme water depths, climate and latitude, maintenance requirements, and project goals (Kadlec and Knight, 1996). Table 2-1 summarizes the major roles of macrophytes in constructed treatment wetlands.

Table 2-1 Summary of the major roles of macrophytes in constructed treatment wetlands[1]

Macrophytes Property	Role in treatment process
Aerial plant tissue	Light attenuation ⇒ reduced growth of phytoplankton Influence on microclimate ⇒ insulation during winter Reduced wind velocity ⇒ reduced risk of resuspension Aesthetic pleasing appearance of the system Storage of the nutrients
Plant tissue in water	Filter effect ⇒ filter out large debris Reduced effluent velocity ⇒ increase rate of sedimentation, reduces risk of resuspension Provide surface area for attached biofilm Excretion of photosynthetic oxygen ⇒ increase aerobic degradation Uptake of contaminants
Roots and rhizomes	Stabilizing the sediment surface ⇒ less erosion Prevents the medium from clogging in vertical flow system Release of oxygen increase degradation and nitrification Uptake of nutrients Release of antibiotics

[1]Adopted from Brix (1997)

2-1-3) Hydraulic Characteristics of Constructed Wetlands

The design of constructed wetlands and ponds requires multi-disciplinary input involving biological and ecological sciences, aquatic chemistry, engineering hydrology, and flow hydraulics.

The hydrologic components of the wetland system include inflow, outflow, precipitation, evaporation and transpiration (considered together as evapotranspiration), and infiltration. Inflow and precipitation represent water inputs to the wetland system, and outflow, evapotranspiration, and infiltration represent water outputs from the wetland system. When all water inputs and outputs are measured over a given time period, a water balance can be conducted to test the accuracy of the measurements. If measurements for a single

hydrologic component are not available, the water balance can be used to estimate the missing values (SRCD, 1999).

Wetland hydrology is a primary driving force influencing wetland ecology, its development and persistent. Increased demand for agricultural and domestic water supplies, the use of wetlands in wastewater treatment, and speculation about the effects of climate change, have raised awareness of the need for accurate estimates of wetland hydrological fluxes. For most wetlands, evapotranspiration is the major component of energy sink (Souch, *et al.*, 1996). Optimal hydrologic effectiveness and hydraulic efficiency provide the most appropriate conditions for promoting the necessary biological and chemical processes for wastewater treatment (Persson, *et al.*, 1999). The hydrologic characteristics of wetlands are usually described through preparation and analysis of a water budget. However, because of the complex nature of wetlands, there is a great deal of uncertainty over the hydrologic budgets and hydrologic functions of different types of wetlands (Arnold *et al.*, 2001).

In the highly unsteady conditions to which most real-world constructed wetlands are subjected, constructing a meaningful residence time distribution is difficult. In flow pattern analysis, combining flow rate and concentrations can be useful for observing when masses of tracer leave the wetland. Still, this form of residence time distribution is dependant on the flow conditions the wetland undergoes. High flow rates mask low concentrations. Tracer tests by Rash and Liehr (1999) on free water surface flow wetlands suggested that these wetlands are not subject to short-circuiting, and that the

nominal detention time is usually a good estimate of actual detention times in the wetland. In general, SF wetlands are more efficient than SSF wetlands in terms of hydraulic efficiency.

Tracer studies also suggest that plug or continuously stirred flow conditions never occur in natural systems and the concentration-time distribution of natural wetland systems lies somewhere between the distributions of plug flow and fully mixed flow conditions (Wood, 1995). Furthermore, the effective volume in constructed wetlands is less than the nominal storage volume. Investigations by Persson *et al.,* (1999) on thirteen wetland configurations and shapes showed that baffled systems (Figure 2-3a) or elongated pond shapes (Figure2-3 b) provided very high hydraulic efficiency. However, care needs to be applied in designing elongated shapes to ensure that increased flow velocity associated with the narrower cross section does not lead to resuspension and remobilization of settled material. Spreading the inflow across the wetland also provided a high hydraulic efficiency (Figure 2-3 c)

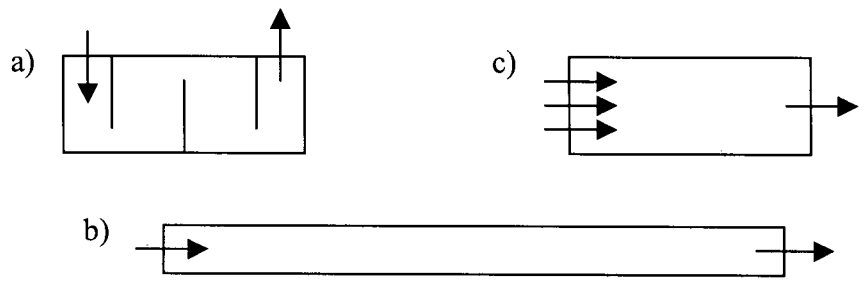


Figure 2-3 The three wetland configurations with the best hydraulic efficiencies:
a) baffled, b) elongated, c) spread inflow
(Adopted from Persson *et al.,* 1999)

2-2) Leachate Control and Treatment

Leachate occurrence is by far the most significant threat to groundwater. Once leachate reaches the bottom of the landfill or an impermeable layer within the landfill, it either travels laterally to a point where it discharges to the ground's surface as a seep, or it will move through the base of the landfill and into the subsurface formations. Depending upon the nature of these formations and in the absence of a leachate collection system, leachate has reportedly been associated with the contamination of aquifers underlying landfills (Walls, 1975).

It is important to locate the landfills in impermeable soils well above the water table, and to prevent it from accumulating in the landfill. Such ideal conditions are not always available, and additional precautions are frequently necessary to protect groundwater supplies from contamination.

Landfill leachate control measures include volume and composition control, treatment, and disposal. Hydraulic barriers (e.g., extraction and relief wells, gradient control wells and trenches, and collection systems are commonly used to control leachate problems. Typically, landfill boundaries (bottom, sides, and top) are covered by a clay or synthetic liner to minimize leachate formation through infiltration or groundwater intrusion. The landfill cover is designed with a sloping surface to enhance surface runoff, which is collected via drainage channels constructed at the surrounding edge of the landfill. Water from precipitation or irrigation that may infiltrate past the landfill cover can be collected

via a leachate collection and removal system located under the cover and/or above the bottom liner. The collected leachate is generally treated either on-site and disposed of in a nearby sewer system or, recirculated (El-Fadel *et al.*, 1997).

Supplementary measures including clay and/or membrane covers, and liners for the landfill, a leachate collection, removal, and treatment facility, and a groundwater monitoring facility are necessary to protect receiving waters from contamination. However, these measures cannot ensure that no seepage will occur. If leakage does occur, attenuation of contaminants as the liquid passes through the soil serves as an additional barrier to surface and mostly groundwater contamination (Henry and Heinke, 1996).

The Characteristics of leachate from landfills vary according to site-specific conditions (Table2-2). Leachates from "old" landfills are often rich in ammonia nitrogen due to the hydrolysis and fermentation of the nitrogenous fractions of biodegradable substrates, with decreases in concentrations are mainly attributed to leachate washout. At landfills where leachate containment, collection and recirculation is practiced to accelerate decomposition of readily biodegradable organic constituents, leachate ammonia nitrogen concentrations may accumulate to higher levels than during conventional single pass leaching, thereby creating an ultimate discharge challenge (Onay and Pohland, 1998).

Laboratory and field studies have shown that leachate organic content is microbially degradable under either aerobic or anaerobic conditions. However, in light of their very

variable nature, leachates may become toxic to microbial communities. For example, leachate with pH values as low as 1.5 and as high as 9.5 have been reported in the literature (El-Fadel *et al.*, 1997). Although a rare occurrence, such extreme pH values could cause a complete inhibition to the growth of microbial communities (e.g. methanogens), which usually grow best at pH values ranging from 6 to 8 (Zehnder *et al.*, 1982).

Table 2-2 Chemical composition of leachate from municipal solid waste
(Source: El-Fadel *et al.*, 1997)

Parameter	Concentration Range ($mg.L^{-1}$)	**Parameter**	Concentration Range ($mg.L^{-1}$)
Alkalinity (as $CaCO_3$)	0 - 20,850	Nitrogen (Ammonia)	0 - 1,250
BOD_5 [1]	0 - 195,000	Phosphorus (Total)	0 – 234
Chloride	11,375	pH	1.5 – 9.5
COD [2]	0 - 89,520	TOC [3]	335,000
Hardness (as $CaCO_3$)	0.1 - 225,000	TVA [4] (as acetic acid)	0 - 19,000
Iron	0 - 42,000	Phenol	0.17 – 6.6

[1] 5-day Biochemical Oxygen Demand, [2] Chemical Oxygen Demand, [3] Total Organic Carbon, [4] Total Volatile acids

Analysis of the leachate provides the basic information for selecting the treatment method. The organic strength, the BOD_5 to COD ratio, and the type of volatile fatty acids present are all related to the age of landfill. Acceptance of the leachate to the municipal treatment facility is seldom possible and on-site treatment is normally required (Henry and Heinke, 1996).

Leachates from "young" landfills (BOD/COD > 0.7) are in the acid fermentation stage with high organic nitrogen. Leachates from "old", stabilized, landfills (BOD/COD ~ 0.1 to 0.3) are in methanogenic stage and contain nitrogen as ammonia. Both leachates, young and old, have been successfully treated in aerobic biological systems. Suspended growth systems, such as activated sludge, are common for BOD removal where as fixed

film (attached growth) systems, such as rotating biological contactors are preferred for nitrification (Forgie, 1988). For the treatment of leachate with a BOD/COD ratio between 0.7 and 0.3, anaerobic treatment has advantages over aerobic processes. These advantages include less sludge production, reduced energy needs, and lower costs. To treat well-stabilized leachates (BOD/COD < 0.1) neither aerobic, nor anaerobic treatment is feasible and physical-chemical methods are needed. The variability in leachate characteristics as a landfill ages, requires flexible treatment systems. This means that over time, a combination of aerobic, anaerobic, and physical-chemical processes will be of the most interest (Henry and Heinke, 1996, U.S. EPA, 1995, Forgie, 1988).

2-3) Woodwaste Leachate Characteristics

Untreated woodwaste disposal can cause significant pollution problems in the receiving environment, especially in surface water and groundwater systems. The water-soluble material dissolved from the wood is called leachate. The leachate seeps out from piles of stored logs, wood bark, and sawmills. Odour, colour, oxygen demand and high concentrations of metals and tannin (measured as tannic acid) are the typical characteristics of woodwaste leachate (Phipps, 1974).

Woodwaste can have a variety of physical and chemical adverse impacts on aquatic life, depending on its form. Woodwaste, like any organic waste, creates a biochemical oxygen demand (BOD) in sediments as it decomposes, and excessive amounts can reduce or eliminate the aerobic zone (Kendall and Michelsen, 1997).

Agricultural use, storage, or land disposal of woodwaste have the potential for generating leachate. A study on groundwater contamination by woodwaste disposal in the Mid-Willamette valley region of Oregon-U.S.A has shown that total iron and manganese were found to be far in excess of normal or background concentrations, and were well above recommended local drinking water standards. An initial drop in pH (less than 5.6) and an increase in total acidity of contaminated groundwater were anticipated due to the leaching of volatile organic acids (VOA) (Sweet and Fetrow, 1975).

Woodwaste leaches and/or degrades into some compounds that can be toxic to aquatic life, such as phenols and methylated phenols, benzoic acid and benzyl alcohol, terpenes, and tropolones (Kendall and Michelsen, 1997). Woodwaste leachate, in sufficient concentrations, can be toxic to salmonids (Phipps, 1974). Aspen leachate proved toxic to aquatic organisms at dilutions between 1% and 10% (Taylor *et al.,* 1996). It has been characterized by amber colour, low pH (4.0), extremely high BOD (>2600 $mg.L^{-1}$), and high conductivity (1140 $\mu s.cm^{-1}$). In addition, the leachate was rich in phenols (30 $mg.L^{-1}$), organic carbon (2480 $mg.L^{-1}$) and organic nitrogen (13 $mg.L^{-1}$). The aged leachate underwent a transition marked by a rise in pH and dissolved oxygen (DO) concentration, a small decline in conductivity, and a colour change from amber to black. Median acute toxicity concentrations were consistently 1% to 2% of full strength leachate for trout and *Daphnia*. Inhibition of bacterial metabolism began at concentrations below 0.3%. Leachate was less toxic to plant life but inhibited algal growth at concentrations of 12% to 16%. In this study, toxicity declined abruptly when the supply of labile toxicants was exhausted, but in certain cases, it increased again from the products of microbial

metabolism. Oxygen depletion, low pH, and phenolic compounds contributed to the toxicity of aspen leachate, but much of the toxic effect was attributed to other, unidentified constituents.

The potential water quality degradation of surface and ground waters from wood bark drainage is significant. It is shown that degradation results from colour, BOD, organic materials potentially toxic to fish, and odour, imparted to the water. Where the bark is stored on the land, rainwater moving through the pile carries out large amounts of pollutant materials. The dissolved oxygen (DO) of a stream would be seriously affected since BOD values as high as 6800 $mg.L^{-1}$ were noted for hardwood bark when it was stored wet at 37 °C for 48 days. The colour in some cases reached as high as 5500 colour units. Gas chromatographic analysis of the liquid from the aerobic region of the water showed the presence of only a few identifiable simple sugars. The amounts of these sugars were less than 5 ppm (Sproul and Clifford, 1968).

Potential contaminants that could contribute to wood leachate toxicity include metals, wood extractives, and chemicals used to control molds and fungi on freshly cut wood. Bailey *et al.,* (1999) have analyzed the acute toxicity of the storm water runoff from sawmills in British Columbia. They have evaluated the potential contribution of metals to toxicity. Concentrations of metals have been compared to available data for rainbow trout toxicity to determine potential causes of toxicity in the samples. They showed that this toxicity is mainly caused by some of the divalent cation species dominated by zinc,

which ranged from 0.04 to 0.94 $mg.L^{-1}$. Other cations were present in the following ranges: aluminium (< 0.01 to 0.04 $mg.L^{-1}$), copper (<0.01 to 0.02 $mg.L^{-1}$), cadmium (< 0.025 $mg.L^{-1}$), manganese (0.006 to 2.12 $mg.L^{-1}$), lead (< 0.08 $mg.L^{-1}$), and nickel (< 0.03 $mg.L^{-1}$). Through the measurements of resin acids, and tannin and lignin, Bailey *et al.* (1999) concluded that toxicity in samples, not attributed to metals, is likely due to wood extractives, in particular tannin and lignin (53 to 108 $mg.L^{-1}$), or other organic acid wood extractives that co-varied with tannin and lignin. Total tannin and lignin greater than 10 $mg.L^{-1}$ were always associated with toxicity.

A study by Thurlow *et al.* (1977) indicates the characteristics of wastewater leached from log storage as follows: the wood and bark wastes generally consisted of tannins, wood sugars, nutrients (nitrogen and phosphorus), and lignin. The quality of organics released into the water is dependent on the wood species, the amount of bark adhering to the wood, the area of the exposed logs, and the circulation flow of the water. Bark contains a higher proportion of extractives than wood and, therefore, the more bark that remained on a log, the more concentrated was the leachate that seeped out. This study also indicated that tannin and lignin often impart a yellowish-brown colour to water and that leaching rates do not differ greatly between saline and fresh water.

The constituents of wood extractives and woodwaste leachate vary significantly depending on the kinds of trees. In a study by Bianco and Savolainen (1997) chromatographic analysis was done to identify tannin fractions in hard and soft wood. They showed that oak tannin contains phenolic compounds (i.e. gallic and ellagic acids)

while acacia tannins contain vanillic acid and syringaldehyde. Spruce and fir tannin fractions did not contain identifiable major phenolic and their tannin concentrations were an order of magnitude less than the above-mentioned woods. However, identified phenolics accounted for only a part of the total tannins (Bianco and Savolainen, 1997). Abietic and pimaric acids are the most abundant resin acids naturally occurring in wood. The resin acid content of the wood leachate also varies significantly within species according to tree age, tree part, growing environment, and storage conditions (Teschke, *et al.,* 1999). In a gas chromatographic study by Becker *et al.* (2001) on the leaching extracts from pine wood (*Pina nigra*) mainly alcohols and ketones were found ($C_7 \sim C_{12}$). These substances originated from the lignite and polyose fraction of the wood. Hemicellulose compounds are among the most dominating extractives in wood leachate (Bertaud *et al.*, 2002, Gabrielii *et al.*, 2000). In a study on hemicellulosic extractions from the poplar wood, xylans were found to be the most predominant component (Sun *et al.*, 2001).

Peters *et al.* (1976) have studied the effect of red cedar leachate on aquatic organisms. The study showed highest concentrations of extractives are found in heartwood. Heartwood extractives can be divided to two main groups, lignans and volatiles. The lignans make up to 8-15% dry weight of the heartwood, and are polyphenolic compounds. Plicatic acid, the major lignan, is a strong organic acid. The volatile fraction, 0.5-2% dry weight of the heartwood, consists mainly of the tropolones, methyl thujate, thujic acid, and neutrals. The tropolones are known for their fungicidal properties. The toxicity data obtained from the laboratory bioassays indicated that under certain

conditions western red cedar leachate had a significant effect on the aquatic environment. The static leachate samples had a strong colour with a pH of 4.3 and a BOD_5 of 715 $mg.L^{-1}$. Tropolones were found to be the primary cause of leachate toxicity to fish.

In addition, Kiparissis *et al.* (1996) have documented that natural constituents of wood such as planar terpenoids may contribute to the overall toxicity potential of the wood pulp leachates. Leachate from the softwood pulp appeared to have more toxic effects on fish, than hardwood pulp.

2-4) Using Constructed Wetlands as an Alternative for Leachate Treatment

The practice of landfilling results in a number of potentially damaging environmental impacts, one of which is the generation of landfill leachate. In addition to the initial moisture content of the solid waste and any liquid waste inputs, water may enter landfills by the ingress of precipitation, surface water or ground water. Contact between this water and the waste generates a leachate contaminated with a range of soluble organic and inorganic substances (Tyrrel *et al.*, 2002).

Treatment wetlands have been successfully used for non-point sources of pollution (i.e. agricultural and urban runoff), municipal wastewater, sludge treatment, pulp mill effluent, acid-mine drainage and mining waste, oil, food and agricultural industry wastewater, coal mining wastewater, and landfill leachate. They have been proved

effective on removal of BOD, COD, suspended solids, nutrients, heavy metals, pathogens, disinfection by-products and also increasing pH in highly acidic influents (Rostad *et al.*, 2000, Gerba *et al.*, 1999, Rash and Liehr, 1999, Tarutis *et al.*, 1999, Martin *et al.*, 1999, Mitsch and Wise, 1998, Bulc *et al.*, 1997, Morris and Herbert, 1997, Schreijer *et al.*, 1997, Kadlec and Knight, 1996, Zachritz *et al.*, 1996, Birkbeck *et al.*, 1990, Liénard *et al*, 1990).

Landfill leachates are classified as problematic wastewaters and represent a dangerous source of pollution for the environment due to their toxicity. Leachate is most often transported to a wastewater treatment plant, where it is treated along with municipal wastewater. Various hazardous substances in the landfill leachate can affect the biological process of the purification. For this reason and because transport represents a risk, it is best to treat landfill leachate on site (Bulc *et al.,* 1997).

Although effective advanced leachate treatment systems exist, some landfill operators seek alternative treatment systems, because of their high capital costs and specialized management requirements. Land-based treatment systems are an attractive alternative for landfill operators as they utilise an existing land resource, are considered cheaper to build and operate, and do not need sophisticated management. Land-based systems may be used in conjunction with a conventional tank-based system to play a polishing role (Tyrrel *et al.*, 2002)

The use of constructed wetlands to treat landfill-generated leachate has become a treatment modality, which has received much attention over the past few years. One factor has caused heightened interest in the use of constructed wetlands for landfill leachate treatment is the variations in quality and quantity of leachate that is produced by different landfills. Not only does leachate composition vary day-to-day, it is also affected by regional climatologic patterns and characteristics of the refuse including its depth and permeability. Therefore, attempts to modify traditional treatment modalities to address these variations can prove very costly (Martin *et al.*, 1999). Because of this inherent variability in composition, no two landfills produce the same quality of leachate. This variability presents landfill managers with the problem of providing cost-effective, reliable, flexible, on-site technologies for pre-treatment and on-site disposal, or off-site disposal such as direct discharge of treated effluent into receiving waters.

Landfill leachates can contain a large variety of hydrocarbons, including priority pollutants, phenolics, and high BOD of many origins. Reports indicate that significant reductions of BOD and total organic carbon (TOC) can be achieved by constructed wetland treatment systems (Kadlec and Knight, 1996). In a study on low-strength leachate, the removal of BOD_5 (from over 50 $mg.L^{-1}$ to less than 20 $mg.L^{-1}$) and ammonia nitrogen removal in the order of 5-6 g ammonia N/m^2 marsh area/day was achieved (Birkbeck *et al.*, 1990). Another study, also suggested that wetlands have excellent organic carbon and nitrogen treatment capabilities (Kozub and Liehr, 1999).

Bulc *et al.*, (1997) have studied a pilot scale treatment wetland receiving landfill leachate. The influent concentrations in this study were 1264 $mg.L^{-1}$ for COD, 60 $mg.L^{-1}$ for BOD_5, and 88 $mg.L^{-1}$ for NH_3-N. They showed that the constructed wetlands were efficient achieving reductions in COD (68%), BOD_5 (46%), NH_3-N (81%), Fe (80%), and bacteria (85%). By studying the ortho-phosphate concentrations, they concluded that low phosphorus levels could limit biomass growth and subsequently the treatment efficiency. They recommended that in spring, when plant growth is accelerated, phosphorous should be added to attain greater biomass.

3) WOODWASTE LEACHATE CHARACTERIZATION

As described in section 2-3, woodwaste leachate is considered "harmful" to the environment. In particular, some studies have shown that it can be toxic to aquatic life. Its toxicity was mostly related to oxygen depletion, low pH, tannin, and phenolic compounds (Bailey *et al.,* 1999, Kiparissis *et al.*, 1996, Peters *et al.,* 1976, Phipps, 1974).

In order to evaluate the effectiveness of an existing constructed wetlands system for treatment of woodwaste leachate, the long-term characterization of the leachate is necessary. In this study, research was restricted to woodwaste leachate from a single wood-processing site due to limitations in available time and funding. However, the volume of the waste on the site is one of the largest in the lower Fraser Valley. The woodwaste leachate was characterized over 34 weeks in two periods: from May to September 2000, and from June to October 2001.

3-1) Methods and Materials

3-1-1) Sampling Protocols

Standard sampling procedures were followed during sampling trips. Surface grab samples were taken from the east bank of the leachate pool. Sufficient sample volumes were collected in pre-washed 1 L bottles to meet the need of analyses. Sample containers were rinsed twice with sample before filling. Headspaces were avoided in the bottles. All

samples were preserved according to the Standard Methods (APHA *et al.*, 1998), (Table 3-1) and were carried in coolers and placed in storage room as soon as they were in the laboratory. All samples were labelled. Temperature and dissolved oxygen of the samples were measured in the field at the time of collection. Appropriate PPE (personal protection equipments) were used during sampling procedures. Laboratory storage was at 4 °C, in the dark. All of the analyses were conducted in first opportunity considering the allowable holding times recommended by accepted protocols (Table 3-1).

Table 3-1 Sample collection, preservation and storage
(Standard Methods, APHA *et al.*, 1998)

Analysis	Container	Min. Sample Vol.	Preservation	Allowable Holding time
Temperature and DO	-	-	-	in Situ
pH and Conductivity	HDPE[1]	-	-	-
Solids	HDPE	200 mL	refrigerate	7 days
Total Metals	HDPE	200 mL	nitric Acid, <pH2	28 days
Ammonia (NH_3-N)	HDPE	200 mL	sulphuric Acid, <pH2 and refrigerate	7 days
Nitrate + Nitrite (NO_x^--N)	HDPE	200 mL	sulphuric Acid, <pH2 and refrigerate	7 days
Ortho-phosphate (PO_4^{3-}-P)	HDPE	200 mL	sulphuric Acid, <pH2 and refrigerate	28 days
Chemical Oxygen Demand (COD)	HDPE	100 mL	refrigerate	7 days
Biochemical Oxygen Demand (BOD_5)	HDPE	1L	refrigerate	6 hours
Total Volatile Fatty Acids (VFAs)	Glass	200 mL	2% Phosphoric acid and refrigerate	7 days
Total Tannin & Lignin	Glass	200 mL	refrigerate	28 days
Total Organic Carbon	HDPE	25 mL	HCl, <pH2	28 days
2-methoxyphenol	Glass	200 mL	refrigerate	28 days

[1] High Density Polyethylene

Quality control measures included the use of field and lab blanks. The field blanks were made by filling the sample bottles with distilled water (distilled water was obtained from the Environmental Engineering laboratory, UBC), which was exposed to atmosphere during sampling procedure. Subsequently, the field and lab blanks were pre-treated and analyzed in exactly the same manner as the samples.

3-1-2) Analytical Protocols

Except for the dissolved oxygen and temperature (field data), the chemical analyses were carried out in the Environmental Engineering Laboratory of the Department of Civil Engineering at the University of British Columbia. Standard analytical protocols were followed in all of the tests. Filed parameters (DO and temperature) were measured using portable DO meter. All laboratory analyses were conducted following the methods, and using the instruments summarized in Table (3-2).

Table 3-2 Methods and instruments used for analyses

Analysis	Method	Instrument
Temperature and DO	In situ probe	YSI Model 75 DO meter
pH	pH probe	Beckman Model Φ 44 pH meter
Specific Conductivity	Conductivity probe	Radiometer Copenhagen Model CDM3 SCT meter
Solids	Std. #[1] 2540C to 2540F	Lindberg Furnace (#51828), VWR Scientific 1350FM faced-air oven, and Mettler AC 100 Digital Scale
Total Metals	Std. #[1] 3111 B	AAS[2] Varian Spectr AA220 FS
Ammonia (NH_3-N)	# 10-107-09-01 of Lachat Quick-Chem	Lachat Quick-Chem 8000
Nitrate + Nitrite (NO_x-N)	# 10-107-04-01 of Lachat Quick-Chem	Lachat Quick-Chem 8000
Ortho-phosphate (PO_4^{3-}P)	# 10-115-01-01 of Lachat Quick-Chem	Lachat Quick-Chem 8000
Chemical Oxygen Demand (COD)	Std. #[1] 5220 D (Closed reflux)	HACH DR/2000 Direct reading spectrophotometer @ λ=600nm
Biochemical Oxygen Demand (BOD_5)	Std. #[1] 5110 B (Seeded)	YSI Model 50 DO meter and Fisher Scientific Model 307 Incubator
Total Volatile Fatty Acids (VFAs)	Supelco Inc., GC bulletin 751 G	Supelco Gas Chromatograph Model HPGC 5880A
Total Tannin & Lignin	Std. #[1] 5550 B	HACH DR/2000 Direct reading spectrophotometer @ λ=700nm
Total Organic Carbon (TOC)	Std. #[1] 5310 B	Shimadzu NDIR[3] (TOC-500)
2-methoxyphenol	Method adopted from Prahacs (1986)	Hewlett Packard GC Model HP6890 (equipped with mass selector 5973 and HP 7673 auto-sampler)

[1] Standard Methods (APHA *et al.* 1998)
[2] Atomic Absorption Spectrophotometer
[3] Non-Disperssive Infrared Analyzer

The BOD bottles were seeded using the forest soil collected from the leachate pool banks. It was assumed that the microbial communities in the forest soil are adapted to wood extractives, including some of the components which might be toxic to other bacteria. Thus, they were the preferred group of microorganisms for seeding. Only 0.1 g (moist weight) of soil was added to each 300 mL BOD bottle. Seeded blanks were used

in all BOD tests in order to make corrections for any possible interference due to seeding. The seeded blanks constantly had an oxygen demand of less than 1 $mg.L^{-1}$ over time. All samples were corrected for this background BOD. BOD samples were also highly diluted (up to 3000 times). Due to this high dilution, there was no concern about the leachate toxicity affecting the results.

Total tannin and lignin was measured using colorimetric method (Method 5550 B, APHA *et al.*, 1998). In order to reduce the usage of toxic reagents and to simplify the method with direct preparation of the sample in spectrophotometer tubes, the method was modified using one tenth of the sample volume recommended in Standard Methods (APHA *et al.*, 1998). Considering the high concentration of analyte present in samples, all samples were diluted up to 500 times. Lab blanks were used to make the standard curve and calibrate the instrument.

Minimum detectable concentrations for these compounds have been reported as low as 0.025 $mg.L^{-1}$ for tannic acid and 0.1 $mg.L^{-1}$ for lignin in a 1 cm cell using a spectrophotometer (APHA *et al.*, 1998). All standards and samples had concentrations higher than these limits. All of the raw data are presented in Appendix A.

Considerable dilutions were required in order to bring the values within the measurable ranges for COD and tannin and lignin. Thus, the possibility of the strong leachate colour affecting results was insignificant.

