***IMPACTS OF HYDRAULIC AND CONSTITUENT LOADING
ON A COMBINED PASSIVE SYSTEM FOR THE
TREATMENT OF ACID MINE DRAINAGE***

By

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A Thesis presented to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Applied Science*

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Ottawa, Ontario

Canada

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Submitted by
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in partial fulfillment of the requirements for the degree of Master of Applied Science

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Dedicated to:

The Baha'i Youth in Iran

And

All the Youth around the World Who Are Deprived of Proper Education

ABSTRACT

Acid mine drainage (AMD) is a major environmental problem at mining sites around the world. This problem starts when sulphide-bearing minerals are exposed to oxygen and water, generating a highly acidic solution containing toxic metals. A combined passive system was developed to allow mitigation of a moderate strength AMD under Canadian climatic conditions. This system consisted of four components including oxidation/sedimentation, peat biofilter, sulphate reducing bacteria and anoxic limestone drain.

Physical/chemical characterizations and the ionic sorption capacity of the utilized peat were evaluated during this investigation. The impact of seasonal AMD fluctuations was evaluated on the performance of the system by a combination of high and low flows and constituent loadings. Dissolved oxygen, redox, pH, alkalinity, acidity, sulphate and metal concentrations were measured regularly. The system adequately treated the synthetic AMD during all the operational conditions. Breakthrough was noted in the peat biofilter and sulphate reduction stages due to their limited adsorption capacities.

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1 INTRODUCTION

1.1 Acid Mine Drainage

Acid mine drainage (AMD) is one of the most significant environmental threats from mining industries in Canada. There are several methods for remediation of acid mine drainage that even under the best scenarios, may require long-term treatment.

AMD occurs when sulphide-bearing minerals in rock are exposed to oxygen and water, changing the sulphide minerals to sulphuric acid. This acid may dissolve heavy metals such as lead, zinc, copper, arsenic, selenium, mercury, and cadmium, which are subsequently released into the ground and surface waters. Certain naturally present bacteria can significantly increase the rate of this reaction. AMD and heavy metal pollution can contaminate ground and surface waters. AMD is therefore capable of disturbing aquatic life and habitat.

Acid mine drainage can develop at several points throughout the mining process: in underground workings, open pit mine faces, waste rock dumps, tailings deposits, and ore stockpiles. Acid generation can last for decades, centuries, or longer, and its impacts can travel many kilometers downstream. Roman mine sites in Great Britain continue to generate acid drainage 2,000 years after mining ceased (EMCBC, 2002).

1.2 Treatment Alternatives

Generally, treatment systems for the remediation of acid mine drainage can be divided into two major categories, active and passive treatment systems. Active systems

are those treatment methods that are based on the addition of alkaline chemicals such as calcium carbonate, sodium hydroxide, sodium bicarbonate or anhydrous ammonia to meet effluent standard limits. In other words, in these methods, the acidity is buffered by the addition of alkalinity, which causes an increase in the pH value up to acceptable levels and consequently decreases the solubility of dissolved metals.

However, these chemicals are relatively expensive and, as the treatment of acid mine drainage generally requires long-term operation and maintenance, this can result in considerable costs. Passive treatment systems are an alternative treatment method to overcome this problem.

During the last two decades, different passive treatment systems have been studied by different organizations at the laboratory bench-scale level. The main concept behind passive treatment is to mitigate the generated acid mine drainage, through naturally occurring chemical and biological reaction procedures, in a controlled environment. The advantage of this system over a conventional active system is the elimination of huge labor costs due to the continuous addition of chemical materials over time.

In 1988, Canada funded a cooperative research program to improve different methods for the prediction, prevention, control and treatment of acid mine drainage. A combined passive treatment system was designed by Champagne (2001) at Carleton University, as an alternative for mitigating acid mine drainage under Canadian climatic and metal mining conditions. It consisted of four individual passive treatment components in series: an oxidation/precipitation basin for excess iron removal; a peat biofilter for heavy metal sorption and the establishment of anoxic conditions; a sulphate

reducing stage for alkalinity generation and sulphate reduction; and an anoxic limestone drain for alkalinity addition.

1.3 Objectives

The main objective of this study was to evaluate the impact of hydraulic and constituent loading on a bench-scale combined passive treatment system for the remediation of acid mine drainage. In order to simulate the different seasonal conditions during a year, this combined system was operated under four different combinations of hydraulic and constituent loadings. Since peat is a key component of the combined system and a new source of peat was utilized for this research, considerable effort was needed to characterize the peat and to determine its metal adsorption capacity.

The following tasks were undertaken to approach this goal:

1. Chemical characterization of the peat.
2. Determination of peat adsorption capacity for heavy metals under different pH conditions.
3. Evaluation of the combined passive treatment system under different hydraulic and constituent loadings of a synthetic AMD in a bench-scale laboratory system.

2 LITERATURE REVIEW

2.1 Background

2.1.1 What is Acid Mine Drainage?

The formation of AMD is primarily a function of the geology, hydrology and mining technology employed at the mine site. AMD is formed by a series of complex chemical and microbial reactions that occur when the mineral pyrite (FeS_2) is exposed to water and oxygen. The resulting water is usually high in acidity and dissolved metals.

Ore is a rock, containing valuable constituents such as metals or coal. In order to extract these valuable minerals, it is necessary to excavate a large amount of ore that consequently leads to the production of waste rock. The extracted ore is crushed into fine particles and subsequently processed with various chemicals to extract the desired metals. The average grade of mined copper in Canada is less than 1 percent, meaning that for every tonne of copper, 99 tonnes of waste material including soil, waste rock and the finely ground tailings must be excavated as well. The amount of gold extracted per tonne of material disturbed is even less (EMCBC, 2002). The mineral industry in Canada generates one million tonnes of waste rock and 950,000 tonnes of tailings per day, totaling 650 million tonnes of waste per year (Government of Canada, 1991).

After the extraction of precious metals, tailings are usually stored above ground in large piles. These free draining piles generally contain acid-generating sulphides, heavy metals and other contaminants. These tailings, as well as waste rock and the exposed excavated rock walls, are the main source of heavy metal contamination of waterways in Canada and other regions in North America (EMCBC, 2002).

2.1.2 The Impact of Acid Mine Drainage

The main problems that can be associated with mine drainage if it remains uncollected and untreated, are contamination of drinking water, disruption of growth and reproduction of aquatic plants and animals and the corroding effects of the acid on parts of infrastructures such as bridges.

According to Reece (1995) in the United State alone, AMD and other toxins from abandoned mines have polluted 180,000 acres of reservoirs and lakes and 12,000 miles of streams and rivers. The clean up costs for these polluted waterways are estimated to be between \$32 billion and \$72 billion for the US government (Kleinman, 1989). In Canada, there are an estimated 351 millions tonnes of waste rock, 510 million tonnes of sulphide tailings, and more than 55 million tonnes of other mining sources which have the potential to cause AMD (Speart, 1995). It has been estimated that cleaning up the existing acid-generating mines in Canada will cost something between \$2 billion and \$5 billion (Government of Canada, 1991).

The Mine Environment Neutral Drainage program of the Canadian government (MEND), characterized Canadian acid mine drainage by studying 72 effluent streams representing all geographic regions. Zinc, iron, and aluminum typically have the highest concentrations in effluent streams. Although the flow rate in spring and fall is generally higher than summer and winter, previous investigations have shown that copper and zinc concentrations are at their highest level in the spring while lead, iron and cobalt peak in the winter. Sulphate and acidity concentrations are highest in the winter and lowest in the spring (Kilborn, 1996).

2.1.3 Predicting Acid Mine Drainage

Due to the gap that exists between the theoretical tests and what happens in the real world, it is not easy to completely predict AMD generation, although from an environmental and economical point of view the prediction of acid mine drainage potential and metal leaching are definitely essential.

When attempting to predict AMD in the different rock types that will be exposed during the mining process, it is necessary to determine a few parameters: the acid generating and neutralizing substances, the potential contaminants or metals, and those conditions under which exposure and transportation of the contaminants can take place (EMCBC, 2002). There are two categories of tests “static” and “kinetic” that can be employed in this regard.

2.1.3.1 Static Testing

Static testing is the first step in evaluating the AMD generation potential at a proposed mine. This test tries to determine the characteristics of the mine rocks and to find those components that have the potential to generate acid or those that buffer or neutralize the acidic drainage generated at the mine site.

Based on an Environmental Mining Council of British Columbia publication (2002), the main preliminary test conducted for evaluating AMD potential is Acid Base Accounting (ABA). This test tends to measure the bulk amount of acid generating or neutralizing materials that potentially exist at mining sites.

