THE TREATMENT OF WOOD LEACHATE USING CONSTRUCTED WETLANDS

by

KEVIN ANTHONY FRANKOWSKI
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We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

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KEVIN FRANKOWSKI

DEPARTMENT OF CIVIL ENGINEERING
THE UNIVERSITY OF BRITISH COLUMBIA
ABSTRACT

Rainfall percolating through wood chip piles, hog fuel, and log storage areas will leach naturally-occurring chemicals from the wood. This leachate is often characterised by high carbon content, strong colour, and high concentrations of tannin and lignin, resin acids and phenolics. This can be very toxic to aquatic life, and has serious implications from an environmental discharge viewpoint. It can lead to regulatory problems for facilities operators.

Research was conducted in a series of phases at a cedar processing site near Mission, British Columbia. It was determined that cedar leachate was amenable to biological treatment. Chemical and ecotoxicological characterization was performed, and combined with the data obtained from treatment screening trials, laboratory-scale constructed wetlands were designed and tested. These constructed wetlands were able to achieve a 90% reduction in toxicity and removal rates of >90% for biochemical oxygen demand (BOD) and 80% for chemical oxygen demand (COD).

A pilot-scale program demonstrated that constructed wetlands were able to treat the cedar leachate under field conditions. Initial data obtained during winter operations produced removal rates for toxicity on the order of 50%. BOD and COD removal was slightly less. The system still needs to undergo optimization, but preliminary results indicate several factors which may yield significant improvements in system performance.

Thus, it has been demonstrated that a wetland-based biological treatment process is potentially a practical and cost-effective treatment technique for wood leachate. Unit treatment costs are much lower than other technologies; effective physio-chemical treatment techniques are 10 - 30 times more expensive, conventional biological treatments at least 6 times. Also, many of the conventional biological systems have failed to demonstrate effective treatment performance for this type of wastewater.
ABSTRACT

In addition to its cost-effective performance, this constructed wetlands system operates in a passive manner. It requires minimal operational attention and infrastructure. No chemical addition or by-products handling is needed. Possible applications include the collection and treatment of wood leachate from chip piles, wood waste landfills, and hog fuel piles, and the treatment of wood extractives in stormwater runoff from log yards, dryland sorts and staging areas. This system is ideally suited for those applications which require effective, economic treatment of fluctuating runoff loads containing a broad, and often changing, spectrum of contaminants.
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**LIST OF ABBREVIATIONS / ACRONYMS**

The following abbreviations and acronyms have been used throughout this document:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APHA</td>
<td>American Public Health Association</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>CER</td>
<td>Controlled Environment Room</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>DOC</td>
<td>Dissolved Organic Carbon</td>
</tr>
<tr>
<td>DIC</td>
<td>Dissolved Inorganic Carbon</td>
</tr>
<tr>
<td>FSF</td>
<td>Free-Surface Flow wetland (see Surface-Flow wetland)</td>
</tr>
<tr>
<td>GCL</td>
<td>Geosynthetic Clay Liner</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Polyethylene plastic</td>
</tr>
<tr>
<td>HRT</td>
<td>Hydraulic Residence Time</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductively Coupled Plasma spectrometer</td>
</tr>
<tr>
<td>LC&lt;sub&gt;50&lt;/sub&gt;</td>
<td>Lethal Concentration: 50%</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operations and Maintenance</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride plastic</td>
</tr>
<tr>
<td>RBC</td>
<td>Rotating Biological Contactor</td>
</tr>
<tr>
<td>SBR</td>
<td>Sequencing Batch Reactor</td>
</tr>
<tr>
<td>SF</td>
<td>Surface Flow wetland</td>
</tr>
<tr>
<td>SPE</td>
<td>Solid-Phase Extraction</td>
</tr>
<tr>
<td>SFF</td>
<td>Sub-Surface Flow wetland</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
</tr>
<tr>
<td>TIEO</td>
<td>Theoretical Oxygen Demand</td>
</tr>
<tr>
<td>TIEI</td>
<td>Toxicity Identification Evaluation</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solids</td>
</tr>
<tr>
<td>VFAs</td>
<td>Volatile Fatty Acids</td>
</tr>
</tbody>
</table>
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1.0 PROBLEM FORMULATION

1.1 Project Context

Access to sources of clean water is an essential requirement for both humans and wildlife. Unfortunately, many industrial processes produce contaminated wastewater. Many others influence nearby water quality indirectly through mechanisms such as stormwater runoff and airborne transport. As we continue to recognize ways to protect our natural resources, and as we accumulate knowledge about just how much of an integral part water plays in almost all ecosystems (National Research Council 1992), a growing recognition will occur among industry, government and the public that responsible stewardship of our aquatic resources is a major factor in the success of any integrated resource management plan.

Protection of our aquatic resources must encompass more than just controlling direct effluent discharges into our surface waters. Stormwater runoff, agricultural discharges, seepage of contaminants into groundwater aquifers, and other forms of nonpoint source pollution must also receive sufficient attention if we are to maintain sustainable sources of clean water.

1.2 Solid Waste Storage and Disposal

The responsible long-term storage and disposal of any solid waste presents a suite of challenges that must be addressed by environmental engineers, facility operators and regulators. The control and treatment of leachate is foremost among these issues. Leachate is produced when water (or other liquid) percolates through a matrix of solid materials, such as crushed rock, landfill waste, or wood chips. The liquid extracts various compounds from the solid matrix and the resulting leachate contains a mixture of suspended solids and dissolved substances (Davis and Cornwell 1998; Shams and Brockway 1994).
1.0 PROBLEM FORMULATION

1.2 Solid Waste Storage and Disposal

While much attention has been paid to leachate control and treatment in municipal landfills and mine tailings piles, insufficient attention has been paid to proper disposal of solid waste from the wood processing industry, which includes wood chips, process trimmings, shredded bark, and sawdust from various saws, planes, and other process machinery. This material, when stored unprotected outside and exposed to precipitation, will produce a leachate that is often characterized by a high carbon content, high oxygen demand, strong colour, an array of dissolved metals, and low levels of nitrate, ammonia and nitrogen (Borga et al. 1996; Slagle 1976; Taylor et al. 1996; Thomas 1977). Naturally-occurring compounds, such as resin acids, tropolones, flavonoids, stilbenes, tannins and lignins, and various steroids and terpenoids, are present in wood. They are used by the trees as structural glues, hormonal controls, and chemical defences against predation by insects, fungi and microbes, and are liberated by the leaching process (Eaton and Hale 1993; Laks 1991; Rowe and Conner 1979). The resulting leachate is often very toxic to aquatic and other life forms (Bailey et al. 1999; Borga et al. 1996; Cameron 1982; Eaton and Hale 1993; Inamori et al. 1991; Taylor et al. 1996).

Within a forest ecosystem, the same leachate hazard does not exist. The natural rate of tree death and degradation ensures that the fallen wood is not an environmental liability. This is due to two factors. Firstly, the forest floor supports a complex array of bacterial and fungal systems specifically adapted for degrading these organic materials. They sequester and metabolize the complex wood chemicals, rendering them into simpler, nontoxic compounds. In addition, the forest soil communities at any given location only have to deal with one, or possibly a handful of fallen trees at any given time. The wood waste generated by a mechanical processing industry far outpaces both the temporal and spatial abilities of the natural mechanisms that would normally facilitate degradation.

Hence the need for the processing industry to recognize how it has affected the naturally-occurring treatment mechanisms and commit itself to implementing the necessary remedies. Since the rate of natural degradation is limited by such factors as temperature, nutrient availability, and oxygen supply, implementing and optimizing a solution requires
1.0 PROBLEM FORMULATION

1.2 Solid Waste Storage and Disposal

attention be paid to these details. Unless properly contained and treated, this toxic runoff will flow into either the nearest stream, lake or other open aquatic environment, or it will percolate down into the groundwater aquifers. Either way, contamination of our water supplies results, and this can lead to public health concerns, degradation of dependent ecosystems, and destruction of associated natural resources (e.g., commercial and tourism fisheries) (Al et al. 1995; Schermer and Phipps 1976; Shams and Brockway 1994; Slagele 1976; Sweet and Fetrow 1975; Triton 1993).

Leachate collection and control techniques are fairly well established, largely due to advances in engineering practices for municipal landfills (see Section 2.2 for details). However many existing wood waste disposal sites fail to take advantage of the state of the art, owing mainly to their age. Many were developed prior to the full realization that something as seemingly innocuous as wood may pose an environmental threat, and therefore these disposal sites were often selected rather casually and without any implementation of liner or leachate collection systems.

Not only are collection and control measures inadequate at many of these sites, but finding a suitable treatment system can also be a problem. Developing a treatment technology specifically suited for wood leachate has received very little attention. Schermer and Phipps (1976) reported that passage through soil provided some attenuation, but the soil displayed a finite capacity for treatment and once sufficient leachate has passed through to exhaust this capacity, no more treatment was delivered. This treatment capacity began to diminish markedly over time, often in as little as 20 days under field conditions. Recycling the leachate back through the wood waste, in order to maximize naturally-occurring oxidation reactions and promote condensation of tannins into biologically-inactive precipitates, was shown to be ineffective (Schermer and Phipps 1976). In another study, Thomas (1977) reported that laboratory-scale aerated lagoons were unsuccessful at removing toxicity from cedar leachate.
1.0 PROBLEM FORMULATION

1.3 BC’s Forest Products Industry

Better success might be achieved by adapting an existing treatment technology from other applications. However, this also has its problems. The treatment technologies currently available from municipal landfill practices are often economically unrealistic for wood processing sites. This is due to several reasons. Firstly, wood processing sites usually occupy a fairly extensive area, and therefore have the potential to generate large quantities of runoff. Often it is not just the chip or waste piles which generate leachate, but also the uncovered work areas, since they are usually littered with an accumulation of fine woody debris. Thus, a treatment system with a high unit treatment cost will impose a significant economic burden upon such a facility, especially if it is located in a region which receives abundant precipitation. Secondly, the remoteness of many of these facilities severely increases the cost of installing and maintaining a complex treatment plant. Convenient access to chemical additives, availability of trained operators, and proper by-products handling also require additional consideration in these remote locales.

The scope of this problem is not insignificant. In regions where forestry is a dominant sector, wood processing facilities and their associated waste streams can represent a major source of the region’s contaminant loading. Recognizing this diffuse source of pollution and responding to it in an economically and environmentally responsible manner is important. Failure to respond may result in serious environmental consequences. In addition, the increasingly stringent regulatory environment amplifies the need for industry to demonstrate due diligence. However, implementing technologies which are not fiscally realistic may result in a decrease in the industry’s ability to compete in a global marketplace, resulting in the local economy experiencing undue economic stress.

1.3 BC’s Forest Products Industry

The forest products industry is British Columbia’s largest, far out-shadowing any other sector of this province’s economy. In 1998, the $15 billion industry represented over 14% of the province’s Gross Domestic Product (GDP). Forest products represented 46%
1.0 PROBLEM FORMULATION

1.3 BC's Forest Products Industry

of BC’s total manufacturing shipments. This accounted for 51% of the province’s total export sales. As BC’s largest industrial employer, forestry provides 15% of the province’s workforce with employment (PricewaterhouseCoopers 1999).

Given the size of both the industry and the province, it is not surprising that its activities cover a very extensive geographical area. The scope of the industry is huge and the associated environmental management must be taken very seriously, especially considering how many other industries and activities are dependent upon the health of this landscape. The forest industry’s processing facilities are a major feature in this management task. Close to 500 primary processing mills exist within BC and are responsible for handling most of the wood harvested each year (65.0 million m$^3$ in 1998) (COFI 1999). The handling, storage and eventual disposal of the waste by-products and residuals is an enormous task. The wood waste from saw mills alone has been estimated at close to 2.8 million bone dry tonnes (bdt) per year (McCloy 1997). To this total must be added the waste generated by the chipping, panel, pulp and other types of mills. Furthermore, in addition to these mills, an unknown number of storage / transportation staging areas and chip piles at various barge loading facilities also require waste management mechanisms, especially with regard to leachate / runoff control and treatment.

Compared to the industry as a whole, the cedar shake and shingle sector is small. There are only 39 mills and most of them are much smaller than facilities typical of other sectors (Ministry of Forests 1999). However, in some ways, this adds to, rather than diminishes, the problem. Unable to access the same economies of scale available to some of the other processors, much of the expensive treatment technology is simply beyond their means. Cedar is generally recognized as having more potent extractives and more toxic leachates than other commercial temperate wood species (Eaton and Hale 1993; McDaniel et al. 1989; Thomas 1977). One of the reasons why cedar is used for shake and shingles is its strong rot-resistance. This resistance is imparted by the various chemicals that the cedar tree produces as a defence against microbial and insect attack,
1.0 PROBLEM FORMULATION

1.4 Research Scope and Objectives

and it is these chemicals which also contribute to the high toxicity of its leachate. Thus, if cedar processors are going to address their leachate generation and runoff problems in a fiscally realistic manner, they need access to a treatment technology that is both economic and effective.

1.4 Research Scope and Objectives

The intent of this research thesis was to address the issue of wood leachate and determine whether suitable control and treatment technologies are feasible. In the interests of time and funding, the scope of this research was restricted to wood waste leachate from cedar processing facilities. However, the results are likely to be equally applicable to leachates and runoff from facilities processing other wood species and operating in temperate regions other than BC. This research proposed the development and demonstration of a wood leachate treatment technology that met the objectives outlined below.

A. Performance objectives:
A.1 Provide effective treatment which reduces the acute toxicity of the leachate to the point where it no longer poses an immediate threat to aquatic life.
A.2 Through the same treatment process, reduce the biochemical oxygen demand (BOD), chemical oxygen demand (COD), and other associated pollutants so that the treatment effluent will result in compliance with anticipated discharge regulations.

B. Design objectives:
B.1 An effective treatment design which is dependable and robust.
B.2 A system which is easy to operate and requires minimal operator training or intervention.
B.3 Inexpensive to implement, operate, and maintain, with a minimum of chemical additions, process monitoring, or by-products handling required.
1.0 PROBLEM FORMULATION

1.4 Research Scope and Objectives

- **Literature Review:**
  - **Target:** Assess the current state of the technology and determine whether appropriate technologies exist for the control and treatment of wood leachate.
  - **Unit Scale:** (library)
  - **Relevant Thesis Section:** 2.0

- **Research Site Acquisition and Startup:**
  - **Target:** Identify research gaps, obtain funding, secure access to an appropriate research site.
  - **Unit Scale:** (desk)
  - **Relevant Thesis Section:** 3.0

- **Leachate Characterization:**
  - **Target:** Characterize the wood leachate with respect to its ecotoxicology and chemistry.
  - **Unit Scale:** (500 mL test tube)
  - **Relevant Thesis Section:** 4.0

- **Screening Trials:**
  - **Target:** Determine whether the wood leachate was amenable to biological treatment.
  - **Unit Scale:** (10 L bench test flask)
  - **Relevant Thesis Section:** 5.0

- **Bench-Scale Testing:**
  - **Target:** Demonstrate the appropriateness of constructed wetlands for the treatment of wood leachate (re: Objectives A.1 & A.2).
  - **Unit Scale:** (30 L column (lab))
  - **Relevant Thesis Section:** 6.0

- **Pilot-Scale Trials:**
  - **Target:** Evaluate the performance of the constructed wetland treatment system under field conditions (re: Objectives A.1 - A.2 & B.1 - B.3).
  - **Unit Scale:** (20,000 L mesocosm (field))
  - **Relevant Thesis Section:** 7.0

*Figure 1.1 Sequence and relationship of research components*
1.0 PROBLEM FORMULATION

1.4 Research Scope and Objectives

The research was comprised of a sequence of components, as outlined in Figure 1.1. Note that each of the components depends upon the information and conclusions of its predecessor. Thus, rather than assemble this Masters thesis in the traditional manner, with one section each for Methodology, Results, and Discussion, it was more appropriate to assign each of these components an independent section. Within each of these sections, the methodology specific for that section could be discussed. Similarly, the results for each component could be presented immediately and discussed within the context of the relevant section. This provided a more logical presentation, since many of the design factors discussed in the methodologies depended on the results and conclusions of the previous component. Each of the components had sufficiently different methodologies that repetition of document content is minimal.
2.0 LITERATURE REVIEW: STATE OF THE TECHNOLOGY

2.1 Leachate Generation at Wood Processing Sites

The manner in which the trees are cut, handled, stored and milled has a strong influence on what environmental effects occur during the process life cycle. Since wood is a fairly impervious material, it is exposed to the elements for much of its storage and transportation. During handling, much of the bark is inadvertently stripped from the logs, especially in dryland sorting yards. In fact, unless specific steps are taken to minimize its buildup, most wood processing areas become underlain by a compacted layer of shredded bark and other woody debris that accumulates over time and is crushed beneath the constant traffic of yard machinery.

After being graded and sorted, raw logs are stored in piles to await processing, with little attempt to shield them from the often-substantial rains. Even in this fairly compact state, the wood will produce a toxic, extractive-laden leachate (Taylor et al. 1996). As the wood is processed into smaller and smaller pieces, their surface-area-to-volume ratio increases substantially, and this accelerates the rate at which the wood chemicals can be leached out.

Prior to entering the main process train, any remaining bark and major surface irregularities on the logs are removed by a set of debarking machines. The stripped bark, which is especially rich in wood extractives (Rowe and Conner 1979), is usually disposed of in the same manner as the rest of the process waste. As the logs are split, sawn, and/or planed during the milling process, sawdust and trimmings are produced. Even with today’s thinner saw blades, the amount of sawdust produced is substantial. What to do with this waste product is a challenge that has yet to be fully resolved.

Open-air burning in beehive burners or unmodified silo burners is almost completely phased out as a legal option, due to associated air pollution, especially particulate matter.
2.0 LITERATURE REVIEW: STATE OF THE TECHNOLOGY

2.1 Leachate Generation at Wood Processing Sites

(Waste Management Act 1996). Placing it in a municipal landfill is prohibitively expensive and not a popular option, as these landfills are attempting to conserve what limited space they still have left. Even using the material as a mulch on walking trails or in equestrian corrals is facing increased scrutiny as the effects of the leachate are being noticed on nearby vegetation. So far the most promising application seems to be using the wood waste as a fuel in electrical cogeneration incinerators, but to date there is only one approved incinerator in the whole province dedicated to using wood waste for this purpose (i.e., Prince George). Pulp mills often have cogeneration boilers into which wood waste can sometimes be fed, but the capacity of wood use in these boilers rarely exceeds the volume of wood waste produced by the mills themselves (Bob Beaty, personal communication). Some efforts have been made to develop other technologies to convert the waste wood into useful products (e.g., charcoal, activated carbon, compost and other soil amendments, cat litter), but no market/technology combination has yet emerged that can utilize the vast quantities of waste produced. In the meantime, the wood waste piles up.

The wood waste consists of only a small portion of the total wood that enters the mills. Most of it exits as processed product and is transported to market. However, even at this stage there is the potential for leachate problems. Once again, much of the wood is transported in a manner which exposes it to precipitation. Loads of dimensional lumber are increasingly being wrapped before being transported, but this is not always practical for other products. Wood chips are sometimes transported in enclosed or covered trailers, but when they arrive at either the barge-loading facility or pulp mill, they are stored in large exposed piles (Figure 2.1). Cedar shakes and shingles are tied into bundles which are then stored in large open areas. In fact, during the summer it is required to sprinkle the shake and shingle storage areas with water, to reduce the fire risk. This, of course, produces more leachate.

Figure 2.1 Wood chip barge-loading facility
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2.2 Leachate Control and Treatment

Some wood processing facilities, in an attempt to reduce the toxicity of their runoff and prevent process chemicals such as antisapstain chemicals from entering nearby aquatic environments, covered certain sections of their work/storage areas with galvanized roofing to shield them from the rain. Unfortunately, the zinc which washed off the metals roofs increased the overall toxicity of the runoff (Bailey et al. 1999). How does one proceed when faced with a challenge such as this, where even seemingly benign materials such as metal roofing and untreated wood are contributing unacceptable levels of toxins to the receiving environment?

As with other examples of pollution control, a three-step process is required. First, the contaminant(s) of concern need to be identified, and the sources elucidated. Secondly, the production of the contaminant(s) must be minimized as much as is practical. With regards to runoff and leachate, this means minimizing the infiltration of precipitation into storage and waste piles, and subsequently, the uncontrolled release into the groundwater and open aquatic environments. However, as illustrated by the galvanized roofing example, there is often a practical limit to the extent these measures can be taken before the net benefits become compromised. The final step is to implement a treatment technique appropriate for the remaining discharges. All three of these steps are necessary for the comprehensive and effective management of such a situation. As with other examples of nonpoint source pollution, capturing and controlling the problem as close to its generation site as possible will secure the greatest benefits, since it reduces both the exposure time and the exposure area of the pollutant(s) to the receiving environment.

2.2 Leachate Control and Treatment

2.2.1 Minimization

Usually the most desirable pollution control measure is minimizing the generation of the waste in the first place (Davis and Cornwell 1998; Gardner 1997). Less generation means less ultimate treatment capacity is required. Since the primary raw material of leachate is infiltrating precipitation (and in some cases, groundwater), leachate
minimization procedures are concerned with reducing this infiltration. In the simplest terms, this may involve covering the solid waste pile with plastic tarps (Gardner 1997; Triton 1993). Another option includes placing the solid waste under a roof or similar shelter (Davis and Cornwell 1998). Large municipal landfills and similar installations use a system of daily covers (usually soil, but occasionally plastic sheeting), followed by a sophisticated, multi-layer final cover that is designed not only to prevent infiltration, but also to control gas emissions and provide structural stability to the upper surface of the landfill (Passos et al. 1994; US EPA 1991b; US EPA 1993).

2.2.2 Collection
Even with the most sophisticated of leachate minimization systems, some leachate will be produced. Moisture present in the waste may be liberated as the wastes undergo compaction and degradation; precipitation may enter the landfill during its active life (i.e., waste placement); and moisture may leak past the final cover barriers. Therefore it is necessary to install an adequate leachate collection system. Many variants exist, but they all follow the same basic premise: prevent infiltration of the leachate into the substrate below the solid waste (and ultimately into the groundwater), and provide some means of removing the accumulated leachate.

Leachate infiltration into the substrate is controlled through the use of impermeable liners. These liners can be constructed of a variety of materials, including synthetic membranes (made of plastics such as PVC, HDPE, CPE, or EPDM, at least 30-60 mils thick); compacted clays (with a hydraulic conductivity of no more than 1x10^{-7} cm/s); or geosynthetic clay liners (GCLs), which are a geosynthetic material impregnated with a layer of bentonite, or other low-conductivity clays (US EPA 1988a). It is not uncommon for an installation to use a combination of these materials in an effort to utilize of their various strengths and advantages. It is also becoming more common to include a leak detection system below the liners, to allow an appropriate response, should the containment system become compromised (Davis and Cornwell 1998; Millano and Hahn 1997; Schneck 1994; US EPA 1989). Figure 2.2 is a schematic of a typical installation.
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2.2 Leachate Control and Treatment

Since the liner system is relatively impermeable, leachate migrating downward will accumulate above it. In order to prevent the liner from being subjected to excessive hydraulic pressures, a drainage system is installed between the solid waste and the liners. This can be accomplished by a layer of course gravel, synthetic geogrid drainage tiles, or a network of perforated drainage pipes supported within a layer of coarse sand. It is usually necessary to provide a protective layer between the underdrain system and the bottom of the solid waste, to prevent any physical damage from occurring during waste placement or compaction. This is often done by placing a permeable geotextile over the drainage system and then a layer of sand (US EPA 1993). Regardless of its construction, this drainage layer should possess a hydraulic conductivity of greater than $1 \times 10^{-2}$ cm/s (US EPA 1993). By sloping the drainage layer (> 2%), the leachate moves through it to predetermined collection points along the outside edge of the landfill. From here the leachate is conducted to a treatment system.

2.2.3 Standard treatment techniques

The choice of leachate treatment techniques depends primarily upon what substance(s) are to be removed from the leachate, the target effluent concentrations, and what facilities are available or feasible for that locale. Additional considerations include the volume of leachate requiring treatment, its flow characteristics (i.e., intensity of variations on a seasonal, diurnal, etc., basis), whether any of the leachate’s characteristics (e.g., low alkalinity; lack of biodegradable carbon; toxicity) make it incompatible with specific treatment methods, and what the local design experience / preferences may be.
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2.2 Leachate Control and Treatment

Much of the existing leachate treatment experience is from municipal landfill systems. Leachate from these landfills often has high levels of BOD, COD, nitrogenous compounds and various metals (Table 2.1) (Diamadopoulos et al. 1997; Gettinby et al. 1996; Horan et al. 1997; Robinson 1999; Stroshein and Fryklind 1996). Its pH is usually acidic and insufficient alkalinity can be a problem. The primary treatment objectives are usually BOD and COD reduction, and eventual conversion of the nitrogenous compounds to nitrogen gas. It may be necessary to adjust the pH and supplement the alkalinity, but

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
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</tr>
<tr>
<td>conductivity [µS/cm]</td>
<td>960 - 16 800</td>
</tr>
<tr>
<td>alkalinity (as CaCO₃)</td>
<td>0 - 22 800</td>
</tr>
<tr>
<td>hardness (as CaCO₃)</td>
<td>500 - 22 800</td>
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<tr>
<td>biochemical oxygen demand (BOD₅)</td>
<td>11 - 57 000</td>
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<tr>
<td>chemical oxygen demand (COD)</td>
<td>20 - 750 000</td>
</tr>
<tr>
<td>total suspended solids (TSS)</td>
<td>10 - 700</td>
</tr>
<tr>
<td>total dissolved solids (TDS)</td>
<td>590 - 45 000</td>
</tr>
<tr>
<td>ammoniacal -N</td>
<td>1 - 1700</td>
</tr>
<tr>
<td>nitrate -N</td>
<td>&lt; 0.1 - 50</td>
</tr>
<tr>
<td>nitrite -N</td>
<td>&lt; 0.3 - 25</td>
</tr>
<tr>
<td>ortho-phosphate -P</td>
<td>&lt; 0.5 - 154</td>
</tr>
<tr>
<td>metals:</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>1.5 - 2.7</td>
</tr>
<tr>
<td>As</td>
<td>0.0006 - 1.6</td>
</tr>
<tr>
<td>Ca</td>
<td>10 - 7200</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt; 0.005 - 9.9</td>
</tr>
<tr>
<td>Cd</td>
<td>0.0005 - 17</td>
</tr>
<tr>
<td>Fe</td>
<td>&lt; 0.5 - 2820</td>
</tr>
<tr>
<td>Pb</td>
<td>0.002 - 12.3</td>
</tr>
<tr>
<td>Ni</td>
<td>0.01 - 130</td>
</tr>
<tr>
<td>Zn</td>
<td>&lt; 0.1 - 370</td>
</tr>
<tr>
<td>Toxicity²</td>
<td>0.064% - &gt;100%</td>
</tr>
</tbody>
</table>

NOTES
1. All values reported in mg/L, unless otherwise noted.
2. Acute toxicity, reported as 96hr LC₁₀

2.0 LITERATURE REVIEW: STATE OF THE TECHNOLOGY

2.2 Leachate Control and Treatment

This is usually a simple matter of dosing the influent with slaked lime (Ca(OH)$_2$), soda ash (Na$_2$CO$_3$) or caustic soda (NaOH). Lime addition can also be used to precipitate some of the dissolved metals (Horan et al. 1997).


With the exception of advanced chemical oxidation and activated carbon, they are all adaptations of standard domestic wastewater treatment techniques. In fact, in situations where the volume of leachate is small relative to total plant inflow (< 5%), it may be acceptable practice to pump the untreated leachate directly into the municipal domestic wastewater treatment plant (Diamadopoulos et al. 1997; Wreford 1995). With stronger leachates, the biological processes may suffer toxicity from elevated concentrations of leachate components such as metals or certain organics (Manoharan et al. 1992; McArdle et al. 1988), in which case, process adaptations or an alternative treatment technique are needed. Many of the treatment techniques (e.g., activated carbon, wet-air oxidation) have substantial unit operating costs (McArdle et al. 1988).