3-2) Results and Discussion

3-2-1) pH, Temperature, Conductivity, and Solids

During the two periods of sampling, in spring-summer 2000 and summer-fall 2001, leachate showed consistent pH values. The pH of the leachate had an average of 3.5 during sampling period. This pH is in the lower limit of the range observed in municipal landfill leachates (Table 2-2).

The leachate always had comparably higher temperatures than nearby water bodies. Its average temperature was 28.4 °C in 2000 and 20.2 °C in 2001, which was 6 to 7 °C higher than other ponds in the area. The higher temperature can be elucidated by the high chemical and biological activities in the leachate. In addition, composting processes occurring in the woodwaste pile could potentially heat up the leachate pool. Another reason for the higher temperature is related to the dark colour of leachate, which absorbs more solar energy compared to clear water.

Table 3-3 Frequently measured leachate characteristics (2000 and 2001)

Parameter	2000 Average[1] (Std. Dev.)	n[2]	2001 Average (Std. Dev.)	n
Temperature (°C) (ambient)	28.4 (2.2)	9	20.2 (4.3)	15
Dissolved Oxygen (ambient)	0.3 (0.1)	13	0.4 (0.1)	14
pH	3.4 (0.1)	13	3.62 (0.2)	14
Specific Conductivity ($\mu s.cm^{-1}$)	1930 (122)	8	1466 (73)	15
Biochemical Oxygen Demand (BOD)	7405 (1227)	19	7786 (1559)	15
Chemical Oxygen Demand (COD)	13774 (3398)	19	12806 (1876)	15
Tannin and Lignin (as tannic acid)	4988 (1357)	19	3445 (489)	15
Total Volatile fatty Acids ($C_2 - C_6$)	2107 (343)	15	2085 (185)	15
Total Suspended Solids	33.6 (26.3)	17	- -	-

[1] All concentrations are reported in $mg.L^{-1}$, unless otherwise noted
[2] n = number of samples

The suspended solids determination is one of the important parameters in treatment methods (Sawyer *et al.,* 1994). Solids were measured during the 19 weeks period from May to September 2001. Leachate contained a very high level of TDS (total dissolved solids) and a very low level of TSS (total suspended solids) (Metcalf and Eddy, 1991). Over 99% of the solids present in the leachate were dissolved, and up to 85% were volatile dissolved solids (see Appendix A). Volatile solids are generally a measure of the organic content of the wastewater.

Specific conductivity measurements can give a practical estimate of the dissolved solids content of the wastewater (Sawyer *et al.*, 1994). The high level of dissolved solids was also noticeable in specific conductivity measurements in the leachate. The average specific conductivity was 1930 $\mu s.cm^{-1}$ in 2000 and 1466 $\mu s.cm^{-1}$ in 2001.

As mentioned above, the leachate was characterized with low level of suspended solids and high level of dissolved solids. Treatments through settling, flocculation, and sedimentation were not practicable options because of the lack of suspended solids. In other words, the leachate pool itself is acting as a sedimentation basin.

3-2-2) VFAs, Tannin and Lignin, COD, and BOD_5, and DO

Volatile fatty acids (VFAs) are short chain carboxylic acids. Their size is represented by the number of carbon atoms they contain, where the smallest VFA is acetic acid with two carbon atoms (C_2). Several different bacteria hydrolyse polymers such as cellulose to sugars and ferment the sugars to VFAs (Madigan *et al.*, 1997).

The leachate contained very high concentration of total VFAs. The average concentration of total VFAs was 2107 $mg.L^{-1}$ in 2000 and 2085 $mg.L^{-1}$ in 2001. These VFAs were, to some extent, responsible for the strong smell and acidic nature (pH ~ 3.5) of the leachate. Measurements of individual VFAs showed that more than half of the total concentration was composed of smaller molecules (e.g. acetic and propionic acid) (Table 3-4).

Table 3-4 Concentrations of individual volatile fatty acids in $mg.L^{-1}$ (2000)

Volatile Fatty Acid	Average	Range	n[1]
Total ($C_2 - C_6$)	2107	1641-2829	15
Acetic	1073	858-1321	15
Propionic	364	252-460	15
Butyric + Iso-butyric	434	254-594	15
Valeric	275	154-324	15
n-Hexanoic	175	92-382	15

[1] n = number of samples

VFAs are readily biodegradable and can act as a source of carbon for microbial communities.

The concentration of tannin and lignin was very high in the leachate. The average T&L concentration was 4989 $mg.L^{-1}$ in 2000 and 3447 $mg.L^{-1}$ in 2001. These levels of tannin and lignin were expected considering the source of leachate. However, they were higher than reported concentrations in other studies (Section 2-3). This class of compounds is highly coloured and is characterized by its recalcitrant nature. They have been reported to be toxic to aquatic life in much lower concentrations (53 to 108 $mg.L^{-1}$) (Bailey *et al.*, 1999).

The COD test is used to measure the total amount of oxygen required for oxidation of organic compounds to carbon dioxide and water regardless of the biological assimilability of the substances. This test cannot differentiate between biologically oxidizable (e.g. VFAs) and biologically inert (e.g. tannin and lignin) organic matter. However, it provides a good approximation of the organic strength of the wastewater (Sawyer *et al.*, 1994). The leachate had an extremely high chemical oxygen demand with the average concentration of 13774 $mg.L^{-1}$ in 2000 and 12806 $mg.L^{-1}$ in 2001. These concentrations are comparable with landfill leachate COD concentrations (Table 2-2).

The COD concentrations in the leachate were not constant during the sampling period. The changes can be partially related to the amount of rainfall and temperature. As shown in Figure 3-1, the COD concentrations were rising as the temperature increased in the summer of 2000 (see Appendix C, Figure 4-14).

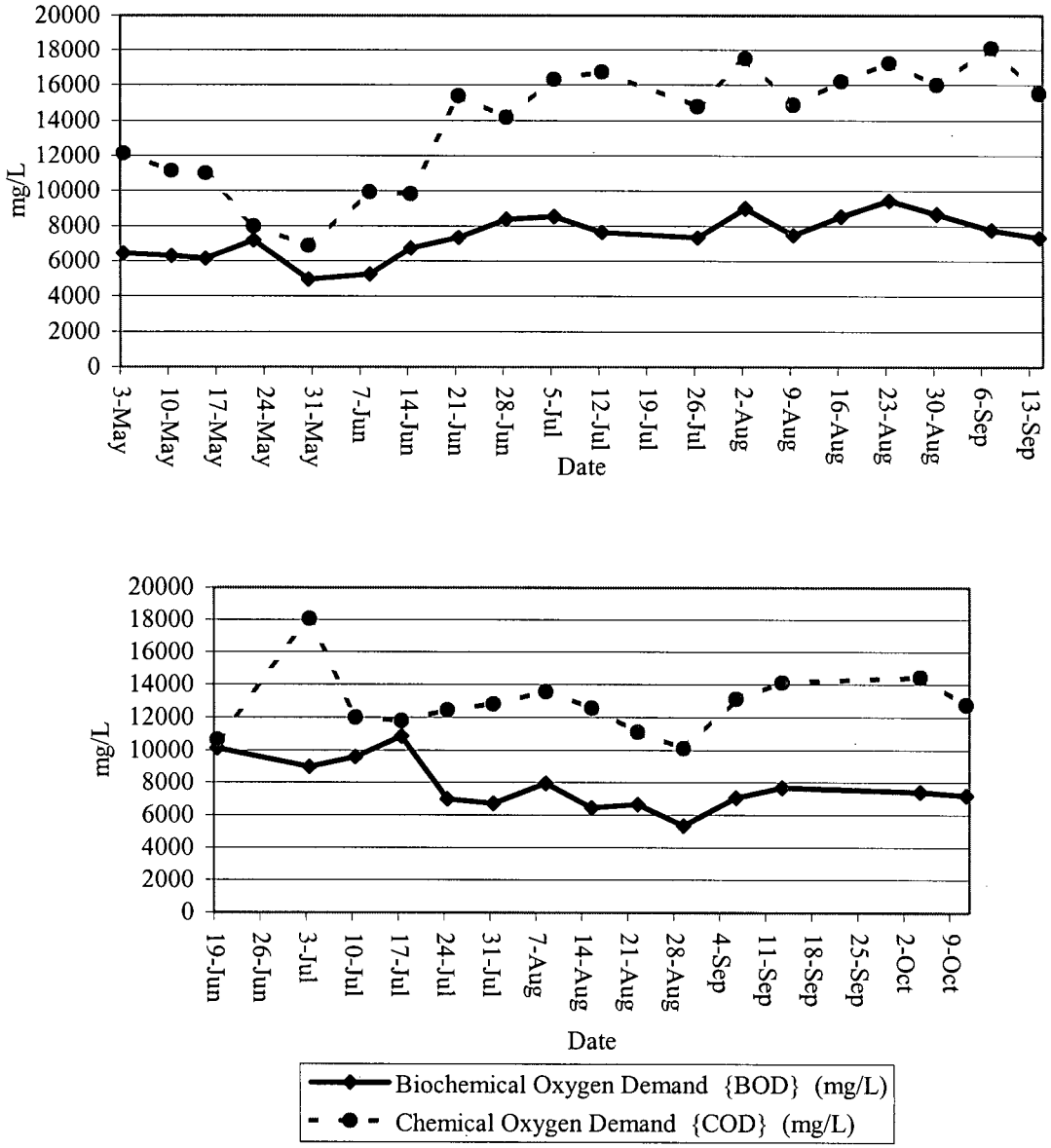


Figure 3-1 BOD and COD changes in leachate (Top: 2000- Bottom: 2001)

This trend can be explained by the higher rate of chemical and biological activities in warmer temperatures. As the mean temperature raised, the higher activity rate, higher

evaporation, and lower precipitation concentrated the leachate. The increase in COD was not significant in 2001. This can be explained by the fact that in 2001, operation was held during cooler and wetter period of the year. Lower temperatures and higher precipitation decreased the strength of the leachate in 2001. A comparison between the changes in leachate strength and climatic data in Appendix C gives a more clear explanation of these changes.

The theoretical oxygen demands (ThOD) were calculated for VFAs and tannin and lignin using balanced oxidation reactions (see Appendix B). These values were then compared to the measured COD, which represents the total oxygen demand. This comparison gave an estimation of the fractions of total COD that correspond to these two classes of compounds. After the entire 34 weeks of sampling, the average ThOD to COD ratio was ~ 0.6. The VFAs ThOD to COD ratio was 0.23 and T&L ThOD to COD was 0.37. These numbers meant that about 60% of the total COD was due to T&L and VFAs. The remaining 40% was due to other groups of compounds, which were not measured in this study. Other groups of compounds accountable for COD could be hemicellulosic compounds, pectins and resin acids (Bertaud *et al.,* 2002, Sun *et al.*, 2001, Gabrielii *et al.*, 2000, Teschke *et al.*, 1999).

BOD is defined as the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions. The test is widely used to determine the pollutional strength of wastewaters in terms of oxygen that they will require if discharged into natural water courses (Sawyer *et al.,* 1994). Theoretically, non-biodegradable compounds would not exert oxygen under test conditions (standard

conditions associated with temperature and light, oxygen, nutrients, and microorganisms availability).

The woodwaste leachate had an average seeded BOD_5 of 7405 $mg.L^{-1}$ (in 2000) and 7786 $mg.L^{-1}$ (in 2001). This high level of BOD was expected given the particularly high COD values discussed earlier. Previous study on the same leachate showed that the leachate had a very aggressive oxygen demand (i.e. BOD_5 k ratio ~ 0.5 d^{-1}) (Frankowski, 2000). Dissolved oxygen measurements on site supported this idea. DO concentrations were consistently below the reliable measurement limit of the DO meter (i.e. < 1 $mg.L^{-1}$).

During the determination of COD, almost all the organic matter is converted to carbon dioxide and water. For example, VFAs and tannin and lignin are both oxidized completely. As a result, COD values are greater than BOD values especially when significant amounts of biologically resistant organic matter (e.g. tannin and lignin) is present. Wood related wastes are perfect examples for their high lignin content (Sawyer *et al.,* 1994). In comparison over the period of sampling of this leachate, the BOD to COD ratio had an average of 0.50. This ratio implies that nearly half of the COD was ascribed to readily biodegradable material. As discussed before, the VFAs were theoretically accountable for almost 23% of COD or about half of this readily biodegradable portion. (It is possible that the other half of COD consisted of recalcitrant compounds. From the total COD, about 37% was calculated to be related to tannin and lignin. This was more that 70% of non-biodegradable portion of COD. Table 3-5 summarizes the results of oxygen demand ratios.

Table 3-5 Oxygen demand ratio comparisons

COD ratio	Average	n[1]
ThOD of VFAs to COD	0.23	30
ThOD of T&L to COD	0.37	34
Total ThOD [2] to COD	0.60	30
BOD ratio	**Average**	n
ThOD of VFAs to BOD	0.46	30
BOD to COD	0.50	34

[1] n = number of samples
[2] Total ThOD = VFAs ThOD + T&L ThOD

In a quick comparison between the results in 2000 and 2001, it can be noticed that, the levels of contaminants were slightly lower in 2001, except for BOD. The greatest decline was in the concentrations of tannin and lignin. The lower concentration of contaminants can also be explained by the general hypothesis that the strength of the leachate reduces as the age of the waste increases (El-Fadel *et al.*, 1999). The other factor affecting the contaminant concentration would be the seasonal changes. In the year 2000, the sampling was done during the warmer and dryer period (May-September). The high level of evaporation and low precipitation raised the strength of the leachate. In 2001, the sampling was done during a relatively cooler and wetter period of the year (June-October), which resulted in a more dilute leachate. In the case of BOD, as the microbial activity breaks down the large molecules, more easily biodegradable compounds become available. The higher level of BOD in the second year can be correlated to the higher level of readily biodegradable compounds (i.e. smaller molecules).

3-2-3) Nutrients and Other Chemicals

During the period of this study, concentrations of ammonia, nitrates and ortho-phosphate were consistently measured. Table 3-6 summarises the concentrations of the nutrients during the two sampling periods. This leachate was also very nutrient poor. The levels of ammonia and nitrates were extremely low. The chemical composition of the biota requires continuous source of nutrients to sustained growth and reproduction of microorganisms. The carbon:nitrogen:phosphorous ratio for plants is roughly 40C:7N:1P by weight (Wetzel, 1975). There were some ortho-phosphate, ammonia, and nitrates present in the leachate. However, comparing to the level of the total organic carbon present (TOC ~ 3775 $mg.L^{-1}$), those levels were very low. The carbon to nutrients ratio for this leachate were as low as 1C:0.0006P:0.0004N. Consequently, there were insufficient nutrients in the leachate for the microorganisms to degrade the carbon load. This is a significant difference between this woodwaste leachate and landfill leachates. There are generally very high loads of soluble nutrients in landfill leachates (Table 2-2). Although these nutrients are a group of primary contaminants of concern in landfill leachates, they also support the microbial degradation of other contaminants.

Table 3-6 Summary of the measured nutrients in the leachate pool

Measured Nutrient	2000 Average[1] (Std. Dev.)	n[1]	2001 Average (Std. Dev.)	n
Ammonia (NH_3-N)	2.94 (1.16)	15	2.29 (0.51)	14
Nitrate + nitrite (NO_x^--N)	0.14 (0.12)	15	0.10 (0.11)	14
Ortho-phosphate (PO_4^{3-}-P)	4.12 (0.96)	15	0.32 (0.25)	14

[1]n = number of samples

Three metals were also measured in the leachate during a one-time trial. The total concentrations of copper, zinc, and chromium were measured in the leachate. Concentrations of chromium and zinc were 41 and 156 $\mu g.L^{-1}$, respectively. The concentration of copper was below detection limits of the instrument (< 1 $\mu g.L^{-1}$).

Although zinc does not pose threatening effects on the human body in low concentrations, it can affect aquatic life. In the study by Bailey *et al.*, (1999), the threshold for acute toxicity of rainbow trout has been reported as low as 14 $\mu g.L^{-1}$ of zinc. That is much lower than the concentration measured in this study where average of one time sampling trial from different locations in the pool was 156 $\mu g.L^{-1}$ (range: 111-218 $\mu g.L^{-1}$).

The concentrations of theses three metals along with other measured parameters are summarized in Table 3-7. Some of the data are adopted from a previous study by Frankowski (2000) on the same leachate.

As shown in Table 3-7, the woodwaste leachate exhibited high acidity, which is not surprising-considering its low pH. On a previous test by Frankowski (2000), this leachate had a LC_{50} (Lethal Concentration for 50% of organisms) of 1.4% v/v (rainbow trout 96-hour). The toxicity tests were conducted under defined standardized characteristics. The pH was adjusted and sufficient oxygen was supplied. In addition to the toxic effect of some metals, part of the toxicity of leachate is likely due to VFAs, tannin and lignin, and some phenolic compounds (Taylor *et al.,* 1996).

Tannin and lignin are considered to be a major toxicant in wood leachate in concentrations as low as 53 $mg.L^{-1}$ (Bailey *et al.,* 1999). The level of tannin and lignin in this leachate was almost 100 times higher than this value. Lignans, a class of compounds similar to lignin, have been reported to have a toxic threshold of ~ 60 $mg.L^{-1}$. Tropolones, an extractive found in heartwood, has a toxic threshold as low as 0.3 $mg.L^{-1}$ (Peters *et al.,* 1976). The Standard Method analysis used for this leachate (Method # 5550B, APHA *et al.*, 1998) detects aromatic hydroxyl groups and is unable to distinguish between tropolones and the tannin and lignin group of compounds. As a result, tropolones were an unknown fraction of tannin and lignin concentrations. After initial detection of phenolic compounds by gas chromatography, concentration of one of the phenolic compounds (2-methoxyphenol) was measured in a one-time trial in this leachate. The average concentration of 2-methoxyphenol in 10 samples collected from the leachate pool was 225 $\mu g.L^{-1}$ (range: 140-270 $\mu g.L^{-1}$). In effluent regulations of the Province of B.C. (1988), the allowable concentration for "total phenol" is 200 $\mu g.L^{-1}$. The concentration of only one phenolic compound (2-metoxyphenol) in this leachate was higher than that allowed by regulations.

Table 3-7 One-time measured components in the leachate

Parameter	**Concentration** [1]
Total Organic Carbon ($mg.L^{-1}$)	3775
Acidity* ($mg.L^{-1}$ as $CaCO_3$)	2651
Copper (total, $\mu g.L^{-1}$)	<1.0
Zinc (total, $\mu g.L^{-1}$)	156
Chromium (total, $\mu g.L^{-1}$)	41
Toxicity* (%v/v)	1.4
Rainbow trout 96 hr LC_{50} [2]	

[1] Average of one-time sampling trial (except toxicity)
[2] "Lethal Concentration" that causes mortality in 50% of the test organisms
* Data adopted from Frankowski (2000)

3-3) Conclusions

The leachate investigated during this research should be considered an industrial wastewater that in some constituents was comparable to very strong landfill leachates. It was highly acidic, with an average pH as low as 3.5. The temperature of the leachate was higher than other stagnant surrounding water bodies. It was concluded that this higher temperature was due to composting processes in the pile, high chemical/biochemical activities in the leachate pool, and higher solar energy absorbance.

The leachate had a very high concentration of dissolved solids. The high concentration of dissolved solids was confirmed by high levels of specific conductivity. However, a very small fraction of total solids (less than 1%) was suspended. This character of leachate made it impossible to consider flocculation, sedimentation, and precipitation as applicable parts of treatment procedure.

The concentration of TOC is correlated with both BOD and COD. Levels of TOC, COD and BOD in the leachate were very high. Because of this high oxygen demand, the leachate had a very low concentration of dissolved oxygen. Significant amounts of tannin and lignin and VFAs were present in the leachate. These two compounds accounted for about 60% of the COD. Further analysis will be needed to clarify the remaining constituents of the measured COD. The BOD: COD ratio was ~ 0.5. This suggested that about half of the COD is due to easily biodegradable compounds.

In addition to VFAs and tannin and lignin, Leachate contained other potential toxicants. Phenolic compounds and trace metals were identified. To explain the issues surrounding the causes of toxicity, further research in this regard is necessary.

The very low levels of nutrients would make the treatment of this leachate rather challenging. The ratios of nutrients to the carbon content of the leachate were too low. Microbial communities need nutrients for the biological degradation of the waste.

The levels of contaminants in the leachate were high enough that its release in the environment without proper treatment would prove harmful. In fact, it poses a serious threat to surface and ground water resources, aquatic life, and even the forestry industry. As mentioned before, because of leachate accumulation in the adjacent property on the site of this research, many trees were killed or damaged.

The characteristics of different wood leachates vary significantly. Such variations are partly related to the source of the woodwaste (i.e. types and parts of trees). It is desirable to perform case specific characterization studies before recommending any site related treatment and control measures.

4) PILOT SCALE TREATMENT EVALUATION

The study by Frankowski (2000) demonstrated that under optimal laboratory conditions, constructed wetlands are capable of providing efficient treatment of woodwaste leachate. However, assessment of the long-term performance of a pilot scale system under external and internal variations was necessary. To this end, Frankowski (2000) designed, constructed, and used six pilot scale treatment wetlands for treatment of leachate in a three-month period. During the period of pilot scale trials, the possibility of the treatment was established. Constructed wetlands were capable of providing efficient treatment of the leachate including substantial reductions in BOD, COD and acute toxicity (Frankowski, 2000).

The pilot scale treatment research re-started on May 2000. The research activities were continued with physical improvement of the system, including hydraulic and mixing modifications. The chemical improvement of the system was also considered. The chemical improvement measures included pH neutralization and nutrients addition. The experimental cells allowed a controlled evaluation of this technology under "real world" operating conditions. Moreover, they gave the potential for a range of concurrent manipulations to be executed during performance optimization.

4-1) Methods and Materials

4-1-1) System Description

Each of the wetland cells were a mixture of three parts: a small front bay, a planted surface flow (SF) section, and a small unplanted sub-surface flow (SSF) section just prior to the effluent outlet. The cells had a length to width ratio greater than 3 for highest hydraulic efficiency (Persson *et al.*, 1999). Bank-full dimensions were 17.5 m long and 5.5 m wide. The cells had a trapezoidal cross section with a side slope angle of ~ 35° and an even depth (except for the inlet bay). The bottom of each cell was covered with a 20 mil (0.5 mm) PVC liner. The liner penetrations had been sealed with flanging and clay plugs. The planting substrate has been backfilled to a depth of 30 cm (Figure 4-1).

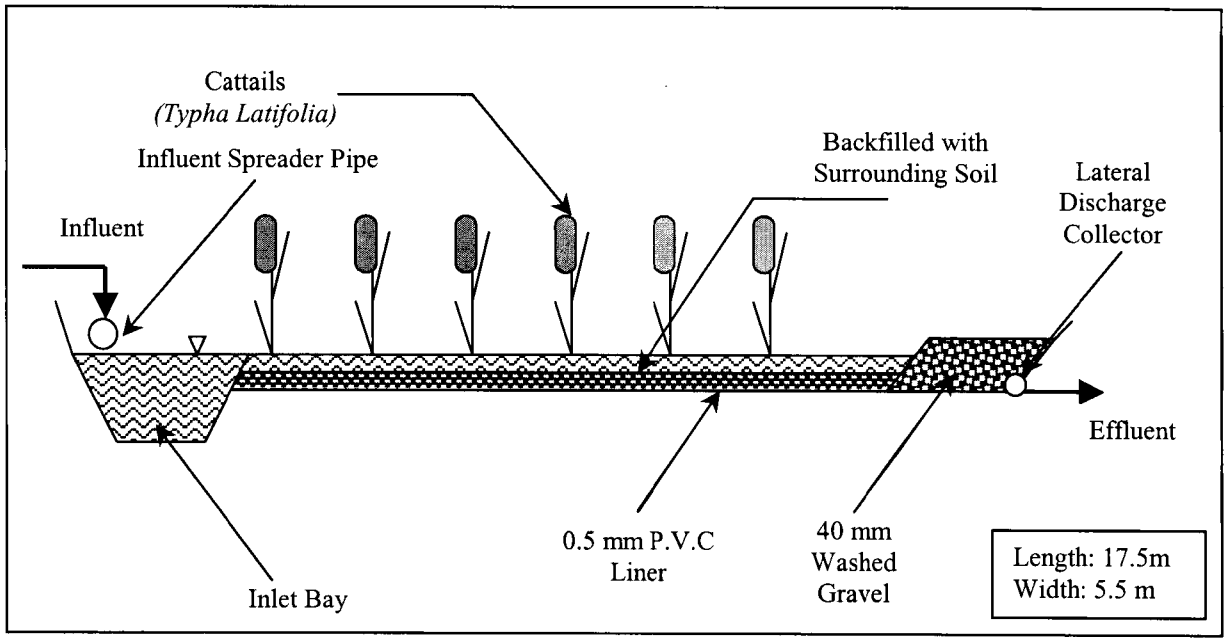


Figure 4-1 Wetland cell cross section

The front bay was intended to provide a small settling basin to prevent any suspended solids entering the system from influent. The main treatment activities were assumed to occur in the large surface flow section. In this section, influent was flowing over the

surface of the soil substrate and through the root mats and stalk of the developing plants. The subsurface flow section was intended to act as a polishing unit. In this section, wastewater was brought in contact with a biofilm layer as it flowed through the gravel matrix. Any large suspended materials, such as algae or detritus, were screened *out in* this section.

A lateral effluent collection pipe (perforated 100 mm PVC pipe) was buried in the bottom of the gravel section, which was connected to a swivelling discharge pipe (100 mm PVC pipe). The design depth was 40 cm. The level of the wastewater in the cells was controlled using the swivelling pipe. At the design depth, the volume of each cell was 20 m^3. HRT was controlled separately for each cell using the influent valves. More sensitive valves were installed downstream to the old valves in order to have a more controlled inflow (Figure 4-2). During the experiment, the effluent was discharged in another separate pipe installed in the cells' surrounding ditch and then collected in the sump (Figure 4-3).

Figure 4-2 Influent inlet, the replaced multi-port inlet, and the influent control valve

Influent was distributed across the width of the cells through multi-port inlets. The spreader pipes together-with the appropriate length to width ratio of the cells provided the best hydraulic efficiency with minimum short circuits and dead spaces. Optimal hydraulic efficiency provides the most appropriate conditions for promoting necessary biological and chemical processes involved in wastewater treatment (Persson *et al.*, 1999). The previous spread pipes were replaced by a set of new and more robust pipes (Figure 4-2).

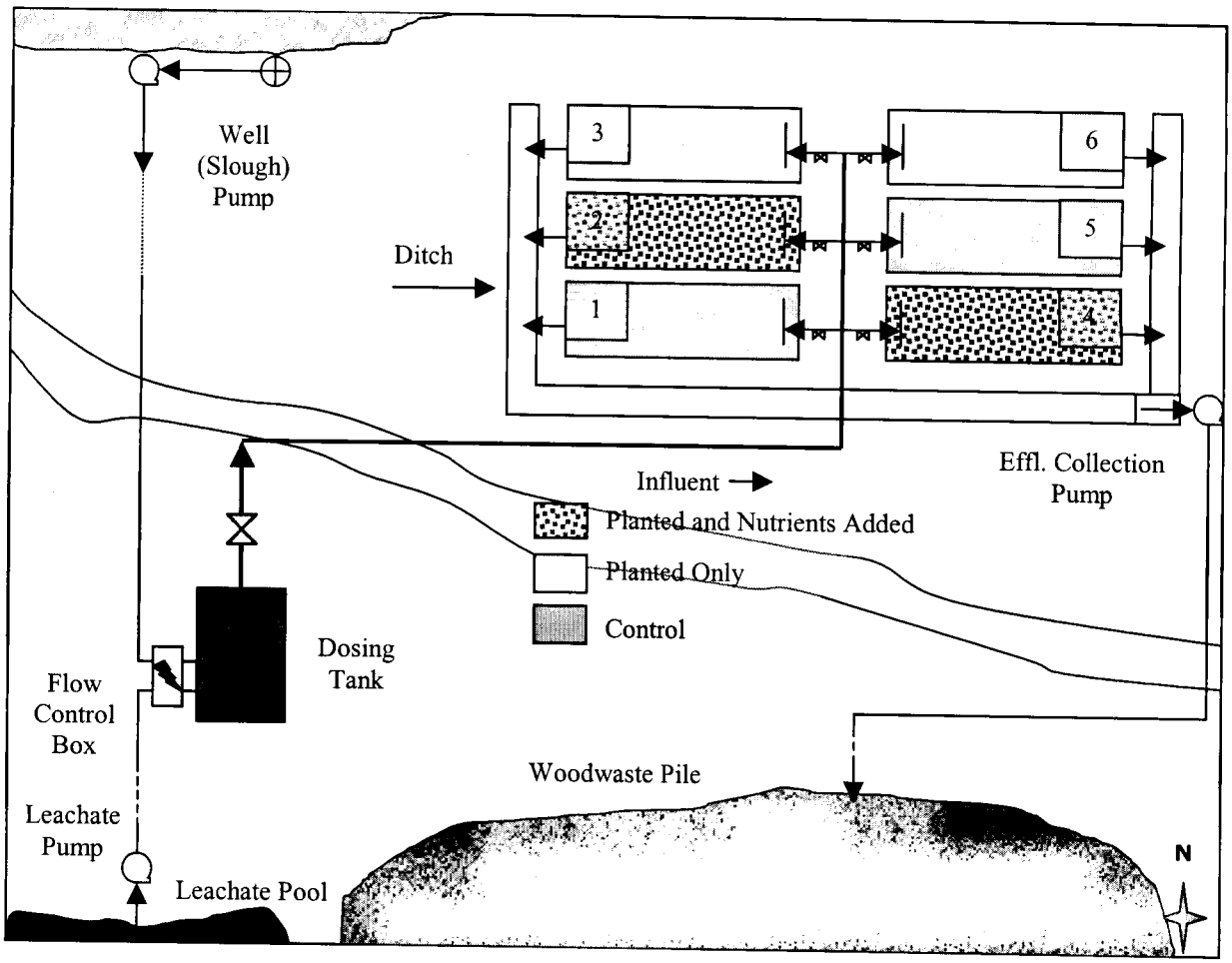


Figure 4-3 Pilot-scale system site diagram
(Not on scale)

Four of the six cells had been randomly chosen and planted. The remaining two cells were identical in construction to the others with the exception of remaining unplanted (Figure 4-4). The unplanted cells were serving as experimental controls. The results from those cells provided an opportunity to define the effect of plants on the treatment performance. Due to their local availability and demonstrated capability to survive in the leachate, broad-leaved cattails (*Typha latifolia*) had been selected as the emergent plants. Each of the four cells was planted with 120 cattails with an approximate of three plants per m^2. The vegetation had been planted in lateral bands in order to ensure that the flow resistance was dispersed evenly across the width of the cells (Frankowski, 2000).