Minerals containing sulphur, particularly sulphides such as pyrite, have the potential to generate acidity when exposed to oxygen and water. On the other hand, other

groups of minerals, such as carbonates like calcium carbonate, can buffer or neutralize acidity. The acid generating compound is then compared with base or neutralizing materials in a theoretical manner to determine whether they may balance each other out, or if there would be a change in the pH of the effluent water.

It should be mentioned that ABA tests are laboratory scale tests that are not able to completely predict all factors that may be present in the field and may alter the chemical interaction between the acidic and basic components of the rock.

2.1.3.2 Kinetic Testing

Kinetic testing is more accurate and is usually the next step after the acid-base accounting test, as it attempts to deal with the field conditions affecting the rate of acid generation. In this test, the technician tries to evaluate the rate of acidification over longer periods of time (months). Humidity cells are one of the typical tests employed that can expose larger samples of mine waste to air, water and bacteria. This test provides a better perspective of AMD generation at proposed mining sites although it would not be possible to predict the accurate levels of pH or concentrations of dissolved metals in the generated AMD. The presence of acid producing bacteria or sulphur reducing bacteria is one of a number of variables that can impact the estimated results in the future (EMCBC, 2002). Interpretation of the obtained results and engineering judgment can lead to a relatively accurate prediction.

Computer modeling is another approach for the prediction of acid mine drainage generation. These models generally incorporate a number of chemical and physical

parameters to describe the chemical reactions of acid generation, microbial catalysis and leaching of the weathering products (Jaynes, 1991; Scharer et al., 1991).

2.1.4 AMD Prevention and Mitigation Techniques

Prevention and mitigation can be categorized by two main approaches (Growitz, 2002):

1. Controlled placement of overburden material
2. Water management

Statistics show that both approaches have been used for more than 20 years and reported results have ranged from no improvement to fully successful prevention.

2.1.4.1 Controlled Placement

For pyrite oxidation, oxygen and water are generally necessary to initiate acid formation. Exclusion of either can control acid production. Placement of pyritic material includes either an attempt to exclude oxygen by complete submergence below the water table; or an attempt to isolate the material from water contact to avoid leaching of metal salts. The other one involves the placement of alkaline materials to inhibit the acid-forming reactions or the neutralization of any acid formed (Growitz, 2002).

2.1.4.2 Water Management

Another option for reducing acid generation is water management strategies both during and after mining. Water management can include the following (Growitz, 2002):

- For preventing pond formation and subsequent infiltration, the excavation can be filled in.
- Removal of pit water can decrease the amount and severity of acid generated.
- Isolation of polluted pit water from non-contaminated sources.
- Prevention on the contact between surface and ground water with the acid forming materials via under-drain system construction.

2.2 Acid Mine Drainage Chemistry

There are different factors that can have an influence on the generation of acid mine drainage. Oxidation of sulphide minerals, metal leaching and microbiological activities are some of the physical, chemical and biological processes that have an effect on AMD properties.

2.2.1 pH, Alkalinity and Acidity

The intensity of the acidic or alkaline condition of a solution is often expressed via pH. It is a measurement of the hydrogen ion concentration or solution's hydrogen activity. In 1909, Sorenson proposed the expression of molar concentration of hydrogen ions in its negative logarithmic value.

$$\text{pH} = -\log \{H^+\} \quad (2-1)$$

Moreover, pH has a range between 0 and 14, from highly acidic to completely alkaline, and pH 7 at 25°C represents neutrality.

The alkalinity and acidity of a solution are dependent on the amount of acid and base species that are contained in that system. In other words, the alkalinity of a solution is a measure of its capacity to neutralize acids and conversely, the acidity of a solution is a measure of its capacity to neutralize bases.

Although many materials may contribute to the alkalinity of water, the major portion of the alkalinity in natural water is caused by three major classes of materials; hydroxides (OH^-), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-).

The acidic character of AMD can be attributed to two types of constituents; protons (H^+) and metal ions (M^+). Proton acidity is generally generated when various constituents react with water and produce H^+ ions. Metal ions such as Fe^{3+} , typically exist in a solution with a certain number of water molecules bonded to them (e.g. $\text{Fe}(\text{H}_2\text{O})_6^{3+}$). The metal or mineral acidity of these metal ions arises from the loss of a proton from an attached water molecule when it reacts with water in the AMD solution (Champagne, 2001). Therefore, as pH only measures the concentration of hydrogen ions in solution, it does not express that part of acidity that is contributed by dissolved metal ions in the acid mine drainage.

2.2.2 Oxidation and Reduction Reactions (Redox)

Redox reactions primarily involve the transfer of electrons between two chemical species. The compound that loses an electron is said to be oxidized, and the one that gains an electron is said to be reduced. Oxidation and reduction always occur simultaneously (redox reactions) and a compound that is oxidized is referred to as a reducing agent, while a compound that is reduced is referred to as the oxidizing agent.

2.2.3 Basic Chemistry of Acid Mine Drainage

Four commonly accepted chemical reactions represent the chemistry of pyrite weathering to generate acid mine drainage. Equation 2-2, presents the overall summary of these reactions:

Pyrite + Oxygen + Water $\rightleftharpoons$ Ferric hydroxide (Yellow boy) + Sulphuric Acid

The first reaction (Equation 2-3), shows the oxidation of pyrite by oxygen. As can be seen, sulphur is oxidized to sulphate and ferrous iron is released. This reaction generates two moles of acidity for each mole of pyrite oxidized.

Pyrite + Oxygen + Water $\rightleftharpoons$ Ferrous Iron + Sulphate + Acidity

The second reaction (Equation 2-4) involves the conversion of ferrous iron to ferric iron that results in the consumption of one mole acidity. The rate of this iron oxidation can be increased by the activity of certain bacteria. The reaction rate is pH dependant and can range from relatively slow under acidic conditions (pH 2-3) to several orders of magnitude faster at pH values near five, without the presence of any bacterial activity. The second reaction (Equation 2-4) is referred to as the "rate determining step" in the overall acid generating sequence.

Ferrous Iron + Oxygen + Acidity $\rightleftharpoons$ Ferric Iron + Water

The third reaction (Equation 2-5) presents the hydrolysis of iron. In this reaction, water molecules split and subsequently produce three moles of acidity. This reaction is pH dependent as well and ferric hydroxide can be precipitated out of solution at pH values above 3.5. Generally, there is little or no solid precipitation at pH levels below 3.5. Many other metals are also capable of undergoing hydrolysis.

Ferric Iron + Water $\rightleftharpoons$ Ferric Hydroxide (yellow boy) + Acidity

The last reaction (Equation 2-6) involves the oxidation of additional pyrite by ferric iron that is generated in the reactions represented in equations 2-3 and 2-4. This is a cyclic reaction that occurs very fast and continues until either ferric iron or pyrite is exhausted. It is noticeable that in this reaction iron is the oxidizing agent, not oxygen.

Pyrite + Ferric Iron + Water $\rightleftharpoons$ Ferrous Iron + Sulphate + Acidity

2.2.4 The Role of Micro-Organisms in Acid Mine Drainage

Generally, microorganisms and most often bacteria have an impact on the chemical alteration of minerals. This alteration by bacteria is usually because, directly or

indirectly, they need minerals or intermediate products of their decomposition for their metabolism. For example, the dissolution of sulphide minerals under acidic conditions, precipitation of minerals under anaerobic conditions, adsorption of metals by bacteria or algae, and the formation and destruction of organometallic complexes are all results of indirect activity of microorganisms. Examples where microorganisms may be directly involved are when minerals are available as soluble trace elements, serve as specific oxidizing substrates, or are electron donors/acceptors in oxidation-reduction reactions (Mills, 2002).

According to Mills (2002), there are three categories of oxidation-reduction reactions for minerals with microorganisms:

- Oxidized by autotrophic (cell carbon from carbon dioxide) or mixotrophic (cell carbon from carbon dioxide or organic matter) organisms. Energy derived from the oxidation reaction is utilized in cell synthesis.
- Electron accepted by minerals (reduction) for heterotrophic (cell carbon from organic matter) and mixotrophic bacteria (Chemical energy is used to create new cell material from an organic substrate).
- Electron donated by minerals (oxidation) for bacterial or algal photosynthesis (reaction is fuelled by photon energy).

2.2.4.1 Natural Oxidation in the Sulphur Cycle

According to Brierley (1978) and Trudinger (1971), generally the genus *Thiobacillus*, the genus *Thiomicrospira*, and the genus *Sulfolobus*, are the bacteria that oxidize sulphur or sulphides to produce energy. One of the products of these bacterial

reactions is sulphuric acid (i.e. hydrogen ions, H⁺, and sulphate ions, SO₄²⁻) as a metabolic by-product.