Leachate from mine tailings and other waste rock is another area that has received considerable attention. This leachate is typified by high levels of dissolved metals (Cu, Pb, Cd, As and Zn being the most deleterious), often accompanied with very low pH levels (< 3.0) (Knapp 1987; Makos and Hrncir 1995; Paine 1987). Due to the acute toxicity of these metals and the low pH levels, the traditional treatment technologies used for municipal landfill leachate often suffer excessive microbe fatality and are rendered ineffective. Other techniques need to be employed. One technique is to use lime addition as a pretreatment for pH adjustment and precipitation of the dissolved metals.
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2.3 Constructed Wetland Treatment Systems

metals (Vachon et al. 1987). Other options include using bioreactors containing populations of alkali-generating microbes, such as iron-reducing or sulphate-reducing bacteria (Kalin et al. 1991), or using a variety of constructed wetland treatment systems, which are more tolerant of the extreme pH and metals content. They employ a suite of aerobic and anaerobic mechanisms to remove the metals from the wastewater and are able to moderate the pH (Eger 1994; Frandsen and Gammons 1999; Karathanasis and Thompson 1993; Pantano et al. 1999; Thomas et al. 1999).

2.3 Constructed Wetland Treatment Systems

2.3.1 Basic features and design premises

Constructed wetland treatment systems operate on the premise that certain features of natural wetlands are capable of removing contaminants from water and that these features can be replicated and optimized in an artificial wetland constructed solely for the purpose of treating wastewater. A constructed wetland mimics its natural counterpart in many respects, including the presence of aquatic vegetation, saturated (anaerobic) soils, and quiescent flow of water either through a soil or gravel substrate (i.e., subsurface-flow wetlands) or through vegetation stalks and root mats on the surface of the soil substrate (surface-flow wetlands). However, in contrast to natural systems, a constructed wetland is usually well-delineated and has a more regular shape, which allows a more predictable and controllable flow regime. In addition, in order to properly contain the wastewater and provide better control over its hydrology, constructed wetlands are usually lined with impermeable geosynthetics, although properly engineered clay liners can also be used if no chemical incompatibilities exist with the wastewater constituents. Water depth is typically between 20 - 80 cm.

Removal of particulate matter (and any associated compounds) is achieved through settling, as a result of the quiescent flow conditions present throughout the whole system. Nutrient removal (i.e., \( \text{NH}_4^+ \), \( \text{NO}_3^- \), \( \text{PO}_4^{3-} \)) is achieved as a result of microbial
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communities utilizing the nutrients to meet their metabolic requirements, and thus there is usually no buildup of these compounds within the system. Similar metabolic fates await biodegradable fractions such as BOD and certain classes of organic compounds (Ellis et al. 1994). Inorganic constituents such as metals are immobilized through a combination of reductive and oxidative chemical reactions, many of which are microbially-mediated (Eger 1994).

In most cases, the macrophyte vegetation does not take up a significant amount of nutrients, organic pollutants, or metals (Albers and Camardese 1993a; Albers and Camardese 1993b; Cacador et al. 1996; Keller et al. 1998; Lacki et al. 1992; Mungur et al. 1997; Reed et al. 1995), but nevertheless it does play an important role in ensuring that the other components within the system are able to perform their removal functions efficiently. The primary roles of the macrophytes are to provide a physical structure for the microbial communities to adhere to, to act as a supplementary carbon source for these communities, to provide a supply of detrital organic matter (the humic material is required for various complexing reactions), and to create aerobic microenvironments in the vicinity of their roots (Cacador et al. 1996; Hammer 1997; Otte et al. 1995; Van den Berg 1998). Due to the saturated nature of wetland soils, the substrates usually have too little oxygen in them to support the growth of rooted vegetation without some provision for oxygen transport. Wetland plants overcome this oxygen deficiency in the substrate by developing extensive internal lacunae or aernchyma, which are networks of tubular channels, the function of which is to transport oxygen down to the root system and remove any gaseous respiratory by-products back up to the atmosphere (Hammer 1997). The net effect of this gas transport system is that the root network of the plant is aerobic, while the surrounding bulk sediment is generally anaerobic. Due to diffusion of oxygen out of the root tissues, a thin layer of aerobic sediment forms around each root fibre (the rhizosphere) (Armstrong et al. 1990; Hammer 1997; Otte et al. 1995). This rhizosphere is a very important contributor to the efficiency and adaptability of constructed wetland treatment systems.
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2.3 Constructed Wetland Treatment Systems

2.3.2 Scope of contaminant targets

Since microbial populations are the source of many of the actual removal mechanisms, the range of possible contaminant sources that constructed wetland systems can be used for is quite broad. Domestic wastewater, agricultural effluent (swine, poultry and cattle feedlots; dairy wash water), wineries, food processing effluent, greenhouse effluent, aquaculture discharges, agricultural non-point source runoff, contaminated groundwater, mine drainage, municipal landfill leachate, military / industrial chemical sites, petrochemical facilities, textile (dye) wastewaters, pulp mill effluents, and urban stormwater runoff have all been successfully treated with constructed wetlands (Best et al. 1999; Burgoon et al. 1999; Crites et al. 1988; Davies and Cottingham 1994; Eger 1994; Ellis et al. 1994; Johnson et al. 1999; Karpiscak et al. 1999; Kemp and George 1997; Knight et al. 1999; Kowalik et al. 1998; Loer et al. 1997; Maddox and Kingsley 1989; Mitchell et al. 1990; Prystay 1997; Raisin et al. 1997; Rochfort et al. 1997; Sakadevan and Bavor 1999; Sands et al. 1999; Sansanayuth et al. 1996; Scholes et al. 1998; Sikora et al. 1997; Simi and Mitchell 1999; Tanner et al. 1995; Thut 1989; US EPA 1988b).

The contaminants of concern ranged from heavy loadings of conventional pollutants such as suspended solids, BOD, COD, pathogens, and nutrients (nitrogen, phosphorus) to more severe pollutants such as pesticides, herbicides, acids, heavy metals, complex organics, crude petroleums, explosives residuals, chlorinated VOCs (volatile organic compounds), solvents, and hydrocarbons (Chong et al. 1999; Crites et al. 1997; Davies and Cottingham 1994; Davis 1995; Eger 1994; Johnson et al. 1999; Knight et al. 1999; Mitchell et al. 1990; Moore et al. 1999; Pardue et al. 1999; Scholes et al. 1998; Sikora et al. 1997; Tanner et al. 1995; Zoh and Horne 1999).

In fact, as long as there exists a mesophilic microbial consortia which is capable of metabolizing / immobilizing a specific contaminant (or class of contaminants), there is a good chance that a constructed wetland system will be an effective treatment. This is because the wetland environment hosts all three types of microbial communities, aerobic,
2.0 LITERATURE REVIEW: STATE OF THE TECHNOLOGY

2.3 Constructed Wetland Treatment Systems

anaerobic and facultative, usually within close proximity to one another. As long as their temperature, electron acceptor and nutritional requirements are met, most microbes have the capability to live within a wetland environment. The remaining task is to adjust the system's ecology in order to optimize the presence and functioning of the specific organisms which are performing the desired task.

2.3.3 System effectiveness and constraints

Common removal efficiencies reported for properly operating constructed wetlands range from 75% to >99% for the full range of contaminants targeted (Adcock et al. 1999; Cooper 1999; Maeseneer and Cooper 1997; Makos and Hrncir 1995; Mungur et al. 1997; Tanner et al. 1995). While loading rates will depend upon the nature of the wastewater, rates as high as 512 lb BOD$_5$/acre/day [574 kg/ha/day] (with maintained removal rates of >90%) have been reported (Behrends et al. 1999). As with other treatment technologies, much depends upon ensuring that the system is designed properly and is being used as intended.

The major advantages that are commonly cited for constructed wetlands include reduced costs and simpler operations and maintenance (Denny 1997; Haberl 1999; Mitchell et al. 1990). While costs will vary with locale, constructed wetlands are typically half to one-tenth the cost of conventional water treatment systems, with some of this cost allocated for land acquisition (Kadlec and Knight 1996). Imaginative design can often reduce this cost even further by making use of marginal land along development edges and other existing corridors. Unlike mechanical systems, constructed wetlands have estimated design lives of 30 - 100+ years (Kadlec and Knight 1996; Webb et al. 1998). Their maintenance requirements are minimal, largely related to ensuring that the physical infrastructure is functioning as intended (e.g., inlet and outlet weirs) and, with proper design and construction, little remedial action is expected (Hammer 1997).

Since their primary energy source is the sun, with water movement usually supplied by gravity (Hammer 1997; Kadlec 1999), constructed wetlands can be designed with little or
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no need for additional sources of energy. Little or no chemical addition is required by this passive mode of treatment. By-products such as sludges, precipitates, or spent absorbents are rarely produced by wetland systems, thereby eliminating the need for costly handling procedures (Batchelor and Loots 1997; Reed et al. 1995). A major functional advantage that constructed wetlands have over most other treatment techniques is the intentional coexistence of aerobic and anaerobic conditions within the same reactor basin. The heterogeneous distribution of fine macrophyte root hairs within the bulk sediment ensures that there is a rich and complex distribution of aerobic rhizospheres within the anaerobic sediment. This patchwork facilitates those reaction cascades which need to switch between oxidative and reductive environments (e.g., conversion of ammonia to elemental nitrogen) (Hammer and Bastian 1989; Xue et al. 1999).

Since constructed wetlands are analogues of an ecotone environment, a certain amount of disturbance is necessary for their maintenance and proper functioning (Hammer and Bastian 1989). This makes them ideally suited for applications with dynamic flow rates, such as leachate and stormwater runoff management (Bastian and Hammer 1993; Kadlec and Knight 1996). Another capacity that they serve in the landscape is the dampening and desynchronization of hydraulic shock loads to aquatic receiving environments.

The primary complaint directed against constructed wetlands is the fact that they require a large area, or “footprint”, per unit of treatment. The need for lower throughput or loading rates, compared to conventional systems, has also been a concern in the past, although this is becoming less of a concern with some of the more efficient systems that have been developed lately (Behrends et al. 1999; Cooper 1999). A more subtle constraint is the fact that constructed wetlands are complex systems and therefore an in-depth knowledge of system ecology and a solid understanding of expected wastewater characteristics are necessary if proper design is going to be achieved and result in an effective facility which is easy to maintain and operate. It must be realized that this is a developing technology and therefore our knowledge and experience concerning certain aspects may be limited. The only way to overcome this is to design, build and operate
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more of these systems in a disciplined manner, and thus gain the necessary experience to improve future designs.

It is important to realize that constructed wetland treatment systems are not the pollution control panacea that some promoters bill them. As with any other technology, they have applications for which they are suited and they rely upon proper design and application of their inherent features in order to deliver effective performance. If designed and operated properly, they can be an efficient and reliable treatment means for a large variety of contaminants. Since constructed wetlands harness some of the many reactions that take place within intricate natural wetland ecosystems, they themselves are very complex systems. Much research and operating experience needs to be accumulated before we can understand the full capabilities of these systems.

Therefore, it is a mistake to quickly group “constructed wetlands” together as a minor footnote in a description of modern water treatment technologies. There may be as much difference between the design and operation of a constructed wetland system treating acid mine drainage and a constructed wetland system removing nitrates from groundwater as there are differences between an activated sludge treatment system and an SBR plant.

Closer attention to the design premises, operating conditions, and performance results will yield a better understanding of the full scope of solutions that constructed wetland systems can offer to the environmental engineering profession. This better understanding will lead to more rigorous designs, which will lead to improved performance and an increase in mechanistic knowledge, which in turn will allow this technology to be employed with more precision and confidence. It would be suboptimum engineering if we failed to make use of such a versatile and powerful tool which is so well suited for many of the environmental contamination challenges that we are currently facing.

2.3.4 Distribution and use of the technology

Constructed wetland treatment systems have been in limited use since at least the 1910’s (Hiley 1990). Using natural wetlands for waste treatment and disposal, a practice that is
2.0 LITERATURE REVIEW: STATE OF THE TECHNOLOGY

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no longer endorsed, goes back for as long as sewage has been collected (Kadlec and Knight 1996). However, it is only within the last 20-30 years that constructed wetland treatment systems have received the attention of a large number of researchers and a formal body of knowledge on their design and operation has begun to develop (Cole 1998; Haberl 1999). Currently over 500 constructed wetlands treatment systems are in use in Europe and more than 600 in the United States (Cole 1998). Their application in developing nations is increasing as the cost and versatility benefits are being recognized (Haberl 1999).

Today they are being used throughout the world, from the tropics (Braungart et al. 1997; Polprasert et al. 1996) to the arctic (Jokela and Pinks 1998, Pries 1994). With the necessary design modifications, they are proving to be useful in an extremely wide range of conditions. Freshwater, estuarine, and saltwater systems all have their own features which make them appropriate for specific applications (Cacador et al. 1996; Chu et al. 1998; Reed et al. 1995). They have been used by single cottages and large towns (Burgan and Sievers 1994; Schoenerkle et al. 1997). They have solved waste management problems for modern chemical plants and rural villages in developing nations (Haberl 1999; Sands et al. 1999). In Europe it is not uncommon to use them as an integral component of a treatment plant which contains more conventional unit processes such as RBCs or SBRs (Griffin et al. 1999; Robinson 1999).

No mention has been found in the literature of constructed wetland systems being used to treat wood leachate, but two other sites in western Canada are known to be currently developing systems for industrial use; Chmainus, BC and Drayton Valley, Alberta; both are Weyerhaeuser mills (EnviroLink Newsletter, October 1999; Mike Woods, personal communication).
3.0 RESEARCH SITE ACQUISITION & STARTUP

3.1 Justification of Research Focus

As described in Sections 2.1 and 2.2, the existing leachate containment and collection technology was sufficiently established to address the current needs of the forest industry. Leachate treatment technologies also existed, but they failed to adequately meet the needs of the forest products industry, especially the smaller processors, specifically with regards to design objectives such as those outlined in Section 1.4 (i.e., Objectives B.1 to B.3). Constructed wetlands were selected as an appropriate technology for evaluation based upon their performance in other applications. Their ability to treat a wide range of contaminants beyond the conventional targets (e.g., BOD, TSS, nutrients, pathogens), combined with their reputation for inexpensive, robust and efficient operations, gave them the greatest potential for meeting both the performance and the design objectives stated for this research.

3.2 Site Acquisition and Legalities

Once the research was refined to the point of selecting constructed wetlands as the technology for further evaluation, it was necessary to acquire a research site and a source of wood leachate. After several months of inquiry, a research site was eventually located in October 1997 and permission was secured from the landowners, Steve and John Wynnyk, in conjunction with Jack Davidson of the BC Shake and Shingle Association, to conduct research on a cedar processing site.

Shortly thereafter it was learned that litigation concerning activities at that site was potentially imminent and that the research activities may have been viewed as constituting an involvement in these activities. The basic issue of the potential litigation surrounded the release of the toxic leachate into the environment (which contravened the Waste Management Act) and the fact that a pool of the leachate had collected in a
3.3 Project Site Description

3.3.1 Location and Current Conditions
The study site was located near Mission, British Columbia, 75 kilometres east of Vancouver, BC, Canada. This area was characterized by a marine coastal climate with

![Figure 3.1 General plan of study site](image-url)
3.0 RESEARCH SITE ACQUISITION & STARTUP

3.3 Project Site Description

mild, wet winters and cool, drier summers. Mean daily temperatures ranged between 18°C in July to 2°C in January (Environment Canada 1982).

The area was a rural setting, with several small wood processing mills (mostly cedar shake and shingle mills) located along a narrow belt on the north bank of the Fraser River (Figure 3.1). Located on 4.1 hectares, the study site had a large pile (approximately 170 m in diameter and over 20 m high) of miscellaneous untreated cedar wood waste. It ranged from sawdust and chips, to bark and off-specification shakes and shingles, and is referred to by the wood processing industry as ‘hog fuel’. Since the cedar hog fuel pile (the Pile) was exposed to the elements, substantial amounts of precipitation fell upon it (approximately 1630 mm annually, with 70% occurring during October - March; Triton, 1993). Due to its absorbent nature, most of the precipitation that fell on the Pile leached through.

A pool of leachate, approximately 20 m by 70 m, had formed on the west side of the Pile and extended onto the adjacent property (Figure 3.1). The leachate was very dark in colour and often had patches of fine white bubbles visible on its surface. A very strong, rank smell emanated from the leachate pool. There were numerous dead trees standing throughout the pool (Figure 3.2).

Due to the Pile’s proximity to the Fraser River (~60 m), there was concern about the effects of this leachate entering the river, which is British Columbia’s most important salmon river (Fraser 1995). Directly underlying the pile was a natural aquitard consisting of silt and clay, ranging from 0.9 to 4.1 m deep. Beneath this aquitard were two aquifers, consisting predominantly of sand and sandy-clay. The top aquifer was thin and discontinuous; the lower one was at least 6.0 m thick throughout the site (Triton 1993).
Given the site's precipitation patterns and the size of the pile, Triton (1993) calculated a hydrologic mass balance for the pile and determined that approximately 23 000 m$^3$ of leachate were produced on an annual basis. Of this total volume, it was estimated that about 1 000 m$^3$ entered the leachate pool and then infiltrated into the ground. The remaining 22 000 m$^3$/yr penetrated the relatively thin aquitard beneath the pile and entered the aquifers. Aside from when the Fraser River flooded, no overland drainage was observed from either the leachate pool or the Pile.

3.3.2 Ownership and History
The area was under private ownership and parcels were leased to the various small independent wood processing facilities (Figures 3.1 and 3.3). The Pile, which was located at the west end of this stretch of mills, was started in a natural depression at the end of the property. Since few legal disposal options currently exist in BC for hog fuel, several of the small mills in the local area decided to pool their cedar wood waste in an effort to gain a sufficient quantity to enable them to either sell it as fuel to electrical cogeneration facilities or use it as a raw material for some other industrial process (e.g., charcoal production). Unfortunately, none of these enterprises were realized and the large hog fuel Pile persisted. Finally in 1999, a pulp mill in Powell River agreed to accept the cedar and burn it, along with other fuel, in their cogeneration boiler. The hog fuel was then being delivered to the pulp mill via barge on an “as-requested” basis.
4.0 CEDAR LEACHATE CHARACTERIZATION

4.1 Introduction

Between October 1997 and December 1999, samples were periodically obtained from the cedar leachate pool and subjected to both chemical and ecotoxicological characterization. The chemical analysis work was conducted in the Environmental Laboratory of the Department of Civil Engineering at the University of British Columbia. Ecotoxicological analysis was supported by EVS Environment Consultants of North Vancouver, BC, who provided me with access to the facilities in their toxicology laboratory.

4.2 Methods and Materials

4.2.1 Sampling Protocols

Accepted standard sampling protocols were followed for all sampling trips. Surface grab samples of the cedar leachate were taken as needed from the east bank of the leachate pool, adjacent to the side of the Pile (Figures 3.1). Due to site and legal constraints, the pool was only accessible from this location.

Sufficient sample volumes were collected in appropriate pre-cleaned containers to meet the needs of the analyses (Table 4.1). Each sample container was rinsed twice with sample prior to filling. Every attempt was made to collect samples with a minimum of disturbance to the sampling location. In an effort to collect representative samples, any floating debris or surface films were avoided.

All samples were labelled and their temperature and other parameters of interest recorded, (e.g., pH, dissolved oxygen (DO), specific conductivity). The samples were preserved as appropriate (Table 4.1) and transported immediately, without any head space. Blanks were utilized as needed. Laboratory storage was at 4°C, in the dark. All analyses were conducted as soon as was possible, within the holding times recommended by the various test protocols (Table 4.1).
### 4.0 CEDAR LEACHATE CHARACTERIZATION

#### 4.2 Methods and Materials

**Table 4.1 Sample collection, preservation and storage specifications**

<table>
<thead>
<tr>
<th>Field</th>
<th>Analysis</th>
<th>Minimum Sample Volume</th>
<th>Container</th>
<th>Preservation</th>
<th>Max. Holding Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field temperature, pH, DO, conductivity</td>
<td>50 mL</td>
<td>-</td>
<td>-</td>
<td>in situ</td>
<td></td>
</tr>
<tr>
<td>Physical solids</td>
<td>200 mL HDPE</td>
<td>refrigerate</td>
<td>7 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colour</td>
<td>500 mL HDPE</td>
<td>refrigerate</td>
<td>48 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical acidity / alkalinity</td>
<td>200 mL HDPE</td>
<td>refrigerate</td>
<td>24 hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness &amp; total metals</td>
<td>500 mL HDPE(A)</td>
<td>sulphuric acid to pH &lt; 2</td>
<td>6 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon (organic &amp; total)</td>
<td>100 mL Glass</td>
<td>sulphuric acid to pH &lt; 2 &amp; refrigerate</td>
<td>7 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrate + nitrite (NO\textsubscript{2} \textsubscript{3} -N)</td>
<td>200 mL HDPE</td>
<td>sulphuric acid to pH &lt; 2 &amp; refrigerate</td>
<td>2 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ortho-phosphate (PO\textsubscript{4} \textsubscript{3} -P)</td>
<td>100 mL HDPE</td>
<td>sulphuric acid to pH &lt; 2 &amp; refrigerate</td>
<td>28 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical oxygen demand (COD)</td>
<td>50 mL Glass</td>
<td>2% phosphoric acid (1 drop per mL\textsuperscript{4})</td>
<td>7 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tannins and lignins</td>
<td>500 mL HDPE</td>
<td>refrigerate, analyze as soon as possible</td>
<td>7 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biological biochemical oxygen demand (BOD\textsubscript{5})</td>
<td>1 L</td>
<td>HDPE</td>
<td>refrigerate</td>
<td>6 hours</td>
<td></td>
</tr>
<tr>
<td>Toxicity (rainbow trout 96hr LC\textsubscript{50})</td>
<td>40 L</td>
<td>HDPE</td>
<td>refrigerate</td>
<td>5 days</td>
<td></td>
</tr>
</tbody>
</table>

**NOTES**

1. HDPE = high density polyethylene plastic
2. refrigeration was in the dark at 4°C
3. HDPE (A) = acid-washed HDPE container (nitric acid)
4. as per Supelco, Inc. GC Bulletin 751G

**Sources:** APHA (1995); Environment Canada (1990)

#### 4.2.2 Analysis protocols

Standard analysis protocols were followed in all cases (see Table 4.2 for specifics). The field parameters (i.e., temperature, DO, pH, specific conductivity) were measured *in situ* with the appropriate meters (Table 4.2).

The acute toxicity of the cedar leachate was evaluated using the standard rainbow trout 96-hour LC\textsubscript{50} procedure (Environment Canada 1990). In essence, a series of dilutions are prepared from the sample and 10 rainbow trout (*Oncorhynchus mykiss*) juveniles are exposed to each sample dilution for a period of 96-hours (under standard conditions of temperature, DO, etc.). By observing how many mortalities occur in which concentrations, a calculation can be performed to determine the concentration at which 50% of the exposed test organisms will die within the 96-hour period. This "lethal concentration" is reported as the LC\textsubscript{50}.

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4.2 Methods and Materials

All other laboratory analyses were performed using the standard methodologies noted in Table 4.2. Hardness was calculated from the ICP measurements of total calcium and magnesium, as per Standard Methods (APHA 1995), because the leachate was too highly coloured to be able to see the visual titration endpoint indicators. The colorimetric analyses for COD and tannin and lignin were not affected by the colour of the raw leachate because in order to bring these values within the range of these two tests, sufficient dilutions were required which rendered the test solutions essentially colourless.

Spectral response of the raw leachate was determined by spectrophotometer scans (190 - 820 nm), using a Spectronic Unicam UV300 UV-visible spectrophotometer. Leachate samples were diluted with distilled water as necessary to bring them within instrument range and the results were later corrected for this dilution factor. Data was downloaded to diskette and processed using Microsoft Excel.

When presenting results, it is often desirable to make comparisons to standard or "typical" situations in order to provide a context for interpretation. Unfortunately, making comparisons between different leachates is fraught with uncertainty, since their compositions vary so widely (Table 2.1). Waste composition in municipal landfills differs greatly between locales, and this affects the leachate composition. Other influences such as rainfall, temperature, and landfill operating practices also play a role (Tchobanoglous et al. 1993). As a result, there is not a "typical" composition for municipal landfill leachate. Much less information is available for wood leachates, which in itself makes defining a "typical" wood leachate difficult. However, wood leachates also vary widely in their composition, although to a somewhat lesser extent than municipal landfill leachates (Cameron 1982; Schermer and Phipps 1976; Slagel 1976; Thomas 1977). Composition will depend upon a number of factors such as wood species, which parts of the tree are exposed (i.e., bark versus sapwood) and how finely divided the wood is (i.e., surface-area-to-volume ratio). For some parameters, conditions such as ambient pH or landfill age are important, yet these are not always reported.
4.0 CEDAR LEACHATE CHARACTERIZATION

4.3 Results and Discussion

Therefore leachates usually do not provide a very useful baseline for comparison. In this report illustrative comparisons will be made between the cedar leachate and other leachates where possible. However, in an effort to provide a more meaningful context, domestic wastewater (i.e., raw sewage) will more often be used as a base of comparison. Although domestic wastewater and wood leachate have completely different sources, there are several reasons why this is still a meaningful comparison. Firstly, although domestic sewage will vary in composition with time and location, the range of this variation in much less than the range of compositional variation observed in leachates. Thus, it is possible to define a “typical” domestic wastewater (Metcalf and Eddy 1991). Secondly, a vast amount of experience has been accumulated in the characterization and treatment of domestic wastewater. Numerous environmental discharge regulations have their roots in mitigating the effects of sewage on receiving environments. Finally, many of the leachate treatment techniques are adapted from standard domestic wastewater treatment processes. This inherent commonality with domestic sewage allows it to be used as a solid base from which to compare other wastewaters and make predictions regarding their possible effects on receiving environments. It needs to be remembered, of course, that there are fundamental differences between domestic sewage and industrial wastewaters and that comparing them is not equivalent to equating them.