Figure 4-4 General view of the pilot scale wetland cells
(as seen from top of the woodwaste pile)

The leachate was too strong for treatment in the wetlands without prior dilution. A dosing tank was used to provide sufficient dilution using nearby sources of water. The tank was

located in a higher elevation than cells in order to supply enough hydraulic head for the influent to flow into the cells. Leachate was transferred from the pool to the dosing tank via an electric pump installed next to the pool. A similar pump was installed beside a nearby slough to provide the dilution water. A third pump was installed at the sump in the surrounding ditch to transfer the effluent back to the pile. G&L® 1hp centrifugal pumps (Model NPE, 230 V, single phase) were used. They were equipped with brass foot valves in order to supply the initial prime. The intake of the pumps was made completely of stainless steel, which prevented them from corrosion. This was necessary considering the low pH of the leachate. Pumps were protected from climatic effects using wooden shelters with concrete floors (Figure 4-5a).

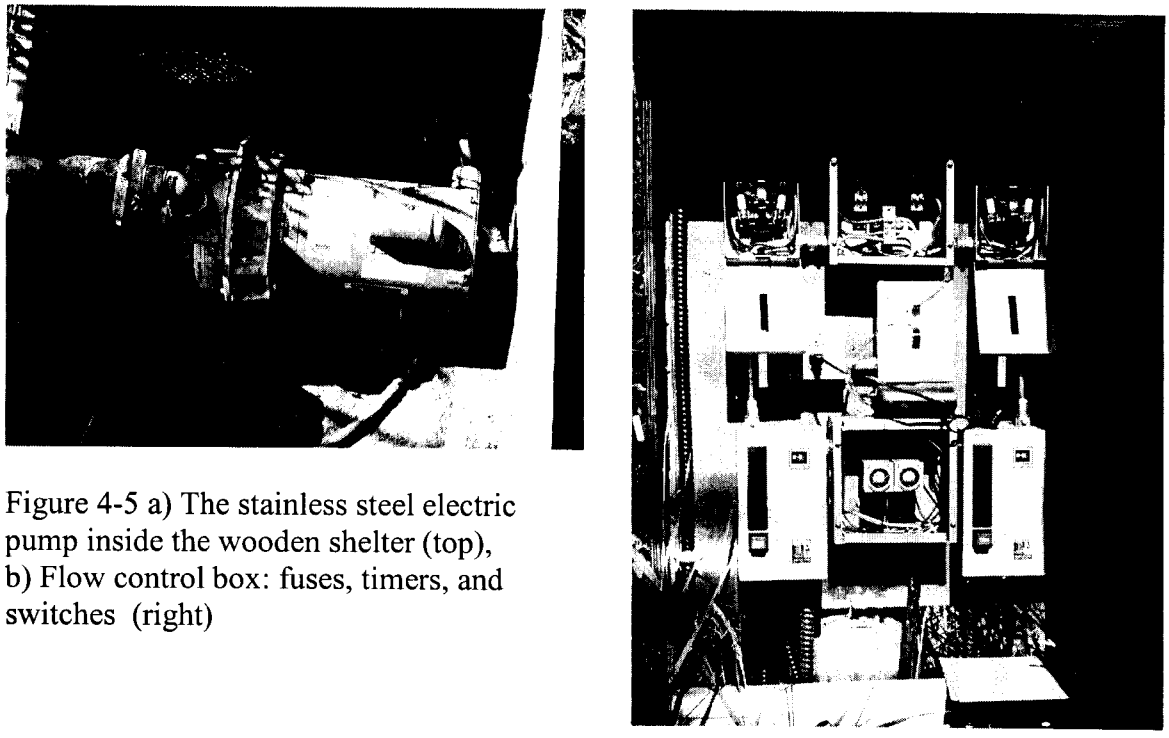


Figure 4-5 a) The stainless steel electric pump inside the wooden shelter (top), b) Flow control box: fuses, timers, and switches (right)

The capacity of the dosing tank was ~10,000 L. The dilution water and leachate were delivered to the tank via 30 mm PVC pipes. The influent was flowing continuously to the cells through 30 mm PVC pipe, and was evenly distributed between them. Dilution ratios were adjustable using timer-controlled pump switches (Figure 4-5b). In addition, the influent level in the tank was maintained using a floating switch. In order to provide the necessary mixing of the leachate and the dilution water, a small fish tank air pump was added to the system on May 2000. The air was pumped near the influent outlet of the tank. Figure (4-6) shows the details of the dilution tank.

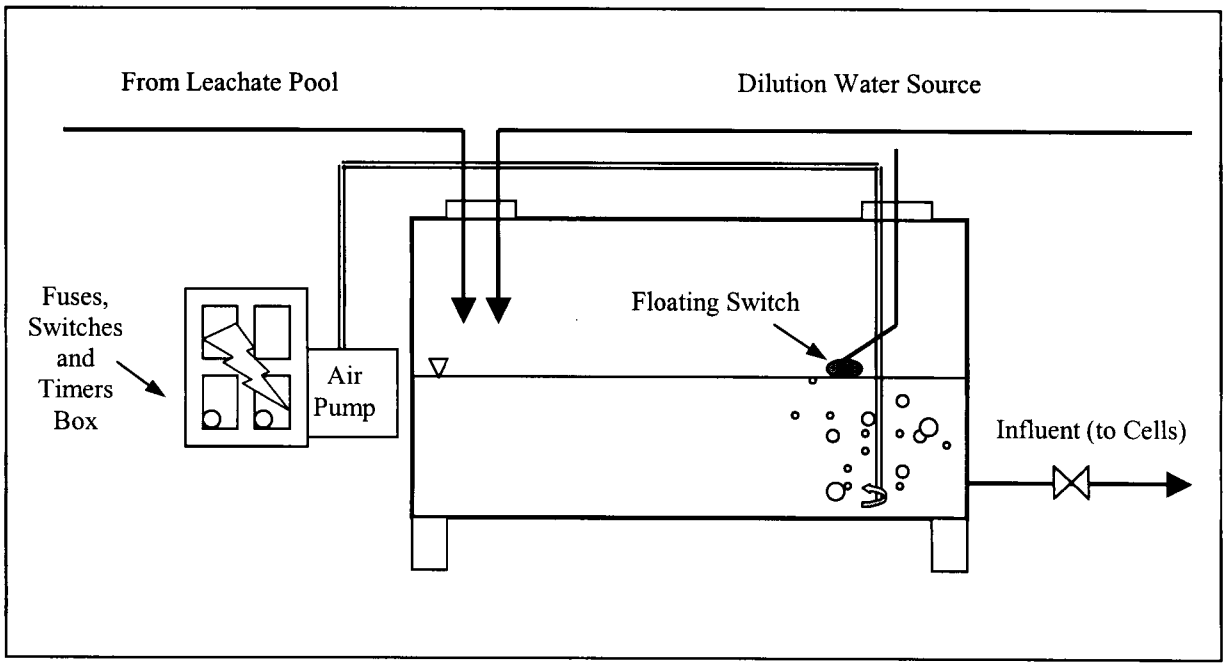
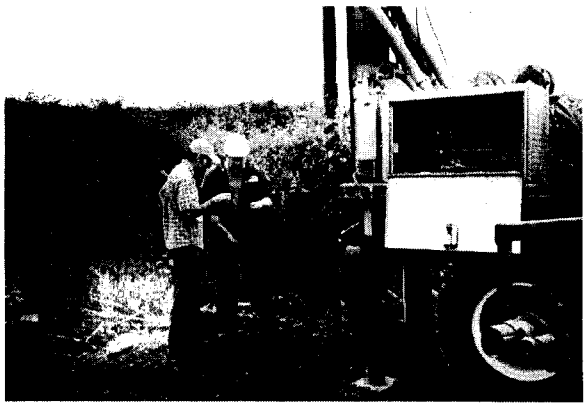


Figure 4-6 Dosing tank cross-section and details

A nearby slough was used as the source of dilution water in the first season of sampling (2000). In the second season, due to lack of precipitation and some construction activities on the dyke road, there was not enough water available in the slough. On June 2001, a 12

m-deep well was drilled as a substitute source of dilution water (Figure 4-7a). Casing was installed at the top 3 meters of the well. The rest of the depth was protected with perforated pipe (screening). The same pump was used to deliver the well water to the dosing tank. Figure 4-7b shows the details of the drilled well.



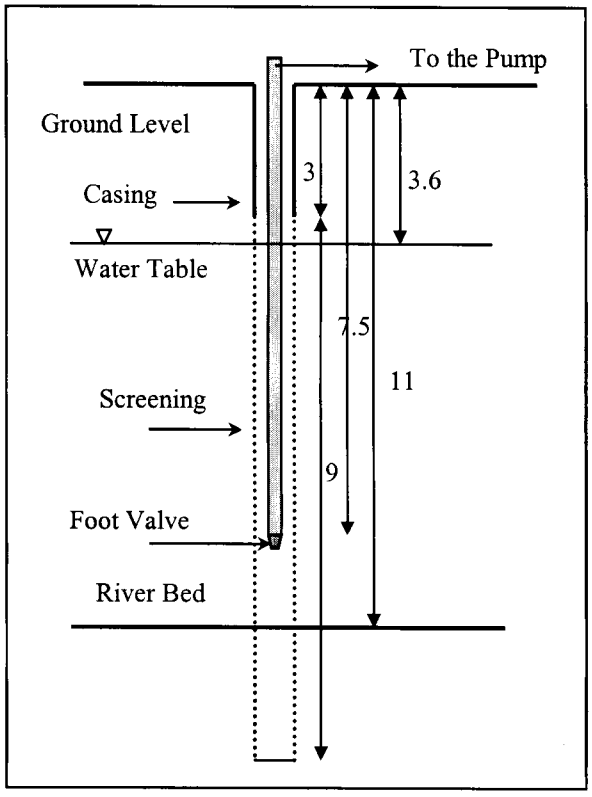


Figure 4-7 a) Drilling a well as the dilution water source replacement (top)- b) Details of the well (right) (dimensions in m)

Previous microcosm study suggested that an HRT of 8 to 15 days results in a considerable amount of pollutant removal in the constructed wetlands (Frankowski, 2000). The HRT in the cells was controlled with the amount of inflow. Because of the transportation and lab work cycle convenient, an HRT of seven days was maintained throughout the research.

4-1-2) Nutrient Addition and pH Adjustment

As discussed in section 3-2, the level of nutrients and nutrient to carbon ratio were very low in the leachate. In an attempt to compensate for this lack of nutrients, phosphorous and urea were added to two of the planted cells. On the last week of June 2000, slow release fertilizer pellets were added to cells #2 and #4 (Figure 4-3). The pellets contained 17% total phosphorus weight ratio (Sterling, 1997). The fertilizers were put in meshed bags and were placed along the width of the cells. Each bag contained 0.5 kg of fertilizer and a total of 2.5 kg was used for each cell. In the first week of July 2001, 2 kg of a different type of fertilizer (Organico®) in meshed bags was added to each of the cells #2 and #4 in order to balance the nitrogen content of the cells. The weight composition of Organico® fertilizer was 20% total N (9% from polymer coated urea), 4% P_2O_5, and 10% K_2O. The nutrient levels were measured inside and in the effluent of the cells in order to estimate the amounts utilized throughout the fertilized cells.

To consider the possibility of neutralization of the pH, 5 kg Dolomite® soil conditioner was added to cell #4. It contained 53% calcium carbonate and 41% magnesium carbonate. The neutralization effect of the soil conditioner on the leachate was investigated in the lab before application.

4-1-3) Sampling and Analytical Protocols

Sampling was conducted for a total of 34 weeks, during two separate periods (May-September 2000 and June-October 2001) on a weekly basis. Effluent samples were collected from the outlet of each cell using the swivelling pipe. A single influent sample was collected from the outlet of the dosing tank. Leachate and dilution water source (i.e. slough in 2000 and well in 2001) were also sampled to measure any seasonal variations. Samples were collected following the same manner discussed in Section 3-1. Temperature and DO were measure at each sampling location using the meter described in Section 3-1.

In addition to temperature and DO, all samples and lab and field blanks were analysed for pH, specific conductivity, BOD, COD, tannin and lignin, VFAs, and nutrients (i.e. ammonia, nitrate and nitrite, and ortho-phosphate). TSS was measured only in 2000. All the analytical protocols were identical to the ones discussed in Section 3-1.

4-2) Results and Discussion

4-2-1) Characterization of Dilution Water Sources

An important step in this experiment was to determine the influence of the dilution water on the influent characteristics. In particular, it was necessary to ascertain that the dilution

water sources (i.e. slough in 2000 and well in 2001) did not contribute to the pollutant character of the influent. Therefore, all appropriate analyses as mentioned in sections 3-2-1 and 3-2-2 for the leachate were carried out for these sources. The results of dilution water source characterization are summarized in Table 4-1.

Table 4-1 Characterization of dilution water sources (slough in 2000 and well in 2001)

Parameter	Slough Average[1] (Std. Dev.)	n[2]	Well Average (Std. Dev.)	n
Temperature (°C) (ambient)	20.8 (2.0)	9	10 (1.2)	3
Dissolved Oxygen (ambient)	2.1 (0.4)	13	2.8 (0.3)	3
pH	6.18 (0.2)	13	6.35 (0.17)	10
Specific Conductivity ($\mu s.cm^{-1}$)	126 (7)	8	257 (27)	10
Biochemical Oxygen Demand (BOD)	12 (6)	19	2.0 (2.0)	13
Chemical Oxygen Demand (COD)	131 (31)	19	24 (25)	8
Tannin and Lignin (as tannic acid)	17 (7)	18	1.0 (1.0)	14
Total Volatile Fatty Acids ($C_2 - C_6$)	30.1 (22.5)	15	26.0 (22.1)	15
Ammonia (NH_3-N)	0.2 (0.2)	15	0.2 (0.1)	14
Nitrate + nitrite (NO_x^--N)	0.08 (0.06)	15	0.08 (0.10)	14
Ortho-phosphate (PO_4^{3-}-P)	0.11 (0.08)	15	0.14 (0.36)	14
Total Suspended Solids	49 (65)	17	- -	- -

[1] All concentrations are reported in $mg.L^{-1}$, unless otherwise noted
[2] n: number of samples

Concentrations of most chemical constituents measured were at least an order of magnitude less than that of the leachate. Both dilution water sources had a pH well above six. Consequently, these sources were appropriate to reduce the strength of the leachate.

4-2-2) Treatment Performance

The pilot-scale constructed wetlands were capable of increasing the pH of the leachate. As mentioned before, the dilution water sources had a pH value greater than 6. However, due to their low buffering capacity, the influent (diluted leachate) still had a very low pH. The average pH of influent was 3.9 in 2000 and 4.3 in 2001 (Table 4-2a, 4-2b). Plants in surface flow wetlands have a major role in pH improvement. Photosynthetically active macrophytes generate oxygen and remove carbon dioxide from the water causing an increase in water pH (Wood, 1995). During this study, reactors were able to increase the pH up to 2 units. The planted cells performed better in increasing pH than the unplanted cells (Figure 4-8). Such a result was expected considering the effect of photosynthetic activity of the plants on the water pH. Adaptation of the wetlands also had a noticeable effect on pH improvement. As it can be seen in both sampling seasons (Figure 4-8), after a few weeks of initial habituation, the pH starts to increase more rapidly in planted cells.

Table 4-2a Field data, pH, and conductivity measurements for influent and effluent, 2000

Parameter	Influent	Effluent		
	Average[2] (Std. Dev.)	Control Average (Std. Dev.)	Planted Average (Std. Dev.)	Nutrient added[1] Average (Std. Dev.)
Temperature (°C)	20.4 (1.7)	21.4 (1.7)	21.3 (1.9)	21.3 (1.8)
pH	3.91 (0.18)	4.60 (0.26)	4.78 (0.71)	5.51 (0.65)
Dissolve Oxygen ($mg.L^{-1}$)	1.1 (0.2)	0.6 (0.2)	0.6 (0.2)	0.6 (0.2)
Specific Conductivity ($\mu s.cm^{-1}$)	582 (390)	415 (113)	466 (77)	425 (110)

[1] These cells were planted
[2] Temp: n = 9 for influent, and n = 18 for each reactor set
pH and DO :n = 13 for influent, and n = 26 for each reactor set
Conductivity: n = 8 for influent, and n = 16 for each reactor set

Table 4-2b Field data, pH, and conductivity measurements for influent and effluent, 2001

Parameter	Influent	Effluent		
	Average (Std. Dev.)	Control Average (Std. Dev.)	Planted Average (Std. Dev.)	Nutrient added[1] Average (Std. Dev.)
Temperature (°C)	12.2 (2.0)	13.3 (4.9)	14.0 (3.2)	14.3 (3.0)
pH	4.33 (0.30)	4.77 (0.28)	4.89 (0.39)	5.10 (0.54)
Dissolve Oxygen ($mg.L^{-1}$)	1.5 (0.9)	0.4 (0.4)	0.3 (0.1)	0.4 (0.3)
Specific Conductivity ($\mu s.cm^{-1}$)	692 (280)	593 (173)	605 (181)	597 (179)

[1] These cells were planted
[2] Temp: n = 14 for influent, and n = 28 for each reactor set
pH and DO: n = 14 for influent, and n = 28 for each reactor set
Conductivity: n = 15 for influent, and n = 28 for each reactor set

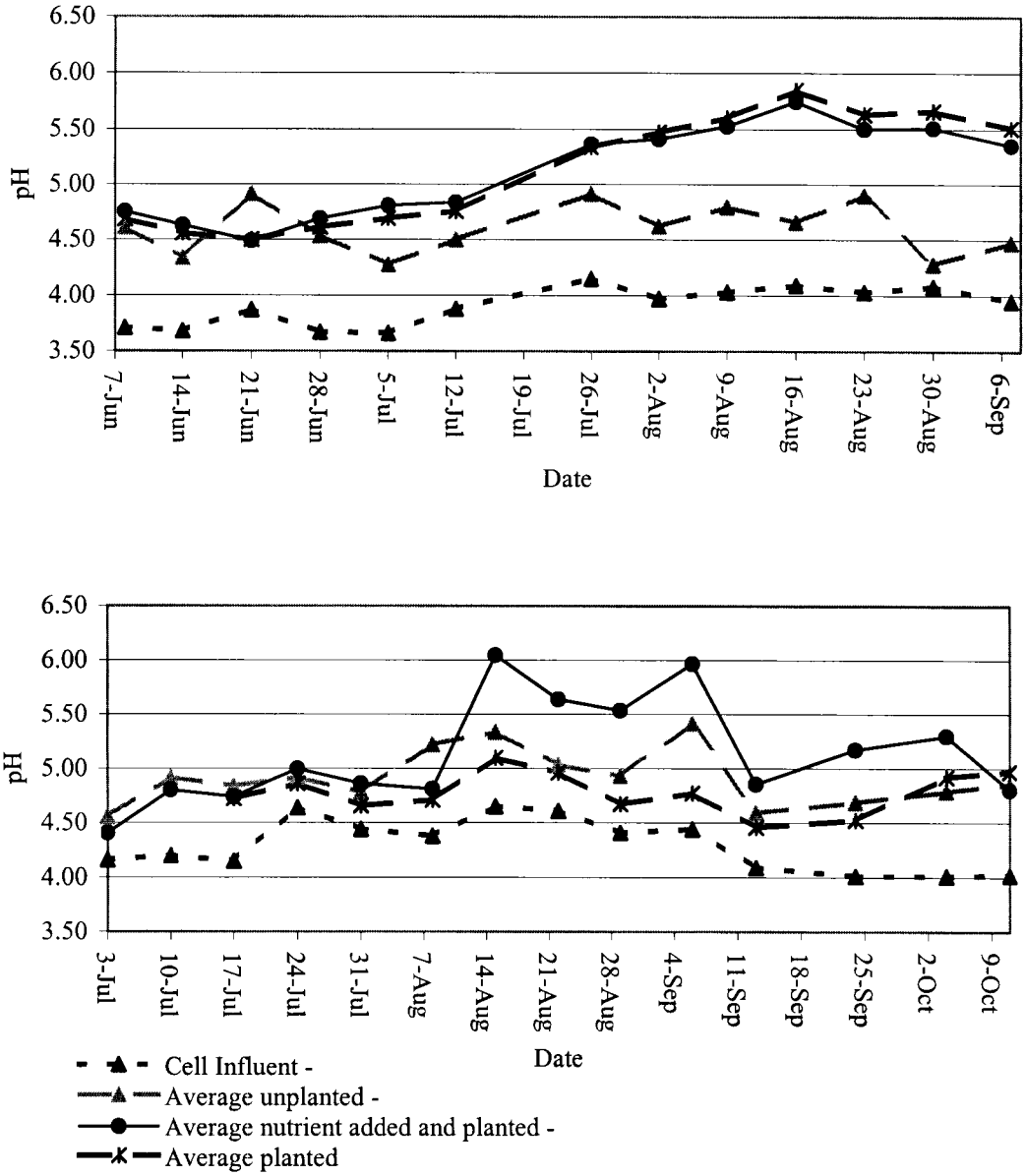


Figure 4-8 Average pH improvement in pilot scale cells (top: 2000, bottom: 2001)
(note: averages are between two identical cells over time)

Because of the higher buffering capacity of the source of dilution water in 2001 (i.e. well), influent had a higher average pH than the previous year (Table 4-2a, 4-2 b). During the second period of treatment trials (2001), leachate neutralization capability of the soil conditioner (Dolomite®) was measured in the lab using pure leachate. The lab results

showed that pH in the leachate started to rise up as soon as it came to contact with the soil conditioner (i.e. in a few seconds). Then, as the soluble, outer layer was dissolved, the pH became stable. Meanwhile, a large amount of the soil conditioner (almost 80% of the weight) remained insoluble after 10 minutes (Figure 4-9). It was concluded that the conditioner is capable of increasing pH without dissolving rapidly, so it can stay in the cells for a long period. Measuring the remaining weight of the soil conditioner located in cell #4 showed that 25% of the 5 kg was used up after 2 weeks. During a stage from end of August to beginning of September 2001 (Figure 4-8), the pH increased noticeably because of this base addition.

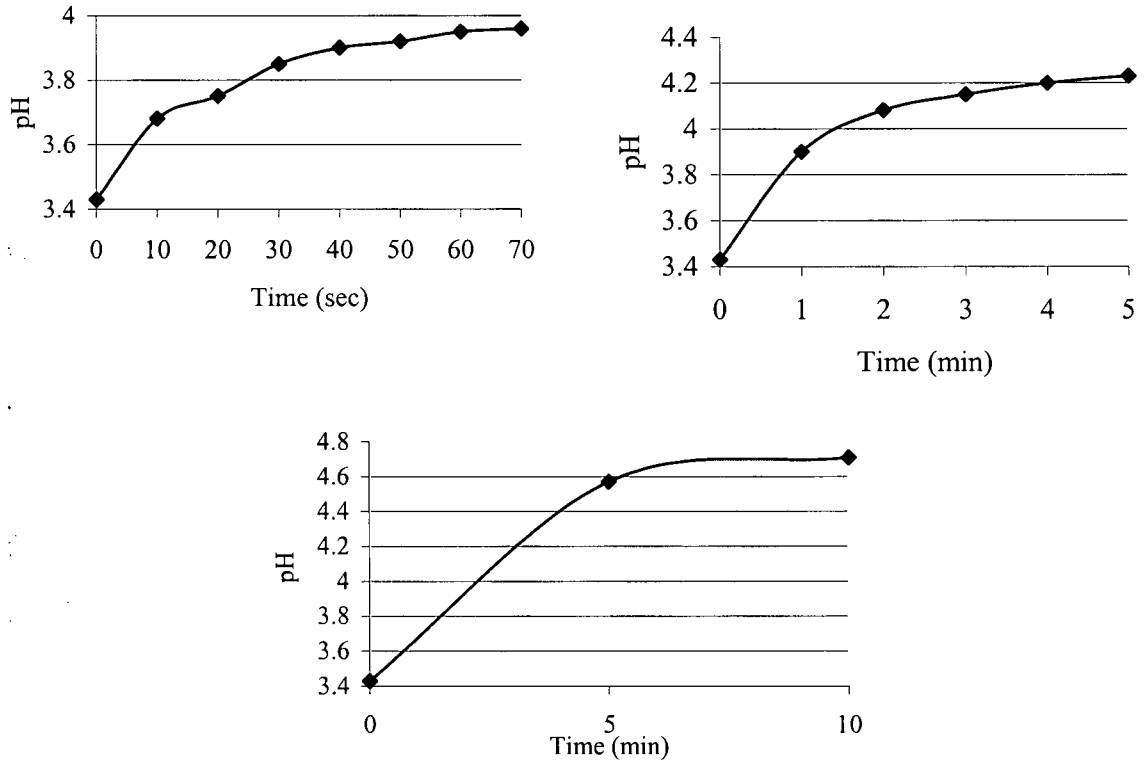


Figure 4-9 pH neutralization measurements during three different time steps using 10 $g.L^{-1}$ limestone (Dolomite®) and pure leachate

Wetlands are generally excellent sediment traps (Kadlec, 1995). During the first season of this study (2000) total suspended solids were reduced from 32.1 $mg.L^{-1}$ in influent to an average of 24 $mg.L^{-1}$ in effluent (Table 4-3a). Specific conductivity measurements indicated that dissolved solids were partially removed in the cells (Table 4-2a, 4-2b). Considering the relatively high conductivity of the dilution water sources (specially in the well water, 2001, Table 4-1), it can be concluded that a portion (21 to 37%) of the dissolved solids in the influent was inorganic and thus very hard to remove through biological processes.

Table 4-3a Summary of removal performances for targeted parameters in the pilot-scale constructed wetlands, 2000*

Parameter	Influent	Effluent					
		Control		*Planted*		*Nutrients Added*[2]	
	Average[1] (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)
Biochemical Oxygen Demand (BOD_5)	1702 (532)	769 (299)	55% (17%)	832 (273)	51% (17%)	642 (259)	62% (12%)
Chemical Oxygen Demand (COD)	3221 (1112)	1609 (533)	50% (24%)	1928 (436)	40% (25%)	1591 (530)	51% (21%)
Tannin and Lignin (as tannic acid)	978 (444)	569 (159)	42% (22%)	675 (197)	31% (26%)	570 (212)	42% (18%)
Total Volatile Fatty Acids (VFAs)	499 (142)	244 (149)	51% (25%)	323 (172)	41% (24%)	163 (138)	69% (24%)
Total Suspended Solids (TSS)	32.1 (32.1)	24.3 (9.9)	- -	22.6 (12.5)	- -	25.0 (9.2)	- -

[1] n = 19 for influent, and n = 38 for each reactor set
[2] These cells were planted
* All values reported in $mg.L^{-1}$

Table 4-3b Summary of removal performances for targeted parameters in the pilot-scale constructed wetlands, 2001*

Parameter	Influent	Effluent					
		Control		*Planted*		*Nutrients Added*[2]	
	Average [1] (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)
Biochemical Oxygen Demand (BOD_5)	3465 (1631)	1414 (760)	59%. (12%)	1442 (668)	63% (11%)	1393 (772)	60% (16%)
Chemical Oxygen Demand (COD)	3980 (1513)	2827 (1219)	29% (15%)	2632 (1031)	34% (16%)	2973 (1253)	25% (23%)
Tannins and Lignin (as tannic acid)	1160 (638)	771 (313)	44% (21%)	769 (276)	40% (21%)	797 (303)	40% (32%)
Total Volatile Fatty Acids (VFAs)	707 (513)	399 (235)	44% (43%)	435 (186)	38% (55%)	439 (241)	37% (56%)

[1] n = 15 for influent, and n = 30 for each reactor set
[2] These cells were planted
* All values reported in $mg.L^{-1}$

Treatment wetlands are efficient users of external carbon sources, manifested by excellent reductions in BOD and COD (Kadlec, 1995). Removal of BOD was observed throughout the experiments. BOD removal had an average of 52-63%. The removal in "planted and nutrient added" cells was better than other cells in year 2000 (Table 4-3a). In general planted cells showed marginally better removal efficiencies than unplanted ones in 2001 (Table 4-3b).