2.2.4.2 Natural Reduction in the Sulphur Cycle

Sulphate reduction in nature is affected by specialized bacteria of the genera *Desulfovibrio* and *Desulfotomaculum*. These bacteria are strictly anaerobic and are able to reduce sulphate ions directly to hydrogen sulphide. These sulphate reducing bacteria (SRB) are heterotrophic (cell carbon from organic compounds) organisms. They use sulphate, thiosulphate, S₂O₃²⁻, sulphite, SO₃²⁻, or other reducible sulphur-containing ions as terminal electron acceptors in their respiratory metabolism and through this process, hydrogen sulphide is produced by reduction of these sulphur-containing ions (Mills, 2002).

Sulphate reducing bacteria require an organic substrate for their respiratory metabolism and consequently in their sulphate reduction procedure. This substrate is usually a short chain acid such as lactic or pyruvic acid. In nature, such substrates required for SRB activity can be met by the fermentation activities of other anaerobic bacteria on more complex organic substrates. Therefore, in natural systems, the availability of a complex organic source and a mixed bacterial system for the generation of short chain acids are essential. According to Cork and Cusanovich (1979), lactate is used by the SRB during anaerobic respiration to produce acetate:

This is the major natural process for the conversion of sulphate ions (Mills, 2002).

2.2.5 Metal Leaching

According to MEND (1999), there are five principle mechanisms which have an impact on increased dissolved metal concentrations at lower pH levels: 1- Oxidation of sulphide minerals; 2- Enhanced solubility; 3- Ion exchange/sorption; 4- Complexation; and 5- Kinetic limitation. These mechanisms are collectively referred to as metal leaching.

Generally, metal leaching and acid generation are processes that have negative impacts on the receiving environment. The environmental impact of metal leaching and acid mine drainage generation depends on their magnitude, the sensitivity of the receiving environment and the degree of neutralization or dilution. The rapid weathering of metal-containing minerals, drainage conditions that increase solubility, and high flow rates through contaminated materials are some factors that enhance metal leaching.

Metal leaching into the water can be enhanced due to high metal solubilities and sulphide weathering rates under acidic conditions. Generally, by increasing the pH level higher than 5.5; metal leaching for many of the rock types will be reduced significantly.

However, even at a neutral pH condition, the generated AMD can cause some negative impacts on the environment due to metal leaching. According to Price and Errington (1998), although the solubilities of aluminum, iron and copper are greatly reduced in neutral pH drainage, other elements such as antimony, arsenic, cadmium, molybdenum, selenium and zinc remain relatively soluble and can leach into the water significantly.

Acid mine drainage generation and metal leaching can greatly be enhanced by human activities. Pons et al. (1982) indicated that in marine soils drained for activities

such as farming, sulphide oxidation could occur and generate acidic waters. Another human activity is excavation of mineralized bedrock for use in construction that can enhance AMD generation. The forestry road building on Northern Vancouver Island is an example of this kind of activity (Koyanagi et al., 1994).

Most precious metals, base metals and some coal deposits are relatively rich in sulphide minerals. By excavating bedrock and through mining procedures, the exposed rock surface increases significantly. Increase in exposed surface rock means more contact of mineral sulphide with oxygen and water. That is why metal leaching and acid mine drainage are the major concerns for the mining industry. In addition, it is a fact that most of the metal mine deposits usually contain high concentrations of one or more potentially toxic trace metals (Price et al., 1998).

Acidity is generally generated when ferric iron precipitates out and hydrogen ions are released into the solution. By increasing the number of free hydrogen ions, the pH level decreases, and the solubility of the metals consequently increase.

The oxidation of sulphide minerals does not always result in acid generation. In many cases, the produced acidity can be neutralized by alkaline materials present in the environment. This neutralization can then result in the precipitation of dissolved metals out of the AMD. Overall, it can be said that AMD can be generated when the rate of acid producing activities is faster than the rate of neutralizing processes. AMD production can also occur when the available neutralization materials in the environment are exhausted. In addition, if there is not enough water for transportation, the acidic products as well as metal leaching and AMD generation may not be a major concern.

2.2.6 Acid Mine Drainage Composition

Drainage constituents and characteristics will differ depending on the mine site. This variability is due to the physical, chemical and hydrological properties of the mine site and the type of mining operation.

2.2.6.1 Water Quality Parameters

The primary water quality parameters that are related to acid mine drainage are thiosalts generated during the milling process, metal concentrations and pH. These are discussed further in the following section.

2.2.6.1.1 Metals

In 1990, the Government of Canada decided to update the Metal Mining Liquid Effluent Regulations (MMLER). Therefore, the Aquatic Effects of Mining was established to review the aquatic impacts of mining in Canada to improve the regulations. In 1996, the results were published in a report entitled AQUAMIN; Assessment of the Aquatic Effects of Mining in Canada.

Metals regulated under the new MMLER presented by Environment Canada (2002), are arsenic, copper, cyanide, lead, nickel, and zinc. The authorized level of metals is presented at Table 2-1:

Table 2-1: Authorized Level of Deleterious Substances (Environment Canada, 2002)

<i>Item</i>	<i>Max. Authorized Monthly Arithmetic Mean Concentration</i>	<i>Max. Authorized Concentration in a composite Sample</i>	<i>Max. Authorized Concentration in a Grab Sample</i>
	<i>(mg/L)</i>	<i>(mg/L)</i>	<i>(mg/L)</i>
<i>Arsenic</i>	0.50	0.75	1.00
<i>Copper</i>	0.30	0.45	0.60
<i>Cyanide</i>	1.00	1.50	2.00
<i>Lead</i>	0.20	0.30	0.40
<i>Nickel</i>	0.50	0.75	1.00
<i>Zinc</i>	0.50	0.75	1.00

2.2.6.1.2 pH

Hydrogen ions (H^+) and hydroxide ions (OH^-) are considered control variables in aqueous systems as they influence physical, chemical and biological processes in the aquatic environment. The authorized level of pH is also regulated under the new MMLER. Although acceptable levels could vary with potential use for agriculture or for drinking, they are generally between 6.0-9.5.

2.2.6.2 Canadian AMD Composition

MEND (Mine Environment Neutral Drainage) studied the characteristics of Canadian acid mine drainage and examined the composition of 72 individual, untreated

AMD streams from 30 different uranium and metal mining sites across Canada. Their findings are summarized in Table 2-2 (MEND, 1994).

The majority of pH values reported for Canadian metal and uranium mines fall between 2 and 5 (MEND, 1994). The most important concern associated with high acidity and low pH level is the mobilization of heavy metal ions (Ritche, 1994).

Table 2-2: Summary of AMD Characteristics at Canadian Mines (Kilborn, 1996)
(Comparison of seasonal values, mg/L)

<i>Response Variables</i>	<i>MMLER</i>	<i>Min. Conc. (Type of Mine)</i>	<i>Max. Conc. (Type of Mine)</i>
<i>PH</i>	5	2.15 (Au)	9.11 (Cu,Zn)
<i>Acidity – Alkalinity</i>	-	3 (U)	60,000 (Au)
<i>Sulphate</i>	-	10 (U)	150,000 (Au)
<i>Fe</i>	-	0.038 (Cu,Ag,Au)	20,000 (Au)
<i>Zn</i>	1.0	0.007 (U)	2,099 (Pb,Zn)
<i>Al*</i>	-	0.0176 (Cu,Ag,Au)	4,800 (Au)
<i>Mn*</i>	-	0.02 (U)	282 (Au)
<i>Ni</i>	1.0	0.003 (Zn, Cu)	36 (Ni,Cu)
<i>Cu</i>	0.6	0.003 (Cu,Zn)	341.7 (Cu,Ag,Au)
<i>Cd*</i>	-	0.001(Ni)	1.92 (Cu,Zn)
<i>K</i>	-	-	-
<i>Na</i>	-	-	-

MMLER: Metal Mining Liquid Effluent Regulations, Max. acceptable concentration in a grab sample. (Except for pH, Minimum acceptable concentration in a grab sample)

Type of Mine: Cu-Copper; Pb-Lead; Zn-Zinc; Au-Gold; Ag-Silver; U-Uranium

*Limited data were available

2.3 Acid Mine Drainage Treatment Alternatives

Remediation of AMD can be achieved through either active or passive systems. Active methods are based on chemical neutralization, which requires continuous operation and maintenance. On the other hand, passive systems are considered to treat AMD on a long-term basis and do not require continuous operational control.

Treatment of AMD by passive strategies generally falls into one of four categories (Kilborn, 1996):

- Anoxic limestone drain (ALD) neutralization;
- Biosorption;
- Bioreaction (alkalinity generation and sulphate reduction); and
- Constructed wetlands.

2.3.1 Active Treatments

In active treatment, acid-polluted waters are neutralized with alkaline chemicals. According to EPA (1997), the following are some common chemical substances that can be used to neutralize generated AMD.