4.3 Results and Discussion

4.3.1 Physical parameters

In addition to its dark appearance and strong smell, the leachate which collected in the pool at the base of the Pile was characterized by a very consistent set of physical parameters. Observations were conducted for more than two years and only slight variations were observed in the various aspects being monitored. No obviously discernible seasonal patterns were observed. While only assessed qualitatively, such characteristics as odour, visual appearance of the leachate, and pool size did not change appreciably over the duration of the project (with the exception of the general flooding which occurred, due to the Fraser River inundating the area during the summer of 1999 -
4.0 CEDAR LEACHATE CHARACTERIZATION

4.3 Results and Discussion

Table 4.2 Cedar leachate characterization data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Average</th>
<th>Std. Dev</th>
<th>n</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature (ambient)</td>
<td>°C</td>
<td>13.0</td>
<td>3.0</td>
<td>7</td>
<td>probe: YSI Model 55 DO Meter</td>
</tr>
<tr>
<td>dissolved oxygen (ambient)</td>
<td>mg/L</td>
<td>0.4</td>
<td>0.1</td>
<td>7</td>
<td>probe: YSI Model 55 (air-calibrated)</td>
</tr>
<tr>
<td>pH (ambient)</td>
<td>-</td>
<td>3.56</td>
<td>0.16</td>
<td>7</td>
<td>probe: Orion Model 230A pH meter</td>
</tr>
<tr>
<td>specific conductivity</td>
<td>uS/cm</td>
<td>903</td>
<td>237</td>
<td>6</td>
<td>probe: YSI Model 33 SCT Meter</td>
</tr>
<tr>
<td>Physical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH (at saturated DO)</td>
<td>-</td>
<td>3.8</td>
<td>n/a</td>
<td>1</td>
<td>gentle aeration, monitored by pH &amp; DO probes</td>
</tr>
<tr>
<td>Solids:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Settled</td>
<td>mL/L</td>
<td>&lt;0.5</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 1840B (filtered (0.45um), then Helige aqua-tester)</td>
</tr>
<tr>
<td>Total</td>
<td>mg/L</td>
<td>6552</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>Fixed (total)</td>
<td>mg/L</td>
<td>960</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>Volatile (total)</td>
<td>mg/L</td>
<td>5592</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>TSS (Total Suspended Solids)</td>
<td>mg/L</td>
<td>21</td>
<td>16</td>
<td>9</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>Volatile (suspended)</td>
<td>mg/L</td>
<td>9</td>
<td>10</td>
<td>9</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>TDS (Total Dissolved Solids)</td>
<td>mg/L</td>
<td>6508</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>Fixed (dissolved)</td>
<td>mg/L</td>
<td>955</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>Volatile (dissolved)</td>
<td>mg/L</td>
<td>5553</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (ICP scan)</td>
</tr>
<tr>
<td>Colour:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apparent (at ambient pH)</td>
<td>APHA CU</td>
<td>1000</td>
<td>n/a</td>
<td>1</td>
<td>visual comparison (Helige aqua-tester)</td>
</tr>
<tr>
<td>True (at ambient pH)</td>
<td>APHA CU</td>
<td>1000</td>
<td>n/a</td>
<td>1</td>
<td>filtered (0.45um), then Helige aqua-tester</td>
</tr>
<tr>
<td>True (at pH &gt;8.5)</td>
<td>APHA CU</td>
<td>20000</td>
<td>n/a</td>
<td>1</td>
<td>filtered (0.45um), then Helige aqua-tester</td>
</tr>
<tr>
<td>Chemical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alkalinity (as CaCO₃)</td>
<td>mg/L</td>
<td>0</td>
<td>n/a</td>
<td>n/a</td>
<td>(because pH &lt; 4.5)</td>
</tr>
<tr>
<td>acidity (as CaCO₃)</td>
<td>mg/L</td>
<td>2651</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (pH titration)</td>
</tr>
<tr>
<td>hardness (as CaCO₃)</td>
<td>mg/L</td>
<td>387</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 2310B (pH titration)</td>
</tr>
<tr>
<td>total metals:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aluminum</td>
<td>mg/L</td>
<td>19</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>calcium</td>
<td>mg/L</td>
<td>83</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>copper</td>
<td>mg/L</td>
<td>&lt;0.1</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>iron</td>
<td>mg/L</td>
<td>75</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>magnesium</td>
<td>mg/L</td>
<td>44</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>nickel</td>
<td>mg/L</td>
<td>&lt;0.1</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>lead</td>
<td>mg/L</td>
<td>&lt;0.4</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>zinc</td>
<td>mg/L</td>
<td>0.4</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>dissolved organic carbon (DOC)</td>
<td>mg/L</td>
<td>3800</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 5310B (NDIR detector)</td>
</tr>
<tr>
<td>dissolved inorganic carbon (DIC)</td>
<td>mg/L</td>
<td>&lt;0.1</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 5310B (NDIR detector)</td>
</tr>
<tr>
<td>ammonia (NH₃-N)</td>
<td>mg/L</td>
<td>0.96</td>
<td>0.82</td>
<td>7</td>
<td>Lachat Quik-Cheh² (Method #10-107-06-01)</td>
</tr>
<tr>
<td>nitrate + nitrite (NO₃-N)</td>
<td>mg/L</td>
<td>0.17</td>
<td>0.22</td>
<td>7</td>
<td>Lachat Quik-Cheh² (Method #10-107-06-01)</td>
</tr>
<tr>
<td>ortho-phosphate (PO₄³⁻-P)</td>
<td>mg/L</td>
<td>3.24</td>
<td>0.73</td>
<td>8</td>
<td>Lachat Quik-Cheh² (Method #10-115-01-01)</td>
</tr>
<tr>
<td>total phosphorus</td>
<td>mg/L</td>
<td>4.0</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 3120B (ICP scan)</td>
</tr>
<tr>
<td>chemical oxygen demand (COD)</td>
<td>mg/L</td>
<td>14116</td>
<td>4074</td>
<td>8</td>
<td>Std Mthd: # 3220D (closed reflux)</td>
</tr>
<tr>
<td>volatile fatty acids (VFAs), C₁₂ - C₁₈</td>
<td>mg/L</td>
<td>1673.7</td>
<td>492.4</td>
<td>7</td>
<td>GC* re; Supelco, Inc. GC Bulletin 751G</td>
</tr>
<tr>
<td>tannins and lignins (as tannic acid)</td>
<td>mg/L</td>
<td>2874.4</td>
<td>742.7</td>
<td>9</td>
<td>Std Mthd: # 5550B (colorimetric)</td>
</tr>
<tr>
<td>Biological</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>biochemical oxygen demand (BOD₁)</td>
<td>mg/L</td>
<td>3110</td>
<td>n/a</td>
<td>1</td>
<td>Std Mthd: # 5210B; unseeded</td>
</tr>
<tr>
<td>biochemical oxygen demand (BOD₂)</td>
<td>mg/L</td>
<td>5555</td>
<td>1847</td>
<td>9</td>
<td>Std Mthd: # 5210B; seeded</td>
</tr>
<tr>
<td>toxicity (adjusted to pH = 4.5 - 5.0)</td>
<td>% v/v</td>
<td>1.4</td>
<td>1.0</td>
<td>7</td>
<td>Rainbow trout 96hr LC₅₀</td>
</tr>
</tbody>
</table>

NOTES
1. Std Mthd = Standard Methods (APHA 1995)
2. APHA CU = APHA colour units
3. ICP = inductively coupled spectrometer
4. NDIR = non-dispersive infrared (Model used = Shimadzu TOC-500)
5. Lachat Quik-Chem 8000 automated flow-injection ion analyzer
6. GC = gas chromatograph (Model used = HPGC 5880A)
7. BOD seed = 0.1 g of pool-side soil per 300 mL BOD bottle
8. LC₅₀ = lethal concentration which causes mortality in 50% of test organisms

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once the floodwaters receded, conditions returned to what they had been previously). The physical parameters which were measured did not exhibit large variations either (Table 4.2). The pH of leachate in the pool was consistently around 3.5, which places it at the lower extreme of the range observed for municipal landfill leachates (Table 2.1). Even in the middle of winter, the cedar leachate was fairly warm (13°C), presumably heated by the composting occurring within Pile. The level of dissolved oxygen present in the pool was consistently less than the DO meter could reliably measure (i.e., <1 mg/L).

Compared to untreated domestic wastewater, the leachate contained a very high level of TDS and a very low level of TSS (Metcalf and Eddy 1991). Over 99% of the solids present in the leachate were dissolved solids and 85% were dissolved volatile solids (i.e., soluble organic compounds) (Table 4.2). In the context of water treatment, “solids” are defined as any matter, other than water, which is present in the liquid. In practice, this means all materials not having a significant vapour pressure (i.e., nonvolatile) when heated to 103 - 105°C, since these materials are lost during the analysis procedure (Sawyer et al. 1994). Thus, the vast majority of the contaminants present in this leachate were in a soluble form. This was reflected in other parameters such as specific conductivity. Even the colour was caused by soluble compounds, as shown by comparing the “apparent” and “true” colour values (Table 4.2). Unfortunately, this lack of suspended solids meant that very little treatment would be achieved through the use of flocculation / settling. In essence, any suspended solids which did seep out of the Pile had already been removed in the leachate pool, which acted as a settling pond, and the leachate was left with its soluble contaminants.

The leachate was highly coloured (Table 4.2), and the colour exhibited the interesting property of being strongly pH-dependent (Figures 4.1 and 4.2), which suggested that it was largely due to some form of weak acid which, as pH changed, caused a shift in its protonation, and therefore its spectral properties. Considering the leachate’s source and appearance, these acids were presumably similar to some of the highly-coloured, organic acids found in pulp mill effluent.
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While these organic acids represent a diverse, and to some extent, still unknown group of compounds, their colour, or more precisely, their spectral properties can sometimes be used to characterize them and gain some understanding about their composition. Since specific functional groups on molecules will have certain spectral responses, spectroscopy can be used as an identification tool.

The presence of absorbance peaks at specific wavelengths is indicative of specific compounds or functional groups (Dyer 1965). The intensity of the absorbance is governed by the concentration of those compounds. (This premise is the foundation of all colorimetric analyses, including the Standard Methods for COD and tannin and lignin.)

Spectrophotometer scans of the raw leachate gave very consistent results, with a very characteristic shape (Figure 4.3). The general shape is strikingly similar to that produced by a pure solution of tannic acid (Figure 4.4). The characteristic double peak is seen for many substituted organics, and the wavelengths of this pair of absorbance peaks have been used to define a "fingerprint" for a list of substituted functional groups (Dyer 1965). For both tannic acid and the raw leachate, the primary peak occurs at 210 nm, followed by a secondary peak at 278 nm. This matches most closely to the spectral fingerprint of a polyphenolic compound containing a hydroxyl group (Dryer 1965). Thus, spectrophotometer scans of the raw leachate could potentially be used as a quick and inexpensive preliminary characterization tool, to help guide more detailed analyses.

4.3.2 Chemical parameters

The organic acid hypothesis was further supported by the very strong acidity which was measured (Table 4.2). Since the pH was below 4.5, by definition (APHA 1995) no
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Figure 4.2 pH-dependant colour change in cedar leachate (note the dilutions)
(left-right: pH 3.0, 4.0, 4.5, 5.0 (all 10% v/v) and pH 6.0, 7.0, 8.0, 9.0, 10.0 (all 2% v/v))

Figure 4.3 Spectral response of raw leachate (UV-visible light).

Figure 4.4 Spectral response of tannic acid (UV-visible light).
alkalinity was present. The degree of hardness (387 mg/L) fell within the “very hard water” classification (APHA 1995). With the exception of calcium and magnesium (i.e., hardness) and iron (a common, relatively innocuous metal) and aluminum, there were low concentrations of metals present in the leachate. A previous study on this same leachate observed a similar composition in 1992 (Triton 1993) (see Appendix D.1 for details). From a toxicological perspective, any trace metals which were present would have had a lower toxicity due to the high hardness of the leachate (Borgmann 1983). However, aluminum was present in high concentrations, possibly due to mobilization from the native soils by the acidic leachate. Despite the mitigating effects of hardness, aluminum concentrations could still have been sufficient to be toxic (Howard Bailey, personal communication).

Although many wood leachates are nutrient-poor, it has been reported that some wood leachates can have a sufficient nutrient supply to cause eutrophication problems in local receiving environments (Thomas 1977). The cedar leachate at this research site was very nutrient-poor. Although some ortho-phosphate (3.2 mg/L) was present, it was very little in relation to the very high organic carbon that was present (3800 mg/L); the ortho-phosphate:carbon ratio was only 0.0012. Even a dilute domestic wastewater will typically have an ortho-phosphate:carbon ratio at least ten times as high (Metcalf and Eddy 1991). The nutrient:carbon ratios for ammonia and nitrates were even lower. This meant that while the leachate had a very high carbon load, there were few nutrients available to supply any of the biological systems which may have been capable of degrading it. (This is in sharp contrast to many municipal landfill leachates, which have solubilized so much nitrogen from the food and other waste that the nitrogenous concentrations are high enough to be toxic to most aquatic life and may represent the primary pollutant of concern.)

Similar to landfill leachate, the COD of the cedar leachate was extremely high (>14 000 mg/L), especially when compared to the typical COD of raw sewage (500 - 1000 mg/L) (Metcalf and Eddy 1991). The COD test is used to determine the total
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amount of oxygen required to carry out all the oxidation reactions within a sample, without regard to the biodegradability of the compounds (Sawyer et al. 1994). While some smaller, simpler compounds, such as volatile fatty acids (VFAs), may be more easily biodegraded than larger, more recalcitrant compounds such as tannin and lignin, this cannot be detected by the COD test. However, the COD measurements are important because they provide an approximation of the total carbon-load present.

VFAs are short-chain fatty acids and their size can be denoted by the number of carbon atoms they contain; the smallest VFA is acetic acid, with only two carbons (i.e., $C_2$). VFAs are produced as by-products of certain fermentation (i.e., anoxic metabolism) processes. The leachate had very high concentrations (>1650 mg/L), and it was these abundant VFAs which were responsible for its strong smell. Examining the individual VFA concentrations (Table 4.3), the smaller compounds (e.g., acetic acid ($C_2$)) were more abundant than the larger acids (e.g., hexanoic acid ($C_6$)). This is as expected, since the smaller molecules are simpler and would be involved with more common, less specialized metabolic applications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average $^1$</th>
<th>Std. Dev.</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Total</em> ($C_2$ - $C_6$)</td>
<td>1674</td>
<td>492</td>
<td>7</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>753</td>
<td>211</td>
<td>7</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>328</td>
<td>97</td>
<td>7</td>
</tr>
<tr>
<td>Butyric acid + Iso-butyric acid</td>
<td>314</td>
<td>130</td>
<td>7</td>
</tr>
<tr>
<td>Valeric acid</td>
<td>169</td>
<td>108</td>
<td>7</td>
</tr>
<tr>
<td>n-Hexanoic acid</td>
<td>110</td>
<td>28</td>
<td>7</td>
</tr>
</tbody>
</table>

*NOTES*
1. All values reported in mg/L

The VFAs are a very easily degraded carbon source and their presence in the leachate provided an alternative food source for those microbial communities which may have had trouble degrading more recalcitrant compounds. The cedar leachate also had a very high concentration of tannin and lignin (>2800 mg/L), which is not surprising, considering its source. This class of compounds is noted for its resistance to biological degradation and
is also suspected as one of the primary toxicants in many wood leachates (Bailey et al. 1999; Eaton and Hale 1993).

The theoretical oxygen demand (ThOD) that these two classes of compounds represent can be calculated from their balanced oxidation reactions (see Appendix C) and this can be compared against the total oxygen demand of the leachate (i.e., COD). In this way, an estimation can be obtained for the proportion of total COD that is represented by these two classes of compounds (Table 4.4). It should be realized that while each VFA (C₂ to C₆) was measured independently, this was not the case with tannin and lignin. Standard Method #5550B (APHA 1995) measures the abundance of aromatic hydroxyl groups (present on tannin and lignin) and reports the concentration in terms of tannic acid. In other words, tannic acid is being used as a surrogate compound to represent what is a very large, diverse, and to some extent, still unknown group of compounds (no alternate, easily-applied analytical method was available). Thus, the ThOD calculated for tannin and lignin will only be an estimation of their actual oxygen demand, and this demand may change over time, undetected, if the concentration of the overall group remains the same but the relative concentrations of the different tannins or lignins change. This should be kept in mind when interpreting the ThOD results.

The ratio of total VFA ThOD to COD was 0.16 (Table 4.4). This means that approximately 16% of the overall COD was due to VFAs. Similarly, the ratio of the tannin and lignin ThOD to COD was 0.21. Taken together, the total ThOD of these two compound classes accounts for only 37% of the COD. From a mass balance perspective, this means that only ~37% of the total oxidizable load present in this leachate was attributable to these compounds. Another 63% was due to unknown compounds. This becomes important when trying to understand and optimize a treatment process.

4.3.4 Biological parameters
In contrast to COD, BOD is a measure of the oxygen demand of all the biologically mediated reactions occurring in a water sample (Sawyer et al. 1994). In a practical sense,
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this means that the consumption (i.e., demand) of oxygen by the microbial communities is measured under standard conditions of temperature, light, and oxygen and nutrient availability. Any compounds which are not biodegradable will theoretically not exert an oxygen demand under these test conditions, and thus the test gives a measure of the amount of oxygen that will be consumed under optimal aerobic conditions as the wastewater undergoes complete biodegradation. Of course, this assumes that the proper microbial communities (i.e., those capable of metabolizing the waste under mesophilic aerobic conditions) are present. If the water sample is lacking these organisms, they must be added ("seeded") before comparable results will be obtained.

Typical domestic wastewaters have a 5-day BOD of ~200 mg/L (Metcalf and Eddy 1991). The cedar leachate sampled from the pool had a seeded 5-day BOD of >5500 mg/L (Table 4.2). This was not unexpected, given the very high COD values discussed earlier. Comparatively, there was a BOD : COD ratio of 0.40 (Table 4.4), which is within the lower end of the range typically reported for domestic wastewater (Metcalf and Eddy 1991). Thus, approximately 40% of the COD is attributable to easily biodegradable substances. Considering that cedar wood is not a readily biodegradable material, this BOD : COD ratio was surprisingly high. Landfill leachate often has a much lower ratio, indicative of the higher proportion of recalcitrant compounds.

Table 4.4 Oxygen demand ratios

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Average</th>
<th>Std. Dev.</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThOD(VFA) : COD</td>
<td>0.16</td>
<td>0.03</td>
<td>6</td>
</tr>
<tr>
<td>ThOD(T&amp;L) : COD</td>
<td>0.21</td>
<td>0.02</td>
<td>6</td>
</tr>
<tr>
<td>ThOD(VFA + T&amp;L) : COD</td>
<td>0.37</td>
<td>0.05</td>
<td>6</td>
</tr>
<tr>
<td>ThOD(VFA) : BOD</td>
<td>0.40</td>
<td>0.06</td>
<td>6</td>
</tr>
<tr>
<td>BOD : COD</td>
<td>0.40</td>
<td>0.08</td>
<td>8</td>
</tr>
</tbody>
</table>

In the same way that the ThOD of known compounds can be compared against the total oxygen demand (i.e., COD), a comparison can be made between the ThOD of readily biodegradable compounds and the BOD. VFAs are considered to be readily biodegradable. Their ThOD, compared against the seeded BOD₅ data gave a ThOD : BOD ratio of 0.40 (Table 4.4). Thus, 60% of the biodegradable load in this leachate was due to unknown compounds.

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It is interesting to note that when the BOD tests were not provided with a seed, the measured BOD was almost half of what was measured otherwise (Table 4.2, Figure 4.5). The seed used in these BOD tests was forest soil taken from the banks of the leachate pool. The theory was that the microbial communities present in a forest soil would be adapted to metabolizing wood chemicals, including some of the extractives that are toxic to other lifeforms, and thus should provide a good inoculant for the development of an appropriate microbial community. Only the equivalent of 0.1 g (moist weight) of soil was added to each 300 mL BOD bottle, thereby preventing this seed from interfering with the BOD results, either in the form of additional oxygen demand, or via providing a substantial amount of bonding sites (on clay particles, etc.) on to which various contaminants could possibly adsorb onto. Seeded blanks were used in every BOD test, and they consistently had an oxygen demand of <1.0 mg/L (all sample results were corrected for this small background oxygen demand).

The BOD results that have been reported so far are all 5-day BOD results, the standard test length. However, this only captures a portion of the total oxygen demand of a wastewater, since some compounds will take longer than five days to metabolize, and thus will still exert an oxygen demand beyond this point. It is generally considered that by Day 20, >99% of the ultimate BOD will have been exerted (Metcalf and Eddy 1991; Sawyer et al. 1994). However, when an extended BOD test was performed on the cedar leachate, it appeared as if this pattern did not hold true for this wastewater. At Day 20, the BOD exertion curve appeared to be still rising (i.e., slope > 1.0) (Figure 4.5). However, it is doubtful that this was due to a very low overall BOD kinetic rate constant (k), as might be expected for a recalcitrant industrial wastewater.
Examination of the seeded data for Day 0 to Day 12 suggested a BOD reaction rate in the order of 0.5 $d^{-1}$, which is extremely fast; the typical rate for domestic wastewater is between 0.10 - 0.17$d^{-1}$ (Metcalf and Eddy 1991; Sawyer et al. 1994). However, this would suggest that by Day 5, almost all of the ultimate BOD would have been exerted, and no more oxygen should be required beyond this point. From the way that the BOD exertion curve (Figure 4.5) rose steeply, reached a plateau, and then began to rise again, it implied that the ultimate BOD was actually higher than the Day 0 - Day 12 data suggested and that the microbial communities may have been switching food sources, using easily degraded sources first (e.g., the VFAs), and then switching to more recalcitrant materials, possibly the lignins or other complex organic molecules, which they continued to degrade at a slow rate over a longer time period.

In addition to possible hints about microbial community dynamics, the oxygen demand kinetics also provided us with information about the short-term behaviour of this wastewater. Since the BOD for this leachate was so high and the short-term kinetic rate constant so fast, the leachate would be expected to have a very "aggressive" oxygen demand. This was supported by the very low DO concentration of the leachate pool. It gained further anecdotal support when the fish toxicity tests were being set up. It was extremely difficult to achieve a sufficient dissolved oxygen level in the test solutions. In order to meet the requirements of the test protocols (Environment Canada 1990), it was necessary to aerate the samples at the maximum allowable rate. If the air supply ever failed, the test sample would very quickly go anoxic (and the test would have to be redone). In an aquatic receiving environment, this characteristic means that, aside from any toxicity which may be present due to its chemical composition, this wastewater would, from an oxygen supply perspective alone, impose a substantial stress upon any organisms (fish, zooplankton, etc.) which came in contact with it inside its nearfield mixing zone.

In order to separate such stressors as oxygen demand from the question of composition-based toxicity, laboratory toxicity tests are employed. These toxicity tests are conducted
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under stringently-defined standardized conditions, including specifications ensuring that sufficient oxygen is supplied to the test organisms. The resulting conditions are such that any observable negative effects to the test organisms (e.g., zooplankton, algae, juvenile fish) are due to composition-based toxicity present in the sample.

As determined by the rainbow trout 96-hour LC$_{50}$ test procedure (Environment Canada 1990), the cedar leachate had an LC$_{50}$ of 1.4% v/v (± 1.0) (Table 4.2). This was consistent with what was measured over seven years earlier for this same leachate (Triton 1993) (see Appendix D.1). Toxicities reported in the literature for other wood leachates ranged from 0.48% to >100%, as measured by the rainbow trout 96-hour bioassay procedure (Cameron 1982; Schermer and Phipps 1976; Slagel 1976). Several factors may be responsible for this range in observed toxicities. Wood species has a profound effect on leachate toxicity (Schermer and Phipps 1976; Slagel 1976; Thomas 1977). Different parts of the tree also produce considerable differences in leachate toxicity, with bark and heartwood generally being the source of the more toxic leachates (Schermer and Phipps 1976; Slagel 1976). Adjusting for these various influences when comparing the variously reported toxicities is usually not possible. Whether the wood waste is of bark or heartwood origin or what species it is from may not be known, since most wood waste is very heterogeneous and has a variety of sources.

Landfill age is also a factor, as older wood waste landfills usually generate less toxic leachate (Schermer and Phipps 1976). However, the exact rate at which toxicity diminishes with landfill age is not something that is easily determined, and in all likelihood is very site-specific. Studies such as Schermer and Phipps (1976) had noted that in small, experimental wood waste landfills, leachate strength diminished rapidly, sometimes in as little as 80 days. In contrast, the composition of the leachate emanating from this Pile had changed little in more than seven years (Triton 1993) (see Appendix D.1). Possible reasons for this contrast include differences in the pattern and total amount of rainfall, the size of the landfills, and their internal conditions. Higher internal
temperatures and more acidic conditions may cause more pronounced degradation of the wood, thereby liberating more wood chemicals to the leaching process.

The toxicity of wood leachate may also be pH-dependent, which would further complicate meaningful comparisons between different leachates. Observations made during this research indicate that the toxicity of the cedar leachate increased with decreasing pH. Just as the colour was affected by changing pH, so may the toxicity be affected. However, separating what is pH-dependent toxicity versus what is organism stress induced solely by low pH is not easy. Various observations indicated that pH-induced stress began to occur at a pH below 4.5. Above a pH of around 6.0, the toxicity of the cedar leachate seemed to diminish markedly. However, the data is limited (see Appendix D.1) and more rigorous testing needs to be done before this characteristic can be established with certainty.

Attempts were made to establish the identity of the toxicants through the use of toxicity identification evaluations (TIEs) (US EPA 1991a), but problems were encountered because the leachate contained such high concentrations of the compounds being examined that column breakthrough occurred quickly when using the commercially available solid phase extraction (SPE) separation columns. It would be necessary to construct custom columns of a much larger size in order to collect a sufficient volume for bioassay testing.

Despite the need for more research in order to determine the exact identities of the toxicants in this leachate, it is still possible to make some preliminary conclusions concerning toxicant identity. Toxic thresholds have been established for many compounds (US EPA 1999), and these can be compared against their measured concentrations in this leachate. While copper and zinc, two trace metals reputed for their toxicity, were not present in significant concentrations, aluminum was present in sufficient concentrations to be a potential toxicant. The concentrations of the individual VFAs were also measured. However, very limited information was available on their
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toxicity to fish. Acetic acid was shown to be toxic to rainbow trout above a threshold of 315 mg/L, while propionic acid had a rainbow trout toxic threshold of 67 mg/L (US EPA 1999). However, no information was provided regarding what pH these tests were conducted at or whether the toxicity of these compounds changed with pH. Assuming no pH-effects, both of these compounds were present at toxic concentrations in the cedar leachate.

It has been suggested that tannin and lignin may represent another of the major organic toxicants in wood leachate (Bailey et al. 1999). While their toxicity seems to be influenced by the species of wood they are extracted from, this class of compounds has been shown to be toxic to fish at concentrations as low as 15 mg/L (Power 1987). The concentrations measured in this cedar leachate were almost 200 times stronger than this threshold (Table 4.2). Lignans, a class of compounds similar to lignins, have been reported as having a more mild toxicity to fish (toxic threshold ≈60 mg/L) (Peters et al. 1976). Tropolones, an extractive found in cedar heartwood, are much more toxic (toxic threshold ≈0.3 mg/L) (Peters et al. 1976). Interestingly, tropolone toxicity is greatly reduced when the pH is increased towards neutrality (Slagel 1976). Since the Standard Methods analysis for tannin and lignin (Method #5550B, APHA 1995) detects aromatic hydroxyl groups, it is unable to distinguish between tropolones and true tannin and lignin. Also, tropolones will be retained on an SPE column along with tannin and lignin and will thus travel with tannin and lignin during any TIE procedure based on SPE fractionation. Using a TIE procedure based on molecular size exclusion may assist in better separating the respective roles of these organics in the toxicity of wood leachate, since tropolones are much smaller molecules (∼C₇ - C₁₄) than tannin and lignin (∼C₂₀ - >C₁₀₀).

While aluminum, tannin and lignin, possibly all the VFAs, and probably tropolones were present at toxic concentrations within this leachate, the overall toxicity of the leachate is a more complex issue than just the simple summation of these various compounds. Interactions often occur between compounds which effect their toxicity (Marking 1985). If two compounds have a greater toxicity when they are present together, compared to the
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4.4 Conclusions

sum of their individual toxicities, they are considered to have a “synergistic” or “cooperative” toxicity. If the opposite is true, and the combined presence results in a decrease in toxicity, compared to the sum of the individual toxicities, this is considered an “antagonistic” interaction. Antagonism may occur, for example, if two toxic compounds form a non-bioavailable complex when present together in the same solution. It is known that many organic compounds will form chelation complexes with certain metals. Tropolones are strong chelators of iron, and possibly aluminum, and this diminishes their toxicity (Peters et al. 1976). Since the cedar leachate had high concentrations of both iron and aluminum, the measured toxicity may have been less than it could have been, had these metals been absent.

This becomes very important when trying to optimize a treatment process, since a unit process which removes only selected toxicants (e.g., metals) may fail to provide a decrease in toxicity, since the net effect may be the removal of antagonistic interactions and the remaining toxicants are now able to exert their full toxic effect. In some cases, an increase in observed toxicity is even possible. A similar phenomenon may occur if the intermediate breakdown products of some compounds are more toxic than the parent compounds. Thus, if a treatment process is only performing a portion of the degradation cascade, the effluent may be more toxic than the influent.

4.4 Conclusions

The cedar leachate from the Pile could be considered an industrial wastewater that was at least an order of magnitude stronger than raw domestic wastewater. It was acidic, nutrient-poor, and had a very high, and aggressive, oxygen demand. Even when its oxygen demand was accounted for, it was still very toxic. This toxicity was unlikely caused by trace metals or ammonia, due to their low concentrations in this leachate. The exception was aluminum, which may represent one of the toxicants. Other possible toxicants include VFAs, tropolones, and tannin and lignin. Complex interactions among the many constituents of this leachate are likely, making the exact determination of the various toxicants an intricate process.
4.0 CEDAR LEACHATE CHARACTERIZATION

4.4 Conclusions

Most of the contaminants present were soluble organics (85% by mass), and the lack of suspended solids presented little opportunity to provide treatment via flocculation or settling techniques. The leachate's strong colour, and possibly its toxicity, were strongly pH-dependent. Substantial concentrations of VFAs and tannin and lignin were present, but these only accounted for ~37% of the COD. Surprisingly, the leachate had a BOD : COD ratio similar to domestic wastewater, but this was where the resemblance ended.

Other wood leachates reported in the literature had similar characterizations, but there existed a broad enough range of reported values that it would be advisable to perform individual characterizations prior to developing any site-specific treatment and control recommendations. This is especially prudent when considering that such site-specific factors as mobilization of metals from native soils may play a very important role in a leachate's toxicity and treatability.

Further research is needed to clarify several issues surrounding the specific causes of the toxicity in this leachate. It is recommended that molecular size exclusion procedures be used in order to determine whether the organic compound toxicity resides with the smaller or larger molecular compounds (e.g., tropolones versus tannin and lignin). Establishing whether tropolones are responsible for much of the observed toxicity will greatly assist in monitoring and optimizing any treatment process. Also, the toxicity of isolated reagents such as individual VFAs, tannic acid or specific tropolones can be tested directly, thereby providing a standard against which to compare the environmental samples. These synthetic analogues of wood leachate could also be manipulated to determine how their toxicity is affected by changes in pH and how much of a role is played by antagonistic and synergistic interactions. The role of aluminum should be elucidated.