Percentage reductions for COD were lower than BOD. During the two stages of performance evaluations, COD was removed with an average of 25-51%. The removal efficiencies were lower in 2001. In the case of COD, there was no definable difference between the three groups of reactors (Table 4-3a, 4-3b).

In both sampling periods, a higher proportion of BOD was removed compared to COD. This can be explained by the fact that easily biodegradable materials (i.e. VFAs) are used up by microbial communities faster than recalcitrant materials (i.e. tannin and lignin). As the microbial communities utilize the readily biodegradable sources of carbon, the amount of BOD decreases faster.

Dissolved oxygen levels in treatment wetlands are normally low (Knight *et al.*, 1993). In the pilot scale study, the dissolved oxygen level was consistently lower than 0.5 $mg.L^{-1}$. Considering the very high levels of oxygen demand in the influent, low dissolved oxygen values were expected. In the absence of free oxygen gas, anaerobic respiration is an alternative catabolic process to aerobic respiration. A lower amount of carbon is degraded during anaerobic respiration (Kadlec and Knight, 1996).

Total tannin and lignin removal rate was in the range of 31-44%. In the case of tannin and lignin, there were no significant removal differences amongst different wetland cells. This demonstrated that the microbial communities that developed in the substrate (water and sediment) of unplanted cells were also capable of contaminant degradation.

VFAs were reduced throughout the treatment process. The reduction rate of VFAs was in the range of 37-69%. The relatively high removal rate of VFAs was supported with noticeable pH improvements through the cells (Figure 4-8). Tables 4-4a and 4-4b summarize the removal of the individual fatty acids.

Table 4-4a Summary of removal performance for volatile fatty acids (C2-C6) in the pilot-scale constructed wetlands, 2000*

Parameter	Influent	Effluent					
		Control		*Planted*		*Nutrients Added*[2]	
	Average[1] (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)
Total VFAs: (C_2 - C_6)	499 (142)	244 (149)	51% (33%)	323 (172)	41% (59%)	163 138	69% (61%)
acetic acid	215 (69)	90 (60)	58% (42%)	107 (71)	50% (33%)	47 (46)	78% (75%)
Propionic acid	85 (21)	39 (23)	54% (42%)	55 (27)	35% (29%)	21 (23)	75% (77%)
butyric + iso –butyric acid	110 (31)	64 (38)	42% (36%)	89 (45)	19% (12%)	48 (37)	56% (48%)
valeric acid	52 (25)	25 (20)	52% (45%)	42 (26)	19% (11%)	20 (19)	62% (59%)
hexanoic acid	37 (28)	26 (43)	30% (42%)	30 (33)	19% (21%)	27 (43)	27% (38%)

[1] n = 19 for influent, and n = 38 for each reactor set
[2] These cells were planted

Table 4-4b Summary of removal performance for volatile fatty acids (C2-C6) in the pilot-scale constructed wetlands, 2001*

Parameter	Influent	Effluent					
		Control		*Planted*		*Nutrients Added*[2]	
	Average[1] (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)	Average (Std. Dev.)	%-Removal (Std. Dev.)
Total VFAs: (C_2 - C_6)	707 (513)	399 (235)	44% (43%)	435 (186)	38% (55%)	439 (241)	38% (56%)
acetic acid	216 (225)	114 (74)	47% (49%)	122 (68)	44% (51%)	117 (18)	46% (29%)
propionic acid	97 (85)	57 (45)	41% (31%)	58 (39)	41% (33%)	64 (49)	34% (36%)
butyric + iso –butyric acid	220 (149)	126 (64)	43% (24%)	131 (55)	40% (22%)	123 (58)	44% (34%)
valeric acid	95 (87)	56 (66)	41% (46%)	69 (51)	28% (32%)	77 (44)	19% (26%)
hexanoic acid	79 (67)	46 (60)	42% (51%)	55 (56)	30% (46%)	58 (57)	27% (41%)

[1] n=15 for influent, and n=30 for each reactor set
[2] These cells were planted
* All values reported in $mg.L^{-1}$

As it was expected, there was a slightly better removal of smaller VFAs (i.e. acetic and propionic) comparing to larger ones (i.e. valeric and hexanoic) in planted cells (Table 4-4a, 4-4b). There was likely production of VFAs in the anoxic conditions presented in the wetland cells. As larger molecules (tannin and lignin, hemicellulose) were broken down.

Lower dilution was applied in the second period of the study. Consequently, a higher strength influent was applied to the cells in the second stage of trials (year 2001). The concentration of BOD in 2001 was twice as high as that in 2000 (Table 4-3a, 4-3b). Other parameters of the influent (i.e. COD, tannin and lignin, and BOD) were also considerably higher in the second year of experiments. The percentage of removals for BOD increased, proving the wetlands could handle higher levels of easily biodegradable material. On the other hand, the removal rate for COD declined. Up to a limit, wetlands provide more treatment if the detention time is increased (Kadlec, 1995). Lower removal rate for COD was because of the fact that microbial communities need longer retention times to break down the more recalcitrant material in the leachate. Despite the higher strength of the influent in 2001, the HRT remained equal to one week. To provide optimal removal, we would have to either reduce the hydraulic loading rate or increase the HRT.

The low BOD to COD ratio may be due to the high cellulose and VFAs content of the treated water (Morris and Herbert, 1997). In this study, the overall BOD to COD ratio was 0.7 for influent and 0.47 for effluent (Table 4-5). These ratios also support the fact

that there was higher BOD removal within the wetlands and that greater recalcitrant portion of COD passed through the system.

4-2-2-1) ThOD Comparisons with Measured COD

The ThODs were calculated for VFAs and tannin and lignin in both influent and effluent using balanced oxidation reactions (Appendix B). These values were then compared to the measured COD, which represents the total chemical oxygen demand. This comparison gave an estimation of the fraction of total COD that correspond to these two classes of compounds. It also provided a qualitative estimate of the utilized fraction of tannin and lignin and VFAs during the treatment process. Table 4-5 summarizes the ThOD to COD ratios over two sampling seasons for influent and effluent.

Table 4-5 Oxygen demand ratio comparisons

Influent	**Average**	n [2]
ThOD of VFAs to COD	0.25	60
ThOD of T&L to COD	0.35	68
Total ThOD [1] to COD	0.60	60
BOD to COD	0.70	68

Effluent	**Average**	n
ThOD of VFAs to COD	0.24	60
ThOD of T&L to COD	0.40	68
Total ThOD [1] to COD	0.64	60
BOD to COD	0.47	68

[1] Total ThOD = VFAs ThOD + T&L ThOD
[2] n: number of samples

Chemically and biologically inactive substances are not easily altered or removed, and so they pass through the system in wetlands (Kadlec, 1995). As shown in Table 4-5, the ThOD to COD ratio for tannin and lignin was slightly higher in the effluent compared to the influent. As discussed before in section 3-2-2, tannin and lignin contain large,

recalcitrant molecules that are not easily biodegradable. This was the main reason that a larger fraction of COD remained in the effluent. The ThOD to COD ratio for VFAs almost stayed the same in influent and effluent. As previously mentioned, this could be due to the possible production of VFAs in the cells.

Figure 4-10 shows that the seasonal changes of COD were consistently followed by changes in total ThOD. In other words, the difference between total ThOD and COD during the sampling periods for both influent and effluent remained constant. As ThODs were calculated using the VFAs and tannin and lignin results, the three sets of measurements are in good agreement. Tannin and lignin and VFAs accounted for over 60% of the COD in both influent and effluent. The remaining compounds contributing to COD were not identified or measured in this study. As discussed in section 3-2-2, those compounds could be hemicellulosic compounds, pectins and resin acids (Bertaud *et al.*, 2002, Sun *et al.*, 2001, Gabrielii *et al.*, 2000, Teschke *et al.*, 1999).

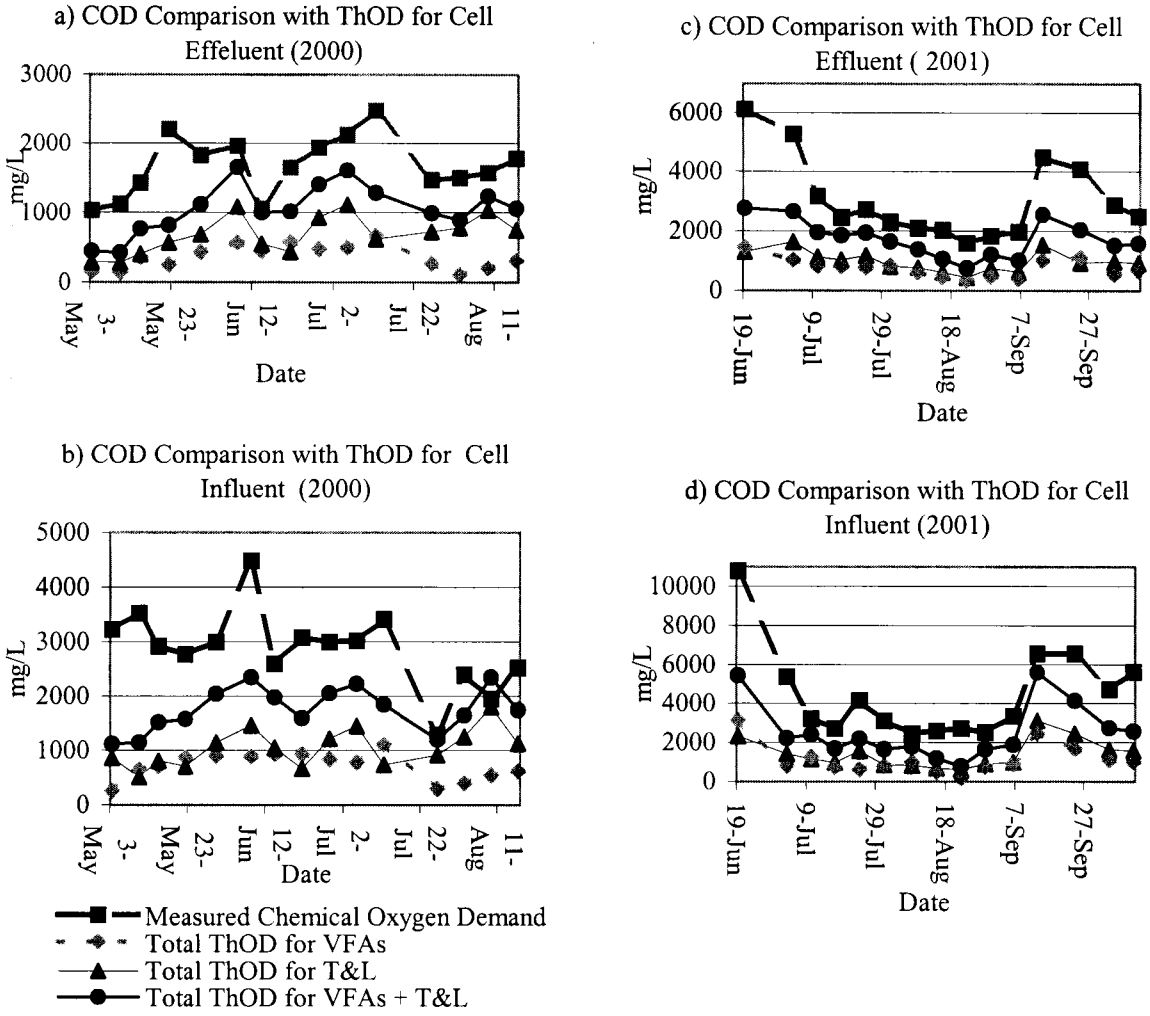


Figure 4-10 COD comparisons with ThOD for VFAs and tannin and lignin: effluent (a and c) and influent (b and d) during two evaluation periods (average values for all 6 cells)

4-2-2-2) Effects of Nutrients on Treatment Performance

It is important to note that the quantity of nutrients, play a key role in the contaminant removal performance of a wetland. In general, in lack or absence of molecular oxygen (i.e. inside the wetland cells), other oxidized inorganic compounds (e.g. nitrate or nitrite)

should be present as electron acceptors to support microbial degradation (Metcalf and Eddy, 1991). The capability of wetlands to remove nutrients has been discussed in most studies of constructed wetlands (Gopal, 1999, Bavor *et al.*, 1995, Kadlec, 1995, Wood, 1995). In particular, those have shown that: 1) phosphorus removal occurs via sorption and plant uptake; and 2) nitrogen removal is through plant uptake, nitrification, denitrification, and sorption processes. The rates of nutrient removal processes depend on the concentrations of the nutrients present and indicate that at low levels, removal does not occur. In fact, due to very low levels of nutrients in the cells in this research (Table 4-6a , 4-6b), nutrient supplement was considered rather than its removal. Reduction of food sources can result in the destruction of microbial communities (Gopal, 1999). Kadlec and Knight (1996) suggest that an N to P mass ratio of 7.2 is required for bacterial mass. As noted in Table 4-6, not only the level of the nutrients was low in the wetlands, but also the N to P ratio was much lower than 7.2.

Table 4-6a Summary of performance for nutrients in pilot-scale constructed wetlands, 2000*

	Influent	**Effluent**		
Parameter	Average[2] (Std. Dev.)	*Control* Average (Std. Dev.)	*Planted* Average (Std. Dev.)	*Nutrients added*[1] Average (Std. Dev.)
Ammonia (NH_3-N)	0.3 (0.3)	0.2 (0.3)	0.2 (0.2)	0.1 (0.1)
Nitrate + nitrite (NO_x^--N)	0.21 (0.09)	0.25 (0.10)	0.24 (0.10)	0.21 (0.10)
Ortho-phosphate (PO_4^{3-}-P)	0.75 (0.20)	0.38 (0.21)	0.54 (0.32)	0.75 (0.73)

[1] These cells were planted
[2] n = 15 for influent, and n = 30 for each reactor set
* All values reported in $mg.L^{-1}$

Table 4-6b Summary of performance for nutrients in pilot-scale constructed wetlands, 2001*

Parameter	Influent	Effluent		
	Average [2] (Std. Dev.)	*Control* Average (Std. Dev.)	*Planted* Average (Std. Dev.)	*Nutrients added* [1] Average (Std. Dev.)
Ammonia (NH_3-N)	0.3 (0.3)	0.2 (0.2)	0.5 (1.3)	1.4 (0.3)
Nitrate + nitrite (NO_x^--N)	0.07 (0.07)	0.06 (0.04)	0.09 (0.14)	0.06 (0.06)
Ortho-phosphate (PO_4^{3-}-P)	1.19 (0.96)	0.63 (0.37)	0.68 (0.29)	1.17 (0.68)

[1] These cells were planted
[2] n = 15 for influent, and n = 30 for each reactor set
* All values reported in $mg.L^{-1}$

A lack of phosphorus can limit biomass growth and subsequently the treatment efficiency. When the plants growth is accelerated (i.e. in spring), phosphorus should be added to wetlands in order to attain greater biomass (Bulc *et al.*, 1997). As mentioned before, nutrient sources were added to two of the planted cells (# 2 and # 4) in June 2000 and July 2001. The level of nutrients inside the cells was measured. In the first year, one week after applying the fertilizer pellets, the level of ortho-phosphate increased to 2.2 $mg.L^{-1}$ inside the cells. However, the effluent of those two cells had lower concentration (average of 1.6 $mg.L^{-1}$ after fertilizer addition). The difference between these two concentrations (~ 0.7 $mg.L^{-1}$) was the amount of phosphorus utilized over one HRT. The level of phosphorous stayed higher in the effluent of those two cells until the entire soluble fraction of the pellets were depleted (Figure 4-11). In year 2001, the pellets were added almost in the beginning of operation period. As a result, the concentration of phosphorous increased constantly throughout the operation period, (Figure 4-11).

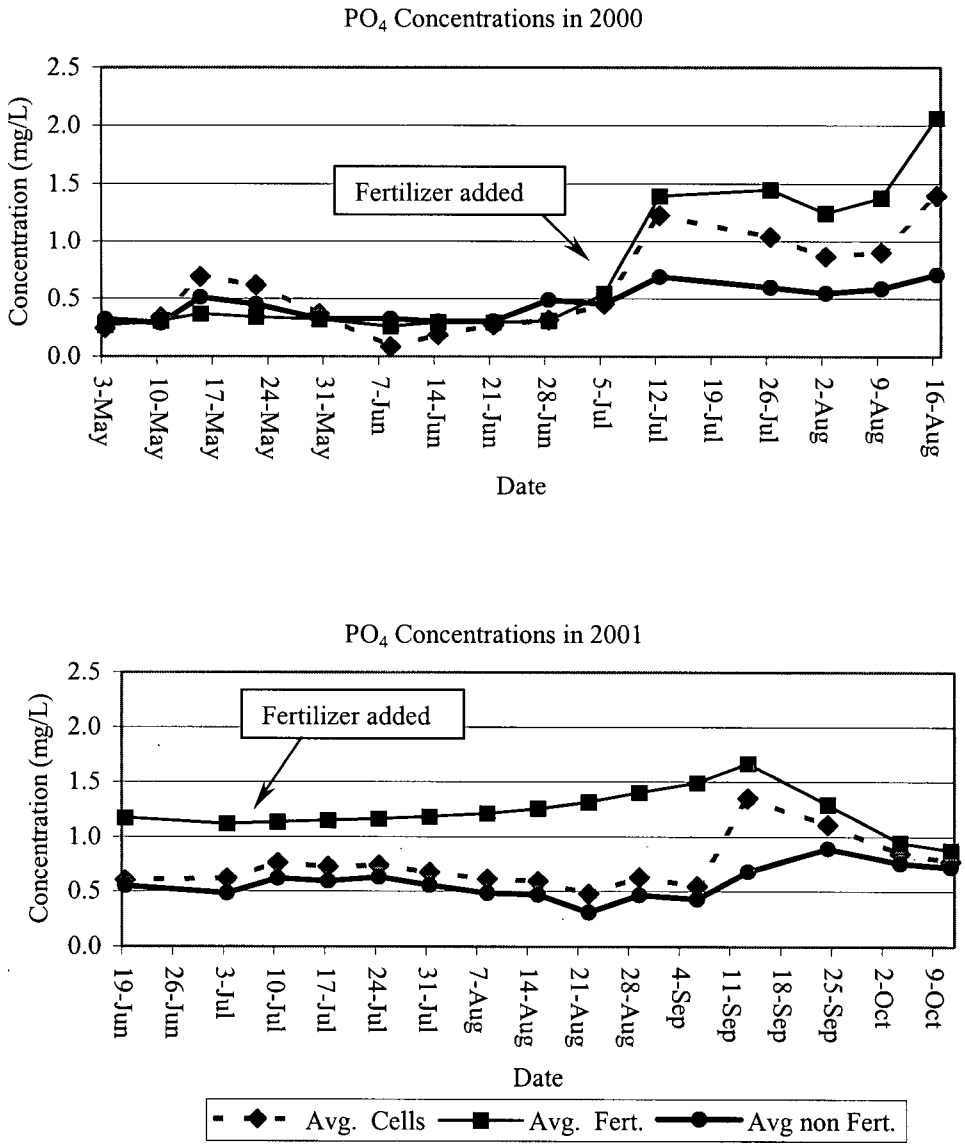


Figure 4-11 The effect of fertilizer addition on ortho-phosphate concentrations of the cells effluent

Partly because of nutrient addition in 2000, the removal ratio for BOD and VFAs for both "nutrients added" cells increased considerably in comparison to the other cells (Table 4-3a and Figure 4-12). This showed that, although the desirable N to P ratio was not satisfied, the efficiency of biological degradation in the cells improved with the addition

of phosphorous alone. There was not an explicable difference in removal ratio of tannin and lignin between these cells (# 2 and # 4) and "planted only" cells. This was attributed to the low biodegradability of these compounds.

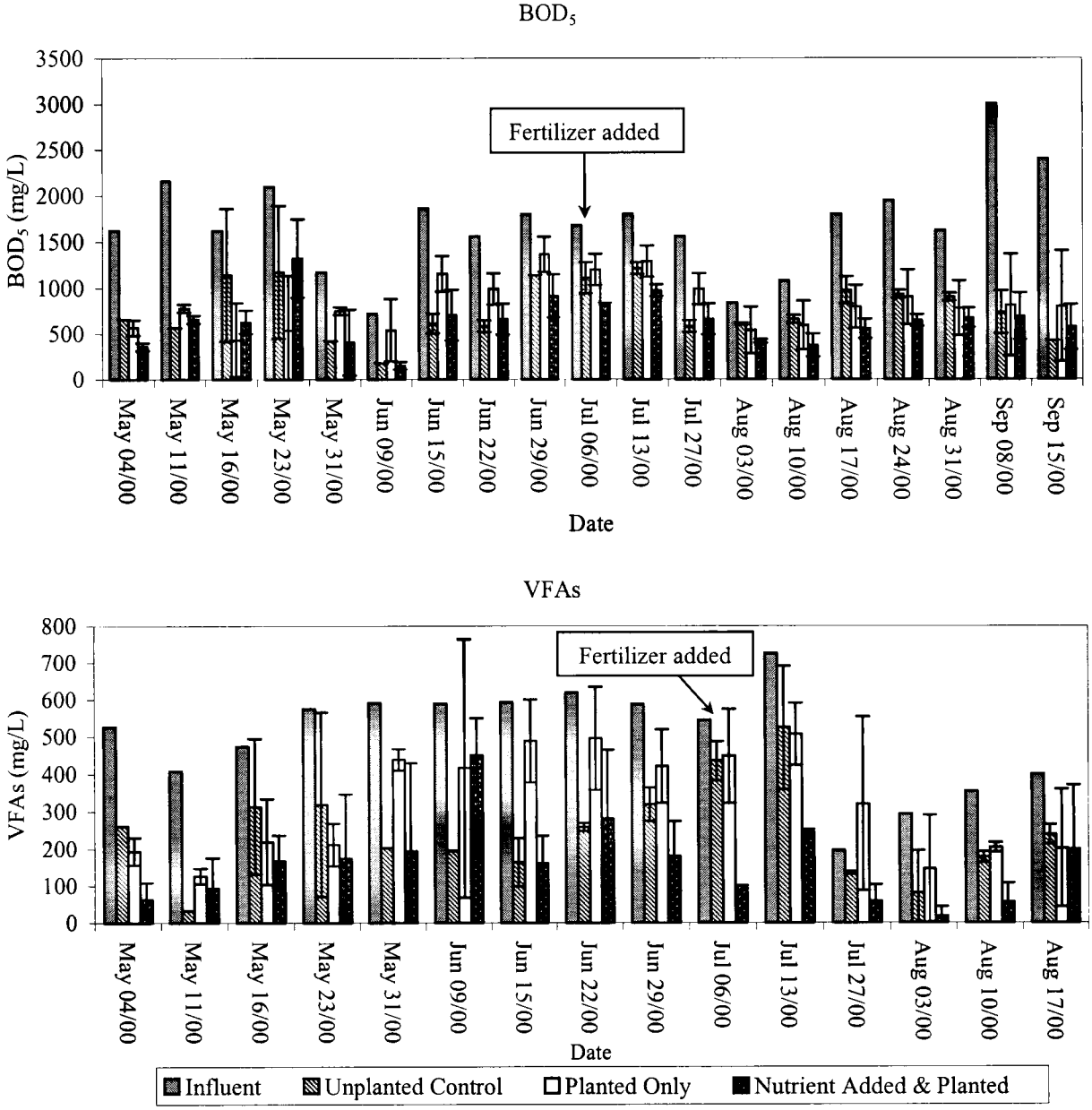


Figure 4-12 Wetlands seasonal variations for BOD_5 and VFAs removal in 2000
(Note the increased efficiency in nutrient added cells after fertilizer addition)

In addition to phosphorous bearing pellets, a different type of fertilizer, which contained urea, was added to cells # 2 and # 4 in 2001 in order to achieve the desirable the N to P

ratio. As a result, the levels of nitrogen ammonia both inside the cells and in their effluent increased (Table 4-6b). In spite of this, no significant treatment improvement was noticed in those cells during the second evaluation period. The urea fertilizer had a very high solubility and disappeared from the meshed bags in less than two weeks.

It should be mentioned that the removal efficiency of cell # 2 significantly dropped after a 2-week shock-loading incident in 2001. The shock loading resulted from a temporary malfunction of the dilution water (well) pump. Consequently, pure leachate was pumped to the cells for two weeks. It affected the general performance of the system and its negative effect persisted for a few weeks thereafter (Appendix D). Although including those data reduced the average removal ratios of the system, these problems may occur in the "real world", and they were not excluded from the calculation.

4-2-2-3) Seasonal Effects on Wetlands Performance

Wetland hydrology is a primary driving force influencing wetland ecology, its development, and persistence (Souch *et al.*, 1996). However, little attention has been paid to the seasonal variations in the concentration of the wastewater and the effects of climate changes on wetlands (Gopal, 1999). Surface flow wetlands respond to rain and evapotranspiration (Kadlec, 1995), and therefore, these should not be ignored in the performance evaluation process. The performance evaluation in this research includes nearly three seasons in two stages (from spring to fall). The climatic data (temperature and precipitation) were obtained during the two assessment episodes. Figures 4-12 and 4-

13 graphically summarize detailed seasonal changes of wetlands' treatment performance for targeted pollutants are in year 2000. The graphical presentation of treatment performance in year 2001 is summarized in Appendix D. Likewise, the climatic changes for the same periods are summarized in 2000 are presented in Figure 4-14 for year 2000 and in Appendix C for 2001.

Precipitation and evapotranspiration influence the water budget and cause unpredictable flow of wastewater through the wetland (Rash and Liehr, 1999). During hot summer days of July and August with minimal rainfall (Figure 4-14), there was almost no outflow from the outlet of the cells. Although the strength of the influent was reduced (i.e. more dilution applied), effluent quality of the system decreased considerably during that period. The main reason was the high amount of evaporation, since wetlands have a large surface area to depth ratio. The concentration of the wastewater in the cells increased to a level that the system was no longer capable to carry out the desirable treatment. Dry and hot weather affected the system during two periods in 2000 (mid-June to mid-July and end of July to mid-August, Figures 4-12,13,14) and second half of August 2001 (Appendix C, Figures C1,2 and Appendix D, Figures D1,2,3,4). Moreover, in two points during the treatment period (Second half of July 2000, Figure 4-14, and end of July 2001, Appendix D), the dilution water pump malfunctioned due to technical problems. This resulted in periods of pumping pure leachate into the cells. These shock loadings affected the performance of the system and the recovery lasted a few weeks. The relationship between climatic changes and wetlands performance can be noticed with a quick look at the related Figures (Appendix C, D).