2.3.1.1 Limestone (calcium carbonate)

To have a more efficient treatment, the calcium content of limestone should be as high as possible. Applying this method has advantages such as low cost, ease of use, and formation of a dense but easily handled sludge. On the other hand, the reaction process is slow and the efficiency of the system can easily decrease due to coating of the limestone

particles with iron precipitates. This method is ineffective in removing manganese and is not adequate for treating AMD with a high ferrous-ferric iron ratio (EPA, 1997).

2.3.1.2 Hydrated Lime (calcium hydroxide)

Treatment of the AMD by hydrated lime is the first choice in most of the coal mining industries. Using this substance as a neutralizer is generally easy, safe, effective and relatively inexpensive. The major disadvantages in this method are the large volume of sludge that is produced compare to use of limestone and the high initial costs due to the size of the treatment plant (EPA, 1997).

2.3.1.3 Soda Ash (sodium carbonate)

One of the best choices for treating small AMD flows in remote areas is by using soda ash briquettes. The major disadvantage of this substance is the higher cost relative to limestone treatment. Furthermore, the produced sludge typically has poor settling properties (EPA, 1997).

2.3.1.4 Caustic Soda (sodium hydroxide)

Another choice for treating low flows in remote locations is caustic soda. It is especially effective for AMD having high manganese content. High cost, dangers involved with handling the chemical, poor sludge settling properties, and freezing problems in cold weather are among the major disadvantages of using this reagent (EPA, 1997).

2.3.1.5 Ammonia

Anhydrous ammonia is effective for the mitigation of high ferrous iron and/or manganese content in AMD. Ammonia costs are less than caustic soda while it has many of the same advantages. However, using ammonia is difficult and dangerous. It can also affect biological conditions in sensitive environments and, more specifically, is toxic to fish and other aquatic life forms. These toxicity levels can be affected by pH, temperature, as well as dissolved oxygen. Due to these reasons, the use of ammonia is not permitted everywhere and additional monitoring is required when using this substance for treating AMD (EPA, 1997).

2.3.2 Passive Treatment Systems

According to Kilborn (1996) passive treatment systems can be summarized as following:

2.3.2.1 Anoxic Limestone Drain (ALD)

Typically, anoxic limestone drains (ALDs) treat AMD by passing the effluent stream through an anaerobic underground limestone bed. AMD is treated by gradually dissolving limestone and releasing calcium and bicarbonate. Figure 2-1 presents a typical ALD system schematic.

Burial of the ALD maintains anoxic conditions, which prevents armoring of the limestone with hydroxide precipitates. Fe^{2+} does not precipitate as $\text{Fe}(\text{OH})_2$ at pH levels below 6.0 and keeping oxygen out of the water helps to prevent oxidation of metals.

Figure 2-1: Schematic Representation of a Typical ALD. (From Hedin et al. 1994)

Anoxic conditions also allow for the development of high CO₂ partial pressures, and results in higher alkalinity than under normal conditions. In ALDs, the acidity reacts with the limestone, releasing carbonic acid (Brant et al., 1995; Brodie et al., 1991).

Then carbonic acid reacts with limestone and produces alkalinity.

By increasing the pH above 6.4, the concentration of bicarbonate in solution increases and hence as the proton acidity reacts with the limestone, alkalinity is directly generated.

The majority of research conducted to date on ALD treatment systems indicates that ALDs increase calcium concentrations, increase alkalinity, reduce acidity, and as a result, increase the pH of the effluent. By increasing the pH, metal removal can occur through oxidation and precipitate down gradient from the ALD.

2.3.2.2 Biosorption

Biosorption is a complex phenomenon where metal ions are adsorbed onto the solid biosorbent through different sorption processes including ion exchange, complexation, chelation, micro precipitation, etc. (Volesky, 1990). The low cost of biosorbents makes the process highly economical and competitive particularly for environmental applications and mitigation of acid mine drainage. Biosorption systems are better employed in conjunction with other treatment systems to be successful through the Canadian winter.

The removal mechanisms in biosorption systems can be sorption to either living cells or non-living biomass. Heavy metals can be efficiently removed from their environment by microorganisms such as bacteria, algae, fungi and yeast. The accumulation process of metal ions through adsorption/ion exchange reactions can be enhanced by maximizing the contact between the influent and the biosorbents. Using living cells as an alternative for treating the acidic waters is limited to conditions where the metal concentrations are below toxic levels (Kilborn, 1996).

Recent research on the biosorption of heavy metals has led to the identification of a number of microbial biomass types, which are extremely effective at concentrating metals. The mold *Rhizopus* or the bacterium *Bacillus subtilis*, which are by-products of

fermentation industry, and *Sargassu*, *Ecklonia* (brown algae) that can be readily collected from the oceans, are some of these microbial organisms. These biomass types can accumulate dissolved heavy metals (such as Pb, Cd, U, Cu, Zn, even Cr), in excess of 25% of their dry weight, serving as a basis for metal biosorption processes (Volesky, 1990).

2.3.2.3 Microbial Reactor Systems

Microbial reactor systems or bioreactors may be in an open or closed configuration. The microbial reactor shell contains a biodegradable substrate (usually agricultural products such as mushroom compost or straw), which supports the growth of microorganisms, which in turn, treat acid mine drainage.

Cellulolytic bacteria can degrade the cellulose of the agricultural products to generate free sugars and other metabolites. These are further metabolized to provide substrates for the fermentative anaerobes. Under anaerobic conditions, these free sugars are fermented to short chain organic acids or short chain fatty acids that can support the growth of sulphate reducing bacteria (SRB) (Kilborn, 1996).

Sulphate reducing bacteria reduce sulphate to hydrogen sulphide, which precipitates metal ions because of the low solubility of metal sulphides. As a result, the sulphate reducing bacteria consume hydrogen ions and produce carbon dioxide during their metabolism. The reduced concentration of free hydrogen ions and the buffering effect of the CO₂/bicarbonate will result in an increase in solution pH.

Pilot plant data available suggest that bioreactors are a feasible technology for the treatment of small AMD streams. Open bioreactors are expected to only be applicable at

Canadian mines with mild or moderate winters. Closed bioreactors can operate anywhere that a relatively constant temperature can be maintained (Kilborn, 1996).

2.3.2.4 *Constructed Wetlands*

Referring to MEND (1999), constructed wetlands are a combination of natural, physical, chemical, microbiological and plant-mediated processes, which are designed for metal removal and the neutralization of AMD. In a constructed wetland, influent AMD drains by gravity through the wetland. In this path, metals are removed by precipitation, chelation and exchange reactions, while neutralization is primarily achieved by the activity of sulphate reducing bacteria (SRB). An increase in the alkalinity of the solution can be achieved through chemical and microbial reactions as well as dissolution of the limestone.

Wetlands as passive systems for the remediation of AMD are generally operated as a combination of natural or constructed wetlands, Sphagnum peat and open ponds, supplemented by limestone and organic substrate to increase alkalinity. Usually, oxidation for the removal of excess iron, hydrolysis and settling in the aerobic stage, followed by SRB activity in an anaerobic stage to raise pH, is an effective combination.

Where sufficient surface area is available, constructed wetlands have the potential for the remediation of AMD at some Canadian sites. Due to severe winters and high amounts of precipitation in Canada, the capacity of the wetlands can be limited during freezing or high flow conditions. As a result, constructed wetlands may be most applicable at sites with milder winters. An alternative treatment method may be required during winter and spring runoff conditions (MEND, 1999).

2.3.3 Passive Treatment Systems Overview

Treatment of effluent during and after closure of a mining property is one of the major problems facing the Canadian mining industry. The effluent can be treated by adding chemical substances into the water in a traditional way but recently greater consideration has been given to passive treatment technologies. Passive treatment systems, which are based on chemical, biological and physical removal processes, have been tested successfully at many locations around the world.

Passive treatment of AMD has a future in Canada, but has some limitations due to specific Canadian climate and aquatic environments. For example, biological treatment systems have low activity in cold temperatures and spring runoff demands flexible systems (MEND, 1999). According to MEND (1999), the application of passive treatment systems in Canada is limited to where:

- Flows are relatively constant.
- Water temperature is greater than 7°C.
- Drainage is low to medium strength in terms of acidity and metal concentration.
- Concentrations of aluminum and iron are low.
- Receiving environment is not sensitive to the passive treatment system.

A summary of individual passive treatment technologies including their applicability, limitations and the approximate costs are presented in Table 2-3 (MEND, 1999).