Additionally, a more detailed study of the long-term exertion of BOD would provide useful information regarding the pattern of microbial degradation and address the substrate-switching hypothesis outlined above. During the course of the long-term BOD
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test, concentrations of various leachate components (e.g., VFAs, small and large molecular class compounds) could be monitored to see how they change, especially in relation to the BOD exertion pattern. In addition to information on degradation kinetics, this will provide valuable insights into what types of organisms are responsible for any observed biodegradation.
5.0 SCREENING TRIALS

5.1 Introduction

The first step in the development of a biological treatment system to treat the cedar leachate was to establish whether the leachate was amenable to biological degradation. Thomas (1977) reported an inability to treat cedar leachate using laboratory-scale (45 litre) completely-mixed aerobic reactors. The reactors were seeded with biological sludge taken from an activated sludge system treating bleached kraft pulp mill effluents and had a hydraulic retention time (HRT) of 14 days. Schermer and Phipps (1976) observed satisfactory treatment when the leachate was passed through a column of soil, but the treatment performance diminished quickly over time, with breakthrough occurring in a little as 20 days. This implies that the treatment was accomplished by a physical absorption-type mechanism and its capacity would be limited by the mass loading it experienced, in a manner similar to ion-exchange or activated carbon systems.

In December 1997, screening trials were conducted to determine whether any of several environmental inoculants had an ability to biodegrade the cedar leachate. Samples of macrophytes, fungi, and soil were collected from the site and used to seed small completely-mixed aerobic reactors. Changes in toxicity were monitored over time. The work was performed at the laboratory facilities of EVS Environment Consultants.

5.2 Methods and Materials

In a laboratory Controlled Environment Room (CER) set at 20 °C, with a 16:8 hr (light:dark) photoperiod, thirty-two aerated batch reactors (1 L acid/acetone-washed glass jars) were set up. A concentration series was prepared from the leachate (100, 10, 1%v/v, plus a distilled water blank) and distributed over eight identical sets of reactors (i.e., each set represented one dilution series).

This setup allowed three environmental inoculants, plus a non-inoculated control, to be
tested in replicate. The inoculants (pool-side soil, duckweed, and fungi) were all sampled from the field site at locations which were periodically exposed to the leachate. The biological systems they represented would have had the opportunity to adapt to the contaminants in the leachate, and therefore they all represented potential seeds specifically suited for this wastewater.

Each 1 L reactor in a dilution series was supplied with 20 g (moist weight) of one of the inoculants, with the exception of the two control sets, which were not inoculated. The batch reactors (Figure 5.1) were aerated continuously to maintain saturated DO levels. Changes in water quality (pH, DO, and conductivity) were monitored daily. After eleven days of aeration, the cultures were allowed to settle and then were poured through a 250 μm sieve to remove any suspended material. The acute toxicity of the filtrate was determined using a modified rainbow trout bioassay (as per Bailey et al. 1999). After the toxicity results were obtained, the solutions were sieved (250 μm) and subjected to a UV-visible spectrophotometer scan (190 - 820 nm) as described in Section 4.2, in case any general differences could be detected in spectral response between the various treatments.

This test matrix allowed each inoculant to be tested in a range of leachate strengths, and its performance compared against the same range of leachate dilutions which had only received aeration (i.e., the control sets). In this way, it was possible to separate reductions in toxicity that were due to degradation caused by aerobic organisms indigenous to the leachate or physical factors such as air-stripping from those reductions that were solely due to the addition of inoculant material.

5.3 Results and Discussion

Monitoring of water quality in the reactors provided assurance that the desired test conditions were being maintained and that the replicate sets of reactors were performing in a similar fashion (see Appendix D.2 for raw data). With the exception of one day of
5.0 SCREENING TRIALS

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![Graphs showing results of screening trials for soil, fungal, control, and duckweed treatments.](image)

Figure 5.2: Screening trial water quality data: dissolved oxygen (L aerated batch reactors using three different inoculants to treat cedar leachate over a range of concentrations).
5.3 Results and Discussion

Figure 5.3: Screening trial water quality data: Conductivity
5.0 SCREENING TRIALS

5.3 Results and Discussion

Figure 5.4: Screening trial water quality data: pH
(1 L aerated batch reactors using three different inoculants to treat cedar leachate over a range of concentrations)
insufficient aeration in the 100% reactors, DO was consistently maintained above saturation until the aeration was turned off at the end of the test (Figure 5.2). Conductivity remained largely unchanged in all treatments (Figure 5.3). In the 10% and 1% concentrations, pH rose to close to neutral in all treatments except the control sets. The 100% concentrations experienced negligible change in pH. In the control sets, pH in the 10% and 1% concentrations exhibited a gradual, and fairly limited rise, presumably indicative of the removal of volatile acids due to air-stripping (Figure 5.4). Although not measured quantitatively, the strong smell characteristic of this leachate was quite pronounced when the bioreactors were initially started, but diminished rapidly, and after a few days was hardly detectable.

After eleven days of treatment, pool-side soil produced the greatest reduction in toxicity (Figure 5.5). Duckweed was also effective, but to a lesser extent. The fungal inoculants actually increased the toxicity and even their distilled water controls (i.e., 0% leachate) showed toxicity. This may have been the result of toxic compounds being leached from the fungal tissues. The control series produced only a slight reduction in toxicity, indicating that aeration alone would not prove an effective treatment technique. No readily interpretable differences between the various treatments were revealed by the spectrophotometer scans (see Appendix D.2).

### 5.4 Conclusions

Based on the above results, the cedar leachate was amenable to biological treatment. Two of the environmental inoculants tested were able to substantially reduce the toxicity beyond what was afforded by aeration alone, with pool-side soil providing the better toxicity reduction. For these reasons, pool-side soil was selected as the inoculant when the biological treatment of the cedar leachate was studied further.
6.0 BENCH-SCALE TREATMENT WITH MICROCOSM WETLANDS

6.1 Introduction

Having established that cedar leachate was amenable to biological toxicity reduction, it was necessary to determine whether constructed wetlands were capable of performing this treatment. Bench scale testing of wetland microcosms inoculated with pool-side soil was performed in February and March 1998, with a repetition of these tests in April and May 1999. Water quality parameters (pH, DO, conductivity) and changes in toxicity were monitored in these batch reactors. The second set of microcosms was also used to gather more detailed data about specific parameters such as tannin and lignin concentrations. The microcosms were set up in the laboratory facilities at EVS Environment Consultants and analytical work was performed in the Environmental Laboratory at the University of British Columbia.

6.2 Methods and Materials

6.2.1 Test setup and conditions

Eight small wetlands were constructed as laboratory batch microcosms (Figure 6.1) and placed in a 22°C CER. Clean 38 L glass fish tanks (25 cm x 50 cm x 30 cm deep) were provided with a 1 cm base of clean silica sand, upon which was placed a 4 cm thick mat of dense root fibres from Broad-leaved Cattails (*Typha latifolia*) that had been harvested from a nearby pond. All soil present in the root mats had been intentionally washed out during harvesting. The root mats contained no emergent vegetation, since they were

![Figure 6.1 Schematic of the lab microcosms](image)

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harvested prior to the spring emergence of the cattails. All dead stalks from the previous season’s growth were trimmed away for ease of handling. The root mats were divided so as to ensure that several large tuber-like root stalks were present in each microcosm, but the majority of the mats were comprised of a dense network of very fine root hairs (Figure 6.2). On top of the root mat was placed a thin layer (<2 cm) of pool-side soil, to act as an inoculant (see Section 5.0 for discussion regarding selection of inoculant).

Two replicate concentration series (75%, 50%, and 10% v/v) were prepared from the leachate. Randomly selected tanks each received 15 L of one these dilutions. A pair of tanks (complete with root mat, etc.) were filled with 15 L of dechlorinated city tap water each and served as replicate controls. In addition, one tank with just sand, 15 L of dechlorinated water and a bubble pump served as “room blank”. Should any effects (e.g., toxicity) appear in the control tanks, this blank would allow separation of those effects caused by the cattail root mat or soil inoculant from those effects caused by materials used in construction of the microcosm or general conditions present in the test room (e.g., contaminants in the aeration supply). Gro-light tubes were placed over the microcosms, to provide simulated sunlight. Unfortunately, this rack of lights could not be connected to the room’s photoperiod timer, so the microcosm wetlands received light 24 hours a day. This did not appear to have any negative effects on the cattails. Bubble circulators were installed in each tank (Figure 6.3) and adjusted to provide a slow circulation of the leachate through the batch reactor while providing the minimum possible aeration (an attempt to simulate anticipated field conditions, where no supplementary aeration would exist).
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When the second set of microcosms were constructed and tested (April - May 1999), all construction and conditions were the same as the 1998 setup, with the following exceptions:

1. The concentrations series was 50%, 25%, 10% v/v;
2. The CER was set to a temperature of 15°C;
3. The setup was monitored for 29 days, rather than 18 days.
4. Small subsamples were obtained from each reactor on Day 8 and Day 16.

6.2.2 Monitoring

Water quality parameters (pH, DO, conductivity) were monitored regularly (see Appendix D.3 for raw data). Changes in acute toxicity were determined by occasionally taking a 500 mL subsample from each reactor and performing a modified rainbow trout bioassay using 2 fish per beaker (as per Bailey et al. 1999). In order to ensure that the fish tests met the DO levels specified by the protocol, each beaker was gently aerated.

Since evapotranspiration would result in a decrease in bioreactor water level over time, the necessary small amounts of dechlorinated tap water to compensate for this were added as needed to each reactor, thereby preventing evapoconcentration of the contaminants. This is common practice in microcosm work (Howard Bailey, personal communication).

After completion of the bioreactor trials, the reactor water (i.e., “final effluent”) was collected from each microcosm as part of the tear down procedure. BOD tests were performed on these samples. For the 1999 microcosms, these samples were also analysed for COD. The analytical methodologies were as described in Section 4.0.

In the 1999 microcosm experiment, the additional subsamples that were taken after eight and sixteen days were analysed for tannin and lignin, as described in Section 4.2. Spectrophotometer scans was also performed on the raw samples, in order to measure the spectral response of the reactor solution, as described in Section 4.2.
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6.3 Results and Discussion

Monitoring of water quality in the reactors provided assurance that the desired test conditions were being maintained and that the replicate sets of reactors were performing in a similar fashion (see Appendix D.3 for raw data). With respect to these parameters, the systems performed similarly to what was observed in the screening trial soil-inoculated bioreactors (see Section 5.2); conductivity remained largely unchanged and pH became more neutral. However, the microcosms differed from the aerated bioreactors in their DO levels. Since the cattails provided less oxygen transfer than the mechanical aerators, the DO levels were lower (as low as 1.5 mg/L at the higher leachate concentrations). This did not seem to affect the cattails. Within a few days of startup, cattail shoots began to appear in all the microcosms. The plants grew very vigorously (as much as 7 cm per day) and there was little observable difference between the plants growing in the higher leachate concentrations (i.e., 75%) compared to the lower leachate concentrations (i.e., 10%).

Due to the spartan setup of the toxicity bioassays, the results were interpreted in a pass/fail fashion (i.e., they determined whether a tested concentration was toxic or nontoxic), rather than depending upon them to deliver higher resolution information (i.e., an exact LC50). This resulted in the data being interpreted in a conservative (i.e., worst-case) fashion. As shown by Figure 6.4, there was a steady decrease in toxicity with increasing treatment time. It should be noted that this figure incorporates data from both the 1998 and 1999 microcosms, and there were no major differences in their detoxification rates, despite the fact that the 1999 microcosm was operating 7 degrees cooler (i.e., at 15°C, rather than 22°C). The difference between the 15-day and 18-day results in Figure 6.4 is not significant, since the pass/fail nature of the data could not provide resolution as to when a particular concentration became nontoxic.

Figure 6.4 Reduction of cedar leachate toxicity in laboratory constructed wetlands
6.0 BENCH-SCALE TREATMENT WITH MICROCOSM WETLANDS

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(i.e., the results are conservative, and the actual rate of detoxification may have had a steeper slope than these data indicate).

Combining the data from both sets of microcosms, the performance of the laboratory constructed wetlands are summarized in Table 6.1. Overall, removal performance of the monitored parameters was very good. BOD and COD %-removals compare very favourably with the performance of conventional treatment plants (e.g., activated sludge, trickling filters, RBCs) treating domestic sewage (Metcalf and Eddy 1991) and are comparable to the performance of some of the more exotic treatment techniques for treating leachate from hazardous waste landfills (McArdle et al. 1988). As could be expected, toxicity and tannin and lignin experienced better removal with increased reaction times.

The tannin and lignin removal performance seemed to be inhibited at higher influent concentrations (Table 6.1). Since the tannin and lignin data were obtained from bioreactors operating at different influent concentrations, it was not meaningful to compare them directly. However, since the original influent dilution factors were known, these could be used to standardize the data, based on 100% influent strength (i.e., the concentration data could be multiplied by the original dilution factors). This provided a data set which was “normalized”, or corrected for dilution factors, and thus the data points could be compared directly with each other and with the constituent concentrations measured in the original raw leachate.

While each reactor continued to reduce tannin and lignin concentrations over time, those reactors that had been fed a more dilute influent were able to achieve a better overall removal (Figure 6.5). This indicates that the higher strength leachate was experiencing a

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average %-Removal</th>
<th>Std. Dev.</th>
<th>n</th>
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</thead>
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<tr>
<td>Toxicity</td>
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<tr>
<td>8-day HRT</td>
<td>78%</td>
<td>0%</td>
<td>2</td>
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<tr>
<td>15-day HRT</td>
<td>90%</td>
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<td>2</td>
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<tr>
<td>29-day HRT</td>
<td>93%</td>
<td>0%</td>
<td>2</td>
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<tr>
<td>COD (29 day HRT)</td>
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<td>3%</td>
<td>6</td>
</tr>
<tr>
<td>Tannin and Lignins</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>8-day HRT: 10% influent</td>
<td>83%</td>
<td>1%</td>
<td>2</td>
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<tr>
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<tr>
<td>50% influent</td>
<td>63%</td>
<td>4%</td>
<td>2</td>
</tr>
<tr>
<td>16-day HRT: 10% influent</td>
<td>87%</td>
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<td>50% influent</td>
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</tbody>
</table>
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Figure 6.5 Effect of influent dilution on tannin and lignin removal performance (corrected for dilution factor)

Reduced treatment efficiency. This may be due to toxic effects of a higher leachate concentration. Another possibility is that there were not a sufficient number of microbes present that were capable of degrading all the tannin and lignin present at higher concentrations (i.e., the degradation process was operating at maximum capacity, given current population levels). Thus, with time their populations should increase, resulting in an improved treatment efficiency.

Diminished treatment performance at higher influent concentrations was also observed in the spectrophotometer results (Figure 6.6). A substantial difference is seen between the Day 8 and Day 16 results for the 25% reactors (Figure 6.6b). The 10% reactors (Figure 6.6a) show a much-reduced secondary peak (the “shoulder”), and, unlike the 25% case, a higher variation between the replicate reactors. The 50% reactors (Figure 6.6c) show less of a difference between Day 8 and Day 16, and the secondary peak is still very pronounced. Taken together with the tannin and lignin data, these results seem to indicate that more efficient performance is achieved with a more moderate influent concentration.

It is interesting to note the peaks in all three sets of the spectrophotometer results (Figure 6.6a-c) have the same general pattern as the peaks observed for the raw leachate (Figure 4.2). This indicates that the same types of compounds were present. However, the peaks from the microcosm samples are much broader than those from the raw leachate. This may be a result of many similar peaks overlapping at slightly different wavelengths,
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Figure 6.6a Influent leachate strength = 10%

Figure 6.6b Influent leachate strength = 25%

Figure 6.6c Influent leachate strength = 50%

Figure 6.6 Spectral response of laboratory constructed wetland effluent (UV-visible light)
6.4 Conclusions

which would indicate that the samples from the bioreactors contain a more complex mix of compounds than what was present in the original leachate, possibly indicative of more degradation intermediaries being present. Compared to the other two sets of microcosms, the 25% reactors have a broader primary peak, comprised of several overlapping peaks (i.e., the various tips overlap, producing a broad, jagged look to the peak top) (Figure 6.6b, versus 6.6a and 6.6c). This may indicate that of the three sets of reactors, the 25% reactors have the most degradation intermediaries present.

Overall, the spectrophotometer data seem to indicate that an influent strength of 25% will produce the clearest differences with changing retention time. In other words, the inherent degradation systems in the 25% reactor seemed to be operating at maximum capacity. In the 10% reactors, the influent may have been too weak to push the degradation systems to their maximum capacity and it seems that the 50% influent overwhelmed this capacity. These reactors did not produce as “tight” a response to changing conditions as did the 25% reactors and thus an influent strength of 25% was likely to yield the best results in further studies.

6.4 Conclusions

Constructed wetlands were able to treat the cedar leachate. Under optimal laboratory conditions, a substantial reduction in toxicity was observed, with a 90% removal achieved in 15 days. Therefore this technology shows significant promise for fulfilling research objective A.1 (see Section 1.4). The BOD and COD results suggest that this technology would also be able to meet its other the performance-based criteria (objective A.2, Section 1.4).

In order to address the design objectives (B.1 to B.3, Section 1.4), it was necessary to evaluate the technology under field conditions. This would also provide a more realistic setting for the evaluation of its treatment performance, including response to seasonal changes in temperature and plant growth / decomposition dynamics.
7.0 PILOT-SCALE TREATMENT

7.1 Introduction

It was demonstrated that under optimal laboratory conditions, constructed wetlands were capable of providing efficient treatment of cedar leachate, including substantial reductions in acute toxicity and BOD. However, it was still necessary to determine how this performance would translate to a larger scale facility operating under field conditions. To this end, six pilot-scale treatment wetlands were designed and constructed at the research site (Figure 7.1). These experimental cells would allow a controlled evaluation of this technology under more realistic operating conditions. Additionally, they would provide the capability for various simultaneous manipulations to be performed during process optimization.

![Figure 7.1 Constructed wetland pilot-scale facility (as viewed from top of hog fuel pile)]
7.0 PILOT-SCALE TREATMENT

7.2 Methods and Materials

7.2.1 Design considerations

Design of the pilot scale facility occurred in May 1998, with the assistance of Ward Prystay and Envirowest Consultants Limited (ECL). Based on the available literature, the lab results obtained to date, and previous design and field experience, several options were considered. The final cell design was a hybrid system which incorporated 3 basic elements (Figure 7.2);

- a) a small forebay,
- b) a planted surface-flow (SF) section
  (also referred to as free-surface flow (FSF) by some authors), and
- c) a small, unplanted subsurface flow (SSF) section just prior to effluent discharge.

In the interests of promoting a simple and predictable hydrology, the cells were rectangular. Bank-full dimensions were 17.5 m long by 5.5 m wide.

The forebay was intended to provide a small settling basin, just in case any suspended solids entered the influent stream (during pumping, etc.). It also assisted in ensuring that the influent entered the main-scale train in as evenly distributed and quiescent a fashion as possible. The majority of the treatment was expected to occur in the large surface-flow section, where the influent would flow over the surface of the soil substrate and through the root mats and stalks of the emergent vegetation. The subsurface section, just prior to discharge, was intended as a small polishing unit, bringing the wastewater in contact with an attached biofilm community as it flowed through a gravel matrix, and
screening out any large suspended matter, such as algae or detritus, which may have been picked up during passage through the surface-flow section. A lateral effluent collection pipe would be buried near the bottom end of the gravel section and attached to the discharge pipe, which travelled through the base of the end berm.

In addition to the lateral effluent collection pipe (Figure 7.3), influent would be dispersed by a lateral spreader bar (Figure 7.4). These measures were intended to promote an even sheet-flow through the system, resulting in a basin-wide plug-flow hydrology, thereby maximizing effective reactor volume and minimizing hydraulic short-circuiting (Persson et al. 1999). A regular bathymetry, with a flat bottom, trapezoidal profile (side slopes =35°), and an even depth (except for the forebay) also contributed to this end. The vegetation was to be planted in lateral bands in order to ensure that flow resistance was distributed evenly across the full width of the wetland.
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Due to their local availability and demonstrated ability to survive and grow in the cedar leachate, Broad-leaved Cattails (Typha latifolia) were the emergent macrophytes selected for the surface-flow component of the cells. Design water depth was 40 cm, as measured to the top of the planting substrate. This depth would be adjustable via a swivelling elbow-type level-control standpipe (Hammer 1997). A substantial freeboard was provided, which gave the ability to subject the wetland cells to a range of water depths. At design depth, total reactor volume was 20 m³. Hydraulic retention time could be controlled independently in each of the six cells via separate influent valves (Figure 7.4).

Four of the six cells would be planted, thus providing two replicate sets for experimental manipulation. The other two cells would be identical in construction to the rest, with the exception of being unplanted, and would serve as a replicate set of experimental controls. This would enable the separation of those effects due to the presence of plants and specific experimental manipulations for all other effects, including leachate-soil interactions.

Cedar leachate would be pumped from the leachate pool to a dosing tank situated so as to provide sufficient head pressure to deliver the influent to the six treatment cells via gravity feed (Figures 7.5 and 7.6). Dilution water from a nearby slough (Figure 3.1) would also be pumped to the dosing tank, thereby allowing influent dilution strength to be controlled as desired. The mixing ratios into the tank would be governed by timer-controlled pump switches. Effluent was to be collected into a single sump and pumped back onto the Pile (Figure 7.6), as per the constraints explained in Section 3.2.

The six cells used in this research project had a total treatment capacity of 120 m³ at design depth. With an HRT of 7 days, this would enable them to process 6 240 m³/yr.

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The hog fuel pile had an estimated leachate production of 23,000 m$^3$/yr (Triton 1993), which meant that this pilot-scale facility represented approximately 25% of full-scale requirements, well within the range recommended for pilot-scale studies (McArdle et al. 1988).

7.2.2 Construction
Construction of the pilot-scale facility began in May 1998. By the end of June, construction of the wetland cells had been completed as per design specifications and, aside from monitoring activities, they were left alone during their establishment period (see Section 7.2.3). In the meantime, construction of the necessary piping and pumping facilities continued. Due to an unexpected need to fund the installation of electrical lines into the site, completion of construction was delayed by almost a year. This delay severely reduced that amount of time allotted for field testing. Another substantial delay was caused when the Fraser River flooded the site on June 16, 1999 (crested the banks at 5.1 m, as measured by Environment Canada's gauge station in Mission) (see Appendix B for river gauge data). The flood waters did not completely recede from the site until the
end of August. Construction was finally completed in October 1999. With the exception of the initial excavation of the basins (2 days; May 1998) and the eventual installation of the power lines and related electrical connections (3 days; March 1999), all the construction was performed by volunteer labour (i.e., Kevin Frankowski, with the generous assistance of many others - please see Acknowledgments).

After the greenfield site had been cleared (Figure 7.7) and the excavation of the wetland cells was completed (Figure 7.8), each cell was lined with 20 mil (0.5 mm) PVC. The planting substrate, native clay-loam, was backfilled to a depth of 30 cm (Figure 7.9). Perforated 100 mm PVC (Schedule 40) pipe formed the lateral effluent collector (Figure 7.3) and was connected to a swivelling discharge standpipe (non-perforated 100 mm PVC (Schedule 40)) (as per Hammer 1997). The liner penetrations were sealed with flanging and clay plugs. Washed gravel (40 mm) was used for the complete depth of the subsurface section in each cell (Figure 7.2).

Cattails were harvested by hand from local roadside ditches (with the permission of the local Public Works Engineering Department) and transplanted into four randomly chosen cells. Each cell received 120 plants, placed in 10 equally-spaced lateral rows, thus giving a planting density of about 3 plants/m\(^2\). Due to logistical constraints, an extensive root mat could not be harvested and transplanted with these cattails. However, each plant had at least 10 cm of a tuber-like root mass, as well as a small mat of associated root hairs (Figure 7.10), and a root mat would develop in situ over time. Immediately upon completing transplantation, each cell, with its standpipe closed, was filled with clean river water. This water would be replenished as needed during the entire establishment phase. A temporary pipeline (~400 m) was assembled between the river and the wetland cells. A portable 5.5 hp gasoline-powered pump delivered the water.

In order to deliver the cedar leachate from the pool to the dosing tank (Figures 3.1, 7.6), a pump was installed beside the leachate pool. Similarly, one was installed beside a nearby slough in order to supply dilution water to the dosing tank. A third pump was installed at
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Figure 7.7 Preparation of greenfield site

Figure 7.8 Excavation of wetland cells

Figure 7.9 Levelling of backfilled soil in preparation for planting

Figure 7.10 Cattails ready for transplanting
(Note the attached root mass on each plant)
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the sump tank, for delivery of the final effluent back to the Pile (Figure 7.6). Due to the need for unattended and autonomous operation, electrical pumps were required. G&L 1 hp centrifugal pumps (Model NPE; 230V single-phase) were selected. Liquid-end construction was completely Type 304 stainless steel, to avoid any corrosion problems due to the low pH of the leachate. A wooden pump shelter, with a concrete floor, embedded mounting bolts, and a locking lid, was built and installed for each of the three pumps (Figure 7.11). Since they were not self-priming, each pump was also fitted with a brass foot valve.

Approximately equidistant between the slough and the leachate, the dosing tank was connected to the slough and leachate pool pumps via 30 mm polyethylene piping (~100 m for each pipeline). The dosing tank was an old 10 000 L steel tank (provided by the landowner), that had previously been used to store fire control water (Figure 7.5). Mixing ratios were set via timer-controlled pump switches. A float switch inside the dosing tank signalled the switch controls when the tank needed refilling. Tank head pressure was sustained so that influent was delivered continuously to the cells (via 30 mm polyethylene piping). Every effort was made to provide all pipe runs with as straight and level a path as possible. This necessitated building several small support-ways to span some low areas.

7.2.3 Establishment and baseline evaluation

Once the four wetland cells had been planted and filled with clean river water, the cattails recovered from their minor transplant shock within a few days. Water level was monitored and additional water was pumped into the cells as needed (e.g., once every month or so). Since the cells had no outflow, the only loss of water was through evapotranspiration. All the cells were sampled several times and analysed for nutrients, TSS, tannin and lignin, BOD, COD and toxicity. In addition, qualitative observations on the state of establishment were made several times throughout the year.
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7.2.4 Commission and operations

Due to the delays encountered during construction, the resulting financial and time constraints allowed only a brief period (October - December 1999) of field trials. The experimental manipulation examined during these field trials was the effect of inoculation on treatment performance. Based upon results from the screening trials (Section 5.3) and comparisons of unseeded versus seeded BOD tests (Section 4.3.4), pool-side soil had been established as an effective inoculant. Therefore, it was hypothesized that inoculating one pair of planted cells with pool-side soil should result in improved treatment performance, relative to the other pair of planted (but non-inoculated) cells. The unplanted, non-inoculated controls were expected to provide only minimal treatment. The hypothesis further expected that over time, the set of planted, non-inoculated cells would gradually develop the necessary microbial communities and thus the differences in performance between these two cells and the two inoculated cells would eventually disappear.

As soon as construction had been completed to the point of the facility being serviceable, the field trials were begun. Prior to using the dosing tank, it was thoroughly flushed out several times, to ensure that any contaminants which may have been present in the tank from prior usage would not be introduced into the treatment wetlands. Several days prior to introducing influent into the cells, two of the planted cells were randomly selected and a slurry of pool-side soil was distributed evenly throughout their central surface-flow section. Each of the two cells received 50 kg (moist weight) of the soil, or an equivalent of 2.5 g per litre of reactor volume.

The microcosm results (Section 6.2) indicated that an HRT of 8 - 15 days produced a measurable removal of toxicity and the other parameters that were monitored. In order to maximize data generation, an HRT of seven days was selected for the field-scale operations. This also allowed a convenient weekly cycle in which to perform all the associated laboratory work. The influent concentration of 25% was selected based on the
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microcosm results, especially the spectrometer results (Figure 6.6), which seemed to indicate that treatment capacity was maximized at this concentration.

To reduce the shock loading effect to the wetland cells, a gradual start-up procedure was followed. Over a two week commissioning period, the leachate concentration (i.e., the mixing ratio) was increased, up to the operational concentration of 25%. The influent displaced the clean water that was previously present from the establishment phase. During the commissioning period, the HRT was gradually reduced to 7 days. At the end of this two-week period, the pilot-scale facility was experiencing the intended operational conditions and weekly monitoring began.