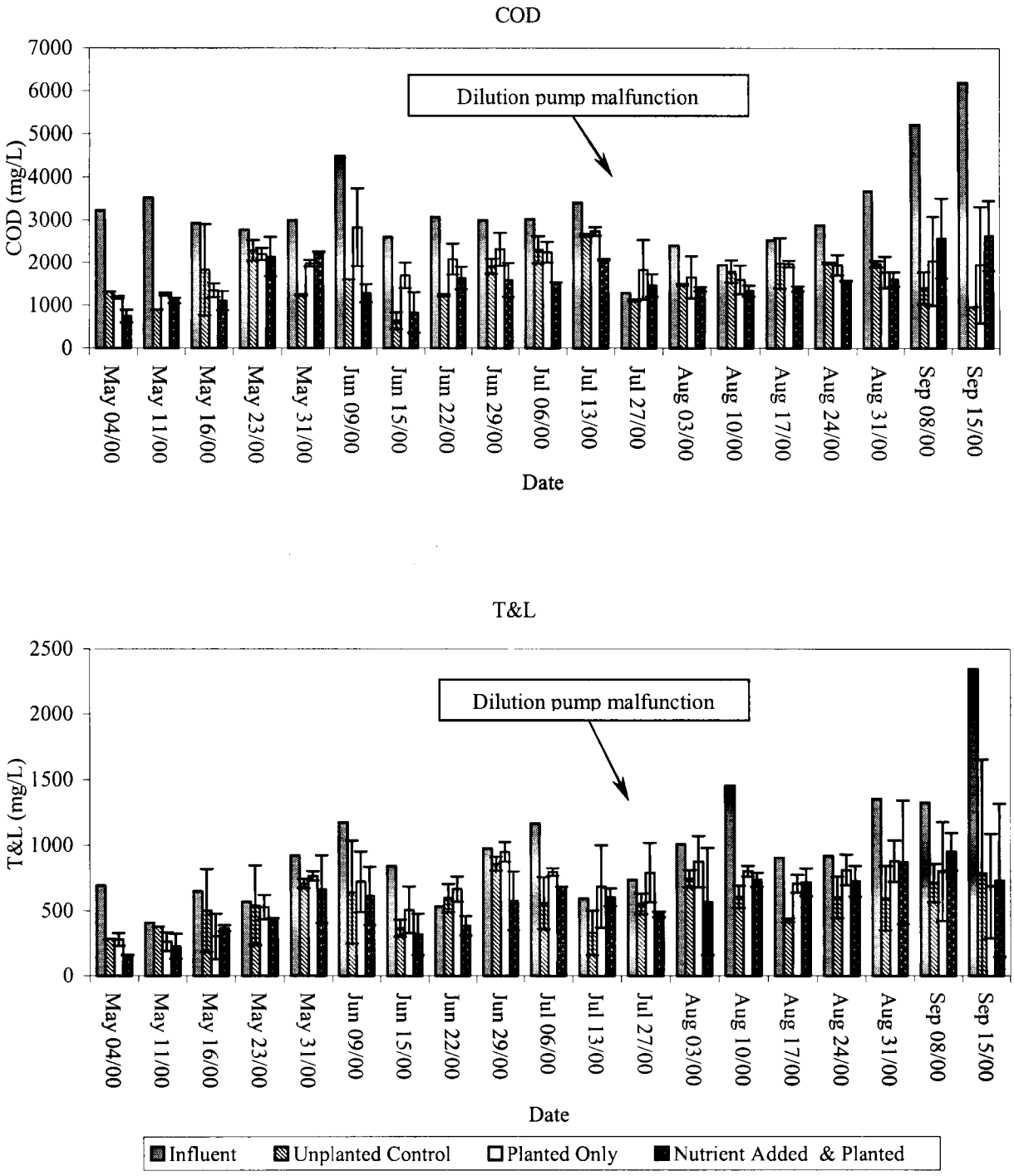


Figure 4-13 Wetland seasonal variations for COD and tannin and lignin removal in 2000
(Error bars represent standard deviations between two identical cells)

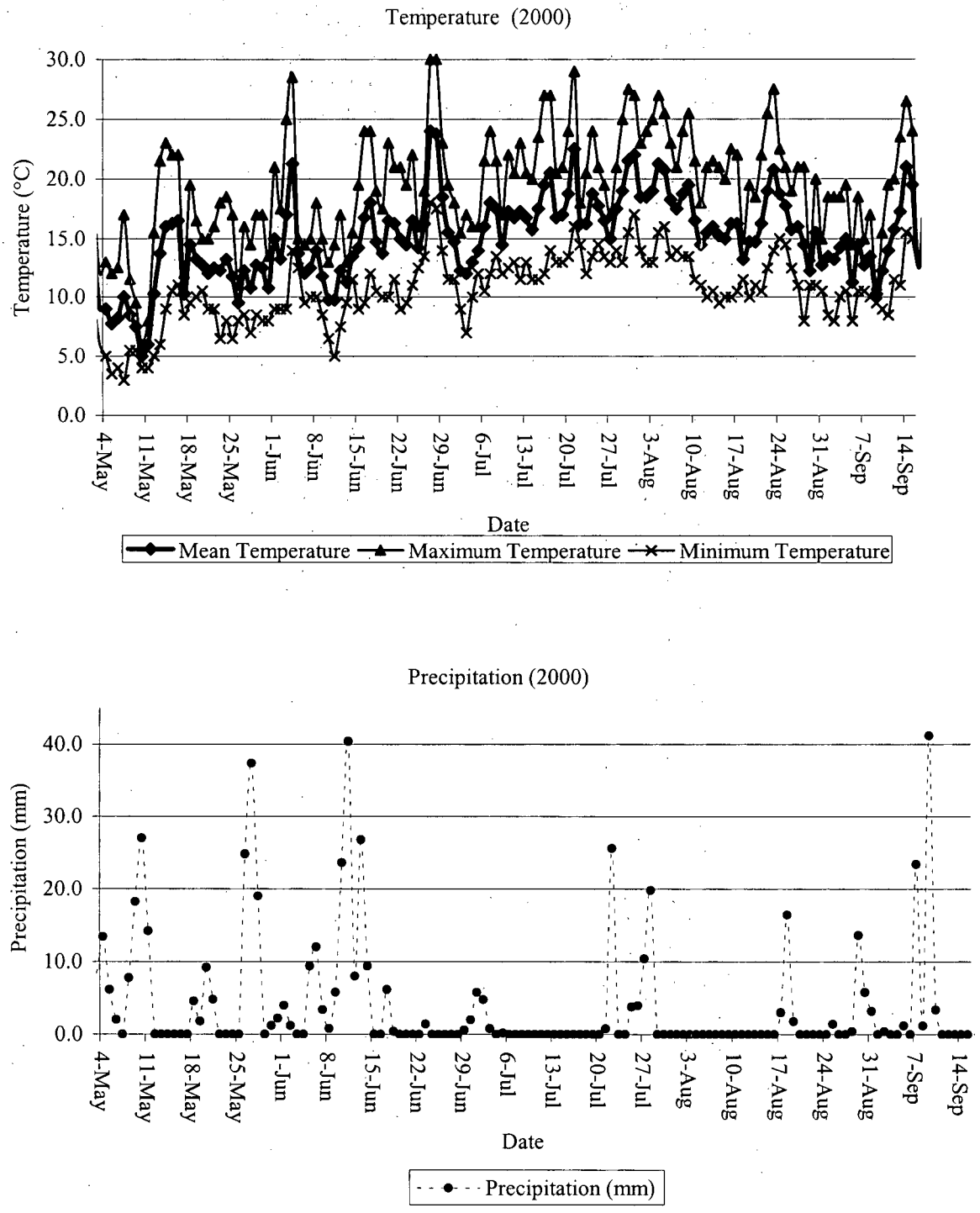


Figure 4-14 Climatic data for year 2000, top: temperature and bottom precipitation

Wetlands require an adaptation period to reach a stationary state. This period includes vegetative aerial fill-in, root and rhizome development, litter development, and microbial community establishment. Therefore, a newly constructed treatment wetland would be expected to require many months, including at least one year to stabilize (Kadlec and Knight, 1996).

Operation of the studied constructed wetlands had been started about six months before the beginning of this study. Due to limited time and other logistical constrains, it was not possible to run the wetlands on a year-round basis. As a result, wetlands were out of operation for a few months during the study period. Therefore, a new habituation phase was started in the beginning of each evaluation period (i.e. May 2000 and June 2001). Still the performance of the wetlands improved due to partial adaptation during the 4 to 5 months of operation. In the last few weeks of each assessment period, the treatment efficiency increased significantly (Figures 4-12, 4-13, and Appendix D). A much better performance of the wetlands would be expected during a continuous, year-round operation as compared to the intermittent situation in this study.

A brief comparison between the results of this study and the previous study on the same system (Frankowski, 2000) shows that the treatment performance has increased in this research. In best cases, average BOD, COD, tannin and lignin, and VFAs removal were 49%, 32%, 46% and 43% respectively and pH never passed over 3.8. Several factors may have contributed to this. The monitoring of wetland performance was conducted during

the colder season (October to December 1999). Average temperatures were much lower in that period (6-8°C) relative to temperatures in this study (20-22°C). Temperature has a significant effect on the biological treatment processes (Metcalf and Eddy, 1991). As mentioned above, the habituation of wetlands increases the treatment efficiencies. As the microbial and macrophytes communities were developed, the system was expected to improve over time. The first result of the better-developed macrophytes was noticeable pH improvements. In the prior study, pH of the effluent rarely increased to a value above four. In this study, effluent pH had an average of ~ 5.0. Thus, the wetland conditions were favourable to a broader range of microbial communities and their activities. As the wetland conditions got closer to optimal, the cells promoted removal. This resulted in 5% to 20% higher removal efficiencies in this study.

4-3) Conclusions

Treatment of woodwaste leachate under field conditions was established in this research. Constant increase of pH was observed. Reductions of BOD_5, COD, tannin and lignin and VFAs were consistently achieved. Closer to neutral pH, along with higher mean temperatures during the warmer period of year, favoured microbial activities. This resulted in better removal efficiencies as compared to the previous study on the same system. An important reason for treatment improvements was the habituation of the wetlands. Still, the wetlands need even more time for full ecological maturation under continuous operational conditions.

The treatment performance of "planted cells" was better in the case of pH improvement. Addition of nutrients to planted cells favoured the treatment efficiency of the wetlands. Taking into account the lack of nutrients in the leachate, it is feasible to consider continuous nutrient addition in order to supply sufficient food source to microbial communities. However, the desirable N to P ratio should be satisfied in order to obtain the optimum results.

Hydrological conditions of the field (i.e. temperature, evaporation, and precipitation) had a great impact on the treatment performance. In hot and dry summer days, the concentration of the contaminants clearly increased in the effluent and there was almost no wastewater flowing out from the outlets. This meant that all of the volume of inflow evaporated and contaminants were remaining inside the cells. Although the wetlands may have been functioning properly, as the wastewater was concentrated inside the cells, removal ratios decreased. Proper dilution along with shorter HRT (i.e. higher flow rate) may lessen this impact.

5) GENERAL CONCLUSIONS AND RECOMMENDATIONS

The woodwaste leachate studied in this research should be considered a strong industrial wastewater, which is harmful to the environment. It was acidic, and had a very high oxygen demand. At least half of this oxygen demand was due to readily biodegradable compounds that supported the biological treatment option for the leachate.

A limited number of studies have evaluated the characteristics of different leachates from wood and woodwaste. However, none has demonstrated a feasible and continuing treatment method for wood leachate.

Constructed wetlands were capable of woodwaste leachate treatment in an earlier study by Frankowski (2000). They were chosen because of their low cost, low monitoring requirements, and high flexibility. The pilot-scale constructed wetlands systems were established as an effective treatment system for woodwaste leachate. After initial hydraulic/mixing modifications in the site, persistent increase in pH, and decrease in BOD, COD, tannin and lignin, and volatile fatty acids concentrations were observed during the period of this study.

The emergent plants proved effective for treatment improvements. The level of pH increased more in planted cells compared to unplanted ones. The positive effects of plants, such as photosynthesis (which was accelerating the rise in pH), oxygen transfer

through the root mass, and creation of larger surface area for microbial attachment, enhanced the treatment effectiveness. On the other hand, unplanted cells were still effective in pollutant reduction. This showed that the substrate soil and the water column above it could support the development of microbial communities responsible for biological degradation of the contaminants without the existent of the plants.

Taking into consideration the low level of nutrients in the leachate, nutrient addition enhanced the treatment ability of the system. As expected from the very high levels of carbon in the leachate, nutrients were undoubtedly a limiting factor in the microbial degradation process. In general, very low levels of nutrients and oxygen in the wetland cells (i.e. the lack of electron acceptors) certainly had a negative effect on the treatment efficiency.

Climatic changes and removal fluctuations were related. Higher temperatures improved the treatment ability and yet, high evaporation concentrated the wastewater in the cells and reduced the system efficiency.

The treatment effectiveness of the cells increased in the last few weeks of each investigation period. This proved that a longer exposure time would increase acclimatization of the whole system and hence its treatment efficiency.

Continuous, year-round operation of the system can help to attain robust results under different climatic conditions. The constant function of the wetlands also gives them the

opportunity to develop the required acclimatization without suffering from the impacts of the intermittent operation. Hydrological studies and a water balance calculation in the wetland cells would be beneficial in elucidating the performance fluctuations. Microbiological studies would also assist to understand the causes of treatment vacillation.

An investigation of the limiting factors is needed to assess the treatment capabilities of constructed wetland systems for treatment of woodwaste leachate. Possible continual addition of nutrient sources (i.e. nitrogen and phosphorous) with the desirable ratio theoretically will increase the ability of microorganisms to biodegrade the targeted pollutants. Also, providing an adequate supply of electron acceptors, such as nitrate for heterotrophic bacteria needs to be investigated in this wetland system with very low levels of dissolved oxygen.

6) REFERENCES

APHA (American Public Health Association), AWWA, WEF (1998) Standard Methods for the Examination of Water and Wastewater (20th ed.), American Public Health Association, Washington, D.C., U.S.A.

Arnold, J. G., P. M. Allen, and D. S. Morgan (2001) Hydrologic Model for Design and Constructed Wetlands, *Wetlands*, 21:(2): 167-178.

Bailey, H. C., J. R. Elphic, A. Potter, E. Chao, D. Konasewich, and J. B. Zak (1999) Causes of Toxicity in Storm Water Runoff From Sawmills, *Environmental Toxicology and Chemistry,* 18:(7): 1485 -1491.

Becker, L., G. Matuschek, D. Lenoir, and A. Kettrup (2001) Leaching Behaviour of Wood Treated with Creosote, *Chemosphere*, 42: 301-308.

Bertaud, F., A. Sundberg, and B. Holmbom (2002) Evaluation of Acid Methanolysis for Analysis of Wood Hemicellulose and Pectins, *Carbohydrate Polymers*, 48: 319-324.

Bavor, H. J., D. J. Roser, and P.W. Adcock (1995) Challenges for the Development of the Advanced Constructed Wetland Technology, *Wat. Sci. Tech.* 22: (3): 13-20.

Bianco, M. A. and, H. Savolainen (1997) Phenolic Acids as Indicators of Wood Tannins, *The Science of the Total Environment*, 203: 79-82.

Birkbeck, A.E., D. Reil, and R. Hunter (1990) Application of Natural and Engineering Wetlands for Treatment of Low-Strength Leachate. Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control, Cambridge, UK, 24-28 September 1990.Cooper, P. F. and B. C. Findlater (Eds.), Pergamon Press, Oxford, UK.

Brix, H. (1997) Do Macrophytes Play a Role in Constructed Treatment Wetlands? *Wat. Sci. Tech.* 35:(5): 11-17.

Bulc, T., D. Vrhovšek, and V. Kukanja (1997) The Use of Constructed Wetlands for Landfill Leachate Treatment, *Wat. Sci. Tech.* 35:(5): 301-306.

Campbell, C.S., and, M.H. Ogden (1999) Constructed Wetlands in the Sustainable Landscape, John Wiley and Sons, Inc. New York, NY, U.S.A.

CHRS (Canadian Heritage River Systems) (2001) Seventeenth Annual Report on the Canadian Heritage River Systems, Ministry of Public Works and Government Services, Ottawa, ON, Canada.

COFI (Council of forest industries) (2000) British Columbia Forest Industry Fact Book, COFI BC, Vancouver, British Columbia, Canada.

Environment Canada (1999) Canadian Climate Normals, Abbotsford, BC, 1944-1990, Published in Ontario, Canada.

El-Fadel, M., A. N. Findikakis, and J.O. Leckie (1997) Environmental Impacts of Solid Waste Landfilling, *J. of Environmental Management,* 50: 1-25.

Forgie, D. J. L. (1988) Selection of the Most Appropriate Leachate Treatment Method, Parts 1, 2, and 3, *Water Pollution Research J. of Canada*, 23:(2): 308-355.

Frankowski, K. (2000) The Treatment of Wood Leachate Using Constructed Wetlands, M.A.Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada.

Fujita Research Co. (1998) Constructed Wetlands for Wastewater Treatment (Report 022), Fujita Research Archived Report, Encino, CA, USA.

Gabrielii, I., P. Gatenholm, W. G. Glasser, R. K. Jain, and L. Kenne (2000) Separation, Canalization and Hydrogel-formation of Hemicellulose from Aspen Wood, *Carbohydrate Polymers*, 43: 367-374.

Gerba, C. P., J. A. Thurson, J. A. Falabi, P. M. Watt, and M. M. Karpisack (1999) Optimization of Artificial Wetland design for Removal of Indicator Microorganisms and Pathogenic Protozoa, *Wat. Sci. Tech.* 40:(4): 363-368.

Gopal, B. (1999) Natural and Constructed Wetlands for Wastewater Treatment: Potentials and Problems, *Wat. Sci. Tech.* 40:(3): 27-35.

Government of British Columbia (1996) Waste Management Act, Conditional Exemption and Agricultural Waste Control Regulation: Code of Agricultural Practice for Waste Management, Oct. 25, 1996. British Columbia, Canada.

Hammer, D. A. and R.K. Bastian (1989) Wetlands Ecosystems: Natural Water Purifiers? in Constructed wetlands for Wastewater Treatment: Municipal, Industrial, Agricultural, (Hammer, D.A. Ed.), Lewis Publishrers Inc. Chelsea, MI, U.S.A.

Henry, J.G. and G.W. Heinke (1996) Environmental Science and Technology, (2nd ed.), Pentrice-Hall Inc. NJ, USA.

Kadlec, R. H. (1995) Overview: Surface Flow Constructed Wetlands, *Wat. Sci. Tech.* 32(3): 1-12.

Kadlec, R.H. and R.L. Knight (1996) Treatment Wetlands, CRC-Lewis publishers. New York, NY, U.S.A.

Kendall, D. and T. Michelsen (1997) Management of Woodwaste Under Dredged Material Management Programs (DMMP) and the Sediment Management Standards (SMS) Cleanup Program, DMMP Issue Paper, SMS Draft Technical Information Memorandum, Seattle, WA, USA.

Kiparissis, Y., C. D. Metcalf, and A. J. Niimi (1996) Induction of Hepatic EROD in Fish Exposed to Leachate from Wood Pulp, *Chemosphere*, 32:(9): 1833-1841.

Knight, R. L., R. W. Ruble, R. H. Kadlec, and S. C. Reed (1993) Database: North American Wetlands for Water Quality Treatment, Phase II report, prepared for USEPA, September, 1993.

Kozub, D. D. and S. K. Liehr (1999) Assessing Denitrification Rate Limiting Factors in a constructed Wetland Receiving Landfill Leachate, *Wat. Sci. Tech.* 40:(3): 75-82.

Liénard, A., D. Esser, A. Deguin, and F. Virloget (1990) Sludge Dewatering and Drying in Reed Beds: An Interesting Solution? General Investigation and First Trials in France,

Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control, Cambridge, UK, 24-28 September 1990.Cooper, P. F. and B. C. Findlater (Eds.), Pergamon Press, Oxford, UK.

Madigan, M. T., J. M. Martinko, and J. Parker (1997) Brock Biology of Microorganisms, (Eighth Ed.), Prentice Hall Inc., New Jersey, USA.

Martin, C. D., K. D. Johnson, and G. A. Moshiri (1999) Performance of a Constructed Wetland Leachate Treatment System at the Chunchula Landfill, Mobile County, Alabama, *Wat. Sci. Tech.* 40:(3): 67-74.

McCloy, B. W. (1997) History and Future of Sawmill Woodwaste Disposal in British Columbia, Residue to Revenue Conference, November 4-5, 1997, Council of Forest Industries of British Columbia. Vancouver, British Columbia, Canada.

Metcalf and Eddy (1991) Wastewater Engineering, Treatment, Disposal, and Reuse, (3rd ed.), revised by G. Tchobanoglous, and F. L. Burton, McGraw-Hill Inc., New York, USA.

Mitsch W.J. and J. G. Gosselink (1993) Wetlands, 2nd ed, Van Nostrand Reinhold, New York, USA.

Mitsch, W.J., and K. M. Wise (1998) Water Quality, Fate of Metals, and Predictive Model Validation of a Constructed Wetland Treating Acid Mine Drainage, *Wat. Res.* 32: (6): 1888-1900.

Morris M., and R. Herbert (1997) The Design and Performance of a Vertical Flow Reed Bed for the Treatment of High Ammonia, Low Suspended Solid Organic Effluents, *Wat. Sci. Tech.* 35:(5): 197-204.

Nepf, H. and E. Koch (1999) Vertical Secondary Flows in Submersed Plant-like Arrays. *Limn. Oceanogr.,* 44:(4): 1072-1080.

Onay, T. T., and F. G. Pohland (1998) *In Situ* Nitrogen Management in Controlled Bioreactor Landfills, *Water Research*, 32 (5), 1383-1392.

Persson, J., N. L. G. Somes, and T. H. F. Wong (1999) Hydraulics Efficiency of Constructed Wetlands and Ponds, *Wat. Sci. Tech.* 40:(3): 291-300.

Peters, G. B., H. J. Dawson, B. F. Hrutfiord, and R. R. Whitney (1976) Aqueous Leachate from Western Red Cedar: Effects on Some Aquatic Organisms, *Journal of the Fisheries Resource Board of Canada,* 33: 2703 -2709.

Phipps, B. J. (1974) Introduction to the Woodwaste Leachate Symposium, Grays Harbour College, Dec. 20, 1974, Aberdeen, WA, USA.

Pohland, .G., J.T. Deryien, and S. B. Gosh (1983) Leachate and Gas Quality Changes during Landfill Stabilization of Municipal Refuse. In *Anaerobic Digestion, Proceedings of the 3rd International Symposium*, Boston, Massachusetts, USA, pp 185-202.

Prahacs, S. M. (1986) An Evaluation of Leeches as in-situ Bio Monitors of Chlorinated Phenolic Compounds Discharged from Bleached Kraft Pulp Mills, M.A.Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada.

Province of British Columbia (1988) Special Waste Effluent Regulations, REG 63/88, Ministry of Environment, Victoria, BC, Canada.

Province of British Columbia, Ministry of Forests (1999) Economics and Trade Branch BC Stats; Exports (BC Origin), Vancouver, British Columbia, Canada

Rash J. K., and S. K. Liehr (1999) Flow Pattern Analysis of Constructed Wetlands Treating Landfill Leachate, *Wat. Sci. Tech.* 40:(3): 309-305.

Rostad, C. E., B. S. Martin, L. B. Barber, J. A. Leenheer, and S. R. Daniel (2000) Effect of a Constructed Wetland on Disinfection By-products: Removal Processes and Production of Precursors. *Environ. Sci. Technol.* 34: 2703-3710.

Sawyer, C. N., P. L. McCarty, and G. F. Parkin (1994) Chemistry for Environmental Engineers (4th ed.), McGraw-Hill Book Company. New York, U.S.A.

Schreijer, M., R. Kampf, S. Toet, and J. Verhoeven (1997) The Use of Constructed Wetlands to Upgrade Treated Swage Effluents Before Discharge to Natural Surface Water in Texel Island, the Netherlands, Pilot Study, *Wat. Sci. Tech.* 35:(5): 231-237.

Sorrel, B. K. and P. I. Boon (1992) Biogeochemistry of Billabong Sediments, II Seasonal Variations in Methane Production, *Freshwater Biol.* 27: 435-445.

Souch, C., C. P. Wolfe, and C. S. B. Grimmond (1996) Wetland Evaporation and Energy Partitioning: Indiana Dunes National Lakeshore, *J. of Hydrology*, 184: 189-208.

Sproul, O. J., and A. S. Clifford (1968) Water Quality Degradation by Wood Bark Pollutants, Water Resource Centre Publications No. 5. University of Maine, Orono, ME, USA, 53 pp.

SRCD (1999) Sacramento Constructed Wetlands Demonstration Project, Five-Year Summary Report 1994-1998, Sacramento Regional Wastewater Treatment Plant, Sacramento, CA, USA.

Statistics Canada (2000) International Trade Division, Catalogue 31-001. Ottawa, Ontario, Canada

Sterling, M. S. (1997) Phosphorus Release from a Slow-release Fertilizer Under Simulated Stream Conditions, M.A.Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada.

Sun, R. C., J. M. Fang, J. Tomkinson, Z. C. Geng, and J. C. Liu (2001) Fractional Isolation, Physico-chemical Characterization and Homogeneous Esterification of Hemicelluloses from Fast-growing Poplar Wood, *Carbohydrate Polymers*, 44: 29-39.

Sweet, H. R., and R. H. Fetrow (1975) Groundwater Pollution by Woodwaste Disposal, *Groundwater*, 13: 227-231.

Tarutis, W. J. Jr., L. R. Stark, and F. M. Williams (1999) Sizing and Performance of Coal Mine Drainage Wetlands, *Ecological Engineering*, 12: 353-372.

Taylor, B. R., J. S. Goudey, and N. B. Carmicheal (1996) Toxicity of Aspen Wood Leachate to Aquatic Life: Laboratory Studies, *Environmental Toxicology and Chemistry,* 15:(2): 150 –159.

Teschke, K., P. A. Demers, H. W. Davies, S. M. Kennedy, S. A. Marion, and V. Leung (1999) Determinants of Exposure to Inhalable Particulate, Wood Dust, Resin Acids, and Monoterpens in a Lumber Mill Environment, *Ann. Occup. Hyg.*, 43:(4): 247-255.

Thurlow and Associates (1977) Literature Review of Wastewater Characteristics and Abatement Technology in the Wood and Timber Processing Industry, Report No. EPS 3-WP-7-2, Water Pollution Control Directorate, Fisheries and Environment Canada. Ottawa, ON, Canada.

Tyrrel, S. F., P.B. Leeds-Harrison, and K. S. Harrison (2002) Removal of Ammoniacal Nitrogen from Landfill Leachate by Irrigation onto Vegetated Treatment Planes, *Water Research*, 36:291-299.

U.S. EPA (1995) Manual for Groundwater and Leachate Treatment Systems, EPA/625/R-94/005. Washington, D.C.: U.S. Environmental Protection Agency.

USGS (1996) U.S. Geological Survey Programs in New York, Fact Sheet FS-032-96, U.S. Geological Survey, U.S. Department of Interior, Troy, NY, USA.

Vymazal, J. (Ed.) (1999) Constructed Wetlands for Wastewater Treatment in Europe Backhuys Publishers, A.H. Leiden, the Netherlands.

Wallace, S. (2001) Advanced Designs for Constructed Wetlands, *Bio Cycle*, 42:(6): 40-43.

Walls, J. S. (1975) Protecting Groundwater from Landfill Leachate, *Water Sewage Works*, 122, 68.

Wetzel, R.G. (1975) Limnology, W. B. Sanders Company, Philadelphia, PA, USA.

Wetzel, R.G. (1993) "Constructed Wetlands: Scientific Foundations are Critical", in Constructed Wetlands for Water Quality Improvement, G. A. Moshiri (Ed.), Lewis Publishers, London, England.

Woods, A. (1995) Constructed Wetlands in Water Pollution Control: Fundamentals to Their Understanding, *Wat. Sci. Tech.* 32:(3): 21-29.

Zachritz, W. H., L. L. Lundie, and H. Wong (1996) Benzoic Acid Degradation by Small, Pilot-Scale Artificial Wetland Filter (AWF) Systems, *Ecological Engineering*, 7:105-116.

Zehnder, A. J. B., K. Ingvorsen, and T. Marty (1982) Microbiology of Methane Bacteria, In Anaerobic Digestion, (D.E. Hughes, ed.), Amsterdam: Elsevier Biomedical Press, pp.45.