**Table 2-3: Summary of Passive Treatment Technologies for Treatment of AMD
(MEND, 1999)**

Microbial Reactor systems	General Comments	<ul style="list-style-type: none"> Relies on microbial reactions, supported by a biodegradable carbon source. Only short-term studies have been completed to date; mainly under very low flow conditions (<1 L/min)
	Applicability/ Limitations	<ul style="list-style-type: none"> Limiting factor is rate of biodegradation of carbon source. Unknown ability to treat moderate or high flows. May be applicable to small effluent streams and could complement other passive or active treatment systems
	Costs	<ul style="list-style-type: none"> Operating are not significant; new substrate required semi-annually. Capital costs for an open reactor (50 to 60 L/min) are estimated at near \$33,500; a closed reactor system to treat 75 to 100 L/min, \$56,000.
Constructed Wetlands	General Comments	<ul style="list-style-type: none"> Designed to optimize processes that occur in a natural wetland. Internal cells focus on either aerobic or anaerobic processes. Must be designed to ensure that the processes are optimized and do not counteract each other.
	Applicability/ Limitations	<ul style="list-style-type: none"> Expected to have the greatest application to mines with moderate winters having secondary active treatment for the winter and spring runoff periods. Ability to treat effluent during cold, harsh winters is unknown.
	Costs	<ul style="list-style-type: none"> Annual operating costs estimated at 10% to 20% of capital cost Generic wetland to treat 60 L/min is estimated at \$85,000 Literature suggests capital costs of US \$5 to US \$32/m² are typical

Table 2-3 (Continued):

Anoxic Limestone Drains (ALD)	General Comments	<ul style="list-style-type: none"> • Low cost form of passive alkalinity addition. • Most research relates to AMD from US coal mines.
	Applicability/ Limitations	<ul style="list-style-type: none"> • Able to operate year round as long as flow continuous. • Strict influent quality limits to ensure long-term alkalinity generation. • Expected to have limited application to Canada
	Costs	<ul style="list-style-type: none"> • Virtually no maintenance costs. • Capital costs in the range of \$4000 for a flow of 7.5 L/min and \$22500 for a flow of 125 L/min.
Biosorption Systems	General Comments	<ul style="list-style-type: none"> • Metals are removed from solution by adsorption/absorption to living cells or non-living biomass. • Few field studies are available; most research is bench scale only.
	Applicability/ Limitations	<ul style="list-style-type: none"> • May have application as a secondary form of treatment when integrated with another treatment system. • Success of systems employed living cells during the winter is doubtful.
	Costs	<ul style="list-style-type: none"> • Insufficient information is available to assess at a full-scale level.

3 COMBINED PASSIVE TREATMENT SYSTEM

As mentioned in previous chapters, due to severe winters in Canada, it is essential to design a practical combination of passive treatment systems to overcome the impact of freezing seasons, as well as high flow rates in the spring, which can considerably reduce the effectiveness of the systems.

3.1 System Components and Their Mechanisms

A combined passive system for treatment of acid mine drainage was designed by Champagne (2001) at Carleton University, Ottawa, Canada. It is composed of four individual components in series including (1) iron oxidation, (2) peat biofilter, (3) sulphate reduction, and (4) anoxic limestone drain. This is the treatment system of interest for this investigation. The system was examined under different hydraulic and constituent loadings. Figure 3-1 shows a conceptual representation of the combined passive treatment system.

3.1.1 Iron Oxidation

By passing AMD over a rock surface, the AMD is aerated and ferrous iron can be oxidized to ferric iron. As a result, precipitation of ferric hydroxide occurs in a settling column. Although this process causes a drop in the pH of the water, it can help to reduce the excess iron in the AMD that could cause armoring of the ALD downstream.

Figure 2-2: Conceptual Representation of Combined Passive Treatment System (Champagne, 2001)

Ferrous Iron + Oxygen + Acidity $\rightleftharpoons$ Ferric Iron + Water

Ferric Iron + Water $\rightleftharpoons$ Ferric Hydroxide + Acidity

3.1.2 *Peat Biofilter*

Peat is formed when vegetation dies and partially decomposes but does not decay completely. In fact, the material is deposited faster than it can decompose. The compressed layers gradually change to the light or dark matters that we call peat. Generally, the upper layers of peat contain more aerobic bacteria, whereas largely anaerobic bacteria live in the lower levels. This is usually due to the consumption of the oxygen by aerobic bacteria at the upper levels of the peat that prevents oxygen from reaching the anaerobic zone. Large quantities of peat can be found in the northern temperate climates of Europe, northern Asia and North America. Sphagnum peat is the most commonly available type.

Sphagnum peat has the ability to adsorb metal ions via cation exchange. Removal of alkaline-earth metal ions such as Ca^{2+} and Mg^{2+} can reduce the hardness of the water as well. In addition, lowering the pH is another effect that is caused through release of H^+ ions into the water via ion exchange. In fact, metal ions fill the "holes" left through the loss of the hydrogen. The degree of acidification of the water depends on the alkalinity of the solution and the source of peat that is utilized. Consumption of dissolved oxygen can also occur in the peat biofilter due to bacterial activity. Amendment layer in this stage can work as a source of carbon for those bacteria.

3.1.3 Sulphate Reducing Bacteria

Sulphate reducing bacteria (SRB) activities can reduce the sulphate concentration of the AMD by flow through a reactor filled with a biodegradable solid waste such as manure, compost, or wood chips, under anaerobic conditions. Although numerous abiotic and microbially catalyzed reactions occur in these systems, it is hypothesized that reducing sulphate concentrations by SRB activities is the primary reason for the pH neutralizations and sulphate and metal removal in this system (Machemer and Wildeman, 1992; McIntire et al., 1990).

SRB consume a number of volatile fatty acids and hydrogen as electron donors. As can be seen in Equations (3-3) to (3-6), SRB activities consume one to two moles of hydrogen ions per mole of sulphate. Two moles of alkalinity are generated because of this sulphate reduction as well. The exact number of protons consumed and alkalinity produced varies with the electron donor as shown below (Widdel, 1988; Drury, 1999):

For pH levels less than 6.3, equations (3-3) and (3-5) will produce carbon dioxide instead of bicarbonate. Equation (3-3) can be written as:

Meanwhile, metal cations react with hydrogen sulphides and produce low solubility metal- sulphides that precipitate out of solution.

Under neutral pH conditions, metals can also be precipitated as metal hydroxides.

Hydrogen ions can be neutralized by the alkalinity produced in equation (3-3) or consumed in equation (3-6).

3.1.4 Anoxic Limestone Drains

By passing AMD through this buried trench of limestone, the acidic water dissolves the limestone, raises the pH, and adds alkalinity to the water. Under anoxic conditions, the limestone does not coat or armor with Fe hydroxides because Fe^{+2} does not precipitate as $\text{Fe}(\text{OH})_2$ at $\text{pH} < 6.0$ (Skousen, 1991).

3.2 Overview of Laboratory Experiments

The following investigations were undertaken in order to assess the impact of hydraulic and constituent loading on the combined system: physical and chemical characterization of the peat, characterization of the adsorption capacity of heavy metals onto peat (equilibrium tests), and evaluation of the bench-scale combined passive system under various hydraulic and constituent loading conditions. The bench scale system

studied was the same system used by Champagne (2001) with the exception of the peat biofilter. The peat biofilter was replaced with a new peat from a different peat source.

3.2.1 Peat Characterization

Characterization experiments of the sphagnum peat were conducted according to the procedures outlined by the American Society for Testing and Materials (ASTM) standards for peat, soils and organic materials (1996). The purpose of this characterization was to provide a basis for comparison between peat materials of different origins.

3.2.2 Heavy Metal Adsorption- Equilibrium Test

Adsorption equilibrium isotherms for the individual heavy metals contained in the standard AMD mixture onto the peat were determined at different pH levels. The purpose of these experiments was to demonstrate the impact of pH on adsorption of different metals within the peat biofilter and to assess which metals had a greater affinity for sorption onto the peat.

3.2.3 Combined Passive Treatment Study-Varying Hydraulic and Constituent Loadings

Assessing the potential effectiveness of the combined passive system under seasonal variability is one of the major goals in this investigation. High flow rates in

spring with relatively low metal concentration or low flow with high constituent concentrations can affect removal mechanisms and the effectiveness of the treatment system.

For this reason, the combined system was operated under four different loading conditions for a total period of 14 months to ensure the achievement of steady-state conditions for each condition. Dissolved oxygen, pH, redox, alkalinity, acidity, sulphate, and dissolved heavy metal concentrations were monitored and considered essential to assessing the performance of the system under these varying conditions.

4 PEAT CHARACTERIZATION

4.1 Experimental Procedures

Chemical characterization of the peat included the evaluation of the elemental composition, extractable ions, cation exchange capacity, and ash and organic content. The following procedures were mainly derived from the American Society for Testing and Materials (ASTM) Standards and adapted from Champagne (2001). The results obtained in this study were then compared with the reported results by Champagne (2001) based on another source of peat. As physical characterization of the peat used in this study was previously determined as part of another investigation conducted by Shibchurn (2001), no more experiments were performed in this regard and the results are included herein.