7.2.5 Monitoring and sampling

Effluent from each cell, along with a single influent sample from the dosing tank, was sampled every week. The leachate pool and the slough were also sampled in case these data would be needed to address any unexpected results. Samples were collected in the manner outlined in Section 4.2. At each location, sample temperature, pH, DO and specific conductivity were also measured, using the same field probes as described in Section 4.2.

All samples, including appropriate blanks, were analysed for TSS, BOD, COD, tannin and lignin, toxicity, VFAs, and nutrients (i.e., NH$_3$, NO$_x$, PO$_4$), using the same methods as those discussed Section 4.2 (raw data is provided in Appendix D.4). With the exception of toxicity, all the analyses were performed at the University of British Columbia. Toxicity analysis was performed at the laboratory facilities of EVS Environment Consultants. Due to project financial constraints, only a limited number of toxicity tests were available.

Toxicity results were converted from LC$_{50}$ values to acute Toxic Unit (TU$_a$) values, since this presented the data in a form more analogous to the mass-based concentrations used
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for reporting the other parameters. Acute toxic units were calculated as per Equation (1) (Metcalf and Eddy 1991).

\[ TU_a = 100 / LC_{50} \]  \hspace{1cm} (1)

According to Equation (1), samples with a \( TU_a < 1.0 \) are nontoxic, while those with \( TU_a > 1.0 \) are toxic. Stated another way, the \( TU_a \) is the dilution factor required to render a given sample nontoxic.

7.3 Results and Discussion

7.3.1 Baseline conditions

Over the course of almost two summers of clean-water establishment, the four planted wetland cells developed a very appreciable resemblance of natural wetland ecology. The cattails produced a very healthy emergent growth and their density increased to more than 12 plants/m² (Figure 7.12), a more than fourfold increase from the initial planting.

During the second summer the cattails developed seed heads (which were cut off prior to them maturing, to prevent the unplanted control cells from becoming seeded). Dragonflies and frogs were in great abundance. Several bird species used the area frequently, including a pair of Red-winged Blackbirds, which built a nest in one of the cells. Hundreds of tadpoles, water boatmen and other aquatic insects were present in each cell.

From a quantitative perspective, it was necessary to establish that the wetlands themselves, prior to introducing any leachate, were “clean” and would not contribute to the detrimental characteristics of the eventual influent. Water temperature varied with the weather, but it was not uncommon for it to be above 16°C, due to the shallow, quiescent nature of the cells. The pH was close to neutral, and the dissolved oxygen was close to, and occasionally even above, saturation (Table 7.1). Results for TSS, BOD and COD were
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all very low, well below any concentration that may be of concern. As might be expected in wetland water samples, some tannin and lignin were present, but again, the concentrations were low enough not to be a concern. Very few nutrients were present in the water column. No toxicity was detected in the any of the pre-operational cells, even after the 1999 flooding, which could potentially have carried leachate into the cells (Table 7.1).

Since the slough water was going to be used as dilution water, to control the strength of the influent, it was necessary to characterize this as well. Samples taken prior to use indicated that all parameters analysed were well below the concentrations found in the leachate, and therefore the slough water was appropriate as a dilution water (Table 7.2).

7.3.2 Performance

The field-scale constructed wetlands were capable of reducing the toxicity of cedar leachate (Figure 7.13). Average removal was 49% for the planted cells, with no significant difference observed between the inoculated and the non-inoculated treatments (Table 7.3). Even the control cells exhibited toxicity removal, but their performance was less reliable (Figure 7.13). This removal performance in the planted cells was well below what was expected (a removal rate of 75-90%), based on the lab study results (Section 6.3).

Removal of BOD, COD, and tannin and lignin was also observed, although there were no significant differences between the performance of the three different reactors (Table 7.3). Tannin and lignin removal was between 30-40%. BOD removal was on the order of 20-30%, while about 40-45% of COD was removed. The fact that a higher proportion

### Table 7.1 Pre-operational characterization of the pilot-scale constructed wetlands

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (Std. Dev.)</th>
<th>n</th>
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<tr>
<td>Dissolved Oxygen</td>
<td>11.3 (1.3)</td>
<td>12</td>
</tr>
<tr>
<td>Toxicity</td>
<td>&lt;1.0 (0.0)</td>
<td>12</td>
</tr>
<tr>
<td>Total Suspended Solids (TSS)</td>
<td>6.2 (4.8)</td>
<td>6</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (BOD)</td>
<td>6 (0.7)</td>
<td>6</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td>33 (3.9)</td>
<td>6</td>
</tr>
<tr>
<td>Tannins and Lignins (as tannic acid)</td>
<td>0.7 (0.12)</td>
<td>6</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.09 (0.07)</td>
<td>12</td>
</tr>
<tr>
<td>Nitrate + nitrite (NO₃-N)</td>
<td>0.07 (0.02)</td>
<td>6</td>
</tr>
<tr>
<td>Ortho-phosphate (PO₄³⁻-P)</td>
<td>0.05 (0.05)</td>
<td>6</td>
</tr>
</tbody>
</table>

**NOTES**
1. All values, except toxicity, reported in mg/L.
2. Sample temperature = 16°C
3. Toxicity, as determined by a 96hr rainbow trout LC50, and reported as Toxic Units (i.e., TU = 100/LC50)
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7.3 Results and Discussion

Table 7.2 Characterization of slough (dilution) water

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average ( (\text{Std. Dev.}) )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature ( [\degree C] )</td>
<td>6.1 ( \pm 1.6 )</td>
<td>6</td>
</tr>
<tr>
<td>pH</td>
<td>6.08 ( \pm 0.18 )</td>
<td>6</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>0.3 ( \pm 0.2 )</td>
<td>6</td>
</tr>
<tr>
<td>Specific Conductivity ( [\mu S/cm] )</td>
<td>71 ( \pm 12 )</td>
<td>6</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (BOD)</td>
<td>21 ( \pm 8 )</td>
<td>6</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td>247 ( \pm 100 )</td>
<td>6</td>
</tr>
<tr>
<td>Tannins and Lignins (as tannic acid)</td>
<td>16 ( \pm 5 )</td>
<td>6</td>
</tr>
<tr>
<td>Total Suspended Solids (TSS)</td>
<td>52 ( \pm 29 )</td>
<td>6</td>
</tr>
<tr>
<td>Ammonia (NH(_3)-N)</td>
<td>1.0 ( \pm 0.5 )</td>
<td>6</td>
</tr>
<tr>
<td>Nitrate + nitrite (NO(_x)-N)</td>
<td>0.05 ( \pm 0.04 )</td>
<td>6</td>
</tr>
<tr>
<td>Ortho-phosphate (PO(_4^2-))</td>
<td>0.22 ( \pm 0.08 )</td>
<td>6</td>
</tr>
<tr>
<td>Volatile Fatty Acids (VFAs): Total (C(_2-C_6))</td>
<td>7.8 ( \pm 4.8 )</td>
<td>6</td>
</tr>
<tr>
<td>Toxicity [TU(_B)]</td>
<td>&lt;1.0 ( \pm 0.0 )</td>
<td>2</td>
</tr>
</tbody>
</table>

NOTES
1. All values reported in mg/L, unless otherwise noted.
2. Toxicity reported as acute Toxic Units (i.e., TU\(_B\) = 100/LC\(_{50}\))

of COD was removed, compared to BOD, is interesting. At first glance, it suggests that recalcitrant materials were being degraded faster than the easily biodegradable material, which doesn’t make sense. However, it is possible that the recalcitrant materials were being broken down into smaller, more biodegradable compounds (i.e., degradation intermediaries), thereby elevating the concentration of these materials within the reactors. If this dual supply of easily biodegradable materials (i.e., influent + within-reactor degradation intermediaries) was greater than the processing capacity of the degradation systems which processed these easily degraded fractions, then a buildup of this fraction would occur.

Figure 7.13 Reduction of cedar leachate toxicity in pilot-scale constructed wetlands
(Note: error bars = std. dev.; \( n = 2 \) for all cells and \( n = 1 \) for influent)
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7.3 Results and Discussion

Table 7.3 Summary of pilot-scale removal performance for targeted parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (^1)</th>
<th>Control (^2)</th>
<th>Planted (^3)</th>
<th>Planted + Inoculated (^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
</tr>
<tr>
<td>Toxicity [TU, (^1)]</td>
<td>45.2</td>
<td>27.7</td>
<td>23.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (BOD)</td>
<td>1728</td>
<td>1139</td>
<td>1341</td>
<td>1234</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD)</td>
<td>5604</td>
<td>2869</td>
<td>3483</td>
<td>3160</td>
</tr>
<tr>
<td>Tannins and Lignins (as tannic acid)</td>
<td>866</td>
<td>491</td>
<td>579</td>
<td>516</td>
</tr>
<tr>
<td>NOTES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. All values, except toxicity, reported in mg/L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. n=7 for influent, and n=13 for each reactor set (except toxicity, where n=2 for influent, and n=4 for each reactor set)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Toxicity, as determined by a 96hr rainbow trout LC (<em>{50}), and reported as acute Toxic Units (i.e., TU, = 100/LC (</em>{50})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4 Removal of volatile fatty acids (C\(_2\) - C\(_6\)) in pilot-scale wetlands

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (^1)</th>
<th>Control (^2)</th>
<th>Planted (^3)</th>
<th>Planted + Inoculated (^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
</tr>
<tr>
<td>Volatile Fatty Acids (VFAs): Total (C(_2) - C(_6))</td>
<td>499</td>
<td>295</td>
<td>396</td>
<td>367</td>
</tr>
<tr>
<td>- acetic acid</td>
<td>209</td>
<td>129</td>
<td>140</td>
<td>108</td>
</tr>
<tr>
<td>- propionic acid</td>
<td>137</td>
<td>67</td>
<td>77</td>
<td>47</td>
</tr>
<tr>
<td>- butyric acid + iso-butyric acid</td>
<td>90</td>
<td>54</td>
<td>76</td>
<td>70</td>
</tr>
<tr>
<td>- valeric acid</td>
<td>26</td>
<td>24</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>- hexanoic acid</td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>NOTES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. All values reported in mg/L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. n=6 for influent, and n=11 for each reactor set</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. %-removal was calculated for each cell, each week, and then averaged. This is more accurate than using the summarized concentration averages to calculate %-removal, since this may mask temporal variations. Hence, the removal suggested by the concentration averages may not match the reported %-removals, but it will be within the range of variation (as indicated by the standard deviations reported for %-removals)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.5 Summary of pilot-scale field data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (^1)</th>
<th>Control (^2)</th>
<th>Planted (^3)</th>
<th>Inoculated (^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
<td>(Std. Dev.)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>8.2</td>
<td>7.3</td>
<td>7.2</td>
<td>7.1</td>
</tr>
<tr>
<td>pH</td>
<td>3.53</td>
<td>3.66</td>
<td>3.69</td>
<td>3.79</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/L)</td>
<td>2.2</td>
<td>0.8</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Conductivity (uS/cm)</td>
<td>417</td>
<td>255</td>
<td>314</td>
<td>287</td>
</tr>
<tr>
<td>NOTES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Inoculated cells were planted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Units as noted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. n=7 for influent, and n=13 for each reactor set</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Masters Thesis
Performance calculations for BOD removal would therefore indicate a lower performance compared to COD, since the mass balance inherent in the calculation assumes no within-reactor source.

Thus, this contrast between the BOD and COD data may be indicative of a two-stage process, where large compounds are broken into smaller compounds by one group of organisms, and these smaller, more available compounds are then metabolized further by another group of organisms, whose processing capacity is being exceeded. This hypothesis is supported by a comparison between the tannin and lignin data (Table 7.3), and the VFA data (Table 7.4). The tannin and lignin data had a stable removal rate similar to COD, while the VFAs had an extremely variable removal rate (note the very large standard deviations for VFA %-removal), and some weeks had effluent concentrations higher than influent concentrations (especially for acetic and valeric acids; see Appendix D.4 for specifics). The larger compounds represented by the tannin and lignin analysis were consistently being broken down, and their breakdown products were probably appearing as other classes of smaller compounds. The production rate of these smaller compounds seemed to be outpacing the system's ability to degrade them. Anoxic conditions were present in all the cells during the whole field trial period and the pH remained low (pH<4; see Table 7.5), another indication that VFA production may be occurring within the reactors.

Treatment performance of the field system was not as high as what was observed for the laboratory systems. Several factors may have contributed to this. Temperatures were a lot lower in the field (6-8°C) than in the lab (15 or 22°C), and temperature is generally assumed to have a profound influence on performance (Metcalf and Eddy 1991). However, there are some indications that its influence may not be as profound for wetlands as it is for some of the more conventional processes (Wittgren and Maehlum 1997). Likely to be of much greater importance is oxygen supply. Since the cattails were in senescence during the winter, their ability to provide oxygen to the root zone was greatly diminished. It would be informative to observe how root zone oxygen status changed on a seasonal basis and what effect this had on treatment efficiency.
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Table 7.6 Summary of pilot-scale removal performance for solids and nutrients

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent Average $^1$ (Std. Dev.)</th>
<th>Control Average (Std. Dev.)</th>
<th>Planted Average (Std. Dev.)</th>
<th>Inoculated Average (Std. Dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Suspended Solids (TSS)</td>
<td>21.6 (14.4)</td>
<td>23.2 (43.5)</td>
<td>12.4 (13.2)</td>
<td>13.3 (9.5)</td>
</tr>
<tr>
<td>Ammonia (NH$_3$-N)</td>
<td>0.7 (0.4)</td>
<td>0.4 (0.4)</td>
<td>0.4 (0.4)</td>
<td>0.2 (0.3)</td>
</tr>
<tr>
<td>Nitrate + nitrite (NO$_x$-N)</td>
<td>0.06 (0.04)</td>
<td>0.08 (0.04)</td>
<td>0.07 (0.04)</td>
<td>0.09 (0.07)</td>
</tr>
<tr>
<td>Ortho-phosphate (PO$_4^3$-P)</td>
<td>1.47 (0.23)</td>
<td>0.78 (0.34)</td>
<td>0.97 (0.23)</td>
<td>0.86 (0.22)</td>
</tr>
</tbody>
</table>

NOTES
1. Inoculated cells were planted
2. All values reported in mg/L
3. n=6 for influent, and n=11 for each reactor set (except TSS where n=7 for influent, and n=13 for each reactor set)

Nutrient status was likely another very important factor affecting performance. Given set conditions of temperature and oxygen supply, total metabolic capability is limited by the number of metabolic units (i.e., organisms) available. If the population of microbes which are responsible for a specific degradation is limited due to insufficient nutrients, providing optimal temperature and oxygen supply will not dramatically improve performance, since these are not the limiting factors. Due to the nature of its influent, all of the treatment cells were very nutrient-poor (Table 7.6). Thus, another important experimental manipulation would be to compare how nutrient addition affects treatment efficiency.

It is very likely that a cascade of metabolic reactions is occurring during the degradation of the cedar leachate, and that the assemblage of required organisms is quite complex. Various bacteria and fungi would have to be present in the right place and in the correct proportions, all performing their various specialized metabolic tasks, before optimal performance would be achieved. In addition, the macrophytes, algae, and even aquatic invertebrates would all perform necessary supporting functions. Fortunately, it is not necessary to fully understand and manage each of these detailed interrelationships. Natural ecosystems and their analogues will respond to a given set of environmental conditions and produce the most appropriate assemblage for those conditions. Our task is
to understand what conditions will produce the needed outcome, and then design and maintain the system accordingly. Over time, the detailed ecological intricacies will develop as necessary. In contrast to conventional systems, the result is a system which improves with age (Kadlec and Knight 1996; Webb et al. 1998). This is especially true when the desired degradation process is a complex one.

Thus, it may take some time before the ecological structure necessary for optimal treatment performance is developed in this pilot-scale system. Of course, it is still necessary to understand the system sufficiently so as to provide the appropriate conditions to allow these systems to reach their full potential. This understanding can be provided by a systematic application of specific experimental manipulations which build upon previous experience and knowledge. Therefore, because there was such a lack of background knowledge in using constructed wetlands to treat cedar leachate, it was necessary to proceed one step at a time from the base case. Rather than supplementing the system with nutrients, oxygen, and the like right from the beginning, which would have contributed little to the understanding of their respective effects, it was necessary to first establish the base case. The results from this first field season have established that the presence or absence of an appropriate microbial seed is not the overall limiting factor, despite their importance in the lab-based studies. This may be due to the fact that the native soil used in all the cells already represented a suitable seed, due to exposure to the leachate in previous years. Another possibility is that the flooding by the Fraser River during the summer of 1999 carried the appropriate microbial inoculant into all the cells. It remains to be seen whether any differences will emerge between the different reactors (i.e., inoculated versus non-inoculated; planted versus unplanted) under the more optimal summer operating conditions.

Overall, the results of the field trials indicate the constructed wetlands have the strong potential for being a viable treatment option for cedar leachate. Obviously, process optimization is required, but the preliminary results generated by this research indicate that it should be possible to develop a full-scale treatment system which meets all the
performance objectives (A.1 - A.2) outlined in Section 1.4. With regards to the design objectives (B.1 - B.3), system robustness and dependability seem high, as evidenced by its ability to withstand several weeks of being submerged under flood waters, then be filled with high-strength, toxic wastewater, and yet still continue to survive and function. Of course, a proper assessment of the system’s robustness and dependability will only be ascertained by continued monitoring. Minimal operator training or intervention (Objective B.2) is assured by the very nature of the wetland treatment mechanisms and the autonomous design of the control structures (i.e., influent and effluent pumping systems). Aside from optimization manipulations, there is little operational activity that can be done.

7.3.3 Construction and operating costs
The final objective (B.3) outlined for this research addressed the need for an inexpensive treatment system which operated with a minimum of monitoring, chemical additions, or by-products handling. By-products handling, including the treatment and disposal of sludges and/or spent absorption media often represents 50% of the annual operation and maintenance (O&M) costs for conventional treatment technologies (McArdle et al. 1988; Metcalf and Eddy 1991). Unlike these systems, constructed wetland systems generally produce no by-products, and therefore are free from this annual expense (Batchelor and Loots 1997; Reed et al. 1995). Similarly, since chemical addition is usually not part of the regular process, this supply cost is also eliminated. Regular O&M activities for constructed wetlands are quite basic, and are usually limited to monitoring and occasional servicing of basic physical infrastructure such as berms and inlet and outlet weirs (Kadlec and Knight 1996).

Aside from research monitoring costs, there were no O&M costs for this facility. However, the operational period was short. The median O&M cost reported for surface-flow constructed wetlands operating in the United States was $400 per acre (less than $0.10/m²/yr) (Kadlec and Knight 1996). Using this value, the O&M costs for the this facility would be less than $50 per year.
Thus, most of the cost associated with wetland treatment systems will reside in their initial construction and implementation (Kadlec and Knight 1996). However, detailed information on construction costs is quite limited in the literature, probably due to the large number of variables which affect these costs. This makes detailed comparison for estimation purposes difficult. Table 7.7 presents the material costs that were incurred during construction of this project's pilot-scale facility. It should be noted that the installation of the electrical service into this site was an exceptional expense, made necessary only by the need for electrical pumps. These pumps were required due to the experimental nature of the facility, providing the ability to autonomously control influent strength and the fate of the effluent. In a optimized, typical full-scale installation, it would be desirable to locate the treatment wetlands such that the influent could be collected and transported via gravity alone, thus eliminating some of the most expensive items from the budget.

Table 7.7 Material costs for the pilot-scale constructed wetland facility

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td></td>
</tr>
<tr>
<td>Excavation</td>
<td>1 000.00</td>
</tr>
<tr>
<td>Liners</td>
<td>2 024.00</td>
</tr>
<tr>
<td>Piping and Supplies</td>
<td>3 516.00</td>
</tr>
<tr>
<td>Sub-total (Basic Cost):</td>
<td>$ 6,540.00</td>
</tr>
<tr>
<td>Pumps</td>
<td>2 864.00</td>
</tr>
<tr>
<td>Electrical Installation</td>
<td>11 257.00</td>
</tr>
<tr>
<td><strong>TOTAL (w/pumps &amp; power lines):</strong></td>
<td><strong>$ 20,661.00</strong></td>
</tr>
</tbody>
</table>

**NOTES**
1. Land access provided by landowner
2. Three 1 hp centrifugal pumps (stainless steel)
3. ~1500' of 220V service, including 10kVA transformer and associated timers, switches, and connections to pumps

Without the pumps and electricity, the basic materials cost for this facility was $6540 (Table 7.7). It must be remembered that this facility was intended for pilot-scale experimental use only. In order to keep costs down, all of the labour (except initial excavation and all electrical work) was volunteer. Also, since it was not intended to withstand the rigours and design life of a full-scale installation, certain aspects were modified (e.g., inlet and outlet flow control structures would normally be set into concrete, rather than just packed earthen supports). However, piping supplies represented approximately half of the materials cost (Table 7.7). In a full-scale installation, there
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would be no need for so extensive a piping network as was used for the experimental facility, since there would be no need for multiple parallel cells or long-distance conveyance of pumped water. Taking these factors into consideration, it seems reasonable to estimate that a similar size facility, designed and built to full-scale standards, would cost approximately double, or about $13,000.

While this is only a rough estimate and ignores many of the factors which affect capital expense, it is sufficient for some very general comparisons to be made with other treatment technologies. McArdle et al. (1988) present cost information (capital and annual O&M) for some conventional leachate treatment technologies. Assuming a design life of 20 years and given the annual O&M costs and treatment throughput rate, cost per unit treatment can be calculated (Table 7.8). The same can be done for the constructed wetland treatment system, based on the cost information presented above. Note that since the land needed for the wetland will have salvage value of at least its net present value, it is typically not included in these types of calculations (Kadlec and Knight 1996).

Table 7.8 Cost comparisons of different leachate treatment technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital</th>
<th>Annual O&amp;M</th>
<th>Unit Treatment Cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet-air oxidation</td>
<td>746,000</td>
<td>145,000</td>
<td>3.67</td>
</tr>
<tr>
<td>Powdered Activated Carbon Treatment</td>
<td>441,000</td>
<td>69,000</td>
<td>1.83</td>
</tr>
<tr>
<td>Activated carbon absorption</td>
<td>115,000</td>
<td>67,000</td>
<td>1.46</td>
</tr>
<tr>
<td>Reverse osmosis</td>
<td>122,000</td>
<td>53,000</td>
<td>1.19</td>
</tr>
<tr>
<td>Activated sludge</td>
<td>326,000</td>
<td>32,000</td>
<td>0.97</td>
</tr>
<tr>
<td>Precipitation/flocculation/sedimentation</td>
<td>303,000</td>
<td>28,000</td>
<td>0.87</td>
</tr>
<tr>
<td>Rotating biological contactor (RBC)</td>
<td>183,000</td>
<td>23,000</td>
<td>0.65</td>
</tr>
<tr>
<td>Constructed wetlands²</td>
<td>13,000</td>
<td>50</td>
<td>0.11</td>
</tr>
</tbody>
</table>

NOTES
1. Costs for all processes, except wetlands, have been converted to 1999 Canadian dollars (from 1986 US dollars), and are based on a system capacity of 25 gal/min (= 49.735 m³/yr) and a 20-year design life. Adapted from McArdle et al. (1988).
2. Wetland costs are reported in 1999 Canadian dollars, and are based upon a system capacity of 6,240 m³/yr, and a 20-year design life.
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The comparison presented in Table 7.8 is very conservative with regards to the wetland treatment system, for a number of reasons. First, the costs presented for all the conventional systems are from much larger-scale systems than the wetland system. Due to the typical economies of scale associated with these types of systems, their per-unit treatment costs would be considerably higher if they were operating at the same scale as the wetlands.

Secondly, the costs presented for the conventional systems are all unit operation costs, and therefore may not reflect the full price of the treatment train. Certain processes may need pretreatment or polishing units, depending upon the nature of the influent, and this will increase the overall costs. It is important to realize that the cost comparison presented here is solely for the purpose of comparing technology costs, without any statements being made with regards to the effectiveness of any given technology at meeting any specific treatment efficiency objectives. Based on an extensive review of the published literature, conventional biological systems (e.g., activated sludge, RBCs) have not been shown to be effective at treating wood leachate.

Finally, while it is typical to use a 20 year design life for mechanical systems, applying this same design life to a wetland system is erroneous, since constructed wetlands have a much longer design life; 50 years is considered more appropriate (Kadlec and Knight 1996), and this would further reduce the unit-treatment cost of the wetland system.

Regardless, even when viewed in such a conservative context, the wetland treatment option compares very favourably against the other leachate treatment options. While activated carbon and wet-air oxidation are probably very effective at removing many of the contaminants from wood leachate, their respective unit-treatment costs are almost 15 and 30 times greater than those for the constructed wetland system (Table 7.8). Even the RBC process, which may not be suited for treating wood leachate, has a unit-treatment cost almost 6 times higher than the wetland system.
7.4 Conclusions

It was demonstrated that constructed wetlands were able to treat cedar leachate under field conditions. Reductions in toxicity, BOD, COD and tannin and lignin content were consistently achieved. Performance of the field-scale system did not match what was observed under laboratory conditions, but this may have been due to lower ambient temperatures, decreased oxygen supply as a result of normal plant senescence, and insufficient nutrients to support the necessary microbial communities. Optimization studies are needed to address these issues. The wetland system may also need more time for full ecological maturation under operational conditions, and therefore treatment performance may improve with system age.

Since optimization of this process largely centers around ecological considerations, the final outcome is unlikely to have a dramatic effect on the overall cost of the system. Therefore, general comparisons with conventional leachate treatment technologies can be made. These demonstrate that this wetland system has the potential to deliver effective treatment with a much better economy than conventional alternatives, with its unit treatment costs being at least 3 times to more than 20 times cheaper than other technologies.
8.0 GENERAL SYNOPSIS AND RECOMMENDATIONS

The leachate produced by the cedar hog fuel pile could be considered a strong industrial wastewater. It was toxic, acidic, and possessed a very high, and aggressive, oxygen demand. Previous studies on similar leachates had failed to demonstrate viable, long-term treatment techniques. Using a step-wise approach, it was determined that this wood leachate was amenable to biological treatment and that constructed wetlands represented a feasible treatment technique. Laboratory-scale wetlands were able to achieve a 90% reduction in toxicity and removal rates of up to 94% for BOD and 80% for COD. Furthermore, a pilot-scale facility demonstrated that constructed wetlands were able to treat this leachate under field conditions. While treatment efficiency in the field was not on par with that observed under optimal laboratory conditions, it must be realized that this process stills needs to be optimized. Preliminary results indicate several factors that may yield significant gains in this respect.

Nutrient availability, oxygen supply, and temperature are likely the most important factors that need to be addressed. While ambient temperature is under climatic control and not realistically available for field manipulation, determining the system’s sensitivity to the seasonal cycles is important from a design perspective. However, it is entirely possible that once issues such as nutrient supply are optimized, the ecological system will be under much less stress and better able to handle fluctuations in ambient conditions such as temperature. Ecological maturity is another factor which may play a role. Given sufficient exposure to chosen operating conditions, the system will produce internal adjustments in the composition of its biological communities, which may, on its own, produce considerable gains in the optimization process. Constructed wetlands possess a feature few other systems can boast of - performance usually improves with age.

Thus, the system needs to be evaluated under different seasonal conditions, preferably for more than a year, to capture a representative sampling of its inherent variability and
8.0 GENERAL SYNOPSIS AND RECOMMENDATIONS

determine what operating conditions need to be adjusted in order to have the field system operate closer to its theoretical capability. Further research is also needed to clarify the specific causes of toxicity in this leachate and its relationship with parameters such as pH. Several techniques, including TIEs based on molecular size exclusion, can be used. The resulting knowledge will provide critical design information.

Therefore, this research should not be considered as complete. The field monitoring only covered a span of three months, and these were during winter, when biological conditions were less than optimal. The ultimate goal should be to produce a system capable of treating the leachate at higher influent concentrations, with shorter retention times, and still yield an effluent suitable for discharge. The preliminary work is done and it has demonstrated that it is feasible for constructed wetlands to meet both the performance and design objectives originally outlined.