APPENDICES

APPENDIX A Raw Data

Table A1 Temperature, pH, DO, and Conductivity in Constructed Wetland Cells in 2000

Temperature (°C):

Sample ID	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00	Aug 24/00	Aug 31/00	Sep 08/00
Cell 1	21.5	19.5	20.0	24.0	18.0	24.0	23.0	22.0	23.0
Cell 5	21.0	20.5	22.0	23.5	19.0	23.5	22.0	21.0	22.0
Cell 3	21.5	19.5	21.0	23.0	17.0	23.0	22.0	22.0	22.0
Cell 6	22.0	19.0	21.0	23.0	18.0	23.0	22.0	22.0	22.0
Cell 2	22.0	19.0	21.5	23.5	18.0	23.5	22.0	21.0	22.0
Cell 4	22.0	20.0	22.0	24.0	16.5	24.0	21.0	20.0	21.0
Cell Influent	21.0	19.0	20.0	23.0	18.0	23.0	20.0	20.0	20.0
Leachate Pool	27.0	26.0	27.0	30.0	25.0	30.0	31.0	29.0	31.0

pH:

Sample ID	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00	Aug 24/00	Aug 31/00	Sep 08/00
Cell 1		4.13	4.83	4.47	4.33	4.51	4.82	4.52	4.66	4.46	4.81	4.35	4.45
Cell 5	4.61	4.54	5.00	4.60	4.22	4.49	5.01	4.72	4.93	4.86	4.99	4.21	4.50
Cell 3	3.98	4.88	4.27	4.10	4.08	4.23	4.44	4.35	4.46	4.49	4.42	4.54	4.42
Cell 6	4.48	4.34	4.53	4.38	4.35	4.51	5.26	5.66	5.83	6.15	6.03	6.12	5.98
Cell 2	5.73	4.08	4.54	5.29	5.34	5.22	5.59	6.05	6.23	6.38	5.97	5.87	5.66
Cell 4	4.55	4.93	4.66	4.68	5.00	5.06	6.06	5.83	5.89	6.38	6.12	6.12	5.98
Cell Influent	3.71	3.68	3.87	3.67	3.66	3.88	4.15	3.97	4.03	4.09	4.03	4.08	3.95
Leachate Pool	3.30	3.29	3.32	3.18	3.25	3.42	3.54	3.31	3.50	3.46	3.36	3.45	3.36
Slough	6.05	6.01	6.29	5.83	5.97	6.27	6.50	6.40	6.43	6.18	6.01	6.26	6.15

Summary DO ($mg.L^{-1}$)

Sample ID	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00	Aug 24/00	Aug 31/00	Sep 08/00
Cell 1	0.4	0.7	0.6	0.8	0.4	0.6	1.0	0.5	0.4	0.5	0.4	0.3	0.4
Cell 5	0.4	0.7	0.7	0.5	0.9	0.8	1.0	0.5	0.4	0.5	0.6	0.7	0.6
Cell 3	0.5	0.8	0.5	0.7	0.7	0.6	0.9	0.4	0.4	0.4	0.7	0.8	0.7
Cell 6	0.8	0.5	0.4	0.4	0.5	0.6	0.9	0.5	0.3	0.5	0.8	0.8	0.8
Cell 2	0.6	0.6	0.4	0.9	0.6	0.8	0.9	0.4	0.5	0.4	0.8	0.9	0.8
Cell 4	0.8	0.6	0.5	0.4	0.6	0.7	0.8	0.6	0.4	0.6	0.7	0.7	0.7
Cell Influent	1.5	1.4	1.3	1.5	1.0	1.1	1.1	1.0	0.8	1.0	0.9	0.9	0.9
Leachate Pool	0.3	0.3	0.2	0.3	0.3	0.3	0.4	0.2	0.1	0.2	0.2	0.2	0.2

Conductivity ($\mu S.cm^{-1}$)

Sample ID	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00	Aug 24/00	Aug 31/00	Sep 08/00
Cell 1	584	306	368	410	495	457	409	123
Cell 5	509	286	383	489	505	490	479	349
Cell 3	490	492	404	328	457	468	479	608
Cell 6	490	492	404	328	457	468	479	608
Cell 2	456	375	317	484	350	420	468	519
Cell 4	434	287	341	494	364	354	388	752
Cell Influent	515	262	404	463	446	483	560	1523
Leachate Pool	1721	1792	1943	1924	2090	2041	1940	1991
Slough	123	116	120	124	122	129	136	135

Table A2 Solids Concentrations in Constructed Wetland Cells in 2000 ($mg.L^{-1}$)

Sample Date:	May 04/00		
Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
Cell 1	-	-	-
Cell 2	22.5	1.0	21.5
Cell 3	30.5	2.5	28.0
Cell 4	74.7	16.7	58.0
Cell 5	45.0	10.0	35.0
Cell 6	20.5	1.5	19.0
Cell Influent	-0.4	2.0	-2.4
Leachate Pool	8.0	0.8	7.2
Slough	58.4	12.4	46.0
Blank	1.2	1.2	0.0

Sample Date:	May 11/00		
Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
Cell 1	-	-	-
Cell 2	25.0	-34.0	59.0
Cell 3	20.0	2.0	18.0
Cell 4	18.0	4.0	14.0
Cell 5	26.0	3.0	23.0
Cell 6	35.0	12.0	23.0
Cell Influent	-5.0	-14.0	9.0
Leachate Pool	17.0	6.0	11.0
Slough	9.0	4.0	5.0
Blank	2.0	0.0	2.0

Sample Date:	May 16/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	26.5	4.0	22.5
	Cell 2	16.0	1.5	14.5
	Cell 3	16.0	3.0	13.0
	Cell 4	13.5	2.5	11.0
	Cell 5	26.0	2.5	23.5
	Cell 6	22.0	3.0	19.0
	Cell Influent	29.0	9.5	19.5
	Leachate Pool	10.5	1.0	9.5
	Slough	7.0	2.0	5.0
	Blank	0.0	-0.5	0.5

Sample Date:	May 23/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	27.0	5.0	22.0
	Cell 2	40.5	7.5	33.0
	Cell 3	28.0	2.5	25.5
	Cell 4	29.5	4.0	25.5
	Cell 5	39.5	4.0	35.5
	Cell 6	25.5	5.5	20.0
	Cell Influent	42.5	9.5	33.0
	Leachate Pool	28.5	5.0	23.5
	Slough	51.5	18.5	33.0
	Blank	0.5	0.5	0.0

Sample Date:	May 31/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	10.5	1.0	9.5
	Cell 2	29.0	3.5	25.5
	Cell 3	24.5	3.5	21.0
	Cell 4	30.0	3.5	26.5
	Cell 5	29.0	5.0	24.0
	Cell 6	21.0	2.0	19.0
	Cell Influent	18.0	2.5	15.5
	Leachate Pool	15.0	2.0	13.0
	Slough	22.0	3.5	18.5
	Blank	0.0	0.5	-0.5

Sample Date:	Jun 09/00		
Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
Cell 1	-	-	-
Cell 2	36.0	1.5	34.5
Cell 3	21.0	1.0	20.0
Cell 4	19.5	0.5	19.0
Cell 5	32.0	2.0	30.0
Cell 6	26.5	2.5	24.0
Cell Influent	12.5	1.0	11.5
Leachate Pool	18.0	3.0	15.0
Slough	15.0	1.5	13.5
Blank	-0.5	-2.0	1.5

Sample Date:	Jun 15/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	13.0	1.5	11.5
	Cell 2	45.5	3.5	42.0
	Cell 3	24.5	1.5	23.0
	Cell 4	22.5	3.0	19.5
	Cell 5	36.5	7.0	29.5
	Cell 6	16.5	0.0	16.5
	Cell Influent	36.0	3.0	33.0
	Leachate Pool	15.0	0.0	15.0
	Slough	21.0	3.0	18.0
	Blank	-1.0	-1.0	0.0

Sample Date:	Jun 22/00		
Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
Cell 1	42.5	4.5	38.0
Cell 2	19.5	2.0	17.5
Cell 3	19.0	1.5	17.5
Cell 4	31.5	6.5	25.0
Cell 5	42.0	7.5	34.5
Cell 6	28.5	4.0	24.5
Cell Influent	87.5	6.5	81.0
Leachate Pool	23.0	4.0	19.0
Slough	46.5	7.0	39.5
Blank	2.0	1.5	0.5

Sample Date:	Jun 29/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	41.0	2.0	39.0
	Cell 2	18.0	1.5	16.5
	Cell 3	25.5	2.5	23.0
	Cell 4	30.0	3.5	26.5
	Cell 5	28.0	4.0	24.0
	Cell 6	22.0	2.0	20.0
	Cell Influent	14.5	1.5	13.0
	Leachate Pool	15.5	3.0	12.5
	Slough	10.5	3.5	7.0
	Blank	1.0	0.5	0.5

Sample Date:	Jul 06/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	27.5	1.5	26.0
	Cell 2	19.5	2.0	17.5
	Cell 3	22.5	2.0	20.5
	Cell 4	-	-	-
	Cell 5	23.5	0.0	23.5
	Cell 6	23.0	2.5	20.5
	Cell Influent	25.5	2.5	23.0
	Leachate Pool	112.0	4.5	107.5
	Slough	16.0	2.0	14.0
	Blank	1.0	0.5	0.5

Sample Date:	Jul 13/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	26.5	-1.5	28.0
	Cell 2	21.0	4.0	17.0
	Cell 3	15.0	0.0	15.0
	Cell 4	15.0	1.5	13.5
	Cell 5	24.5	2.5	22.0
	Cell 6	12.5	0.5	12.0
	Cell Influent	63.0	4.0	59.0
	Leachate Pool	37.5	7.0	30.5
	Slough	39.5	15.5	24.0
	Blank	0.0	-0.5	0.5

Sample Date:	Jul 27/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	19.5	3.0	16.5
	Cell 2	22.5	3.0	19.5
	Cell 3	44.0	4.5	39.5
	Cell 4	21.5	6.5	15.0
	Cell 5	41.5	10.0	31.5
	Cell 6	18.0	4.0	14.0
	Cell Influent	24.0	5.5	18.5
	Leachate Pool	47.5	12.0	35.5
	Slough	23.5	10.5	13.0
	Blank	0.0	1.0	-1.0

Sample Date:	Aug 03/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	24.0	3.0	21.0
	Cell 2	18.0	0.0	18.0
	Cell 3	18.0	1.5	16.5
	Cell 4	14.5	2.5	12.0
	Cell 5	25.5	6.0	19.5
	Cell 6	17.0	3.0	14.0
	Cell Influent	16.0	2.5	13.5
	Leachate Pool	67.0	12.5	54.5
	Slough	33.0	8.0	25.0
	Blank	2.5	2.0	0.5

Sample Date:	Aug 10/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	26.5	2.0	24.5
	Cell 2	19.5	3.5	16.0
	Cell 3	4.0	-2.0	6.0
	Cell 4	16.0	1.5	14.5
	Cell 5	24.0	5.0	19.0
	Cell 6	0.0	4.0	-4.0
	Cell Influent	16.5	0.5	16.0
	Leachate Pool	32.0	3.5	28.5
	Slough	57.5	12.5	45.0
	Blank	0.0	-0.5	0.5

Sample Date:	Aug 17/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	6.0	0.5	5.5
	Cell 2	9.0	1.0	8.0
	Cell 3	11.0	1.0	10.0
	Cell 4	6.0	3.0	3.0
	Cell 5	13.0	3.5	9.5
	Cell 6	21.5	4.5	17.0
	Cell Influent	25.0	7.5	17.5
	Leachate Pool	60.5	14.5	46.0
	Slough	140.5	106.0	34.5
	Blank	1.0	1.0	0.0

Sample Date:	Aug 24/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	37.5	11.5	26.0
	Cell 2	27.5	5.5	22.0
	Cell 3	15.0	1.0	14.0
	Cell 4	14.0	3.5	10.5
	Cell 5	17.0	6.5	10.5
	Cell 6	22.0	3.0	19.0
	Cell Influent	19.0	3.5	15.5
	Leachate Pool	30.5	5.0	25.5
	Slough	19.5	12.5	7.0
	Blank	-0.5	-0.5	0.0

Sample Date:	Aug 31/00			
	Sample ID	TSS (mg/L)	FSS (mg/L)	VSS (mg/L)
	Cell 1	18.5	4.5	14.0
	Cell 2	16.5	2.5	14.0
	Cell 3	33.0	3.0	30.0
	Cell 4	17.0	2.0	15.0
	Cell 5	21.0	3.0	18.0
	Cell 6	24.0	3.0	21.0
	Cell Influent	122.7	20.0	102.7
	Leachate Pool	34.0	5.5	28.5
	Slough	270.5	150.5	120.0
	Blank	2.0	0.5	1.5

Table A3 BOD, COD, and Tannin and Lignin Raw Data In Constructed Wetland Cells in 2000

BOD_5, ($mg.L^{-1}$)

Sample ID	04-May-00	11-May-00	16-May-00	23-May-00	31-May-00	09-Jun-00	15-Jun-00	22-Jun-00	29-Jun-00	06-Jul-00
Cell 1			1650	1680	420		539	540	1139	990
Cell 5	660	570	630	660	420	180	689	630	1139	1230
Cell 3	630	810	150	120	780	780	1289	1110	1499	1320
Cell 6	510	750	720	960	720	300	1019	870	1229	1080
Cell 2	330	630	540	1620	150	120	899	540	749	840
Cell 4	390	690	720	1020	660	180	509	780	1079	
Cell Influent	1620	2160	1620	2100	1170	720	1859	1560	1799	1680
Leachate Pool	6450	6300	6150	7200	4950	5250	6749	7350	8399	8550
Slough	8	12	4	10	12	3	28	9	11	13

13-Jul-00	27-Jul-00	03-Aug-00	10-Aug-00	17-Aug-00	24-Aug-00	31-Aug-00	08-Sep-00	15-Sep-00	Average
1170	540	600	690	1080	960	930	899	-	922
1260	630	615	630	870	900	870	569	424	714
1410	1110	720	780	960	1110	990	1199	1224	947
1170	870	360	405	630	690	570	419	374	718
930	540	405	285	480	690	750	869	749	637
1020	780	435	465	630	600	600	509	399	637
1800	1560	840	1080	1800	1950	1620	2999	2399	1702
7650	7350	9000	7500	8550	9450	8700	7799	7349	7405

COD, ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00
Cell 1			2588	2450	1225		500	1213	2037.5	2075.0
Cell 5	1313	900	1075	2113	1250	1607	775	1250	1787.5	2525.0
Cell 3	1163	1275	1463	2100	1925	3472	1913	2338	2587.5	2412.5
Cell 6	1200	1238	1238	2300	2038	2183	1488	1825	2037.5	2075.0
Cell 2	850	1063	950	1813	2263	1131	1163	1450	1312.5	1537.5
Cell 4	638	1150	1263	2463	2250	1429	500	1825	1875.0	
Cell Influent	3225	3525	2925	2775	3000	4484	2600	3075	3000.0	3025.0
Leachate Pool	12125	11125	11000	8000	6875	9921	9813	15375	14187.5	16312.5
Slough	178	135	155	148	140	123	73	108	100.0	115.0

Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00	Aug 24/00	Aug 31/00	Sep 08/00	Sep 15/00	AVERAGE
2622.7	1124.0	1459.9	1975.0	2400	1975.0	2012.5	1675.0	-	1822
2661.5	1098.2	1498.7	1600.0	1562.5	2000.0	1912.5	1137.5	962.5	1528
2803.6	2325.6	2002.6	1837.5	2025	2112.5	2037.5	2775.0	2912.5	2183
2661.5	1343.7	1304.9	1362.5	1912.5	1775.0	1512.5	1300.0	987.5	1673
2054.3	1653.7	1343.7	1237.5	1425	1562.5	1725.0	1912.5	2050.0	1500
2080.1	1279.1	1408.3	1425.0	1337.5	1575.0	1487.5	3237.5	3212.5	1691
3410.9	1292.0	2403.1	1950.0	2525	2875.0	3675.0	5225.0	6200.0	3221
16731.3	14793.3	17506.5	14875.0	16187.5	17250.0	16000.0	18125.0	15500.0	13774
113.7	103.4	118.9	117.5	125	147.5	162.5	115.0	210.0	131

Total Tannin and Lignin ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00
Cell 1	-	-	668	779	545	621	338	426	883	1016.1
Cell 5	316.76	252.07	217	346	495	1177	431	274	808	732.7
Cell 3	292.61	250.41	349	317	698	698	707	500	951	1023.0
Cell 6	225.85	349.92	102	450	647	1026	457	365	847	981.6
Cell 2	177.56	76.29	325	422	285	1019	479	219	658	732.7
Cell 4	176.14	213.93	292	422	651	704	254	323	340	-
Cell Influent	693.18	407.96	651	570	922	1177	842	535	978	1168.2
Leachate Pool	2642	3325	4271	3720	3288	5482	2862	3651	5485	5806.5
Slough	6.53	-	4	23	18	27	18	4	13	12.8

Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00	Aug 24/00	Aug 31/00	Sep 08/00	Sep 15/00	AVERAGE
121.1	477	734	864	420	561	586	329	1610	646
363.2	365	640	743	399	336	934	535	383	513
370.5	938	945	916	710	838	982	1156	995	718
816.0	617	668	974	613	671.7	760	623	431	612
704.6	536	104	706	805	623.7	411	898	489	509
610.2	565	684	782	656	790.4	1078	1099	1317	609
595.6	737	1008	1451	905	919.2	1354	1326	2346	978
5447.9	5326	6527	6260	5190	6603.5	6517	6516	5847	4988
16.8	17	23	21	18	21.7	22	22	17	17

Table A4 Total Volatile Fatty Acids Raw Data in Constructed Wetland Cells in 2000

Total Volatile Fatty Acids ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	0	442	493	237	108	118	251	351	399	409	138	0	168	220
Cell 5	261	66	186	144	169	284	211	267	288	473	643	133	162	188	258
Cell 3	220	142	301	172	419	171	568	595	491	538	567	486	249	213	313
Cell 6	168	112	138	252	459	663	411	399	352	360	449	156	44	195	90
Cell 2	31	35	118	54	27	521	214	152	115	202	250	91	0	20	321
Cell 4	96	152	216	297	361	381	108	411	247	0	239	27	36	92	76
Cell Influent	526	409	474	576	591	590	593	619	588	545	726	197	294	355	400
Leachate Pool	2311	1876	1822	1867	2135	2175	1894	1879	1995	2413	2523	2829	2505	1641	1741
Slough	0	6	17	12	27	46	0	41	11	21	48	45	50	57	70

Acetic Acid ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	168	275	87	39	28	54	133	179	183	75	-	90	97
Cell 5	93	-	68	55	80	91	44	46	84	188	188	52	93	108	127
Cell 3	87	33	99	-	140	51	194	186	193	221	226	136	144	134	135
Cell 6	61	14	-	88	154	285	127	123	109	132	133	45	8	15	15
Cell 2	13	-	45	-	10	177	81	48	49	80	56	18	-	14	122
Cell 4	45	35	74	128	122	67	7	116	71	-	55	6	11	31	9
Cell Influent	261	128	196	285	241	254	226	259	287	269	305	87	162	131	141
Leachate Pool	1091	858	1018	1056	949	1061	945	1011	1141	1321	1151	1177	1167	-	-
Slough	0	6	10	8	13	19	-	15	11	18	19	22	26	28	34
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Propionic Acid ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	102	61	53	13	21	27	59	69	75	23	-	33	46
Cell 5	60	16	41	-	42	44	18	14	42	71	87	26	41	45	54
Cell 3	43	34	64	-	79	24	92	84	80	83	89	61	48	40	47
Cell 6	36	37	48	-	83	114	52	54	52	55	60	15	-	6	4
Cell 2	4	12	24	-	2	87	31	16	17	31	23	15	-	-	63
Cell 4	24	43	55	-	65	29	2	46	32	-	21	1	3	7	5
Cell Influent	89	103	101	-	106	101	97	110	99	91	112	35	67	78	77
Leachate Pool	423	342	-	-	369	317	275	252	288	378	375	460	405	406	436
Slough	0	-	0	0	3	3	-	2	0	2	4	5	5	5	7
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Butyric + iso-butyric) Acids ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	112	120	55	35	31	66	-	102	95	27	-	34	53
Cell 5	58	29	-	64	31	101	61	76	106	144	152	38	24	28	54
Cell 3	54	57	85	125	117	64	156	155	-	156	171	104	44	32	81
Cell 6	39	-	-	119	133	122	121	124	128	115	122	40	24	141	33
Cell 2	-	19	32	39	12	149	63	46	31	59	65	23	-	-	85
Cell 4	18	52	67	124	104	75	38	120	89	-	74	11	-	25	34
Cell Influent	105	106	-	166	110	107	105	124	122	-	146	40	-	-	109
Leachate Pool	511	395	478	496	394	345	280	254	292	421	451	588	455	554	594
Slough	0	-	4	4	4	4	-	2	0	0	3	4	18	6	6
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Valeric Acid ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	28	38	27	16	14	42	66	49	29	12	-	5	15
Cell 5	25	10	20	25	2	48	30	38	57	69	66	16	2	1	9
Cell 3	22	19	32	46	56	33	77	76	75	78	73	46	2	1	27
Cell 6	18	9	23	45	60	90	52	59	63	58	59	19	11	17	20
Cell 2	3	4	16	14	3	72	29	24	18	31	39	24	-	1	33
Cell 4	4	21	1	45	47	35	19	60	55	-	45	9	7	14	15
Cell Influent	71	31	30	61	74	81	74	86	79	69	80	20	15	31	50
Leachate Pool	280	154	177	191	300	294	302	270	273	292	320	324	307	315	324
Slough	0	-	0	0	6	19	-	23	0	0	22	15	0	19	20
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Hexanoic Acids ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	32	-	15	5	25	62	-	-	24	-	-	3	4
Cell 5	25	12	4	-	13	-	58	93	-	-	140	-	3	1	7
Cell 3	14	-	21	-	27	0	50	94	-	-	1	125	4	2	14
Cell 6	13	-	-	-	29	52	60	39	-	-	64	26	1	10	11
Cell 2	5	-	-	-	-	36	11	17	-	-	54	-	-	-	14
Cell 4	4	-	19	-	23	176	43	69	-	-	30	-	3	7	7
Cell Influent	1	42	49	64	60	46	91	40	-	-	83	15	5	45	24
Leachate Pool	-	127	148	124	123	157	92	92	-	-	223	277	166	359	382
Slough	0	-	4	0	0	0	-	0	0	-	0	0	1	0	2
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A5 Nutrients Raw Data in Constructed Wetland Cells in 2000

NH_3 ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	0.2	0.3	0.1	-	0.0	0.0	0.9	0.81	0.47	0.16	0.11	0.12	0.23
Cell 5	0.0	0.0	-	0.0	-	-	0.0	0.0	0.5	0.7	0.4	0.1	0.1	0.1	0.1
Cell 3	0.0	0.0	-	-	0.0	-	0.0	0.0	0.7	0.7	0.4	0.4	0.2	0.2	0.2
Cell 6	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.1	0.7	0.71	0.39	0.14	0.13	0.11	0.10
Cell 2	0.0	0.0	-	-	-	0.0	0.0	0.0	0.3	0.4	0.3	0.2	0.1	0.3	0.3
Cell 4	0.0	0.0	-	-	-	-	0.1	0.0	0.5	-	0.17	0.11	0.06	0.11	0.11
Cell Influent	0.1	0.1	0.5	0.7	0.2	-	0.0	0.2	0.7	0.7	0.4	0.0	0.1	0.1	0.1
Leachate Pool	2.3	1.7	2.0	1.9	1.6	2.7	2.2	2.8	5.1	5.6	3.2	3.2	3.7	2.7	3.3
Slough	0.1	0.6	0.2	0.0	0.4	0.2	0.2	0.1	0.2	0.1	0.5	0.1	0.3	0.3	0.2
Blank	-	-	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NO_X ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	0.11	0.14	0.14	0.20	0.12	0.20	0.41	0.38	0.24	0.16	0.32	0.32	0.39
Cell 5	0.30	0..084	0.08	0.20	0.19	0.19	0.16	0.20	0.32	0.39	0.24	0.15	0.35	0.35	0.39
Cell 3	0.20	0.12	0.11	0.14	0.18	0.19	0.22	0.25	0.34	0.35	0.18	0.13	0.38	0.33	0.34
Cell 6	0.25	0.11	0.13	0.19	0.17	0.14	0.19	0.22	0.35	0.37	0.21	0.17	0.37	0.39	0.40
Cell 2	0.14	0.10	0.12	0.17	0.14	0.18	0.15	0.15	0.28	0.31	0.15	0.15	0.31	0.43	0.45
Cell 4	0.15	0.12	0.12	0.14	0.18	0.23	0.13	0.18	0.34	-	0.16	0.18	0.30	0.32	0.39
Cell Influent	0.32	0.10	0.11	0.18	0.13	0.14	0.18	0.20	0.26	0.27	0.16	0.11	0.30	0.35	0.31
Leachate Pool	0.42	0.11	0.15	0.16	0.14	0.08	0.21	0.18	0.24	0.31	0.14	0.00	0.00	0.00	0.00
Slough	0.05	0.08	0.17	0.17	0.08	0.06	0.10	0.09	0.14	0.13	0.08	0.00	0.00	0.00	0.00
Blank	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PO_4 ($mg.L^{-1}$)

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	1.0	0.8	0.3	0.1	0.2	0.3	0.4	0.455	0.596	0.415	0.364	0.470	0.514
Cell 5	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.7	0.4	0.5	0.3	0.3	0.4	0.6
Cell 3	0.3	0.3	0.4	0.4	0.5	0.2	0.5	0.5	0.5	0.6	1.1	1.3	1.2	1.1	1.3
Cell 6	0.4	0.4	0.4	0.4	0.4	0.8	0.3	0.3	0.3	0.4	0.5	0.4	0.4	0.4	0.4
Cell 2	0.2	0.3	0.3	0.2	0.0	0.5	0.2	0.2	0.2	0.5	1.2	1.4	1.2	1.7	2.6
Cell 4	0.2	0.3	0.4	0.4	0.5	0.1	0.2	0.3	0.3	-	1.9	1.7	1.4	1.3	2.3
Cell Influent	0.9	1.0	0.9	1.2	0.8	0.8	0.6	0.7	0.6	0.7	0.9	0.4	0.5	0.7	0.7
Leachate Pool	3.6	3.2	3.7	3.4	2.9	3.9	3.1	3.7	3.9	4.2	4.5	5.2	4.9	5.6	6.1
Slough	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.0	0.0	0.0	0.0
Blank	-	-	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A6 Temperature, pH, DO, and Conductivity Raw Data in Constructed Wetlands in 2001

Temperature (°C):

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	0.0	0.0	15.5	15.0	15.0	16.0	16.0	15.5	16.5	15.0	17.0	15.0	9.0	7.5
Cell 5	-	8.0	17.0	15.0	15.5	16.5	16.0	16.0	16.0	17.0	16.5	16.0	15.0	7.5	7.0
Cell 3	-	11.0	16.0	14.5	15.2	16.0	16.0	16.0	15.0	17.0	14.5	17.0	15.0	9.5	7.0
Cell 6	-	7.5	16.5	15.0	15.0	14.5	16.2	16.2	15.5	17.0	13.5	15.5	14.3	8.5	7.0
Cell 2	-	9.0	18.0	15.0	15.6	16.0	16.5	16.5	15.5	16.5	15.0	16.5	14.5	9.0	8.5
Cell 4	-	9.0	16.0	15.0	15.5	15.5	16.0	16.0	16.0	17.0	14.5	15.5	15.0	9.0	8.0
Cell Influent	-	7.0	14.0	12.5	13.0	12.0	13.7	13.7	12.0	14.0	13.0	11.0	14.2	11.0	10.0
Leachate Pool	-	11.5	14.0	20.0	20.0	22.0	23.0	23.0	22.5	24.0	23.0	27.0	20.8	16.5	15.5

pH:

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	4.62	4.78	4.61	4.56	5.19	4.81	4.61	5.08	4.40	4.39	4.70	4.41
Cell 5	-	4.62	4.85	4.82	4.94	4.70	4.86	5.00	5.11	4.73	4.46	4.52	4.66	5.14	5.53
Cell 3	-	4.45	4.80	4.77	4.92	4.56	4.57	4.98	5.02	4.97	4.99	4.53	4.45	4.71	4.72
Cell 6	4.01	4.66	5.03	4.90	4.91	5.00	5.87	5.69	5.04	4.89	5.84	4.65	4.92	4.86	4.99
Cell 2	4.05	4.31	4.70	4.71	4.94	4.71	4.79	6.27	5.62	5.42	5.71	4.97	5.45	5.47	4.89
Cell 4	-	4.50	4.90	4.77	5.05	5.01	4.83	5.82	5.66	5.65	6.22	4.74	4.89	5.12	4.71
Cell Influent	-	4.16	4.20	4.15	4.64	4.44	4.38	4.65	4.61	4.41	4.44	4.09	4.01	4.01	4.02
Leachate Pool	-	3.35	3.58	3.43	3.73	3.51	3.36	3.78	3.45	3.89	3.65	3.68	3.64	3.98	3.67
Well	-	6.46	-	-	-	6.34	-	6.78	6.26	6.20	6.29	6.31	6.18	6.27	6.37

DO ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	0.0	0.0	0.4	0.3	0.6	0.6	0.3	0.6	0.2	0.2	0.3	0.3	0.4	0.3
Cell 5	-	0.1	0.2	0.2	0.2	2.3	0.3	0.3	0.4	0.3	0.3	0.5	0.3	0.4	0.5
Cell 3	-	0.0	0.2	0.3	0.3	0.5	0.3	0.3	0.7	0.2	0.2	0.3	0.3	0.4	0.3
Cell 6	-	0.2	0.1	0.3	0.3	0.4	0.4	0.3	0.7	0.3	0.3	0.4	0.3	0.5	0.4
Cell 2	-	1.1	0.1	0.4	0.3	1.8	0.4	0.3	0.5	0.3	0.3	0.2	0.3	0.4	0.2
Cell 4	-	0.6	0.2	0.3	0.3	0.2	0.3	0.3	0.5	0.4	0.4	0.4	0.4	0.5	0.4
Cell Influent	-	3.1	1.0	2.0	2.1	2.8	3.2	0.7	1.1	1.2	1.2	1.1	0.5	0.5	1.1
Leachate Pool	-	0.5	0.2	0.6	0.6	0.4	0.4	0.4	0.2	0.3	0.3	0.5	0.4	0.5	0.5

Conductivity ($\mu S.cm^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	435	590	537	490	497	420	464	493	834	797	622	657
Cell 5	-	687.0	644	561	591	553	462	530	205	561	552	927	756	444	378
Cell 3	-	600.0	632	572	610	553	563	489	441	433	482	711	686	651	623
Cell 6	1036.0	626.0	634	604	591	494	264	448	420	474	357	824	711	577	516
Cell 2	978.0	1087.0	783	748	788	732	76	639	530	527	522	906	778	707	666
Cell 4	-	671.0	657	588	588	537	504	464	352	380	391	927	755	602	600
Cell Influent	1390.0	581.0	582	549	669	551	508	449	410	540	594	1257	777	799	729
Leachate Pool	1345.0	1513.0	1380	1437	1473	1482	1632	1400	1397	1513	1489	1504	1553	1441	1433

Table A7 BOD, COD, and Tannin and Lignin Raw Data In Constructed Wetland Cells in 2000