4.1.1 Elemental Composition

Using the wet-ashing sample preparation, the total heavy metal content of peat was determined (McKeagge, 1978). First, 50 mL of concentrated HNO_3 was added to three 1.0 g air-dried and finely ground ($<500 \mu\text{m}$) peat specimens. Then the mixture was covered and boiled for one hour at a temperature of $100\text{--}150^\circ\text{C}$. After cooling, 20 mL of concentrated HClO_4 was added and the mixture was covered and boiled for at least one hour at a temperature of $200\text{--}250^\circ\text{C}$. After cooling, 10 mL of concentrated HF was added and the mixture was covered and boiled for an hour at 80°C . Then the mixture was uncovered, the temperature raised gradually to 250°C . The mixture was boiled until all except 3 mL had been evaporated. The mixture was allowed to cool, then 25 mL of 1 N

HCl was added to dissolve any residue present. The mixture was covered and brought to a boil and allowed to cool. Oxidation of Cr^{3+} with 10 mL of 30% H_2O_2 followed and the excess H_2O_2 was evaporated. When the digestion was completed, 5% HCl was added to increase the volume of the solution to 50 mL (Champagne, 2001). The element concentrations were determined using Inductively Coupled Plasma Emission Spectrometry (ICP) at Carleton University.

4.1.2 Extractable Ions

The peat was air-dried and finely ground ($<500\ \mu\text{m}$). Three 500 mg samples of the ground peat were shaken in 100 ml of 0.5 N HCl for 30 minutes to displace any mobile cations and saturate adsorption complexes with H^+ . The peat samples were then filtered using Whatman No. 41 filter paper. The filtrate was collected and then analyzed for arsenic, calcium, cadmium, cobalt, copper, chromium, lead, magnesium, nickel, phosphorous, potassium, selenium, sodium and zinc, using ICP test at Carleton University. Metal removal by Millipore filter paper was evaluated by Champagne (2001) and verified that the impact of the filtering process on the accuracy of the metal concentration values was negligible.

4.1.3 Cation Exchange Capacity

Based on Day *et al.* (1979) and as described by Champagne (2001), the cation exchange capacity of the peat was determined using the HCl- $\text{Ba}(\text{OAc})_2$ method. The peat was initially air-dried, oven-dried and finely ground ($<500\ \mu\text{m}$). Then three 500 mg

peat samples were shaken in 100 mL of 0.5 N HCl for 30 minutes to remove cations and saturate adsorption complexes with H^+ . The peat samples were filtered by Whatman No. 41 filter paper and then the filtrate discarded. The peat samples were then rinsed with distilled water to remove excess acid. To replace the adsorbed H^+ with Ba^{2+} ions, samples were shaken with 100 mL of 0.5 N $Ba(OAc)_2$ for 30 minutes. Next, the peat samples were filtered using Whatman No. 41 filter paper. The filtrate was collected and was then titrated with 0.1N NaOH using phenolphthalein indicator. Equation 4-1 was used to calculate the cation exchange capacity of the peat.

$$CEC \text{ (meq / 100g)} = \frac{(\forall N)100}{M_p} \quad (4-1)$$

In this equation, the cation exchange capacity is given as milliequivalent per 100 grams (meq/100 g) of oven-dried peat, $\forall$ represents the volume of NaOH titrated (mL), N is the normality of the NaOH solution and M_p is the mass of the dried peat sample (g).

4.1.4 Moisture Content

The moisture content test was conducted according to ASTM Standards (D 2974-87). As described by Champagne (2001), eight samples of peat were sieved using a ¼" sieve and air-dried for a 72-hour period. Half the mass of each of the eight samples was finely ground (<500 μ m) and samples containing 10.0 g of sieved peat and 2.0 g of ground peat were dried at 90°C for 48 hours. A temperature of 90°C was used instead of 105°C to avoid the loss of organic material due to the highly organic nature of the peat. Samples were allowed to cool in a desiccator for two hours and then the final specimen

mass was measured. Equation 4-2 was used to determine the moisture content of peat on a dry mass basis:

$$\text{Moisture (\%)} = \frac{A - B}{B} 100 \quad (4-2)$$

In this equation, the moisture content is expressed on dry mass basis, A represents the initial mass of the air-dried peat specimen (g) and B is the sample mass remaining after drying at 90°C (g).

4.1.5 Ash and Organic Matter Content

The ash and organic matter content of the peat were determined according to ASTM Standards (D 2974-87). The eight sieved samples from the moisture content procedure were placed in a muffle furnace. The temperature was gradually increased to a temperature of 440°C and the samples were ignited for two hours. After a two-hour cooling period in a desiccator, the specimens were weighed and the remaining mass after ignition was recorded. Equation 4-3 presents the ash content of peat.

$$\text{Ash (\%)} = \frac{D}{B} 100 \quad (4-3)$$

The fraction of material that was ignited and volatilized represents the organic matter content (Equation 4-4). Where the ash and organic matter content of the peat were reported on an oven-dried mass basis and D represents the mass of ashes remaining after ignition (g).

$$\text{Organic Matter (\%)} = \frac{(B - D)}{B} 100 \quad (4-4)$$

4.2 Results and Discussion

To compare the results obtained with existing data or future investigations, the characterization of the peat utilized in this research was essential. The raw data for the chemical characterization tests can be found in Appendix B.

4.2.1 Chemical Characterization Tests

The elemental ion composition of the peat can be divided into two categories, fixed and extractable ions. The fixed fraction is regarded as those ions that are not expected to move under experimental conditions such as high hydraulic flow rate and high acidic drainages. On the other hand, extractable ions are that fraction of ions that are able to move out of the peat matrix and leach into solution.

Table 4-1 represents the elemental composition as well as the extractable ions of the peat utilized in this work. According to this table, zinc and iron had the highest fraction of extractable ions amongst the heavy metal ions of concern in this study. Density of the peat packed in the peat column was not measured in this study. Based on the range of densities given by Shibchurn (2001) the mass of peat in the peat biofilter column was assumed approximately 1.5 kg. This corresponds to approximately 360 and 27 mg of potentially extractable iron and zinc ions within the peat column. In comparison to the total mass loading over the study period, these masses were negligible ($< 0.01\%$).

Other results of chemical characterization of the peat, including cation exchange capacity (CEC), air-dried moisture content, ash content and organic matter content are presented in Table 4-2. The CEC value indicates the potential capacity of the peat to

adsorb heavy metal ions. In the other words, higher CEC indicates a higher adsorption capacity of the peat. In this investigation, peat had an average CEC of 153.3 meq/100 g, which represents a moderate ion adsorption capacity (Levesque et al., 1980, and Champagne, 2001).

Table 4-1: Total and Extractable Ion Concentrations in the Peat

<i>Element</i>	<i>Elemental Composition (ug/g)</i>	<i>Extractable Ions (ug/g)</i>
<i>Fe</i>	6800	240
<i>Zn</i>	110	18
<i>Cu</i>	58	B.D.
<i>Mn</i>	320	B.D.
<i>Ni</i>	46	B.D.
<i>Cd</i>	2	5
<i>Ca</i>	8400	1200
<i>K</i>	4300	2900
<i>P</i>	1000	240
<i>Mg</i>	4800	980
<i>As</i>	91	6
<i>Na</i>	5300	660
<i>Se</i>	B.D.	B.D.
<i>Co</i>	16	B.D.
<i>Cr</i>	35	B.D.
<i>Pb</i>	1300	B.D.

B.D. = Below Detection Limit

In order to determine the moisture content of the peat utilized in this research, the large sticks and peat clods were removed and the remaining sample was air-dried for 72 hours before any tests were carried out. On average, the moisture content for this peat was found to be 8.73 %. Small variations in the moisture content of the peat samples

were noticed. The raw data for the determination of moisture content can be found in Appendix B.

Table 4-2: Summary of Chemical Characterization of the Peat

<i>Parameter</i>	<i>Ave.</i>	<i>St. Dev.</i>
<i>CEC (meq/100 g)</i>	153.3	11.02
<i>Moisture Content (%)</i>	8.73	0.18
<i>Ash Content (%)</i>	1.39	0.25
<i>O.M. Content (%)</i>	98.61	0.25

The values for ash content were relatively low (1.93%) and according to ASTM D4427-92 -“Standard classification of peat samples by laboratory testing”- this peat can be classified as a low ash content peat (less than 5% ash). Correspondingly, the average organic content was 98.61%, which is relatively high.

In order to compare the peat characterization results in this investigation with that found from literature, Table 4-3 is presented. This table shows the obtained data in this research with respect to that reported by Shibchurn (2001) for the same source of peat (provided by Premier Tech Ltd.) and by Champagne (2001) for another source of peat (New Brunswick).