In a way, the "worst-case" conditions have been tackled first. The strength of the leachate, in terms of toxicity, BOD and COD, is probably much worse than the leachate or runoff produced at most wood processing sites. Also, the field results are based upon the winter operations of a sub-optimized system. From this perspective, the technology holds much promise for successfully addressing the leachate and runoff concerns that exist at other wood processing sites. The contaminants and their sources are known, and this knowledge is in the process of being refined. Collection and control technologies already exist for effective minimization and control of runoff and leachate. The final step in an effective environmental management scenario is to provide a reliable and realistic treatment technology for the remaining discharges. As shown by this research, constructed wetlands represent such a technology. They are ideally suited for applications which require distributed, autonomous and economic treatment of fluctuating loads containing a broad, and often changing, spectrum of contaminants.
9.0 LITERATURE CITED


Beaty, Bob. personal communication. Section Head. Emissions and Standards Section, Air Resources Branch, Ministry of Environment, Lands and Parks. Victoria, BC, Canada.


Kevin Frankowski 85 UBC CIVIL ENGINEERING Masters Thesis


9.0 LITERATURE CITED


9.0 LITERATURE CITED


9.0 LITERATURE CITED


9.0 LITERATURE CITED


9.0 LITERATURE CITED


9.0 LITERATURE CITED


9.0 LITERATURE CITED


Waste Management Act. B.C. Reg. 519/95 [NOTE: includes amendments up to B.C. Reg. 171/99].


APPENDIX A

EXCLUSION-OF-LIABILITY AGREEMENTS
the south edge of the flood control dike, and the western boundary of the Site. The treatment objective of this system is toxicity reduction of the Pile's leachate.

In the event that the containment integrity of this facility is compromised, action will be taken to repair the problem. If it is deemed that such integrity cannot be restored, the facility will be decommissioned and the area returned to its original state. This will include the following:

- All drainage ditches will be filled in with their original substrate, all associated piping and pumping will be removed, and all inputs to the wetlands will cease.
- The wetland cells will be excavated, and the plants and liners removed. The excavations will be filled in with their original substrate.

Upon completion of the research, the treatment plant will either be decommissioned as described above, or, if the Ministry consents, surrendered to the landowner for continued operation, at which point the landowner will assume full responsibility for the treatment facility.

When we discussed the details of the project on March 17, 1998, you indicated that the Ministry would have no problems with either the project in general or the proposed configuration of the pilot-scale treatment plant (as described above), especially considering its experimental status and its role in exploring treatment solutions. You stated that since the treatment plant would be recycling leachate back into the work site, the Ministry does not consider this to represent a discharge to the environment, and as such, there is no need for a discharge permit.

In order to obtain permission from the University of British Columbia to proceed with this research project, I require confirmation from the Ministry that no action will be taken by the Ministry against the University or its Board of Governors, faculty, staff, or students (including myself) as a result of any activities undertaken in connection with this research project, provided that the research project is carried out as outlined above. I would therefore be most grateful if you would confirm the Ministry's agreement to the foregoing by signing a copy of this letter in the space provided and returning it to me at your earliest convenience.

Sincerely,

Kevin Frankowski
M.A.Sc. Candidate
University of British Columbia

Acknowledged and agreed to by and on behalf of the Ministry of the Environment, Lands, and Parks:

Kevin Frankowski
Upon completion of the research, the treatment plant will either be shut down as described above, or given to yourself, the landowner, for continued operation.

In order to properly conduct this research project, the following support is required:
• Access to the Site over the duration of this research project, which is anticipated to last from October 1997 to May 2000.
• Commitment from the landowners (you and John) and the BC Shake and Shingle Association of continued support of this research project for its duration.
• Assistance with the construction of the wetlands, mainly in the form of excavation (i.e., machine and operator) for approximately 3 to 4 days during initial construction.

As a result of supporting this project, you will receive the following:
1. Detailed laboratory analysis of the cedar leachate and corresponding data analysis and interpretation of these lab results.
2. Bench-scale testing and development of an economical biological treatment process capable of significantly reducing the toxicity of the surface cedar leachate.
3. Collaborative planning and design of a pilot-scale experimental wetlands-based treatment system.
4. Final design review and approval options available to both yourself and Jack Davidson.
5. Construction, operation, monitoring and maintenance of the pilot-scale treatment system, with periodic reporting on system performance.
6. Final copy of the resulting Civil Engineering thesis.

I will also require the latitude to reveal sufficient details about the project and its findings to such parties who may require such knowledge (e.g., thesis supervisor; technical advisors; project collaborators). This privilege will also extend to disseminating written project information and results to impartial review bodies (e.g., scholarship and funding applications; thesis publication).

Finally, in order to obtain permission from the University of British Columbia to construct and conduct research at this facility, I require your agreement to indemnify and hold harmless the University, its Board of Governors, faculty, staff, and students (including me) from and against any and all claims, actions, charges, and fines that may be brought against such parties as a result of any activities undertaken in connection with this research project. I am also seeking similar agreements from the Ministry of the Environment, Lands and Parks as well as from Scott Paper.

Kindly confirm your agreement to the foregoing by signing a copy of this letter in the space provided and returning it to me at your earliest convenience.

Sincerely,

Kevin Frankowski
Masters Candidate
UBC Civil Engineering

Acknowledged and agreed to by and on behalf of
Steve Wynnyk:

Kevin Frankowski
100
UBC CIVIL ENGINEERING
Masters Thesis
APPENDIX C

CALCULATION OF THEORETICAL OXYGEN DEMANDS
Theoretical Oxygen Demands

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

**Acetic Acid:**

\[
\text{CH}_3\text{COOH} + 2O_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O} \\
\text{ThOD} = 2\text{ moles of } O_2 \text{ per mole of acetic acid} \\
\text{Molecular weight of acetic acid: } 60.06 \text{ g/mol} \\
\text{Molecular weight of } O_2 : 32.0 \text{ g/mol} \\
\text{Therefore, ThOD} = (2 \times 32.0) \text{ g/mol} / 60.06 \text{ g/mol} \\
= 1.07 \text{ mg } O_2 \text{ per mg of acetic acid}
\]

**Propionic Acid:**

\[
\text{C}_3\text{H}_4\text{COOH} + \frac{3}{2}O_2 \rightarrow 3\text{CO}_2 + 3\text{H}_2\text{O} \\
\text{ThOD} = \frac{3}{2} \text{ moles of } O_2 \text{ per mole of propionic acid} \\
\text{Molecular weight of propionic acid: } 74.09 \text{ g/mol} \\
\text{Molecular weight of } O_2 : 32.0 \text{ g/mol} \\
\text{Therefore, ThOD} = \left(\frac{3}{2} \times 32.0\right) \text{ g/mol} / 74.09 \text{ g/mol} \\
= 1.51 \text{ mg } O_2 \text{ per mg of propionic acid}
\]

**Butyric Acid:**

\[
\text{C}_4\text{H}_6\text{COOH} + \frac{3}{2}O_2 \rightarrow 4\text{CO}_2 + 4\text{H}_2\text{O} \\
\text{ThOD} = \frac{3}{2} \text{ moles of } O_2 \text{ per mole of butyric acid} \\
\text{Molecular weight of butyric acid: } 88.12 \text{ g/mol} \\
\text{Molecular weight of } O_2 : 32.0 \text{ g/mol} \\
\text{Therefore, ThOD} = \left(\frac{3}{2} \times 32.0\right) \text{ g/mol} / 88.12 \text{ g/mol} \\
= 1.82 \text{ mg } O_2 \text{ per mg of butyric acid}
\]

**Valeric Acid:**

\[
\text{C}_5\text{H}_8\text{COOH} + \frac{3}{2}O_2 \rightarrow 5\text{CO}_2 + 5\text{H}_2\text{O} \\
\text{ThOD} = \frac{3}{2} \text{ moles of } O_2 \text{ per mole of valeric acid} \\
\text{Molecular weight of valeric acid: } 102.15 \text{ g/mol} \\
\text{Molecular weight of } O_2 : 32.0 \text{ g/mol} \\
\text{Therefore, ThOD} = \left(\frac{3}{2} \times 32.0\right) \text{ g/mol} / 102.15 \text{ g/mol} \\
= 2.04 \text{ mg } O_2 \text{ per mg of valeric acid}
\]

**Hexanoic Acid:**

\[
\text{C}_6\text{H}_{10}\text{COOH} + \frac{3}{2}O_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} \\
\text{ThOD} = \frac{3}{2} \text{ moles of } O_2 \text{ per mole of hexanoic acid} \\
\text{Molecular weight of hexanoic acid: } 116.18 \text{ g/mol} \\
\text{Molecular weight of } O_2 : 32.0 \text{ g/mol} \\
\text{Therefore, ThOD} = \left(\frac{3}{2} \times 32.0\right) \text{ g/mol} / 116.18 \text{ g/mol} \\
= 2.20 \text{ mg } O_2 \text{ per mg of hexanoic acid}
\]

Tannin & Lignin (uses tannic acid as a surrogate)

**Tannic Acid:**

\[
\text{C}_{16}\text{H}_{12}\text{O}_{46} + 66 O_2 \rightarrow 76\text{CO}_2 + 26\text{H}_2\text{O} \\
\text{ThOD} = 66 \text{ moles of } O_2 \text{ per mole of tannic acid} \\
\text{Molecular weight of tannic acid: } 1701.28 \text{ g/mol} \\
\text{Molecular weight of } O_2 : 32.0 \text{ g/mol} \\
\text{Therefore, ThOD} = \left(66 \times 32.0\right) \text{ g/mol} / 1701.28 \text{ g/mol} \\
= 1.24 \text{ mg } O_2 \text{ per mg of tannic acid}
\]
APPENDIX D.1

RAW DATA: LEACHATE CHARACTERIZATION
## APPENDIX D.1 RAW DATA: LEACHATE CHARACTERIZATION

### Summary:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Settable</th>
<th>Total</th>
<th>Total Fixed</th>
<th>Total Volatile</th>
<th>TSS</th>
<th>FSS</th>
<th>VSS</th>
<th>TDS</th>
<th>FDS</th>
<th>VDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank (avg)</td>
<td></td>
<td>93</td>
<td>85</td>
<td>8</td>
<td>0.4</td>
<td>0.0</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leachate Pool (a)</td>
<td>&lt; 0.5 mL/L</td>
<td>6562</td>
<td>960</td>
<td>5802</td>
<td>43.2</td>
<td>3.6</td>
<td>39.6</td>
<td>6519</td>
<td>956</td>
<td>5562</td>
</tr>
<tr>
<td>Leachate Pool (b)</td>
<td></td>
<td>6518</td>
<td>958</td>
<td>5560</td>
<td>43.6</td>
<td>5.6</td>
<td>38.0</td>
<td>6474</td>
<td>952</td>
<td>5522</td>
</tr>
<tr>
<td>Leachate Pool (c)</td>
<td></td>
<td>6554</td>
<td>954</td>
<td>5600</td>
<td>47.2</td>
<td>5.2</td>
<td>42.0</td>
<td>6507</td>
<td>949</td>
<td>5558</td>
</tr>
<tr>
<td>Leachate Pool (d)</td>
<td></td>
<td>6574</td>
<td>968</td>
<td>5606</td>
<td>43.2</td>
<td>4.8</td>
<td>38.4</td>
<td>6531</td>
<td>963</td>
<td>5568</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>6552</td>
<td>960</td>
<td>5592</td>
<td>44.3</td>
<td>4.8</td>
<td>39.5</td>
<td>6508</td>
<td>955</td>
<td>5553</td>
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<tr>
<td>Std Dev.</td>
<td></td>
<td>24</td>
<td>6</td>
<td>21</td>
<td>1.9</td>
<td>0.9</td>
<td>1.8</td>
<td>24</td>
<td>6</td>
<td>21</td>
</tr>
</tbody>
</table>

### NOTES

- **Vacuum**-filtered through a Whatman 934-AH glass microfibre filter (effective retention = 1.5 um).
- **Tare**: filter paper and weighing boat are pre-fired for at least 1 hour, then cooled to room temp. in desiccator.
- **Dry**: dried @ 105 C until constant weight (at least 2 hrs), then cooled to room temp. in desiccator.
- **Fired**: fired @ 550 C until constant weight (at least 1 hr), then cooled to room temp. in desiccator.
- **TSS** = Total Suspended Solids (i.e., matter larger than filter pore size)
- **VSS** = Volatile Suspended Solids (i.e., approximates organic matter)
- **TDS** = Total Dissolved Solids (i.e., matter smaller than filter pore size)
- **FDS** = Fixed Dissolved Solids (i.e., approximates inorganic matter)
- **VDS** = Volatile Dissolved Solids (i.e., approximates organic matter)
## Solids [TSS, etc.] (cont.)

### Raw Data:

#### Total Solids

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Volume (mL)</th>
<th>Tare (g)</th>
<th>Dry (g)</th>
<th>Fired (g)</th>
<th>Total Solids (mg/L)</th>
<th>Total Fixed (mg/L)</th>
<th>Total Volatile (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leachate Pool (a)</td>
<td>50.0</td>
<td>47.5087</td>
<td>47.8368</td>
<td>47.5567</td>
<td>6562</td>
<td>960</td>
<td>5602</td>
</tr>
<tr>
<td>Leachate Pool (b)</td>
<td>50.0</td>
<td>47.0151</td>
<td>47.3410</td>
<td>47.0630</td>
<td>6518</td>
<td>958</td>
<td>5560</td>
</tr>
<tr>
<td>Leachate Pool (c)</td>
<td>50.0</td>
<td>48.0539</td>
<td>48.3816</td>
<td>48.1016</td>
<td>6554</td>
<td>954</td>
<td>5600</td>
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<tr>
<td>Leachate Pool (d)</td>
<td>50.0</td>
<td>47.4002</td>
<td>47.7289</td>
<td>47.4486</td>
<td>6574</td>
<td>968</td>
<td>5606</td>
</tr>
<tr>
<td>dH2O Blank (a)</td>
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<td>50.1488</td>
<td>50.1538</td>
<td>50.1537</td>
<td>100</td>
<td>98</td>
<td>2</td>
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<tr>
<td>dH2O Blank (b)</td>
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<td>47.1172</td>
<td>47.1215</td>
<td>47.1208</td>
<td>86</td>
<td>72</td>
<td>14</td>
</tr>
</tbody>
</table>

Sample Date: Nov 20/98  
Date Analyzed: Dec 02/98  
Technician: KAF

#### Suspended Solids

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Volume (mL)</th>
<th>Tare (g)</th>
<th>Dry (g)</th>
<th>Fired (g)</th>
<th>TSS (mg/L)</th>
<th>FSS (mg/L)</th>
<th>VSS (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leachate Pool (a)</td>
<td>250.0</td>
<td>1.5512</td>
<td>1.5620</td>
<td>1.5521</td>
<td>43.2</td>
<td>3.6</td>
<td>39.6</td>
</tr>
<tr>
<td>Leachate Pool (b)</td>
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<td>1.5476</td>
<td>1.5585</td>
<td>1.5490</td>
<td>43.6</td>
<td>5.6</td>
<td>38.0</td>
</tr>
<tr>
<td>Leachate Pool (c)</td>
<td>250.0</td>
<td>1.5462</td>
<td>1.5580</td>
<td>1.5475</td>
<td>47.2</td>
<td>5.2</td>
<td>42.0</td>
</tr>
<tr>
<td>Leachate Pool (d)</td>
<td>250.0</td>
<td>1.5591</td>
<td>1.5699</td>
<td>1.5603</td>
<td>43.2</td>
<td>4.8</td>
<td>38.4</td>
</tr>
<tr>
<td>dH2O Blank (a)</td>
<td>250.0</td>
<td>1.5341</td>
<td>1.5343</td>
<td>1.5341</td>
<td>0.8</td>
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<td>0.8</td>
</tr>
<tr>
<td>dH2O Blank (b)</td>
<td>250.0</td>
<td>1.5611</td>
<td>1.5611</td>
<td>1.5611</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Sample Date: Nov 20/98  
Date Analyzed: Jan 21/99  
Technician: KAF
### Metals

**Civil 599 - Masc Thesis**  
**Constructed Wetlands Project**

Leachate Characterization: *Metals (mg/L)*

#### Summary:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Data Type</th>
<th>Dilution Factor</th>
<th>Al (mg/L)</th>
<th>Ca (mg/L)</th>
<th>Cu (mg/L)</th>
<th>Ni (mg/L)</th>
<th>P (mg/L)</th>
<th>Pb (mg/L)</th>
<th>Zn (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leachate - digested (a)</td>
<td>Diluted: 4</td>
<td>4.72</td>
<td>20.15</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full-strength: 19</td>
<td>19</td>
<td>8.1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leachate - digested (b)</td>
<td>Diluted: 4</td>
<td>4.76</td>
<td>20.73</td>
<td>0.02</td>
<td></td>
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<td>Full-strength: 19</td>
<td>19</td>
<td>8.3</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leachate - undigested (c)</td>
<td>Diluted: 1</td>
<td>15.13</td>
<td>69.27</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full-strength: 17</td>
<td>17</td>
<td>7.6</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Blank</td>
<td>Diluted: 2.0</td>
<td>0.02</td>
<td>0</td>
<td>0.02</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Raw Data:

For digested samples (ie, Leachate a & b, blank), started with 500 mL sample + 50 mL concentrated nitric acid and slowly boiled down to <50mL, then reconstituted to 100mL.

For undigested sample (ie, Leachate c), mixed 100 mL sample + 10 mL concentrated nitric acid and submitted as is.

Stored in dark, at 4°C.

Submitted to Carol Dyck (Soils Lab, 822-5965) for ICP scan (selected metals)
## APPENDIX D.1 RAW DATA: LEACHATE CHARACTERIZATION

### Metals (cont.)

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>ELEMENT</th>
<th>READING</th>
<th>STD DEV</th>
<th>% RSD</th>
<th>DETECTION LIMIT</th>
<th>QUANTITATION LIMIT</th>
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</thead>
<tbody>
<tr>
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## Extended Biochemical Oxygen Demand [BOD]

**Summary:**

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### Raw Data:

**NOTES:** Seed = 1.27 g (moist wt.) of poolside soil per 300mL BOD bottle

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<th>Bottle ID</th>
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**Date:** Feb 15/98 Feb 18/98 Feb 23/98 Feb 25/98 Mar 05/98

Kevin Frankowski 112 UBC CIVIL ENGINEERING Masters Thesis
### Extended BOD (cont.)

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Kevin Frankowski

UBC CIVIL ENGINEERING
Masters Thesis
## Oxygen Demand Ratios

### Civil 599 - MAS: Thesis

**Constructed Wetlands Project**

Leachate Characterization Data: *Theoretical Oxygen Demand & BOD:COD, etc. ratios*

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<td>0.330</td>
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<td>0.46</td>
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<td>0.51</td>
<td>0.36</td>
<td>0.35</td>
<td>0.35</td>
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</tr>
</tbody>
</table>
Toxicity [pH-effects]

**Civil 599 - MASc Thesis**

**Construct Wetlands Project**

**Leachate Characterization: pH-effects on acute toxicity**

### Raw Data:

**NOTES:**
- Acute toxicity measured using modified LC50 bioassay (2 fish per 1L beaker)
- Temp = 15 C; minimum aeration provided, to prevent fish fatigue due to excessive turbulence
- pH adjusted using HCl or NaOH

**NOTE:** a power outage caused failure of the aeration equipment at -65 hr, thereby preventing any new mortalities observed at 72 hr to be properly attributed to leachate toxicity

**Survival Data:**

<table>
<thead>
<tr>
<th>pH</th>
<th>Exposure period (hrs)</th>
<th>Concentration (% v/v)</th>
<th>0</th>
<th>24</th>
<th>48</th>
<th>72</th>
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<tbody>
<tr>
<td>8</td>
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<td>2/2</td>
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<td>-</td>
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<tr>
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<td></td>
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<td>2/2</td>
<td>1/2</td>
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<td></td>
<td>32</td>
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</table>

Comments: * may have been insufficient aeration to overcome oxygen demand

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<th>48</th>
<th>72</th>
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<td>-</td>
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<td>1/2</td>
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</table>

Comments: * may have been insufficient aeration to overcome oxygen demand

<table>
<thead>
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<th>Exposure period (hrs)</th>
<th>Concentration (% v/v)</th>
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<td>2/2</td>
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<td>2/2</td>
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</table>

Comments: * aeration failure (due to power outage)

<table>
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<th>Exposure period (hrs)</th>
<th>Concentration (% v/v)</th>
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<th>48</th>
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<td>-</td>
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<td>2/2</td>
<td>2/2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH</th>
<th>Exposure period (hrs)</th>
<th>Concentration (% v/v)</th>
<th>0</th>
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<th>48</th>
<th>72</th>
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</thead>
<tbody>
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</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
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<td>0</td>
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<td>-</td>
</tr>
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</tr>
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<td></td>
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<td>0</td>
<td>-</td>
<td>-</td>
</tr>
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<td>Blank</td>
<td>2/2</td>
<td>1/2</td>
<td>0/2</td>
<td>-</td>
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</tbody>
</table>

Comments: * Control Failure (due to pH?)

<table>
<thead>
<tr>
<th>pH</th>
<th>Exposure period (hrs)</th>
<th>Concentration (% v/v)</th>
<th>0</th>
<th>24</th>
<th>48</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
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<td>2/2</td>
<td>0</td>
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<td>-</td>
</tr>
<tr>
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<td></td>
<td>75</td>
<td>2/2</td>
<td>0</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>2/2</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32</td>
<td>2/2</td>
<td>0</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>Blank</td>
<td>2/2</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Comments: * Control Failure (due to pH?)
Toxicity

**Construction Wetlands Project**

Leachate Characterization: *Acute toxicity (as Rainbow Trout 96hr LC50, %v/v)*

### Summary:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Leacht. (pH&lt;5.5)</th>
<th>Leacht. (pH&gt;5.5)</th>
<th>Leacht. (pH&gt;6.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seep- North</td>
<td>Oct 28/97 1.74</td>
<td>Nov 20/98 &lt;3%</td>
<td>Jan 27/99 0.71</td>
</tr>
<tr>
<td>Slough (west)</td>
<td>Dec 15/97 22.36</td>
<td>Nov 20/98 &gt;6.25%</td>
<td>Mar 31/99 35.36</td>
</tr>
<tr>
<td>Slough (east)</td>
<td>Oct 28/97 &gt;50%</td>
<td>Nov 20/98 &gt;25%</td>
<td>Mar 31/99 &gt;3%</td>
</tr>
<tr>
<td>Seep- Downstrm</td>
<td>Oct 28/97 &gt;50%</td>
<td>Nov 20/98 &gt;100%</td>
<td>Mar 31/99 &gt;100%</td>
</tr>
</tbody>
</table>

### Lower 95%

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Leacht. (pH&lt;5.5)</th>
<th>Leacht. (pH&gt;5.5)</th>
<th>Leacht. (pH&gt;6.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seep- North</td>
<td>Oct 28/97 1.092</td>
<td>Dec 15/97 2.763</td>
<td>Jan 27/99 2.000</td>
</tr>
<tr>
<td>Slough (west)</td>
<td>Dec 15/97 10.000</td>
<td>Nov 20/98 50.000</td>
<td>Mar 31/99 6.250</td>
</tr>
<tr>
<td>Slough (east)</td>
<td>Dec 15/97 -</td>
<td>Nov 20/98 -</td>
<td>Mar 31/99 -</td>
</tr>
</tbody>
</table>

### Upper 95%

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Leacht. (pH&lt;5.5)</th>
<th>Leacht. (pH&gt;5.5)</th>
<th>Leacht. (pH&gt;6.9)</th>
</tr>
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<tbody>
<tr>
<td>Seep- North</td>
<td>Oct 28/97 2.763</td>
<td>Dec 15/97 50.000</td>
<td>Jan 27/99 6.250</td>
</tr>
<tr>
<td>Slough (west)</td>
<td>Dec 15/97 -</td>
<td>Nov 20/98 -</td>
<td>Mar 31/99 -</td>
</tr>
</tbody>
</table>

---

Kevin Frankowski 116 UBC CIVIL ENGINEERING Masters Thesis
## Toxicity (cont.)

### Raw Data

**NOTES:** Samples submitted for analysis by EVS (technician as noted)  
Unless otherwise noted, LC50s were calculated using the Trimmed Spearman-Karber method.

<table>
<thead>
<tr>
<th>Sample Date</th>
<th>Sample ID</th>
<th>Hour 0 - # fish alive per tank</th>
<th>Hour 96 - highest conc. &gt;50% alive</th>
<th>Hour 96 - lowest conc. &lt;50% alive</th>
<th>LC50 (%)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>pH (at Hour 0)</th>
<th>Date Analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 28/97</td>
<td>Seep- North</td>
<td>10</td>
<td>50%</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>&gt;50%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Seep- Downstrm</td>
<td>10</td>
<td>50%</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>&gt;50%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dec 15/97</td>
<td>Leach.(pH&lt;5.5)</td>
<td>10</td>
<td>1%</td>
<td>6</td>
<td>10%</td>
<td>0</td>
<td>1.737</td>
<td>1.092</td>
<td>2.763</td>
</tr>
<tr>
<td></td>
<td>Leach.(pH&gt;5.5)</td>
<td>10</td>
<td>10%</td>
<td>10</td>
<td>50%</td>
<td>0</td>
<td>22.4</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Nov 20/98</td>
<td>Leach.(pH&lt;5.5)</td>
<td>7</td>
<td>0%</td>
<td>7</td>
<td>3%</td>
<td>0</td>
<td>&lt;3%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Leach.(pH&gt;6.9)</td>
<td>7</td>
<td>6.25%</td>
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<td>-</td>
<td>&gt;6.25%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Seep- North</td>
<td>7</td>
<td>25%</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>&gt;25%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Slough (west)</td>
<td>7</td>
<td>100%</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Slough (east)</td>
<td>7</td>
<td>100%</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jan 27/99</td>
<td>Leach.(pH&lt;5.5)</td>
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<td>0.5%</td>
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<td>1%</td>
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<td></td>
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<td>50%</td>
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<td>0</td>
<td>&gt;3%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Slough (west)</td>
<td>10</td>
<td>100%</td>
<td>10</td>
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<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Slough (east)</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mar 31/99</td>
<td>Leach.(pH&lt;5.5)</td>
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<td>2%</td>
<td>7</td>
<td>6%</td>
<td>0</td>
<td>3.54</td>
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<td>6.25</td>
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<tr>
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<td>0.5%</td>
<td>10</td>
<td>1%</td>
<td>0</td>
<td>0.71</td>
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</table>

See Appendix D.4 for further data...
### Colour

**Data:**

NOTES: Determined with a Hellige Aqua-tester (APHA Color Units)

*Measured only on raw leachate (from Leachate Pool), but over a range of pH*

<table>
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<th>Sample Date:</th>
<th>Oct 29/99</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>Measured colour</th>
<th>Dilution Factor</th>
<th>Colour @ 100%</th>
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<tbody>
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<td>3.6</td>
<td>10</td>
<td>100</td>
<td>1000</td>
</tr>
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**Date Analyzed:** Oct 30/99

**Technician:** KAF

---

### 1992 Leachate Characterization (from Triton 1993)

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<th>Parameter</th>
<th>Triton (1993) data</th>
<th>Value</th>
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<td>Field temperature (ambient)</td>
<td>°C</td>
<td>28.4</td>
</tr>
<tr>
<td>dissolved oxygen (ambient)</td>
<td>mg/L</td>
<td>2370</td>
</tr>
<tr>
<td>pH (ambient)</td>
<td>-</td>
<td>685</td>
</tr>
<tr>
<td>specific conductivity</td>
<td>us/cm</td>
<td>33.8</td>
</tr>
<tr>
<td>Physical: Solids</td>
<td>mg/L</td>
<td>130</td>
</tr>
<tr>
<td>TSS (Total Suspended Solids)</td>
<td>mg/L</td>
<td>0.032</td>
</tr>
<tr>
<td>TDS (Total Dissolved Solids)</td>
<td>mg/L</td>
<td>87.4</td>
</tr>
<tr>
<td>True Colour (pH=7)</td>
<td>mg/L</td>
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</tr>
<tr>
<td>Chemical</td>
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</tr>
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</tr>
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<tr>
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</tr>
<tr>
<td>calcium</td>
<td>mg/L</td>
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<tr>
<td>copper</td>
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<tr>
<td>iron</td>
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</tr>
<tr>
<td>magnesium</td>
<td>mg/L</td>
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<td>nickel</td>
<td>mg/L</td>
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</tr>
<tr>
<td>lead</td>
<td>mg/L</td>
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</tr>
<tr>
<td>zinc</td>
<td>mg/L</td>
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<td>chemical oxygen demand (COD)</td>
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<td></td>
</tr>
<tr>
<td>ammonium and nitrogen (as nitrate)</td>
<td>mg/L</td>
<td></td>
</tr>
<tr>
<td>nitrite and nitrate</td>
<td>mg/L</td>
<td></td>
</tr>
<tr>
<td>nitrite and nitrate (as nitrogen)</td>
<td>mg/L</td>
<td></td>
</tr>
<tr>
<td>nitrite and nitrate (as nitrogen)</td>
<td>mg/L</td>
<td></td>
</tr>
</tbody>
</table>