BOD_5, ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	1433	974	1337	1109	869	490	1247	963	2549	1298	1598
Cell 5	-	1979	3153	1535	1043	1289	1007	608	446	1208	1134	2789	782	779
Cell 3	-	1883	3255	1541	1103	1361	1055	899	497	833	984	1979	1433	1304
Cell 6	1219	1625	2961	1541	896	863	593	608	425	860	747	2033	1355	1238
Cell 2	1099	3239	3459	1703	1382	1637	1241	1088	493	1028	1023	1817	1283	533
Cell 4	-	1961	3201	1523	782	1139	1115	751	428	644	756	2153	1100	1325
Cell influent	5959	3779	4747	3749	2909	2759	3269	1574	1029	1949	1980	6734	3629	4439
Leachate Pool	10139	8984	9597	10859	6989	6719	7949	6449	6644	5339	7050	7679	7409	7199
Well	-	3	0	0	0	2	0	3	3	2	3	3	8	2

COD, ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01
Cell 1	0	-	-	1825	2550	2200	2050
Cell 5	0	5100	3050	2350	2500	2125	1125
Cell 3	0	4600	3025	2425	2600	2200	2450
Cell 6	6395	4600	2975	2375	2475	1800	1825
Cell 2	5879	6850	3775	3325	3625	3325	3075
Cell 4	0	5250	3050	2450	2600	2150	2025
Cell Influent	10788	5375	3225	2725	4150	3100	2475
Leachate Pool	10659	18063	12000	11813	12438	12813	13563
Well	-	25	-	-	-	-	-

Sample ID	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	2100	1525	2100	2150	4850	4475	3050	3200
Cell 5	1875	1450	2375	2550	5925	3825	2800	1875
Cell 3	1800	1725	1650	1875	3950	4425	3025	2875
Cell 6	1575	1450	1800	1625	4325	4250	2700	1300
Cell 2	2925	1925	1850	1975	3550	3675	2975	2975
Cell 4	1925	1475	1238	1675	4325	3825	2700	2725
Cell Influent	2600	2725	2525	3350	6563	6563	4725	5625
Leachate Pool	12563	11125	10125	13125	14125	14438	12750	12500
Well	3	3	-	28	28	80	10	18

Tannin and Lignin ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01
Cell 1	-	-	-	614	913	702	496
Cell 5	-	1322.65	856	776	934	690	453
Cell 3	-	1050.10	876	863	964	644	853
Cell 6	1380.31	1042.08	909	819	792	545	368
Cell 2	731.66	1935.87	1026	1056	1255	719	1056
Cell 4	-	1216.43	878	859	827	621	485
Cell Influent	2316.60	1138.28	927	776	1259	687	658
Leachate Pool	4305	4228	3117	3691	3515	3289	4135
Well	0.00	-	0	0	0	1	0

Sample ID	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	452	415	669	542	1261	1036	1116	967
Cell 5	411	216	734	671	1665	559	486	450
Cell 3	504	427	575	528	1180	651	905	899
Cell 6	406	367	546	392	1137	816	632	620
Cell 2	724	321	573	488	1083	727	882	881
Cell 4	470	352	481	397	1117	702	706	620
Cell Influent	555	489	728	791	2511	1983	1320	1258
Leachate Pool	2912	2842	2897	3131	3167	3578	3151	3744
Well	2	3	2	1	3	3	3	2

Table A8 Total Volatile Fatty Acids Raw Data in Constructed wetland Cells in 2001

Total Volatile Fatty Acids ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	0	0	203	364	605	531	282	248	399	308	784	865	375	752
Cell 5	-	458	539	510	436	433	298	104	106	427	394	702	719	223	103
Cell 3	-	561	493	466	450	637	465	337	269	263	334	683	666	458	437
Cell 6	866	495	448	430	473	345	49	218	272	328	79	650	738	398	323
Cell 2	920	1195	432	583	585	704	557	497	197	225	172	395	430	294	450
Cell 4	-	573	325	295	556	361	363	260	157	132	97	702	544	292	446
Cell Influent	2039	517	744	449	361	473	564	295	109	476	577	1616	1106	716	558
Leachate Pool	1978	1963	2078	2194	2322	2224	2408	2017	1827	1987	2312	2111	1763	1942	2153
Well	0	3	71	23	0	56	0	23	32	51	42	13	19	24	6

Acetic Acid ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	4	15	32	29	20	19	29	18	57	48	35	47
Cell 5	0	35	19	20	36	31	18	5	8	26	22	53	34	17	-
Cell 3	0	36	5	2	30	38	33	23	18	17	21	47	42	35	26
Cell 6	38	33	4	31	34	22	2	14	22	25	3	47	34	24	22
Cell 2	53	76	6	10	40	53	41	36	14	12	6	35	12	9	27
Cell 4	0	35	5	10	28	21	21	13	7	9	5	45	28	14	28
Cell Influent	153	36	44	24	10	20	28	16	4	34	40	125	102	55	7
Leachate Pool	145	909	173	195	193	190	222	157	161	141	203	193	140	139	168
Well	0	3	5	2	0	4	0	2	3	5	3	2	2	2	-
Blank	0	0	0	2	1	2	1	0	0	0	0	1	0	1	0

Propionic Acid ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	9	16	13	10	8	7	11	6	21	18	12	45
Cell 5	0	22	19	13	15	12	6	1	3	11	8	24	16	6	4
Cell 3	0	20	16	12	13	13	11	7	5	4	5	15	17	12	10
Cell 6	41	20	6	13	14	8	1	5	7	9	-	19	14	10	8
Cell 2	38	42	22	17	20	23	16	15	4	7	7	14	13	8	10
Cell 4	0	26	15	10	11	7	6	4	2	3	1	17	12	5	9
Cell Influent	72	19	19	18	15	16	11	8	4	12	15	47	13	18	19
Leachate Pool	72	7	66	67	71	65	75	57	53	54	67	57	40	47	55
Slough	0	0	0	0	0	0	0	-	-	1	-	-	-	5	-
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Butyric + iso-butyric) Acids ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	17	26	27	24	18	16	28	22	47	34	-	-
Cell 2	52	68	32	30	31	35	30	26	10	13	10	29	30	22	30
Cell 3	0	32	-	25	25	-	30	22	18	-	24	43	43	29	29
Cell 4	0	30	23	19	23	25	27	20	11	-	7	40	34	23	31
Cell 5	0	23	24	-	22	26	21	8	-	28	28	44	23	-	-
Cell 6	53	27	22	22	26	22	-	13	-	21	7	44	33	28	24
Cell Influent	108	28	-	27	29	35	27	-	-	-	36	95	34	-	51
Leachate Pool	96	132	101	102	116	110	109	114	92	121	118	103	98	126	131
Slough	0	0	9	2	0	8	0	-	-	4	5	-	-	-	-
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Valeric Acid ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	8	10	12	9	7	8	12	10	22	74	6	15
Cell 5	0	7	11	11	9	11	9	5	4	13	14	12	70	4	4
Cell 3	0	15	15	14	13	13	13	10	9	9	11	22	22	11	16
Cell 6	23	12	11	12	12	11	4	7	8	10	6	9	68	13	11
Cell 2	22	33	17	17	16	19	16	15	7	8	7	1	21	14	16
Cell 4	0	15	14	12	12	12	12	10	7	6	6	38	35	12	15
Cell Influent	41	12	13	12	12	15	12	8	5	13	15	36	72	18	24
Leachate Pool	45	40	44	42	50	46	40	47	33	53	42	40	45	52	48
Slough	0	0	-	0	0	0	0	-	-	1	-	-	-	5	-
Blank	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0

Hexanoic Acids ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	3	5	37	34	3	-	-	5	10	-	3	7
Cell 5	0	4	34	40	5	6	5	2	-	7	7	7	-	2	2
Cell 3	0	8	36	39	8	36	7	5	5	5	6	10	10	5	6
Cell 6	19	7	46	8	7	6	3	4	4	-	-	11	-	5	-
Cell 2	19	20	10	42	10	11	10	8	4	5	4	-	9	6	7
Cell 4	0	9	9	8	37	7	6	5	4	-	-	-	-	5	6
Cell Influent	34	9	47	8	7	9	35	9	-	7	9	20	-	8	11
Leachate Pool	37	32	31	32	35	34	36	29	26	29	33	30	29	26	29
Slough	0	0	-	0	0	0	0	-	-	-	-	-	-	-	-
Blank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A9 Nutrients in Constructed wetland Cells in 2001

NH_3 ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.0	0.3	0.7	0.3	0.4
Cell 5	0.0	0.5	0.4	0.3	0.2	0.2	0.2	0.2	0.0	0.0	0.1	0.6	0.6	0.1	0.1
Cell 3	0.0	0.4	0.5	0.3	0.5	0.3	0.3	0.2	0.1	0.1	0.0	0.2	6.8	0.5	0.4
Cell 6	0.0	0.4	0.5	0.3	0.3	0.1	0.0	0.1	0.0	0.1	0.0	0.3	0.5	0.3	0.1
Cell 2	0.0	1.0	0.7	0.5	0.9	0.6	0.8	0.6	0.1	0.1	0.0	5.8	4.2	1.6	0.7
Cell 4	0.0	0.4	0.9	0.6	0.3	0.2	0.2	0.1	0.0	0.0	0.0	12.8	4.7	0.5	0.3
Cell Influent	0.0	0.3	0.3	0.2	0.1	0.1	0.2	0.1	0.0	0.0	0.2	1.1	0.4	0.1	0.7
Leachate Pool	0.0	2.9	2.5	2.2	2.3	2.5	3.4	2.3	2.3	1.1	2.0	2.1	2.2	2.0	2.4
Well	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2
Blank	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NO_X ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	0.00	-	0.02	0.00	0.00	0.07	0.05	0.08	0.07	0.05	0.08	0.05	0.12	0.08
Cell 5	-	0.14	0.12	0.03	0.00	0.00	0.09	0.07	0.03	0.10	0.06	0.12	0.06	0.06	0.06
Cell 3	-	0.12	0.13	0.03	0.00	0.00	0.05	0.03	0.06	0.06	0.05	0.06	0.04	0.16	0.80
Cell 6	0.15	0.12	0.11	0.02	0.00	0.00	0.06	0.03	0.05	0.06	0.05	0.10	0.00	0.11	0.06
Cell 2	0.26	0.09	0.13	0.03	0.00	0.00	0.06	0.03	0.09	0.06	0.05	0.05	0.00	0.07	0.05
Cell 4	-	0.13	0.13	0.02	0.00	0.00	0.06	0.03	0.04	0.05	0.05	0.10	0.00	0.06	0.06
Cell Influent	0.22	0.12	0.09	0.02	0.00	0.00	0.03	0.03	0.03	0.10	0.08	0.07	0.00	0.19	0.09
Leachate Pool	0.32	0.09	0.08	0.00	0.00	0.00	0.00	0.11	0.22	0.22	0.09	0.00	0.00	0.28	0.08
Well	0.00	0.18	0.21	0.03	0.00	0.00	0.00	0.28	0.03	0.02	0.04	0.03	0.23	0.03	0.07
Blank	0.00	0.00	0.00	0.07	0.00	-0.03	-0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PO_4 ($mg.L^{-1}$)

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	0.0	-	0.6	0.6	0.6	0.0	0.3	0.4	0.5	0.4	1.4	1.2	0.8	0.9
Cell 5	-	0.7	0.6	0.6	0.6	0.6	0.5	0.6	0.1	0.6	0.5	1.6	1.2	0.5	0.5
Cell 3	-	0.6	0.6	0.6	0.6	0.6	0.9	0.5	0.4	0.4	0.5	1.1	1.2	1.0	0.9
Cell 6	1.1	0.6	0.6	0.6	0.6	0.5	0.6	0.4	0.3	0.4	0.3	1.4	1.0	0.7	0.6
Cell 2	2.7	1.1	1.1	1.2	1.2	0.9	0.9	0.9	1.0	1.2	1.0	1.9	1.7	1.0	0.7
Cell 4	-	0.7	0.8	0.8	0.7	1.0	0.9	0.8	0.6	0.7	0.6	3.7	2.3	1.1	1.0
Cell Influent	3.2	0.6	0.8	0.8	0.6	0.9	0.5	0.4	0.2	0.7	1.0	3.2	1.0	2.4	1.5
Leachate Pool	3.0	2.9	3.1	3.3	3.3	3.7	3.7	3.2	3.2	2.9	3.4	3.5	3.5	3.5	3.5
Well	0.0	0.2	0.1	1.4	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Blank	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX B Theoretical Oxygen Demand Calculations

APPENDIX B.1
Theoretical Oxygen Demand Calculations

Fatty Acids (general form): $C_nH_{2n+1}COOH$

Acetic Acid: $CH_3COOH + 2O_2 \rightarrow 2\ CO_2 + 2\ H_2O$
MW = 60.06 g/mol and MW of O_2 = 32.0 g/mol
Therefore ThOD = 1.07 mg O_2 per 1 mg of acetic acid

Propionic Acid: $C_2H_5COOH + 3.5O_2 \rightarrow 3\ CO_2 + 3\ H_2O$
MW = 74.09 g/mol and MW of O_2 = 32.0 g/mol
Therefore ThOD = 1.51 mg O_2 per 1 mg of acetic acid

Butyric Acid: $C_3H_7COOH + 5O_2 \rightarrow 4\ CO_2 + 4\ H_2O$
MW = 88.12 g/mol and MW of O_2 = 32.0 g/mol
Therefore ThOD = 1.82 mg O_2 per 1 mg of acetic acid

Valeric Acid: $C_4H_9COOH + 6.5O_2 \rightarrow 5\ CO_2 + 5\ H_2O$
MW = 102.15 g/mol and MW of O_2 = 32.0 g/mol
Therefore ThOD = 2.04 mg O_2 per 1 mg of acetic acid

Hexanoic Acid: $C_5H_{11}COOH + 8O_2 \rightarrow 6\ CO_2 + 6\ H_2O$
MW = 116.18 g/mol and MW of O_2 = 32.0 g/mol
Therefore ThOD = 2.20 mg O_2 per 1 mg of acetic acid

Tannin and Lignin (uses tannic acid as surrogate)

Tannic Acid: $C_{76}H_{52}O_{46} + 66\ O_2 \rightarrow 76\ CO_2 + 26\ H_2O$
MW = 1701.28 g/mol and MW of O_2 = 32.0 g/mol
Therefore ThOD = 1.24 mg O_2 per 1 mg of acetic acid

Table B1 Total ThOD for VFAs, 2000

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00
Cell 1	0.00	0.00	664.13	0.00	360.99	168.21	200.80
Cell 5	134.91	121.50	279.08	225.98	238.69	443.80	372.68
Cell 3	48.30	226.86	467.44	322.16	654.35	273.33	894.60
Cell 6	400.46	183.92	240.35	401.54	717.74	995.10	670.03
Cell 2	0.00	60.47	176.63	100.54	42.64	816.64	329.41
Cell 4	331.08	240.52	328.30	452.89	563.11	708.94	211.29
Cell Influent	257.06	637.88	708.93	869.68	899.54	884.88	929.71
Leachate Pool	749.39	2740.91	2640.30	2687.57	3166.57	3182.58	2748.75

Sample ID	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	440.50	534.67	579.89	591.67	188.05	0.00	223.17	308.43
Cell 5	490.57	460.49	710.73	1050.38	195.21	213.87	239.54	351.43
Cell 3	967.82	738.28	802.52	834.92	794.52	317.96	270.00	448.14
Cell 6	643.63	555.66	551.04	716.72	240.25	76.55	337.94	146.90
Cell 2	247.24	170.72	303.92	410.59	132.74	0.00	18.26	477.28
Cell 4	686.03	397.40	0.00	383.58	45.52	51.28	134.55	125.03
Cell Influent	930.53	839.57	775.79	1105.37	291.16	397.54	546.43	617.74
Leachate Pool	2671.96	2739.61	3339.04	3755.99	4286.78	3672.39	3051.86	3236.27

Table B2 Total ThOD for Tannin and Lignin, 2000

Sample ID	May 04/00	May 11/00	May 16/00	May 23/00	May 31/00	Jun 09/00	Jun 15/00	Jun 22/00	Jun 29/00	Jul 06/00	Jul 13/00	Jul 27/00	Aug 03/00	Aug 10/00	Aug 17/00
Cell 1	-	-	829	967	677	770	419	528	1097	1261	150	592	911	1072	522
Cell 5	393	313	269	430	614	1461	535	341	1003	910	451	453	794	922	495
Cell 3	363	311	433	394	866	866	878	621	1181	1270	460	1164	1173	1137	882
Cell 6	280	434	126	558	803	1273	567	453	1052	1219	1013	766	830	1209	761
Cell 2	220	95	404	524	354	1265	595	271	817	910	875	666	130	876	1000
Cell 4	219	266	362	524	808	874	315	401	422	-	757	702	849	971	814
Cell Influent	861	506	808	708	1144	1461	1046	664	1214	1450	739	915	1251	1802	1123
Leachate Pool	3280	4128	5302	4617	4081	6806	3553	4533	6810	7208	6763	6611	8103	7771	6443

Table B3 Total ThOD for VFAs, 2001

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	-	599	1041	917	441	377	612	504	1220	1446	542	1150
Cell 2	1474	1895	767	1094	919	1089	871	779	313	371	296	565	756	514	730
Cell 3	-	885	937	910	713	1076	731	537	433	426	544	1083	1067	705	710
Cell 4	-	900	582	510	976	592	595	441	269	208	163	1123	902	492	719
Cell 5	-	683	956	922	657	679	482	178	163	688	648	1065	1230	338	188
Cell 6	1430	768	890	674	735	554	89	351	415	500	140	1006	1268	643	505
Cell Influent	3131	805	1260	727	621	791	985	489	183	747	906	2472	1684	1100	1004
Leachate Pool	3057	2980	3129	3259	3507	3340	3539	3095	2720	3112	3444	3125	2719	3042	3304

Table B4 Total ThOD for Tannin and Lignin, 2001

Sample ID	Jun 20/01	Jul 04/01	Jul 11/01	Jul 18/01	Jul 25/01	Aug 01/01	Aug 09/01	Aug 16/01	Aug 23/01	Aug 30/01	Sep 07/01	Sep 14/01	Sep 25/01	Oct 05/01	Oct 12/01
Cell 1	-	-	-	762	1133	871	616	561	516	831	672	1566	1286	1386	1200
Cell 5	-	1642	1062	963	1160	856	562	510	269	912	833	2067	694	603	558
Cell 3	-	1304	1087	1071	1196	800	1059	626	530	714	656	1464	808	1123	1116
Cell 6	1714	1294	1128	1017	984	677	457	504	455	678	487	1412	1013	785	769
Cell 2	908	2403	1273	1312	1558	893	1311	899	399	712	606	1345	903	1095	1094
Cell 4	-	1510	1089	1066	1027	772	602	583	437	597	493	1386	871	876	769
Cell Influent	2317	1413	1151	963	1563	853	817	689	607	904	982	3117	2462	1639	1562
Leachate Pool	4305	5249	3870	4582	4364	4083	5134	3615	3529	3597	3887	3931	4441	3912	4648

APPENDIX C Climatic Data

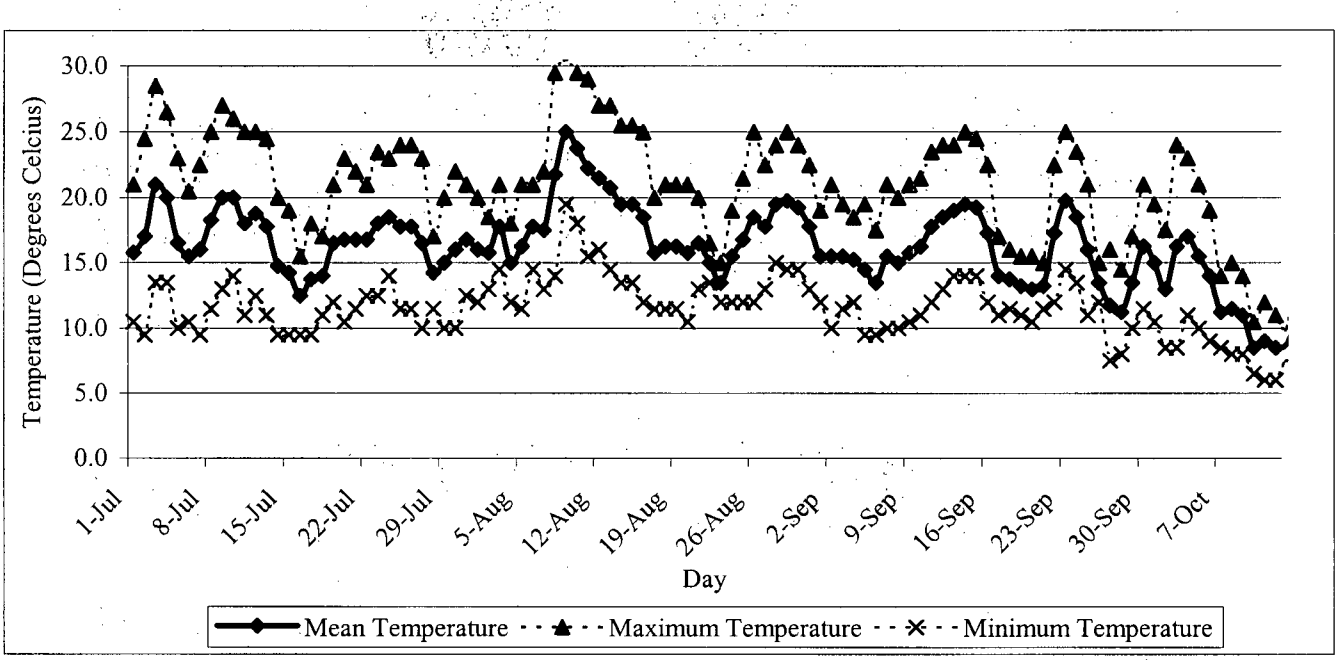


Figure C1 Temperature Data of Abbotsford, B.C. for 2001 (Source: Environment Canada, 2001)

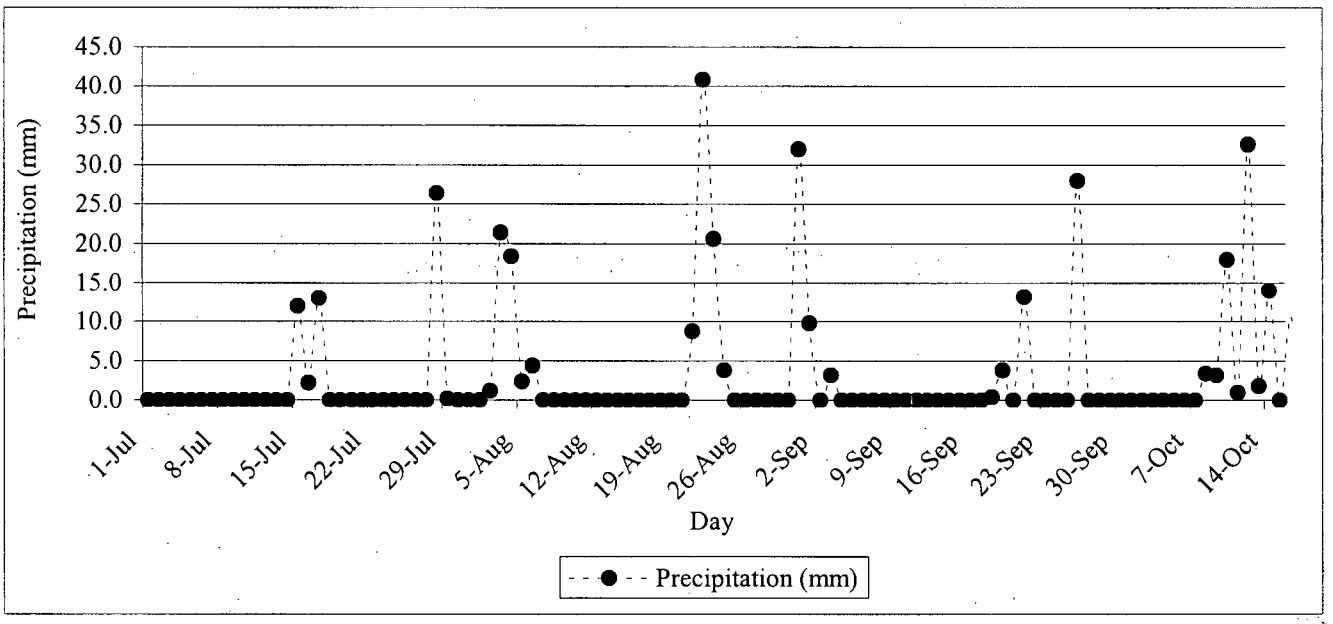


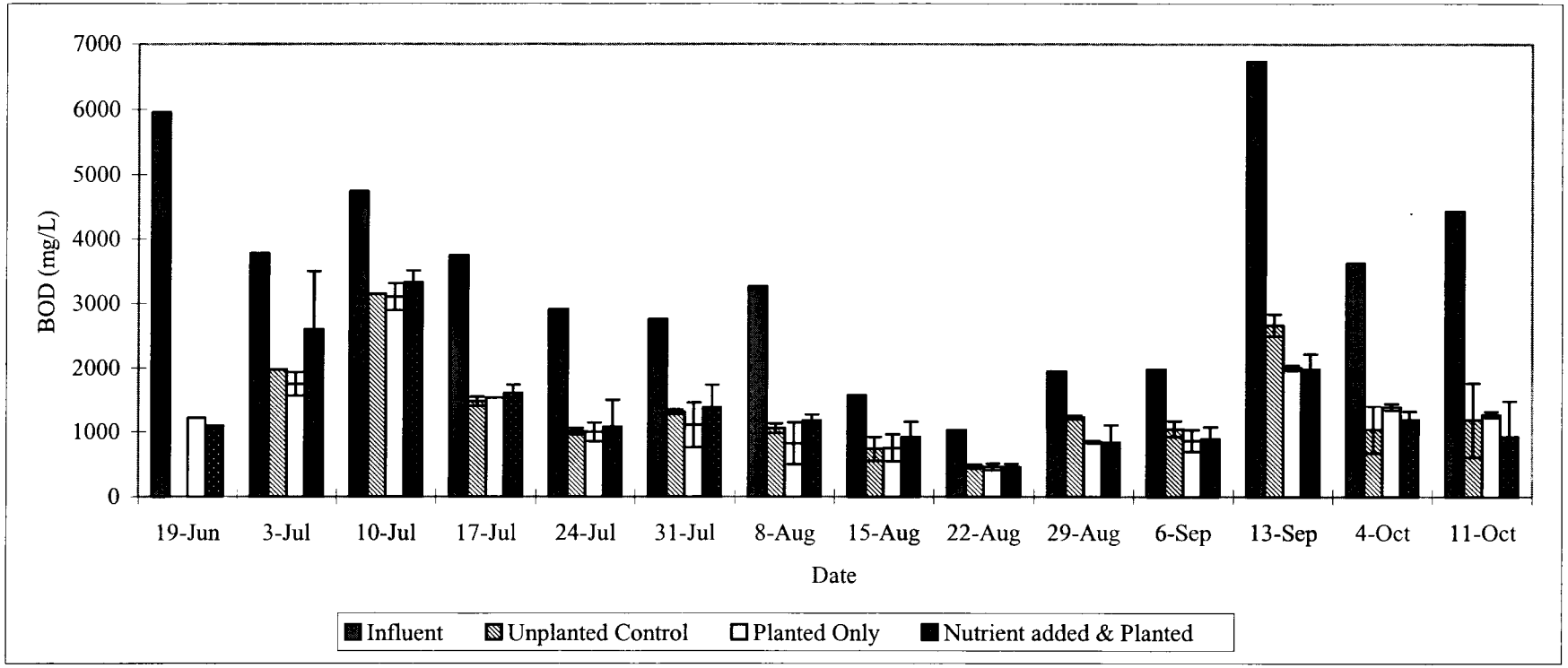
Figure C2 Precipitation Data of Abbotsford, B.C. for 2001 (Source: Environment Canada, 2001)