As can be seen, the obtained results in this study were consistent with that presented by Shibchurn for the same peat. Shibchurn classified this peat as low ash content, with moderate fiber content (fibric H1-H3 Von Post Scale) and highly acidic in both water and calcium chloride solution according to ASTM D4427-92. As hydraulic conductivity values decrease exponentially with increasing dry density of the peat, a log-linear relation is usually used to express this relationship. Shibchurn reported the

saturated hydraulic conductivity as $24.62 e^{(-0.0438 \cdot \rho_d)}$ for the peat employed in her study. In this equation, ρ_d represents the dry density of the peat (kg/m^3).

Champagne (2001) classified the peat utilized in her study as humic (33% < fiber content < 67%), high ash (ash content > 15%) and highly acidic (pH < 4.5). The difference in ash content and fiber content is mainly due to the source of the peat. Further, she reported a cation exchange capacity of 119.3 (meq/100 g), which was less than the CEC for the peat employed in this study (153.3). It was consistent with organic matter content of peat in these two studies, as higher organic matter content result in higher CEC values. The hydraulic conductivity relationship described by Champagne (2001) is fairly consistent with that reported by Shibchurn (2001).

Table 4-3: Comparison of Utilized Peat

<i>Parameter</i>	<i>Peat This Study</i>	<i>Same Source of Peat Shibchurn (2001)</i>	<i>Different Source of Peat Champagne (2001)</i>
<i>CEC (meq/100 g)</i>	153.3	-	119.3
<i>Moisture Content (%)</i>	8.7	8.4	11.2
<i>Ash Content (%)</i>	1.39	1.05	21.1
<i>O.M. Content (%)</i>	98.61	98.9	78.9
<i>Fiber Content (%)</i>	-	83.5	65.9
<i>pH in H₂O</i>	-	4	3.8
<i>pH in CaCl₃</i>	-	3.2	3
<i>Hydraulic Conductivity (cm/s)</i>	-	$24.62 \cdot e^{(-0.0438 \cdot \rho_{\text{dry}})}$	$25.2 \cdot e^{(-0.04 \cdot \rho_{\text{dry}})}$

5 HEAVY METAL ADSORPTION-EQUILIBRIUM TEST

In order to evaluate the heavy metal adsorption capacity of the peat utilized in this study, equilibrium tests were undertaken. Langmuir curves were fit to each set of data and the sorption capacity of the peat for each metal was calculated.

5.1 Experimental Procedures

For each metal including iron (Fe), aluminum (Al), zinc (Zn), manganese (Mn), copper (Cu), cadmium (Cd), and nickel (Ni), two sets of 7 peat specimens weighing 0.1, 0.25, 0.5, 1.0, 1.5, 2.0 and 4.0 g plus a control 0.0 g were placed in 250 mL serum bottles. Then 5 mM concentration of each metal sulphate salt was dissolved in distilled water and the pH was initially fixed to 3.0 using concentrated HCl. To better characterize the isotherm for certain metals, some additional tests also were conducted with higher metal concentrations when required.

150 mL of each of the single metal solutions was added to each sample contained in the set of 8 peat specimens (7 plus the control) and the test was conducted in duplicate. The samples were then shaken at 200 rpm for 18 hours. The pH of each sample was measured and then the samples were filtered using 0.45 μm Millipore filter paper. The filtrate was acidified with 3 drops of concentrated HCl and metal concentrations were determined via ICP analysis (Champagne, 2001).

This procedure was repeated at pH 4.0. Overall, 262 tests were conducted for 7 metals with 8 different peat masses in duplicate for pH 3.0 and 4.0, as well as 38 additional tests to improve the characterization of the isotherm.

5.2 Data Analysis

By contacting AMD with peat, there will be an equilibrium established between the dissolved metals in the aqueous phase and the corresponding metals bonded to the peat matrix. In 1916, Irving Langmuir developed an isotherm to describe the partitioning between two phases as a function of applied pressure (Nix, 1999). Temkin and Freundlich are other types of isotherms that differ in one or more of the assumptions made in deriving the expression for the surface coverage (Nix, 1999). In this research, the Langmuir isotherm was selected as it is usually employed for describing metal sorption onto peat in single-component metal ion solution (Champagne, 2001; Brown et al., 2000; McKay et al., 1998; Viraraghavan et al., 1995) and allowed a comparison with previous investigations.

The Langmuir isotherm can be expressed by the following equation:

$$q_e = \frac{q_s b C_e}{1 + b C_e} \quad (5-1)$$

Where q_e is the equilibrium amount of metal adsorbed per unit weight of adsorbent (mM/g), q_s stands for the maximum amount of metals that can be adsorbed per unit weight of adsorbent in a mono layer around the peat (mM/g), b is the adsorption equilibrium constant (L/mM), and C_e represents the liquid phase equilibrium concentration of the dissolved metals (mM/L).

For calculating the equilibrium amount of heavy metal adsorbed onto the peat, the following equation was used (Champagne, 2001).

$$q_e = \frac{(C_o - C_e) \nabla}{M} \quad (5-2)$$

Where C_0 represents the concentration of heavy metal in the bottle with 0.0 g of peat (m mol/L), V is the volume of sample (L) and M is the mass of peat (g). C_0 was employed to eliminate the impact of any other metal removal mechanisms such as precipitation in this calculation (Equation 5-2).

5.3 Results and Discussion

Figures 5-1 to 5-7 illustrate the pH response and equilibrium isotherm adsorption of each metal onto the peat. As can be seen, metal solutions initially adjusted to a pH of 4.0 dropped to a pH of approximately 3.0 (natural pH of the peat) after reaching equilibrium conditions. For this reason, the data for each metal were sorted according to their final pH and classified in the ranges of 2.8 (2.7 to 2.9), 3.0 (2.9 to 3.1) and 3.2 (3.1 to 3.3). With the exception of copper where the first range was set to 2.7 (2.5 to 2.9). The remaining results with the pH values outside of these ranges were not considered in the calculations. The Langmuir constants were then computed by fitting a curve to the sorption capacities using Microsoft Excel Solver. Table 5-1 presents these values along with their standard errors.

The Langmuir isotherm is based on monolayer adsorption of metals onto the peat. As can be seen, the monolayer saturation adsorption capacities (q_s) for the metals of interest, decreased with decreasing solution pH. At a pH of 3.2, the relative single metal maximum sorption capacities observed on a molar basis were: $Cu > Fe > Al > Mn > Zn > Ni$, based on their calculated saturation adsorption capacity parameters. The relative order of adsorption capacity at a final pH of 3.0 was: $Cu > Fe \approx Al > Zn > Ni > Mn$. At a final pH 2.8, the results were: $Cu > Fe > Al > Cd > Zn > Mn$. Due to the final pH level of the

metal solutions and lack of sufficient data, no isotherm curve could be fit for Cd at the pH of 3.2 and 3.0, as well as Ni at pH level of 2.8.

Figure 5-1: Equilibrium Isotherm and pH Response for Iron Adsorption onto Peat

Figure 5-2: Equilibrium Isotherm and pH Response for Aluminum Adsorption onto Peat

Figure 5-3: Equilibrium Isotherm and pH Response for Zinc Adsorption onto Peat

Figure 5-4: Equilibrium Isotherm and pH Response for Manganese Adsorption onto Peat

Figure 5-5: Equilibrium Isotherm and pH Response for Nickel Adsorption onto Peat

Figure 5-6: Equilibrium Isotherm and pH Response for Copper Adsorption onto Peat

Figure 5-7: Equilibrium Isotherm and pH Response for Cadmium Adsorption onto Peat

Table 5-1: Langmuir Adsorption Isotherm Constants and Standard Errors

Metal	pH	q_s (mmol/g)	St. Err (q_s) (mmol/g)	b (L/mmol)	St. Err (b) (L/mmol)
Fe	3.2	0.33	0.041	4.28	2.698
	3.0	0.21	0.015	2.65	0.590
	2.8	0.20	0.012	1.57	0.221
Al	3.2	0.32	0.022	8.62	2.412
	3.0	0.21	0.047	4.85	2.711
	2.8	0.14	0.028	2.03	1.094
Zn	3.2	0.14	0.019	3.32	2.165
	3.0	0.13	0.009	1.37	0.270
	2.8	0.10	0.009	1.22	0.238
Mn	3.2	0.19	0.036	0.62	0.270
	3.0	0.08	0.016	2.07	1.881
	2.8	0.08	0.017	0.86	0.774
Ni	3.2	0.11	0.017	2.70	1.476
	3.0	0.12	0.009	1.46	0.407
	2.8	-	-	-	-
Cu	3.2	0.35	0.193	0.42	0.774
	3.0	0.35	0.060	0.44	0.275
	2.7	0.22	0.035	0.65	0.357
Cd	3.2	-	-	-	-
	3.0	-	-	-	-
	2.8	0.12	0.005	0.59	0.014

As mentioned before, the relative order of adsorption capacity obtained at a pH of 3.0 for the peat employed in this investigation was $\text{Cu} > \text{Fe} \approx \text{Al} > \text{Zn} > \text{Ni} > \text{Mn}$. Champagne (2001) presented the relative order of $\text{Cu} \approx \text{Fe} > \text{Al} \approx \text{Mn} \approx \text{Ni} > \text{Zn} > \text{Cd}$ at a pH of 3.0 under similar experimental conditions but with a different source of peat. As can be seen, for both studies the relative orders of adsorption capacities were similar for Cu, Fe and Al. However, it should be noted that the estimated adsorption capacities for Mn, Ni, Cd, and Zn were within a relatively narrow range of 0.08 and 0.14 mmol/g with the exception of Mn at a pH of 3.2 (0.19 mmol/g). Table 5-1 presents the obtained isotherm adsorption capacity constants as well as relative standard errors for each metal.