**NOTES**

1. APHA CU = APHA colour units
APPENDIX D.2

RAW DATA: SCREENING TRIALS
### APPENDIX D.2 RAW DATA: SCREENING TRIALS

#### Monitoring Data: pH

**Civil 599 - MASc Thesis**  
**Constructed Wetlands Project**  
**Screening Trials: Aerated Bioreactors - Monitoring Data (pH)**

**NOTES** - Rep "A" = "Door"; Rep "B" = "Wall"

**Treatment: Control Treatment**

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**Treatment: Fungal Treatment**

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## Monitoring Data: DO

**Civil 599 - MASc Thesis**  
**Constructed Wetlands Project**  
**Screening Trials: Aerated Bioreactors - Monitoring Data (DO)**

### NOTES: - Rep "A" = "Door"; Rep "B" = "Wall"

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# Monitoring Data: Conductivity

## Civil 599 - MASc Thesis

**Constructed Wetlands Project**

**Screening Trials: Aerated Bioreactors - Monitoring Data (Conductivity)**

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<td>1500</td>
<td>1500</td>
<td>220</td>
<td>220</td>
<td>40</td>
<td>40</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>16-Dec-97</td>
<td>1500</td>
<td>1300</td>
<td>260</td>
<td>260</td>
<td>20</td>
<td>40</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>18-Dec-97</td>
<td>1500</td>
<td>1500</td>
<td>260</td>
<td>270</td>
<td>40</td>
<td>50</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>20-Dec-97</td>
<td>1500</td>
<td>1800</td>
<td>260</td>
<td>200</td>
<td>50</td>
<td>50</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>26-Dec-97</td>
<td>1500</td>
<td>2000</td>
<td>240</td>
<td>230</td>
<td>50</td>
<td>60</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>29-Dec-97</td>
<td>1700</td>
<td>1800</td>
<td>260</td>
<td>270</td>
<td>80</td>
<td>80</td>
<td>70</td>
<td>90</td>
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</tr>
</tbody>
</table>

### Treatment: Duckweed Treatment

<table>
<thead>
<tr>
<th>Date</th>
<th>Replicate</th>
<th>100% - A</th>
<th>100% - B</th>
<th>10% - A</th>
<th>10% - B</th>
<th>1% - A</th>
<th>1% - B</th>
<th>0% - A</th>
<th>0% - B</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-Dec-97</td>
<td>1500</td>
<td>1500</td>
<td>210</td>
<td>210</td>
<td>35</td>
<td>40</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>16-Dec-97</td>
<td>1400</td>
<td>1300</td>
<td>150</td>
<td>230</td>
<td>30</td>
<td>30</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>18-Dec-97</td>
<td>1400</td>
<td>1400</td>
<td>230</td>
<td>210</td>
<td>20</td>
<td>20</td>
<td>1</td>
<td>10</td>
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</tr>
<tr>
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<td>1600</td>
<td>1600</td>
<td>220</td>
<td>180</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>26-Dec-97</td>
<td>1700</td>
<td>1700</td>
<td>250</td>
<td>160</td>
<td>30</td>
<td>30</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>29-Dec-97</td>
<td>1700</td>
<td>1600</td>
<td>300</td>
<td>190</td>
<td>90</td>
<td>90</td>
<td>50</td>
<td>60</td>
<td></td>
</tr>
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</table>

### Treatment: Fungal Treatment

<table>
<thead>
<tr>
<th>Date</th>
<th>Replicate</th>
<th>100% - A</th>
<th>100% - B</th>
<th>10% - A</th>
<th>10% - B</th>
<th>1% - A</th>
<th>1% - B</th>
<th>0% - A</th>
<th>0% - B</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-Dec-97</td>
<td>1500</td>
<td>1500</td>
<td>220</td>
<td>240</td>
<td>45</td>
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<td>20</td>
<td>40</td>
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</tr>
<tr>
<td>16-Dec-97</td>
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<td>1500</td>
<td>270</td>
<td>240</td>
<td>60</td>
<td>70</td>
<td>20</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>18-Dec-97</td>
<td>1500</td>
<td>1400</td>
<td>240</td>
<td>230</td>
<td>100</td>
<td>100</td>
<td>110</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>20-Dec-97</td>
<td>1700</td>
<td>1700</td>
<td>190</td>
<td>200</td>
<td>110</td>
<td>140</td>
<td>160</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>26-Dec-97</td>
<td>1700</td>
<td>1800</td>
<td>260</td>
<td>260</td>
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<td>190</td>
<td>190</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>29-Dec-97</td>
<td>2200</td>
<td>1700</td>
<td>330</td>
<td>360</td>
<td>190</td>
<td>250</td>
<td>230</td>
<td>270</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D.2 RAW DATA: SCREENING TRIALS

Tannin and Lignin

Civil 599 - MASc Thesis
Constructed Wetlands Project
Screening Trials: Tannins and Lignins (T&L) (mg/L as Tannic Acid)

Summary:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>T&amp;L (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>control A 10%</td>
<td>138.35</td>
</tr>
<tr>
<td>control B 10%</td>
<td>133.01</td>
</tr>
<tr>
<td>Soil A 10%</td>
<td>115.12</td>
</tr>
<tr>
<td>Soil B 10%</td>
<td>114.58</td>
</tr>
<tr>
<td>Duckweed A 10%</td>
<td>93.75</td>
</tr>
<tr>
<td>Duckweed B 10%</td>
<td>95.62</td>
</tr>
<tr>
<td>Fungal A 10%</td>
<td>95.35</td>
</tr>
<tr>
<td>Fungal B 10%</td>
<td>95.35</td>
</tr>
<tr>
<td>Fungal A 0%</td>
<td>34.19</td>
</tr>
<tr>
<td>Fungal B 0%</td>
<td>30.98</td>
</tr>
</tbody>
</table>

Summary (Total ThOD for T&L):

<table>
<thead>
<tr>
<th>Sample Date</th>
<th>T&amp;L ThOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 15/97</td>
<td>138.35</td>
</tr>
<tr>
<td></td>
<td>133.01</td>
</tr>
<tr>
<td></td>
<td>115.12</td>
</tr>
<tr>
<td></td>
<td>114.58</td>
</tr>
<tr>
<td></td>
<td>93.75</td>
</tr>
<tr>
<td></td>
<td>95.62</td>
</tr>
<tr>
<td></td>
<td>95.35</td>
</tr>
<tr>
<td></td>
<td>95.35</td>
</tr>
<tr>
<td></td>
<td>34.19</td>
</tr>
<tr>
<td></td>
<td>30.98</td>
</tr>
</tbody>
</table>

Raw Data:

NOTES: Reagents: Folin phenol (0.1 mL), carbonate tetrate (1.0 mL) (allow 30 min for colour development)
Sample volume was 5.0 mL.

Sample Date: Dec 15/97 ("Final effluent" samples, taken during jar test teardown)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dilution Factor</th>
<th>Absorbance (@ 700 nm)</th>
<th>T&amp;L (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>control A 10%</td>
<td>25</td>
<td>0.518</td>
<td>138.35</td>
</tr>
<tr>
<td>control B 10%</td>
<td>25</td>
<td>0.498</td>
<td>133.01</td>
</tr>
<tr>
<td>Soil A 10%</td>
<td>25</td>
<td>0.431</td>
<td>115.12</td>
</tr>
<tr>
<td>Soil B 10%</td>
<td>25</td>
<td>0.429</td>
<td>114.58</td>
</tr>
<tr>
<td>Duckweed A 10%</td>
<td>25</td>
<td>0.351</td>
<td>93.75</td>
</tr>
<tr>
<td>Duckweed B 10%</td>
<td>25</td>
<td>0.358</td>
<td>95.62</td>
</tr>
<tr>
<td>Fungal A 10%</td>
<td>25</td>
<td>0.357</td>
<td>95.35</td>
</tr>
<tr>
<td>Fungal B 10%</td>
<td>25</td>
<td>0.128</td>
<td>34.19</td>
</tr>
<tr>
<td>Fungal A 0%</td>
<td>25</td>
<td>0.118</td>
<td>30.98</td>
</tr>
</tbody>
</table>

Sample Date: Dec 15/97 ("Final effluent" samples, taken during jar test teardown)

Standard Curve:

<table>
<thead>
<tr>
<th>Concentration (mg/L)</th>
<th>Absorbance (@ 700 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.191</td>
</tr>
<tr>
<td>4</td>
<td>0.370</td>
</tr>
<tr>
<td>8</td>
<td>0.750</td>
</tr>
</tbody>
</table>

Standard Curve slope: 0.0936

Date Analyzed: May 26/99
Technician: KAF & Angelika

T&L Standard Curve:

<table>
<thead>
<tr>
<th>Concentration (mg/L)</th>
<th>Absorbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>0.30</td>
<td>0.60</td>
</tr>
<tr>
<td>0.50</td>
<td>0.80</td>
</tr>
</tbody>
</table>

y = 0.9936x
R² = 0.9999

Kevin Frankowski
123
UBC CIVIL ENGINEERING
Masters Thesis
## Toxicity

### Civil 599 - MSc Thesis
**Constructed Wetlands Project**

**Screening Trials: Acute toxicity (as Rainbow Trout 96hr LC50, %v/v)**

### Summary:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>LC50s Dec 29/97</th>
<th>LC50 95% Confidence Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>control A</td>
<td>3.16</td>
<td>0.01</td>
</tr>
<tr>
<td>control B</td>
<td>3.16</td>
<td>0.01</td>
</tr>
<tr>
<td>Soil A</td>
<td>31.60</td>
<td>0.1</td>
</tr>
<tr>
<td>Soil B</td>
<td>31.60</td>
<td>0.1</td>
</tr>
<tr>
<td>Duckweed A</td>
<td>10.00</td>
<td>0.020</td>
</tr>
<tr>
<td>Duckweed B</td>
<td>31.60</td>
<td>0.1</td>
</tr>
<tr>
<td>Fungal A</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>Fungal B</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>Blank (dechlor) A</td>
<td>&gt;100%</td>
<td>1</td>
</tr>
<tr>
<td>Blank (dechlor) B</td>
<td>&gt;100%</td>
<td>1</td>
</tr>
</tbody>
</table>

### Raw Data:

**NOTES:** Samples submitted to analyzed by EVS (technician as noted).

Unless otherwise noted, LC50s were calculated using the Trimmed Spearman-Karber method.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Date</th>
<th>Hour 0 - &lt;50% alive per tank</th>
<th>Hour 96 - &lt;50% alive at this conc.</th>
<th>LC50 (%)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>control A</td>
<td>Dec 29/97</td>
<td>2</td>
<td>1%</td>
<td>2</td>
<td>10%</td>
<td>0</td>
<td>3.16</td>
</tr>
<tr>
<td>control B</td>
<td>Dec 29/97</td>
<td>2</td>
<td>1%</td>
<td>2</td>
<td>10%</td>
<td>0</td>
<td>3.16</td>
</tr>
<tr>
<td>Soil A</td>
<td>Dec 29/97</td>
<td>2</td>
<td>10%</td>
<td>2</td>
<td>100%</td>
<td>0</td>
<td>31.6</td>
</tr>
<tr>
<td>Soil B</td>
<td>Dec 29/97</td>
<td>2</td>
<td>10%</td>
<td>2</td>
<td>100%</td>
<td>0</td>
<td>31.6</td>
</tr>
<tr>
<td>Duckweed A</td>
<td>Dec 29/97</td>
<td>2</td>
<td>10%</td>
<td>2</td>
<td>100%</td>
<td>0</td>
<td>31.6</td>
</tr>
<tr>
<td>Duckweed B</td>
<td>Dec 29/97</td>
<td>2</td>
<td>10%</td>
<td>2</td>
<td>100%</td>
<td>0</td>
<td>31.6</td>
</tr>
<tr>
<td>Fungal A</td>
<td>Dec 29/97</td>
<td>2</td>
<td>10%</td>
<td>2</td>
<td>100%</td>
<td>0</td>
<td>31.6</td>
</tr>
<tr>
<td>Blank (dechlor) A</td>
<td>Dec 29/97</td>
<td>2</td>
<td>100%</td>
<td>2</td>
<td>100%</td>
<td>2</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>Blank (dechlor) B</td>
<td>Dec 29/97</td>
<td>2</td>
<td>100%</td>
<td>2</td>
<td>100%</td>
<td>2</td>
<td>&gt;100%</td>
</tr>
</tbody>
</table>
Spectrophotometric Response

**Spectrophotometer Response**
*Original Jar Test (ambient pH)*

- Control A
- Control B
- Soil A
- Soil B
- Duckweed A
- Duckweed B
- Fungal A
- Fungal B
- Fungal A 0%
- Fungal B 0%

Absorbance

Wavelength (nm)
Acidity

**NOTES:** Since initial pH of all samples were close to or below 4.5, no alkalinity was considered present.
Initial pH of all samples were above 3.7, therefore no mineral acidity was considered present.
All acidity present can be considered as CO$_2$ acidity.
Due to the dark colour, a visual indicator could not be used. A pH meter was used instead
(a Beckman Model 44 meter, with Oakton epoxy-body pH probe (Cat# WD-35801-00)).
Titration was carried to an endpoint of pH 8.2-8.4 (the "phenolphthalein endpoint").
Titration Base: NaOH (0.5001 N)

<table>
<thead>
<tr>
<th>Sample Vol (mL)</th>
<th>Initial pH</th>
<th>Final pH</th>
<th>Initial burette vol (mL)</th>
<th>Final burette vol (mL)</th>
<th>Total vol of NaOH used (mL)</th>
<th>Acidity (mg/L as CaCO3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. Pool (rep A)</td>
<td>20</td>
<td>3.89</td>
<td>8.35</td>
<td>3.40</td>
<td>5.52</td>
<td>2.12</td>
</tr>
<tr>
<td>L. Pool (rep B)</td>
<td>20</td>
<td>3.98</td>
<td>8.29</td>
<td>5.52</td>
<td>7.64</td>
<td>2.12</td>
</tr>
</tbody>
</table>

**Sample Date:** Oct 29/99

**Date Analyzed:** Nov 02/99

**Technician:** Priscilla
APPENDIX D.3

RAW DATA: BENCH-SCALE TESTING
## Monitoring Data [pH, DO, Conductivity]

### Summary (Misc):
- **Series #1**: Date of original leachate sample: Jan 30/98
- **Series #2**: Date of original leachate sample: Apr 05/99
- All tanks in a laboratory Controlled Environment Room (CER).
- Temp = 22°C
- Photoperiod = 24:0 hr

### Summary (pH):

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Day 1</th>
<th>Measurement Day (Setup #1)</th>
<th>Day 2</th>
<th>Day 7</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Blank (a)</td>
<td>7.15</td>
<td>7.13</td>
<td>7.06</td>
<td>7.44</td>
<td>7.27</td>
<td>7.34</td>
</tr>
<tr>
<td>10% (a)</td>
<td>5.72</td>
<td>6.46</td>
<td>7.69</td>
<td>7.71</td>
<td>7.60</td>
<td>7.59</td>
</tr>
<tr>
<td>10% (b)</td>
<td>5.62</td>
<td>6.30</td>
<td>7.65</td>
<td>7.91</td>
<td>7.94</td>
<td>7.85</td>
</tr>
<tr>
<td>50% (a)</td>
<td>4.26</td>
<td>4.47</td>
<td>5.76</td>
<td>7.15</td>
<td>7.45</td>
<td>7.36</td>
</tr>
<tr>
<td>50% (b)</td>
<td>4.34</td>
<td>4.53</td>
<td>6.71</td>
<td>7.63</td>
<td>7.66</td>
<td>7.59</td>
</tr>
<tr>
<td>75% (a)</td>
<td>4.20</td>
<td>4.33</td>
<td>5.26</td>
<td>6.61</td>
<td>6.61</td>
<td>6.29</td>
</tr>
<tr>
<td>75% (b)</td>
<td>4.34</td>
<td>4.51</td>
<td>5.00</td>
<td>7.12</td>
<td>7.62</td>
<td>7.55</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>7.21</td>
<td>7.12</td>
<td>7.39</td>
<td>7.46</td>
<td>7.30</td>
<td></td>
</tr>
</tbody>
</table>

### Summary (DO) (mg/L):

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Day 1</th>
<th>Measurement Day (Setup #1)</th>
<th>Day 2</th>
<th>Day 7</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Blank (a)</td>
<td>8.1</td>
<td>7.5</td>
<td>5.8</td>
<td>4.8</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>10% (a)</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>5.7</td>
<td>6.1</td>
<td>5.1</td>
</tr>
<tr>
<td>10% (b)</td>
<td>7.5</td>
<td>5.4</td>
<td>6.0</td>
<td>5.5</td>
<td>6.6</td>
<td>4.2</td>
</tr>
<tr>
<td>50% (a)</td>
<td>6.5</td>
<td>2.1</td>
<td>1.3</td>
<td>1.8</td>
<td>1.0</td>
<td>5.9</td>
</tr>
<tr>
<td>50% (b)</td>
<td>7.8</td>
<td>6.6</td>
<td>3.9</td>
<td>0.8</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>75% (a)</td>
<td>7.6</td>
<td>4.7</td>
<td>1.1</td>
<td>0.7</td>
<td>0.6</td>
<td>5.2</td>
</tr>
<tr>
<td>75% (b)</td>
<td>7.6</td>
<td>5.6</td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>8.7</td>
<td>8.1</td>
<td>8.0</td>
<td>8.5</td>
<td>8.7</td>
<td></td>
</tr>
</tbody>
</table>

### Summary (conductivity) (uS/cm):

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Day 1</th>
<th>Measurement Day (Setup #1)</th>
<th>Day 2</th>
<th>Day 7</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Blank (a)</td>
<td>8.0</td>
<td>120</td>
<td>350</td>
<td>450</td>
<td>540</td>
<td>630</td>
</tr>
<tr>
<td>10% (a)</td>
<td>270</td>
<td>240</td>
<td>550</td>
<td>650</td>
<td>750</td>
<td>850</td>
</tr>
<tr>
<td>10% (b)</td>
<td>270</td>
<td>300</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td>800</td>
</tr>
<tr>
<td>50% (a)</td>
<td>900</td>
<td>1300</td>
<td>1500</td>
<td>1700</td>
<td>1900</td>
<td>2100</td>
</tr>
<tr>
<td>50% (b)</td>
<td>1200</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
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<tr>
<td>75% (a)</td>
<td>1300</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>75% (b)</td>
<td>1300</td>
<td>1500</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>30</td>
<td>40</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

### Raw Data:
- **DO** measured with an YSI Model 37 DO probe, calibrated each day
- **pH** measured with an Orion Model 230A, with gel-body probe
- **Conductivity** measured with a YSI Model 33 SCT probe, calibrated each day

### Data measured:
- **Day 1**: Feb 21/98
- **Day 1**: Apr 13/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Conductivity (uS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank (a)</td>
<td>7.15</td>
<td>8.1</td>
<td>80</td>
</tr>
<tr>
<td>dH2O Blank (b)</td>
<td>7.19</td>
<td>8.2</td>
<td>50</td>
</tr>
<tr>
<td>10% (a)</td>
<td>5.72</td>
<td>6.0</td>
<td>270</td>
</tr>
<tr>
<td>10% (b)</td>
<td>5.62</td>
<td>7.5</td>
<td>270</td>
</tr>
<tr>
<td>50% (a)</td>
<td>4.26</td>
<td>6.5</td>
<td>900</td>
</tr>
<tr>
<td>50% (b)</td>
<td>4.20</td>
<td>7.8</td>
<td>1200</td>
</tr>
<tr>
<td>75% (a)</td>
<td>4.20</td>
<td>7.0</td>
<td>1300</td>
</tr>
<tr>
<td>75% (b)</td>
<td>4.30</td>
<td>7.6</td>
<td>1300</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>7.21</td>
<td>8.7</td>
<td>30</td>
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<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank (a)</td>
<td>6.72</td>
<td>9.0</td>
</tr>
<tr>
<td>dH2O Blank (b)</td>
<td>6.22</td>
<td>4.4</td>
</tr>
<tr>
<td>10% (a)</td>
<td>5.27</td>
<td>5.1</td>
</tr>
<tr>
<td>10% (b)</td>
<td>4.22</td>
<td>4.2</td>
</tr>
<tr>
<td>50% (a)</td>
<td>4.12</td>
<td>5.9</td>
</tr>
<tr>
<td>50% (b)</td>
<td>3.86</td>
<td>2.4</td>
</tr>
<tr>
<td>75% (a)</td>
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</tr>
<tr>
<td>75% (b)</td>
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<td>3.2</td>
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</table>

Technician: KAF (at EWS)
### Monitoring Data [pH, DO, Conductivity] (cont.)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Conductivity (uS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank (a)</td>
<td>7.13</td>
<td>7.5</td>
<td>120</td>
</tr>
<tr>
<td>dH2O Blank (b)</td>
<td>7.24</td>
<td>7.6</td>
<td>80</td>
</tr>
<tr>
<td>10% (a)</td>
<td>6.46</td>
<td>6.0</td>
<td>260</td>
</tr>
<tr>
<td>10% (b)</td>
<td>6.30</td>
<td>5.4</td>
<td>310</td>
</tr>
<tr>
<td>50% (a)</td>
<td>4.47</td>
<td>2.1</td>
<td>1000</td>
</tr>
<tr>
<td>50% (b)</td>
<td>4.53</td>
<td>6.6</td>
<td>1300</td>
</tr>
<tr>
<td>75% (a)</td>
<td>4.33</td>
<td>4.7</td>
<td>1400</td>
</tr>
<tr>
<td>75% (b)</td>
<td>4.51</td>
<td>5.6</td>
<td>1500</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>7.12</td>
<td>8.1</td>
<td>40</td>
</tr>
</tbody>
</table>

Technician: KAF (at EVS)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Conductivity (uS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank (b)</td>
<td>4.47</td>
<td>6.0</td>
<td>240</td>
</tr>
<tr>
<td>10% (a)</td>
<td>6.46</td>
<td>6.0</td>
<td>400</td>
</tr>
<tr>
<td>10% (b)</td>
<td>6.65</td>
<td>6.0</td>
<td>500</td>
</tr>
<tr>
<td>50% (a)</td>
<td>5.76</td>
<td>1.3</td>
<td>1300</td>
</tr>
<tr>
<td>50% (b)</td>
<td>6.71</td>
<td>3.9</td>
<td>1300</td>
</tr>
<tr>
<td>75% (a)</td>
<td>5.26</td>
<td>1.1</td>
<td>1800</td>
</tr>
<tr>
<td>75% (b)</td>
<td>5.50</td>
<td>0.9</td>
<td>1900</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>7.39</td>
<td>8.0</td>
<td>70</td>
</tr>
</tbody>
</table>

Technician: KAF (at EVS)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Conductivity (uS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank (a)</td>
<td>7.06</td>
<td>5.8</td>
<td>350</td>
</tr>
<tr>
<td>dH2O Blank (b)</td>
<td>7.40</td>
<td>6.0</td>
<td>240</td>
</tr>
<tr>
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<td>7.69</td>
<td>6.0</td>
<td>400</td>
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<tr>
<td>10% (b)</td>
<td>7.65</td>
<td>6.0</td>
<td>500</td>
</tr>
<tr>
<td>50% (a)</td>
<td>5.76</td>
<td>1.3</td>
<td>1300</td>
</tr>
<tr>
<td>50% (b)</td>
<td>6.71</td>
<td>3.9</td>
<td>1300</td>
</tr>
<tr>
<td>75% (a)</td>
<td>5.26</td>
<td>1.1</td>
<td>1800</td>
</tr>
<tr>
<td>75% (b)</td>
<td>5.50</td>
<td>0.9</td>
<td>1900</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>7.39</td>
<td>8.0</td>
<td>70</td>
</tr>
</tbody>
</table>

Technician: KAF (at EVS)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Conductivity (uS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank (a)</td>
<td>7.44</td>
<td>4.8</td>
<td>450</td>
</tr>
<tr>
<td>dH2O Blank (b)</td>
<td>7.27</td>
<td>4.4</td>
<td>350</td>
</tr>
<tr>
<td>10% (a)</td>
<td>7.71</td>
<td>5.7</td>
<td>500</td>
</tr>
<tr>
<td>10% (b)</td>
<td>7.81</td>
<td>5.5</td>
<td>500</td>
</tr>
<tr>
<td>50% (a)</td>
<td>7.12</td>
<td>1.8</td>
<td>1200</td>
</tr>
<tr>
<td>50% (b)</td>
<td>7.63</td>
<td>0.8</td>
<td>1200</td>
</tr>
<tr>
<td>75% (a)</td>
<td>6.91</td>
<td>0.7</td>
<td>1500</td>
</tr>
<tr>
<td>75% (b)</td>
<td>7.12</td>
<td>0.8</td>
<td>1600</td>
</tr>
<tr>
<td>Sand Blank</td>
<td>7.45</td>
<td>8.5</td>
<td>70</td>
</tr>
</tbody>
</table>

Technician: KAF (at EVS)
Tannin and Lignin

Raw Data: BENCH-SCALE TESTING

Microcosm Monitoring Data: Tannins and Lignins (T&L) (mg/L as Tannic Acid)

Summary (Series #2, Day 8 & 16):

<table>
<thead>
<tr>
<th>Sample Date:</th>
<th>Apr 20/99</th>
<th>Apr 28/99</th>
</tr>
</thead>
<tbody>
<tr>
<td>dH2O Blank</td>
<td>3.1</td>
<td>3.9</td>
</tr>
<tr>
<td>10% (a)</td>
<td>49.7</td>
<td>36.3</td>
</tr>
<tr>
<td>10% (b)</td>
<td>45.4</td>
<td>36.9</td>
</tr>
<tr>
<td>25% (a)</td>
<td>235.0</td>
<td>207.3</td>
</tr>
<tr>
<td>25% (b)</td>
<td>240.4</td>
<td>209.4</td>
</tr>
<tr>
<td>50% (a)</td>
<td>574.2</td>
<td>510.1</td>
</tr>
<tr>
<td>50% (b)</td>
<td>502.1</td>
<td>446.0</td>
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</tbody>
</table>

Graph Data:

<table>
<thead>
<tr>
<th>Category</th>
<th>Influent</th>
<th>10% (a)</th>
<th>10% (b)</th>
<th>25% (a)</th>
<th>25% (b)</th>
<th>50% (a)</th>
<th>50% (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 8</td>
<td>2874</td>
<td>497</td>
<td>363</td>
<td>454</td>
<td>490</td>
<td>828</td>
<td>962</td>
</tr>
<tr>
<td>Day 16</td>
<td>355</td>
<td>383</td>
<td>309</td>
<td>267</td>
<td>723</td>
<td>838</td>
<td>397</td>
</tr>
</tbody>
</table>

% removal:

- Day 8: 363%
- Day 16: 371%

Notes:

- Reagents: Folin phenol (0.1 mL), carbonate titrate (1.0 mL) (allow 30 min for colour development)
- Sample volume was 5.0 mL

Sample Date:

- Apr 20/99 (Day 8)
- Apr 28/99 (Day 16)

T&L Standard Curve

Kevin Frankowski

UBC Civil Engineering
Masters Thesis
APPENDIX D.3 RAW DATA: BENCH-SCALE TESTING

Chemical Oxygen Demand [COD]

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>COD (mg/L)</th>
<th>corrected</th>
<th>%-removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Blank</td>
<td>0</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>dH2O Blank</td>
<td>17</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>10% (a)</td>
<td>254</td>
<td>2537</td>
<td>0.82</td>
</tr>
<tr>
<td>10% (b)</td>
<td>286</td>
<td>2861</td>
<td>0.80</td>
</tr>
<tr>
<td>25% (a)</td>
<td>930</td>
<td>3721</td>
<td>0.74</td>
</tr>
<tr>
<td>25% (b)</td>
<td>587</td>
<td>2348</td>
<td>0.83</td>
</tr>
<tr>
<td>50% (a)</td>
<td>1383</td>
<td>2766</td>
<td>0.80</td>
</tr>
<tr>
<td>50% (b)</td>
<td>1423</td>
<td>2846</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Summary (Series #2, Day 30 teardown):

- Influent COD (from Table 4.2)
- Average %-removal: 0.80
- Std. dev.: 0.03

NOTES: Digestion reagent was 20-800 mg/L range, without mercury (ie, no chloride interference).
Sample volume was 2.0 mL.