Table C1 Climate Normals, Abbotsford, BC, 1944-1990 (Environment Canada 1999)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature													
Daily Maximum (°C)	5.4	8.4	10.9	13.9	17.4	20.4	23.2	23.6	20.5	14.9	9	5.7	14.4
Daily Minimum (°C)	-1	0.7	1.7	3.8	6.5	9.4	10.9	10.9	8.5	5.1	2.2	-0.5	4.9
Daily Mean (°C)	2.2	4.6	6.3	8.8	12	14.9	17.1	17.3	14.5	10	5.6	2.6	9.7
Extreme Maximum (°C)	17.7	20.6	22.8	29.7	36	34.7	37.8	36.3	37.5	29.3	20.6	18.2	
Extreme Minimum (°C)	-21.1	-18.9	-12.8	-4.4	-2.2	1.1	2.2	3.3	-1.7	-7.5	-16.7	-20	
Degree-Days													
Above 18 °C	0	0	0	0.1	2.1	6.6	20.2	21.5	5	0.1	0	0	56
Below 18 °C	489.6	378.9	361.7	274.7	189.1	98.1	48.9	43.8	109.3	247.9	371.2	480	3093
Above 5 °C	16.8	30.6	57.2	116.4	215.9	298.5	374.3	380.7	285.7	156.7	51.1	20	2004
Below 0 °C	29.7	7.1	1.5	0	0	0	0	0	0	0.2	5.3	26.2	70
Precipitation													
Rainfall (mm)	174.2	151.1	139.1	113.3	89.2	66.7	50.7	53.1	85.4	156.2	215.7	191.5	1486.2
Snowfall (cm)	26.3	12.8	5.5	0.3	0	0	0	0	0	0	5.8	23.9	74.6
Precipitation (mm)	201.4	163.5	144.6	113.8	89.2	66.7	50.7	53.1	85.4	156.2	221.8	216.6	1562.9
Extreme Daily Rainfall (mm)	78.2	83.1	76.2	59.9	53.8	49.5	70.1	44.2	53.7	83.3	95	89.6	
Extreme Daily Snowfall (cm)	49.8	26.4	33	3.8	0	0	0	0	0	1	31.8	43.8	
Extreme Daily Precipitation (mm)	89.7	83.1	76.2	59.9	53.8	49.5	70.1	44.2	53.7	83.3	95	89.6	
Month-end Snow Cover (cm)	2	1	0	0	0	0	0	0	0	0	1	5	
Days With													
Maximum Temperature >0°C	28	28	31	30	31	30	31	31	30	31	29	28	357
Measurable Rainfall	16	16	16	15	14	11	7	7	10	15	19	18	166
Measurable Snowfall	5	3	2	*	0	0	0	0	0	*	1	5	16
Measurable Precipitation	19	17	17	16	14	11	7	7	10	15	20	21	174
Freezing Precipitation	1	*	*	0	0	0	0	0	0	0	*	*	3
Fog	4	3	1	*	*	*	1	3	5	7	3	5	34
Sunshine (Hrs)	N	N	N	166.4	203.9	216.9	287.6	254.5	182.3	N	67.9	N	N
Station Pressure (kPa)	101.02	100.96	100.84	100.96	100.99	100.95	101.01	100.91	100.94	101.04	100.85	100.97	100.95
Moisture													
Vapour Pressure (kPa)	0.6	0.67	0.71	0.82	1.02	1.24	1.4	1.43	1.26	1	0.77	0.65	0.96
Rel. Humidity - 0600L (%)	83	84	85	86	86	86	87	90	91	90	86	85	
Rel. Humidity - 1500L (%)	74	67	61	58	58	58	56	56	59	67	73	76	
Wind													
Speed (km/h)	12	12	11	11	10	9	8	8	8	9	11	12	10
Extreme Hourly Speed (km/h)	72	80	71	80	56	45	48	53	56	89	76	80	
Direction	S	S	SW	S	S	S	S	E	S	S	S	SE	
Extreme Gust Speed (km/h)	121	137	103	121	84	68	64	63	80	145	113	121	

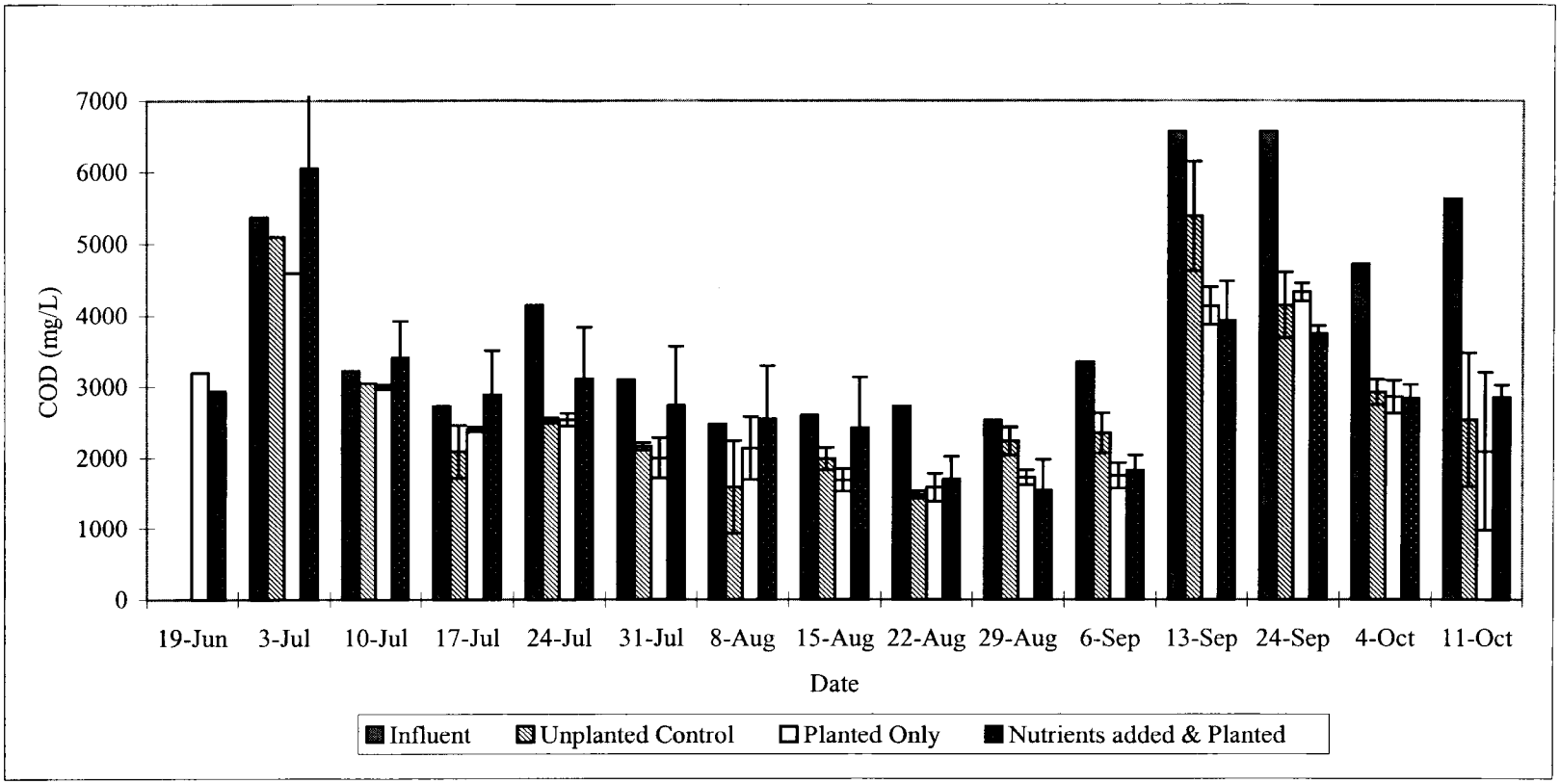
APPENDIX D Seasonal Changes in Wetlands Performance

Figure D1 Seasonal Variability in BOD_5 in Constructed Wetlands Cells in 2001*



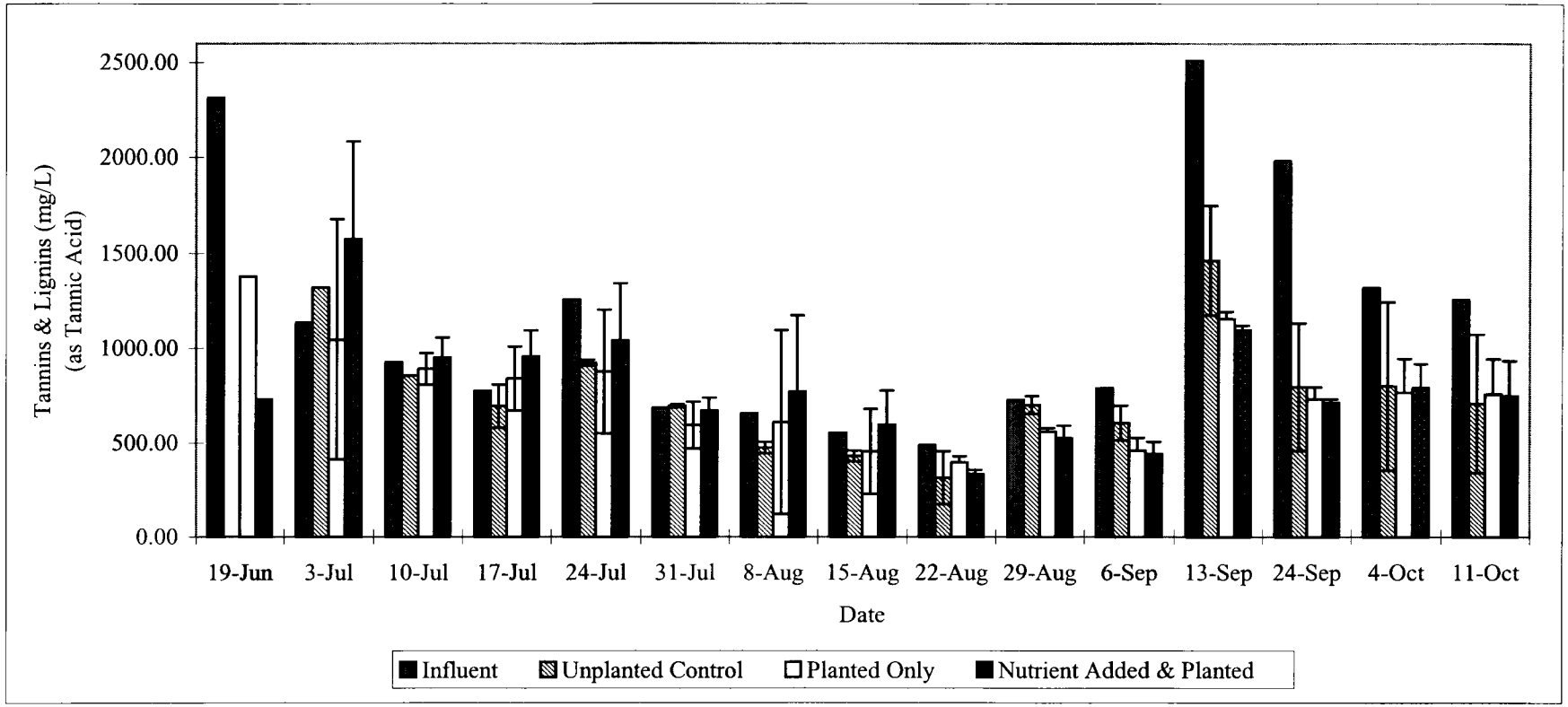
* Error bars show standard deviations for replicate cells

Figure D2 Seasonal Variability in COD in Constructed Wetlands Cells in 2001



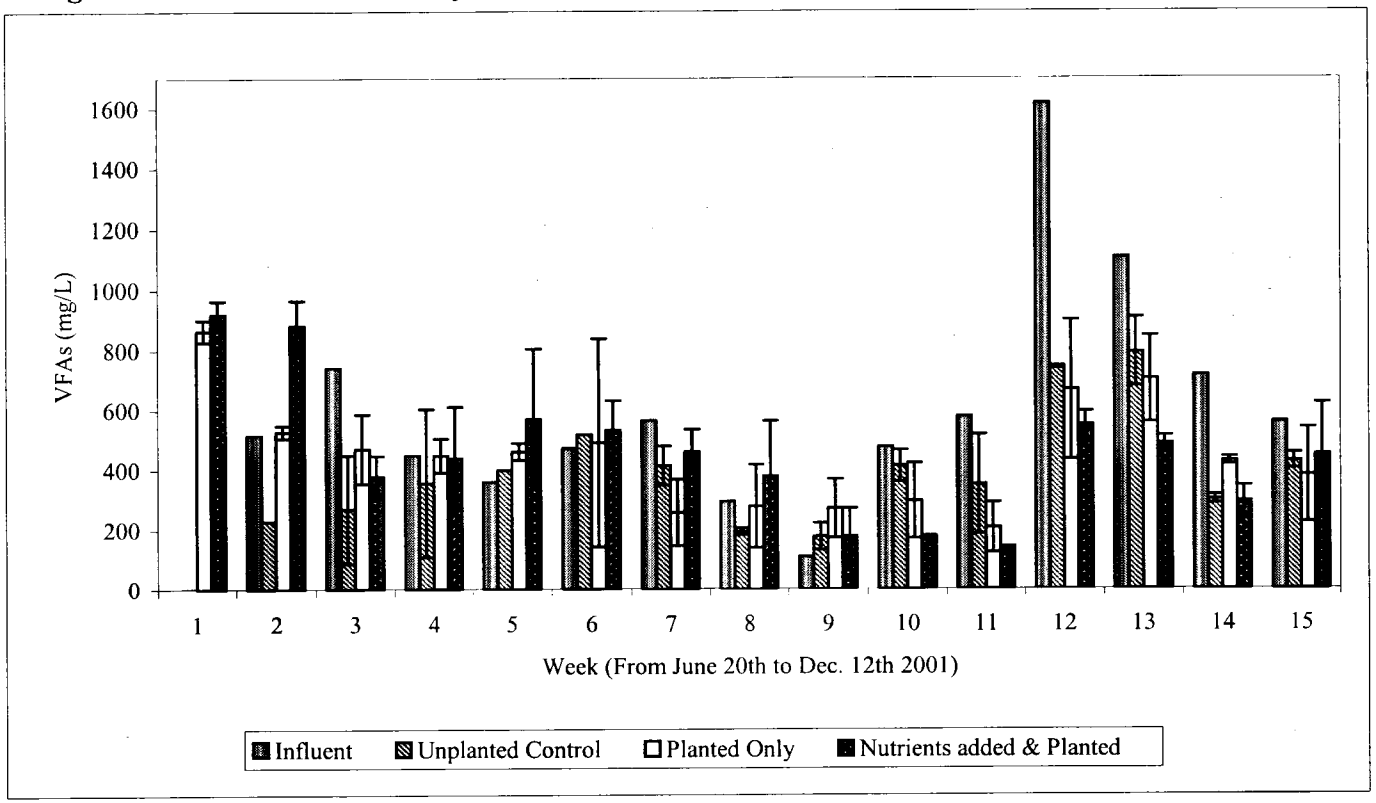
* Error bars show standard deviations for replicate cells

Figure D3 Seasonal Variability in Tannin and Lignin in Constructed Wetlands Cells in 2001*



* Error bars show standard deviations for replicate cells

Figure D4 Seasonal Variability in Volatile fatty Acids in Constructed Wetlands Cells in 2001*



* Error bars show standard deviations for replicate cells

Figure D5 Seasonal variability in Ammonia in Constructed Wetland Cells in 2000

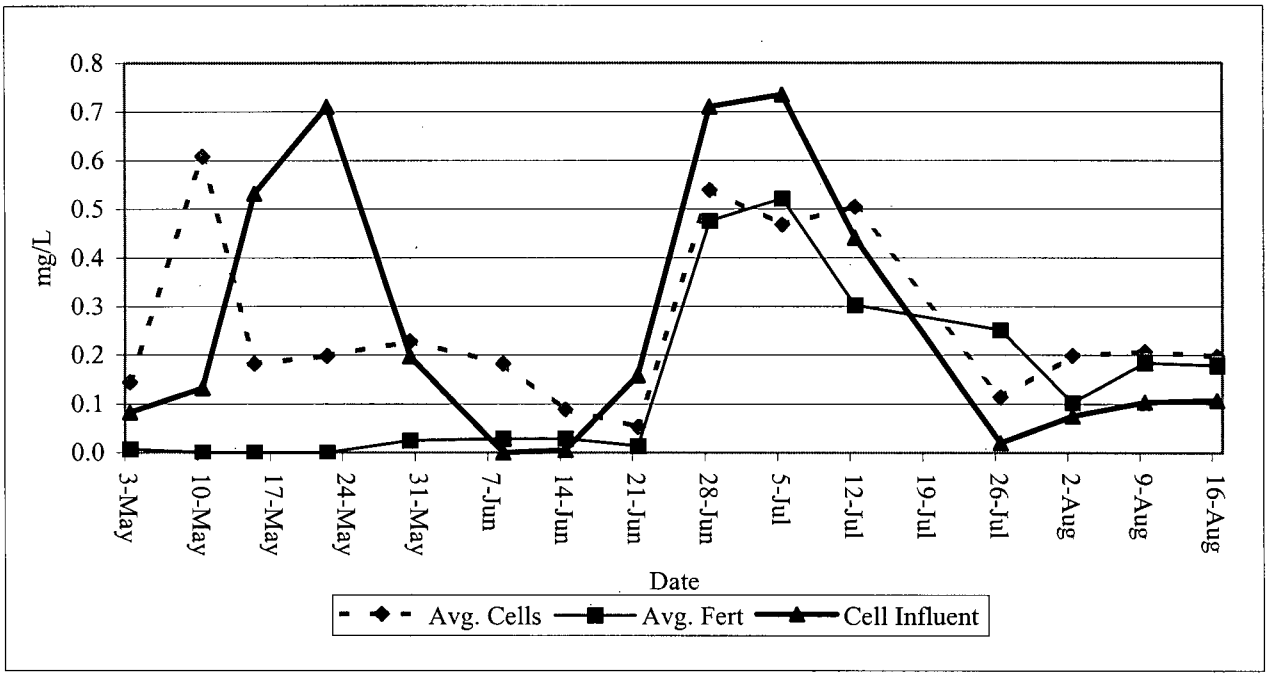


Figure D6 Seasonal variability in Ammonia in Constructed Wetland Cells in 2001

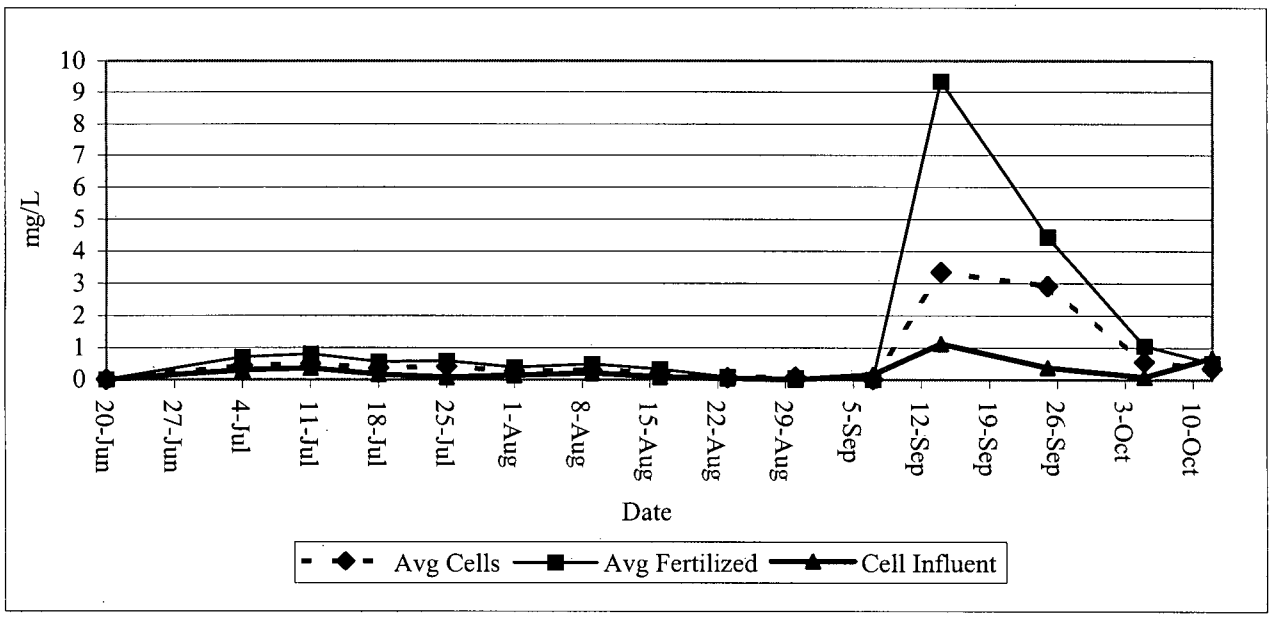


Figure D7 Seasonal variability in Nitrate+Nitrite in Constructed Wetland Cells in 2000

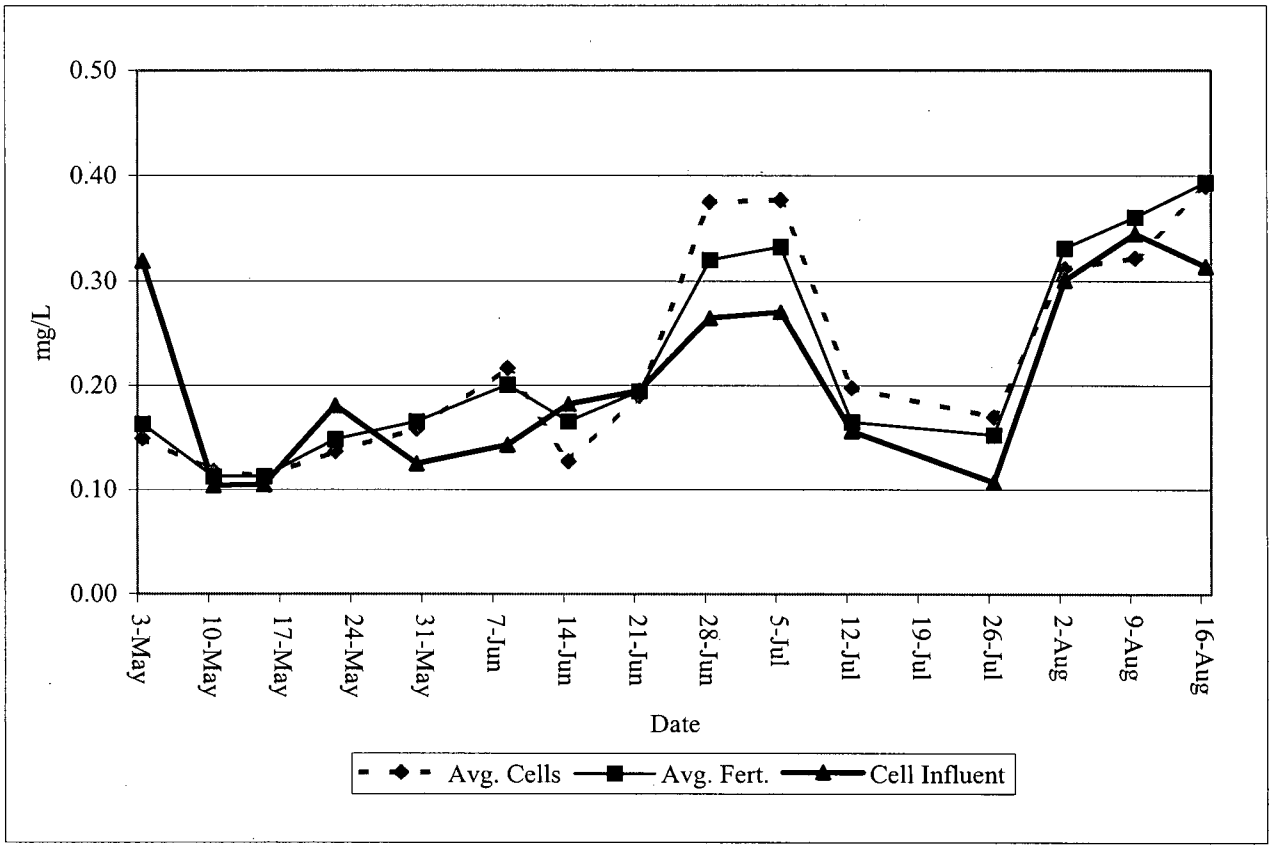


Figure D8 Seasonal variability in Nitrate+Nitrite in Constructed Wetland Cells in 2001

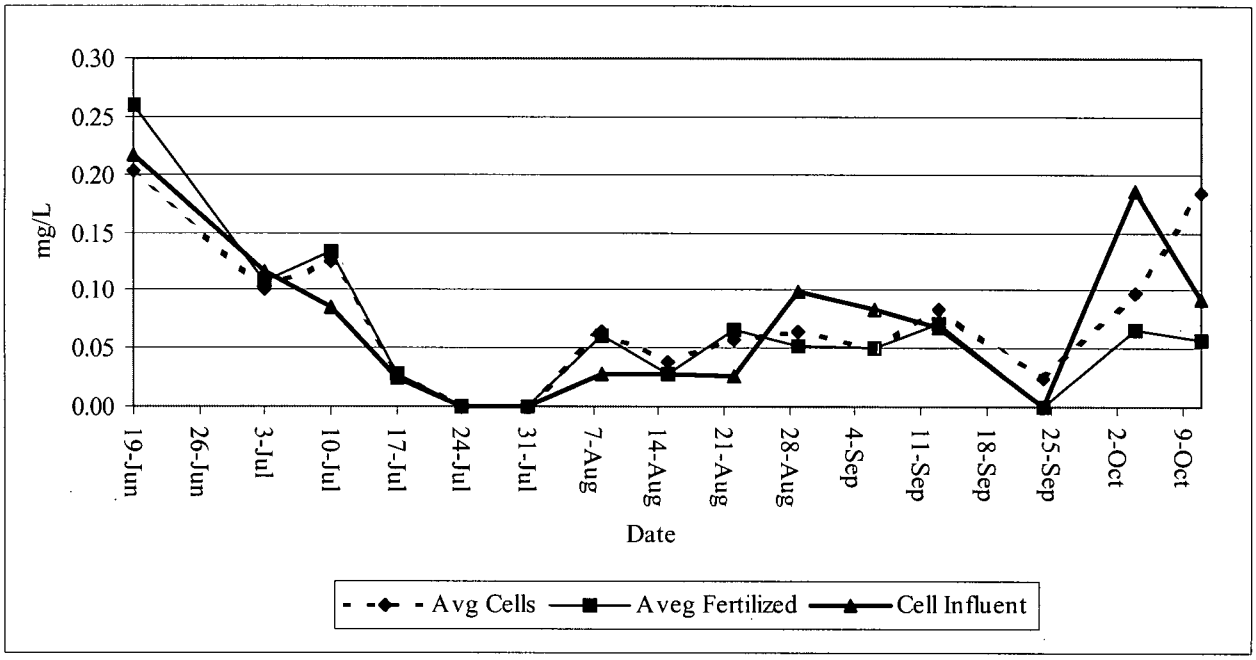


Figure D9 Seasonal Variability in ortho-Phosphate in Constructed Wetland Cells in 2000

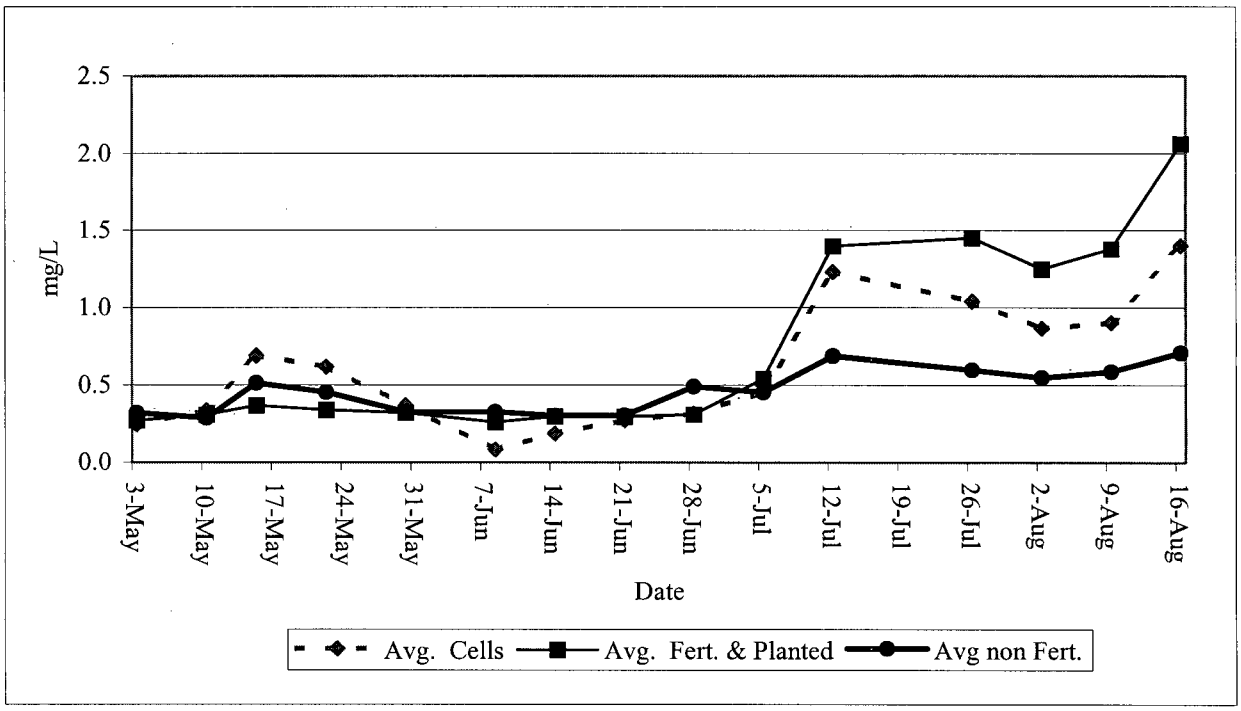


Figure D10 Seasonal Variability in ortho-Phosphate in Constructed Wetland Cells in 2001