Raw Data:

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dilution Factor</th>
<th>Absorbance (@ 600 nm)</th>
<th>COD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Blank</td>
<td>1</td>
<td>0.004</td>
<td>10.0</td>
</tr>
<tr>
<td>dH2O Blank</td>
<td>1</td>
<td>0.047</td>
<td>116.9</td>
</tr>
<tr>
<td>10% (a)</td>
<td>1</td>
<td>0.102</td>
<td>253.7</td>
</tr>
<tr>
<td>10% (b)</td>
<td>1</td>
<td>0.115</td>
<td>286.1</td>
</tr>
<tr>
<td>25% (a)</td>
<td>2</td>
<td>0.187</td>
<td>930.3</td>
</tr>
<tr>
<td>25% (b)</td>
<td>2</td>
<td>0.118</td>
<td>587.1</td>
</tr>
<tr>
<td>50% (a)</td>
<td>4</td>
<td>0.139</td>
<td>1383.1</td>
</tr>
<tr>
<td>50% (b)</td>
<td>4</td>
<td>0.143</td>
<td>1422.9</td>
</tr>
</tbody>
</table>

COD Standard Curve

- Std curve slope: 0.0004
- y = 0.0004x
- R² = 0.9995

Kevin Frankowski
UBC CIVIL ENGINEERING
Masters Thesis
Biochemical Oxygen Demand [BOD]

Civil 599 - MSc Thesis
Constructed Wetlands Project
Microcosm Monitoring Data: Biochemical Oxygen Demand (BOD) (mg/L)

Summary: 1998 Microcosms (Series #1)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>corrected</th>
<th>Sample Date</th>
<th>to 100%</th>
<th>%-removal</th>
<th>Influent BOD</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>dechlor blank # 1</td>
<td>2.06</td>
<td>n/a</td>
<td>n/a</td>
<td>dechlor blank # 2</td>
<td>121.50</td>
<td>486</td>
</tr>
<tr>
<td>10% # 1</td>
<td>34.02</td>
<td>340</td>
<td>0.94</td>
<td>10% # 2</td>
<td>27.66</td>
<td>277</td>
</tr>
<tr>
<td>50% # 1</td>
<td>121.50</td>
<td>5555</td>
<td>50% # 2</td>
<td>88.50</td>
<td>354</td>
<td>0.94</td>
</tr>
<tr>
<td>75% # 1</td>
<td>226.50</td>
<td>453</td>
<td>75% # 2</td>
<td>226.50</td>
<td>453</td>
<td>0.92</td>
</tr>
<tr>
<td>Sand / room blank</td>
<td>3.78</td>
<td>N/A (BOD blank)</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Raw Data: 1998 Microcosms (Series #1)

NOTES: BOD samples were not seeded, since the microcosm tanks already contained a seeding of pool-side soil.
BOD5 (seeded) of influent = 5016 mg/L

Comparison of BOD5 for 25-day effluent from different microcosm concentrations

\[ y = 2.7797x - 0.1365 \]

\[ R^2 = 0.9295 \]

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Masters Thesis
Biochemical Oxygen Demand (cont.)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample Date: May 12/99</th>
<th>corrected to 100%</th>
<th>%-removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Blank</td>
<td>1</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>dH2O Blank</td>
<td>4</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>10% (a)</td>
<td>7</td>
<td>66</td>
<td>0.99</td>
</tr>
<tr>
<td>10% (b)</td>
<td>10</td>
<td>105</td>
<td>0.96</td>
</tr>
<tr>
<td>25% (a)</td>
<td>165</td>
<td>660</td>
<td>0.88</td>
</tr>
<tr>
<td>25% (b)</td>
<td>93</td>
<td>370</td>
<td>0.93</td>
</tr>
<tr>
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<td>114</td>
<td>228</td>
<td>0.96</td>
</tr>
<tr>
<td>50% (b)</td>
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<td>240</td>
<td>0.96</td>
</tr>
<tr>
<td>BOD Blank</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Note: BOD samples were not seeded, since the microcosm tanks already contained a seeding of pool-side soil.)

<table>
<thead>
<tr>
<th>Sample Date: May 12/99 (Day 30 - teardown)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample ID</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Sand Blank</td>
</tr>
<tr>
<td>dH2O Blank</td>
</tr>
<tr>
<td>10% (a)</td>
</tr>
<tr>
<td>10% (b)</td>
</tr>
<tr>
<td>25% (a)</td>
</tr>
<tr>
<td>25% (b)</td>
</tr>
<tr>
<td>50% (a)</td>
</tr>
<tr>
<td>50% (b)</td>
</tr>
<tr>
<td>BOD Blank</td>
</tr>
</tbody>
</table>

Date Analyzed: May 12/99
Technician: KAF & Angelika
### Toxicity

#### Microcosm Monitoring Data: Acute toxicity (as Rainbow Trout Pass/Fail)

**Raw Data:** Test volume = 500mL (in 1L beaker)
2 fish per beaker

<table>
<thead>
<tr>
<th>Microcosm Series</th>
<th>Sample Date</th>
<th>Treatment Length (days)</th>
<th>Non-toxic concentration (%)</th>
<th>Treatment Length (d)</th>
<th>LC50</th>
<th>TU</th>
<th>% removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Feb 21/98</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>15.81</td>
<td>6.3</td>
<td>0.78</td>
</tr>
<tr>
<td>1998</td>
<td>Feb 27/98</td>
<td>8</td>
<td>0.10</td>
<td>15</td>
<td>35.56</td>
<td>2.8</td>
<td>0.90</td>
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NOTES: Test volume = 500mL (in 1L beaker)
2 fish per beaker

NOTES: Used data from 1999 series
TU = 100/LC50

**Raw Data:**
APPENDIX D.4

RAW DATA: PILOT-SCALE TRIALS
## Field Monitoring Data - Summary

**Civil 599 - MAsc Thesis**  
**Constructed Wetlands Project**  
**Mesocosm Monitoring Data:** Field data (temp, pH, DO, cond)

### Summary (Temp) (degrees C):

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Kevin Frankowski  
136  
UBC CIVIL ENGINEERING  
Masters Thesis
Field Monitoring Data

**Raw Data:**
- Temp & DO measured with an YSI Model 55 digital DO-probe, calibrated each field day
- pH measured with an Orion (Model 230A, w/gel-body probe) pH-meter, calibrated each field day
- Conductivity measured with a YSI Model 33 SCT probe, calibrated each field day

### Oct 29/99

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**Date Analyzed:** Oct 29/99  
**Technician:** Paula P.

### Nov 05/99

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**Date Analyzed:** Nov 05/99  
**Technician:** Paula P.

### Nov 12/99

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**Technician:** Paula P.
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**Sample Date:** Dec 10/99  
**Date Analyzed:** Dec 10/99  
**Technician:** Paula P.
## Biochemical Oxygen Demand [BOD] - Summary

**Civil 599 - MASc Thesis**  
**Constructed Wetlands Project**  
**Mesocosm Monitoring Data: Biochemical Oxygen Demand [BOD] (mg/L)**

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## Biochemical Oxygen Demand [BOD]

### Raw Data:

NOTES: Seed was 0.1g (moist wt) of pool-side soil per 300 mL bottle (weighed using the water suspension method)

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**Date Analyzed:** Jun 10/99  
Technician: KAF & Angelika

### Sample Date: Oct 29/99

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**Date Analyzed:** Nov 04/99  
Technician: KAF & Priscilla

### Sample Date: Nov 05/99

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**Date Analyzed:** Nov 12/99  
Technician: KAF & Priscilla
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**Date Analyzed: Nov 12/99**

**Date Analyzed: Nov 19/99**

**Date Analyzed: Nov 26/99**

Technician: KAF & Priscilla
Biochemical Oxygen Demand (cont.)

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Sample Date: Dec 03/99
Technician: KAF & Priscilla

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Sample Date: Dec 10/99
Technician: KAF & Priscilla
# Chemical Oxygen Demand [COD] - Summary

**Civil 599 - MASC Thesis**  
**Constructed Wetlands Project**  
**Mesocosm Monitoring Data:** Chemical Oxygen Demand [COD] (mg/L)

### Graph Data:

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## Chemical Oxygen Demand [COD]

### Raw Data:
- **NOTES:** Digestion reagent was 20-900 mg/L range, without mercury (i.e., no chloride interference)
- Sample volume was 2.0 mL

### Sample Date: Jun 09/99

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**Date Analyzed:** Jun 18/99
**Technician:** Angelika

### Sample Date: Oct 29/99

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**Date Analyzed:** Nov 04/99
**Technician:** KAF & Priscilla

### Standard Curve

- **Std Curve slope:** 0.0004
- (no standards this week; slope value from Nov 05/99 used)
APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS

Chemical Oxygen Demand (cont.)

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Date Analyzed: Nov 10/99  
Technician: KAF & Priscilla

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Std Curve slope: 0.0002

| Sample Date: | Nov 12/99
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Date Analyzed: Nov 16/99  
Technician: KAF & Priscilla

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Std Curve slope: 0.0002

Kevin Frankowski  
UBC CIVIL ENGINEERING  
Masters Thesis
# Chemical Oxygen Demand (cont.)

**Sample Date:** Nov 19/99

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<td>0.046</td>
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**Date Analyzed:** Nov 22/99

Technician: KAF & Priscilla

### Standard Absorbance (mg/L) @ 600 nm

<table>
<thead>
<tr>
<th>Concentration (mg/L)</th>
<th>Absorbance</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>50</td>
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</tr>
<tr>
<td>100</td>
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<tr>
<td>250</td>
<td>0.066</td>
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<tr>
<td>500</td>
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</tr>
<tr>
<td>750</td>
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<tr>
<td>1000</td>
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</tr>
<tr>
<td>1500</td>
<td>0.352</td>
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</table>

Std Curve slope: 0.0002

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**Sample Date:** Nov 26/99

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<th>Sample ID</th>
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<th>COD (mg/L)</th>
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<tbody>
<tr>
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<td>4381.0</td>
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<tr>
<td>Cell 5</td>
<td>4</td>
<td>0.279</td>
<td>4428.6</td>
</tr>
<tr>
<td>Cell 6</td>
<td>4</td>
<td>0.280</td>
<td>4444.4</td>
</tr>
<tr>
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<td>8</td>
<td>0.250</td>
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**Date Analyzed:** Dec 01/99

Technician: KAF & Priscilla

### Standard Absorbance (mg/L) @ 600 nm

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<thead>
<tr>
<th>Concentration (mg/L)</th>
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</thead>
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<tr>
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<tr>
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Std Curve slope: 0.0003
APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS

Chemical Oxygen Demand (cont.)

Sample Date: Dec 03/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dilution Factor</th>
<th>Absorbance (@ 600 nm)</th>
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<tbody>
<tr>
<td>Cell 1</td>
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<tr>
<td>Cell 2</td>
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<td>Cell 3</td>
<td>5</td>
<td>0.154</td>
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<td>0.180</td>
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<tr>
<td>Cell 5</td>
<td>5</td>
<td>0.100</td>
<td>2049.2</td>
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<tr>
<td>Cell 6</td>
<td>5</td>
<td>0.163</td>
<td>3340.2</td>
</tr>
<tr>
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<td>10</td>
<td>0.120</td>
<td>4918.0</td>
</tr>
<tr>
<td>Leachate Pool</td>
<td>25</td>
<td>0.110</td>
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<td>Slough</td>
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<td>0.056</td>
<td>229.5</td>
</tr>
</tbody>
</table>

Date Analyzed: Dec 06/99
Technician: KAF & Priscilla

COD Standard Curve

\[ y = 0.0002x \]
\[ R^2 = 0.9978 \]

Sample Date: Dec 10/99

<table>
<thead>
<tr>
<th>Sample ID</th>
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<th>Absorbance (@ 600 nm)</th>
<th>COD (mg/L)</th>
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</thead>
<tbody>
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<td>Cell 1</td>
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<td>5</td>
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<td>0.169</td>
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Date Analyzed: Dec 13/99
Technician: KAF & Priscilla

COD Standard Curve

\[ y = 0.0002x \]
\[ R^2 = 0.9992 \]
## Total Suspended Solids [TSS]

### Summary:

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<th></th>
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</thead>
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<td>7.2</td>
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<tr>
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<td>14.0</td>
<td>16.8</td>
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<td>-0.4</td>
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</tbody>
</table>

**Raw Data:**

- **NOTES:** Vacuum-filtered through a Whatman 934-AH glass microfibre filter (effective retention = 1.5 um).
- **Tare:** filter paper and weighing boat are pre-fired for at least 1 hour, then cooled to room temp. in desiccator.
- **Dry:** dried @ 105 C until constant weight (at least 2 hrs), then cooled to room temp. in desiccator.
- **Fired:** fired @ 550 C until constant weight (at least 1 hr), then cooled to room temp. in desiccator.
- **TSS** = Total Suspended Solids
- **FSS** = Fixed Suspended Solids (i.e., approximates inorganic matter)
- **VSS** = Volatile Suspended Solids (i.e., approximates organic matter)

### Sample Date: Jun 09/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Vol Filtered (mL)</th>
<th>Tare (g)</th>
<th>Dry (g)</th>
<th>Fired (g)</th>
<th>TSS (mg/L)</th>
<th>FSS (mg/L)</th>
<th>VSS (mg/L)</th>
</tr>
</thead>
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**Date Analyzed:** Jun 10/99

**Technician:** Angelika KAF & Priscilla

### Sample Date: Oct 29/99

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<th>Fired (g)</th>
<th>TSS (mg/L)</th>
<th>FSS (mg/L)</th>
<th>VSS (mg/L)</th>
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**Date Analyzed:** Nov 02/99

**Technician:** KAF & Priscilla
# Total Suspended Solids (cont.)

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<td>Cell 2</td>
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<td>Cell 3</td>
<td>250</td>
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<tr>
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<table>
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</tr>
</thead>
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<td>Cell 2</td>
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<tr>
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**Date Analyzed:** Nov 08/99  
**Technician:** KAF & Priscilla

**Date Analyzed:** Nov 08/99  
**Technician:** KAF & Priscilla

**Date Analyzed:** Nov 15/99  
**Technician:** KAF & Priscilla

**Date Analyzed:** Nov 24/99  
**Technician:** KAF & Priscilla
## Total Suspended Solids (cont.)

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<th>Tare (g)</th>
<th>Dry (g)</th>
<th>Fired (g)</th>
<th>TSS (mg/L)</th>
<th>FSS (mg/L)</th>
<th>VSS (mg/L)</th>
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</thead>
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**Tannin and Lignin - Summary**

**Civil 599 - MASc Thesis**  
**Constructing Wetlands Project**  
**Mesocosm Monitoring Data: Tannins and Lignins (T&L) (mg/L as Tannic Acid)**

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Tannin and Lignin

**Raw Data:**

Reagents: Folin phenol (0.1 mL), carbonate tertrate (1.0 mL) (allow 30 min for colour development)

Sample volume was 5.0 mL.

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**T&L Standard Curve**

\[ y = 0.0936x \]

\[ R^2 = 0.9999 \]

**T&L Standard Curve**

\[ y = 0.0832x \]

\[ R^2 = 0.9996 \]
### Tannin and Lignin (cont.)

**APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS**

#### Oct 29/99

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**Date Analyzed:** Nov 04/99  
**Technician:** KAF & Priscilla

---

#### Nov 05/99

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**Date Analyzed:** Nov 10/99  
**Technician:** KAF & Priscilla

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#### T&L Standard Curve

**Equation:**  
\[ y = 0.0789x \]  
\[ R^2 = 0.9999 \]

---

Kevin Frankowski  
UBC Civil Engineering  
Masters Thesis
### APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS

**Tannin and Lignin (cont.)**

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**Standard Curve**

- Standard Absorbance (mg/L) vs. Absorbance (@ 700 nm)
  - 0: 0
  - 2: 0.141
  - 4: 0.278
  - 8: 0.514

- Std Curve slope: 0.0655

**T&L Standard Curve**

![T&L Standard Curve](image)

**Sample Date: Nov 19/99**

| Sample ID | Dilution Factor | Absorbance (@ 700 nm) | T&L (mg/L) |
| Cell 1 | 100 | 0.352 | 463.2 |
| Cell 2 | 100 | 0.448 | 589.5 |
| Cell 3 | 100 | 0.518 | 681.6 |
| Cell 4 | 100 | 0.528 | 694.7 |
| Cell 5 | 100 | 0.528 | 694.7 |
| Cell 6 | 100 | 0.550 | 723.7 |
| Influent | 100 | 0.595 | 782.9 |
| Leachate Pool | 500 | 0.472 | 3105.3 |
| Slough | 5 | 0.171 | 11.3 |

**Standard Curve**

- Standard Absorbance (mg/L) vs. Absorbance (@ 700 nm)
  - 0: 0
  - 2: 0.163
  - 4: 0.309
  - 8: 0.603

- Std Curve slope: 0.076

**T&L Standard Curve**

![T&L Standard Curve](image)
### Tannin and Lignin (cont.)

#### Sample Date: Nov 26/99

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**Standard Curve**

- **Absorbance (mg/L)**
  - 0: 0
  - 2: 0.142
  - 4: 0.313
  - 8: 0.607

**Std Curve slope:** 0.0761

#### Sample Date: Dec 01/99

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<th>Sample ID</th>
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**Standard Curve**

- **Absorbance (mg/L)**
  - 0: 0
  - 2: 0.138
  - 4: 0.264
  - 8: 0.504

**Std Curve slope:** 0.0639

---

Kevin Frankowski

UBC Civil Engineering
Masters Thesis
## Tannin and Lignin (cont.)

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**T&L Standard Curve**

- **Std Curve slope:** 0.0612

![T&L Standard Curve Diagram](image)
### Nutrients - Summary

**Civil 599 - MSc Thesis**  
**Constructed Wetlands Project**  
Mesocosm Monitoring Data: Nutrient (NH3, NOx, PO4, VFAs) (mg/L)

#### Summary (NH3):

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**NOTES:**  
NH3, NOx, PO4: each 5 mL of undiluted sample was acidified to pH < 2 using sulphonic acid, then stored in fridge until Paula analyzed  
using Lachat Quick-Chem 8000 automated flow-injection ion analyzer  
NOx = NO2 + NO3  
VFAs: each 1 mL of undiluted sample was preserved with 1 drop of 2% phosphoric acid, then stored in fridge until Paula analyzed  
using HPGC 3680A gas chromatograph, as per Supelco, Inc. GC Bulletin 751G

Kevin Frankowski  
158  
UBC Civil Engineering  
Masters Thesis
## Nutrients

### Raw Data:

**Sample Date:** May 19/99

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<th>Sample ID</th>
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<th>( \text{NO}_x ) (mg/L)</th>
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**Date Analyzed:** May 27/99
**Technician:** Paula P.

**Sample Date:** Jun 09/99

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**Date Analyzed:** Jun 23/99
**Technician:** Paula P.

**Sample Date:** Oct 29/99

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**Date Analyzed:**
**Technician:** Paula P.
### Nutrients (cont.)

#### Sample Date: Nov 05/99

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**Date Analyzed:** Nov 08/99  
**Technician:** Paula P.

#### Sample Date: Nov 12/99

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**Date Analyzed:** Nov 17/99  
**Technician:** Paula P.

#### Sample Date: Nov 19/99

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**Date Analyzed:** Dec 03/99  
**Technician:** Paula P.
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#### Nov 26/99

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#### Dec 03/99

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Kevin Frankowski  
161  
UBC CIVIL ENGINEERING  
Masters Thesis
## Volatile Fatty Acids [VFAs] - detailed data

**Civil 599 - MASc Thesis**

**Constructed Wetlands Project**

**Mesocosm Monitoring Data:** VFA data (detailed)

### Summary (Total VFAs):

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Kevin Frankowski

UBC CIVIL ENGINEERING
Masters Thesis
## Volatile Fatty Acids (cont.)

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### APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS

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Toxicity - Summary

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### APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS

#### Toxicity

**Raw Data:** Samples submitted to analyzed by EVS (technician as noted)

Unless otherwise noted, LC50s were calculated using the Trimmed Spearman-Karber method.

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<th>Hour 96 - highest conc. &gt;50% alive</th>
<th>Hour 96 - lowest conc. &lt;50% alive</th>
<th># fish alive at this conc.</th>
<th># fish alive at this conc.</th>
<th>LC50 (%)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=7.3</td>
</tr>
<tr>
<td>Cell 2</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=7.3</td>
</tr>
<tr>
<td>Cell 3</td>
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<td>10</td>
<td>10</td>
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<td>-</td>
<td>&gt;100%</td>
<td>-</td>
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<tr>
<td>Cell 4</td>
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<td>-</td>
<td>&gt;100%</td>
<td>-</td>
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<tr>
<td>Cell 5</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=7.3</td>
</tr>
<tr>
<td>Cell 6</td>
<td>10</td>
<td>100%</td>
<td>9</td>
<td>1%</td>
<td>0</td>
<td>0.71</td>
<td>0.5</td>
<td>1</td>
<td>pH=4.9</td>
<td></td>
</tr>
</tbody>
</table>

**Sample Date: Sep 29/99**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Hour 0 - # fish alive per tank</th>
<th>Hour 96 - highest conc. &gt;50% alive</th>
<th>Hour 96 - lowest conc. &lt;50% alive</th>
<th># fish alive at this conc.</th>
<th># fish alive at this conc.</th>
<th>LC50 (%)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
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<tr>
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<td>100%</td>
<td>9</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=8.0</td>
</tr>
<tr>
<td>Cell 3</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=8.0</td>
</tr>
<tr>
<td>Cell 4</td>
<td>10</td>
<td>100%</td>
<td>8</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=8.0</td>
</tr>
<tr>
<td>Cell 5</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=7.9</td>
</tr>
<tr>
<td>Cell 6</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Sample Date: Oct 05/99**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Hour 0 - # fish alive per tank</th>
<th>Hour 96 - highest conc. &gt;50% alive</th>
<th>Hour 96 - lowest conc. &lt;50% alive</th>
<th># fish alive at this conc.</th>
<th># fish alive at this conc.</th>
<th>LC50 (%)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=7.7</td>
</tr>
<tr>
<td>Cell 2</td>
<td>10</td>
<td>100%</td>
<td>9</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=8.0</td>
</tr>
<tr>
<td>Cell 3</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=8.0</td>
</tr>
<tr>
<td>Cell 4</td>
<td>10</td>
<td>100%</td>
<td>8</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=8.0</td>
</tr>
<tr>
<td>Cell 5</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td>pH=7.9</td>
</tr>
<tr>
<td>Cell 6</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Techician: Andy Diedwald (EVS)

Data calculated by: KAF
### APPENDIX D.4 RAW DATA: PILOT-SCALE TRIALS

#### Toxicity

**Sample Date:** Oct 29/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th># fish alive per tank</th>
<th>Hour 0 - highest conc.</th>
<th># fish alive at this conc.</th>
<th>Hour 96 - lowest conc.</th>
<th># fish alive at this conc.</th>
<th>LC50 (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>3.125%</td>
<td>0</td>
<td>&lt;3.125%</td>
<td>pH-unadjusted (=4.7)</td>
</tr>
<tr>
<td>Cell 2</td>
<td>10</td>
<td>3.125%</td>
<td>9</td>
<td>6.250%</td>
<td>0</td>
<td>4.13</td>
<td>3.628</td>
</tr>
<tr>
<td>Cell 3</td>
<td>10</td>
<td>3.125%</td>
<td>10</td>
<td>6.250%</td>
<td>0</td>
<td>4.42</td>
<td>3.125</td>
</tr>
<tr>
<td>Cell 4</td>
<td>10</td>
<td>3.125%</td>
<td>10</td>
<td>6.250%</td>
<td>0</td>
<td>4.42</td>
<td>3.125</td>
</tr>
<tr>
<td>Cell 5</td>
<td>10</td>
<td>3.125%</td>
<td>10</td>
<td>6.250%</td>
<td>0</td>
<td>4.42</td>
<td>3.125</td>
</tr>
<tr>
<td>Cell 6</td>
<td>10</td>
<td>3.125%</td>
<td>9</td>
<td>6.250%</td>
<td>0</td>
<td>4.13</td>
<td>3.628</td>
</tr>
<tr>
<td>Cell Influent</td>
<td>10</td>
<td>1.6%</td>
<td>10</td>
<td>3.125%</td>
<td>0</td>
<td>2.24</td>
<td>1.6</td>
</tr>
</tbody>
</table>

**Sample Date:** Nov 05/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th># fish alive per tank</th>
<th>Hour 0 - highest conc.</th>
<th># fish alive at this conc.</th>
<th>Hour 96 - lowest conc.</th>
<th># fish alive at this conc.</th>
<th>LC50 (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Influent</td>
<td>10</td>
<td>1.6%</td>
<td>8</td>
<td>3%</td>
<td>0</td>
<td>1.63</td>
<td>1.46</td>
</tr>
<tr>
<td>Leachate Pool</td>
<td>10</td>
<td>0.5%</td>
<td>8</td>
<td>1.5%</td>
<td>0</td>
<td>0.66</td>
<td>0.469</td>
</tr>
<tr>
<td>Slough</td>
<td>10</td>
<td>100%</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>&gt;100%</td>
<td>-</td>
</tr>
</tbody>
</table>

**Date Analyzed:** Oct 31/99

Technician: Andy Diewald (EVS)

Data calculated by: KAF

---

Kevin Frankowski

UBC Civil Engineering

Master's Thesis
### Appendix D.4: Raw Data: Pilot-Scale Trials

**Toxicity**

#### Sample Date: Nov 26/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Hour 0 - highest conc.</th>
<th>Hour 96 - highest conc.</th>
<th>Hour 96 - lowest conc.</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Influent</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>2.191</td>
<td>1.6</td>
<td>pH-unadjusted (=4.0)</td>
</tr>
<tr>
<td>Leachate Pool</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0.868</td>
<td>0.5</td>
<td>pH-unadjusted (=4.2)</td>
</tr>
<tr>
<td>Slough</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>&gt;100%</td>
<td>-</td>
<td>pH-unadjusted (=7.4)</td>
</tr>
</tbody>
</table>

**Date/Ana!yzed:** Nov 26/99  
**Technician:** Andy Dieulard (EVS)  
**Data calculated by:** KAF

#### Sample Date: Dec 03/99

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Hour 0 - highest conc.</th>
<th>Hour 96 - highest conc.</th>
<th>Hour 96 - lowest conc.</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.74</td>
<td>4.157</td>
<td>pH-unadjusted (=4.4)</td>
</tr>
<tr>
<td>Cell 2</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.42</td>
<td>3.125</td>
<td>pH-unadjusted (=4.0)</td>
</tr>
<tr>
<td>Cell 3</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.42</td>
<td>3.125</td>
<td>pH-unadjusted (=4.0)</td>
</tr>
<tr>
<td>Cell 4</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.42</td>
<td>3.125</td>
<td>pH-unadjusted (=4.1)</td>
</tr>
<tr>
<td>Cell 5</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.42</td>
<td>3.125</td>
<td>pH-unadjusted (=4.2)</td>
</tr>
<tr>
<td>Cell 6</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4.42</td>
<td>3.125</td>
<td>pH-unadjusted (=4.3)</td>
</tr>
</tbody>
</table>

**Date/Ana!yzed:** Dec 26/99  
**Technician:** Andy Dieulard (EVS)  
**Data calculated by:** KAF
Spectrophotometric Response

Spectrophotometer Response - Field Cells (Monitoring: HRT #2)

Spectrophotometer Response - Field Cells (Monitoring: HRT #3)

Spectrophotometer Response - Field Cells (Monitoring: HRT #4)
Spectrophotometric Response (cont.)

Spectrophotometer Response -
Field Cells (Monitoring: HRT #5)

Spectrophotometer Response -
Field Cells (Monitoring: HRT #6)

Spectrophotometer Response -
Field Cells (Monitoring: HRT #7)
Spectrophotometric Response (cont.)

**Spectrophotometer Response - Field Cells (Baseline Assessment)**

Absorbance vs. Wavelength (nm)

- Cell 1
- Cell 2
- Cell 3
- Cell 4
- Cell 5
- Cell 6

**Spectrophotometer Response - Field Cells (QA/QC Replicates)**

Absorbance vs. Wavelength (nm)

- Rep. 1
- Rep. 2

[Cell 1, Nov 12/99]