According to this table, it can be expected that Mn and Ni would be amongst the first metals that break through the peat biofilter due to their lower adsorption capacities.

Based on Figures 5-1 to 5-7, it can be said that, generally, isotherm saturation adsorption capacities of the metals onto the peat increased with increasing pH of the solution. In addition, it was found that at an initial pH condition of 4.0, the final pH of the solution decreased respectively with increasing peat sample weight. This phenomenon follows the substitution theory of H^+ with metal ions between peat and the solution mentioned in Chapter 3, hence, reducing the pH of the samples.

Iron, aluminum, manganese, zinc and copper were more sensitive to pH fluctuations as the saturation adsorption capacity parameters of these metals increased rapidly with increasing solution pH. They increased 57%, 52%, and 138% for Fe, Al and Mn respectively, when pH increased from 3.0 to 3.2. Similarly, increases of 30% and 59% were noted for Zn and Cu from pH 2.8 to 3.0.

Table 5-2 presents the comparison between the results obtained for Langmuir isotherm adsorption capacity constants in this study compared to results reported by Champagne (2001). All the data presented in this table represent pH conditions of approximately 3.0 with the exception of Cd for which a pH of 2.8 is given for this study.

As can be seen, in spite of higher CEC value (Table 4-2), the peat utilized in this investigation had relatively lower Langmuir isotherm adsorption capacities. It could be partially attributed to different pH ranges used to determine the relationship at pH 3.0 in these two studies. As can be seen, Langmuir isotherm adsorption capacity constants are extremely pH dependent and a wider range of pH (3.0 to 3.9) was attributed to pH 3.0 isotherms presented by Champagne (2001) in comparison to what was defined in this

study. Further more, in contrast with her classification, final pH of the samples (after establishment of equilibrium conditions) was considered in this research rather than the initial sample solution pH.

Table 5-2: Langmuir Adsorption Isotherm Constant Comparison at pH 3.0

<i>Metal</i>	<i>This Study</i>			<i>Champagne (2001)</i>		
	q_s (mmol/g)	b (L/mmol)	$b q_s$ (L/g)	q_s (mmol/g)	b (L/mmol)	$b q_s$ (L/g)
<i>Cu</i>	0.35	0.44	0.15	0.46	2.06	0.95
<i>Cd</i>	0.12	0.59	0.07	0.17	0.43	0.07
<i>Al</i>	0.21	4.85	1.02	0.37	8.03	2.97
<i>Zn</i>	0.13	1.37	0.18	0.26	0.44	0.11
<i>Fe</i>	0.21	2.65	0.56	0.50	1.11	0.56
<i>Ni</i>	0.12	1.46	0.18	0.32	0.21	0.07
<i>Mn</i>	0.08	2.07	0.17	0.36	0.42	0.15

In this investigation, manganese, nickel, cadmium and zinc had the lowest adsorption capacity of all the metals evaluated and hence it could be expected that breakthrough of these metals occur first. It should be mentioned again that these results were based on the individual metal adsorption onto the peat.

Competition between metal ions in a multi-ion composition solution (AMD) can impact the relative order of metal ion adsorption onto the peat. Generally, lower metal ion adsorption capacities are expected for multi-component solutions compared to the single-component adsorption capacities under the same experimental conditions. Referring to American Water Work Association (1990), Langmuir model as well as many other competitive models cannot represent multi-component metal ion adsorption onto the peat and a more complex analysis is required to include various types of surface adsorption mechanisms (Champagne, 2001).

6 COMBINED PASSIVE TREATMENT STUDY

For evaluating the performance of the combined passive treatment system, a bench-scale laboratory system designed by Champagne (2001) was utilized. This system was previously operated by Champagne under high constituent loadings and flow rate of 1.585 L/day for 270 days. At the beginning of this investigation, the peat in the peat biofilter column was replaced with a new source of peat as breakthrough had occurred in the previous study. The materials in the other components were not replaced as no sign of breakthrough had been exhibited. Then the system was operated under four different combinations of hydraulic and constituent loadings.

6.1 Experimental Configuration

As shown in Figure 6-1, this system consisted of six individual columns in series, including: 1) oxidation tank, 2) settling tank, 3) peat biofilter, 4) 1st sulphate reducing bacteria (SRB) column, 5) 2nd SRB column, 6) anoxic limestone drain. Synthetic AMD was pumped to the oxidation tank using a digital peristaltic pump. The columns were fabricated from stainless steel and all were connected by Teflon tubing. The empty bed volume was 9.4 L for the oxidation column, 9.0 L for the sedimentation tank, 9.4 L for the peat biofilter, 10.5 L for each SRB column, and 1.4 L for the ALD column. Dimensions for each of the components and a summary of their treatment mechanisms are shown in Figure 6-1.

As described by Champagne (2001), the first column, the oxidation tank (A), was filled with river wash rock and covered with a piece of glass wool for better AMD

distribution. The settling tank (B) allowed for precipitation and sedimentation to occur following the oxidation column. The effluent from the settling tank then entered the peat biofilter column (C). This column was filled with *Sphagnum* peat. The peat was sieved with a ¼" sieve and air-dried for 72 hours before compaction. The peat was packed with five 10 cm lifts of sphagnum peat and at the end covered with 15 cm layer of amendment.

Figure 6-1: Combined Passive Treatment System Bench-Scale Schematic (Champagne, 2001)

The amendment was a mixture of 70 to 30 volume ratio of paper mill sludge and limestone, respectively. This amendment acted as a source of alkalinity and carbon for the peat biofilter. Before running the system, this column was completely saturated by pumping distilled water through the column. This procedure was repeated several times in order to completely saturate the peat biofilter and minimize possible short-circuiting in the peat column.

The next stage included the two SRB columns (D) in series, which operate as a biological process based on the activity of a group of diverse microorganisms called sulphate-reducing bacteria. As described by Champagne (2001), these columns were packed with a mixture of cultured SRB and spent mushroom compost. As this system component requires anaerobic conditions, the columns were sealed completely in order to minimize exposure to oxygen. The SRB were cultured in advance using 1.0 L of primary clarifier effluent and 0.5 L of dewatered sludge from a pulp and paper mill, then mixed with 0.5 L of mixed liquor from a wastewater treatment plant. Na_2SO_4 was used as a source of sulphate to the SRB during the culturing period. Then the SRB were inoculated by mixing the culture with spent mushroom compost.

The last component was the anoxic limestone drain (ALD); column (E). This column was packed with crushed limestone (0.5 cm to 1.0 cm in diameter) with a bulk density of 1.9 g/cm^3 . Again, to maintain anaerobic conditions, this column was completely sealed (Champagne, 2001).

6.2 Operational Conditions

As shown in Table 6-1, four different combinations of hydraulic and constituent loadings were employed to examine the efficiency of the combined passive treatment

system. These four conditions were selected to represent seasonal fluctuations in acid mine drainage strength and discharge. For instance, high-flow rate with relatively low constituent loading represents the AMD characterization during the spring and low-flow with high heavy metal concentrations simulate acid mine drainage during the summer.

Table 6-1: Operational Conditions

<i>Operational Condition</i>	<i>Hydraulic Flow Rate</i>	<i>Constituent Concentration</i>	<i>Overall HRT (day) (Empty Bed)</i>
1	High	High	10
2	Low	High	20
3	Low	Low	20
4	High	Low	10

Table 6-2 represents the metal concentrations for synthetic AMD that were fed into the system. The metal compositions during the first two operational conditions in this study with high constituent loadings were the same as that used by Champagne (2001). These metal compositions were based on a study conducted by MEND (1994) for 30 different mining sites across Canada. The AMD solutions were prepared by dissolving the proper amounts of each metal sulphate salt (Appendix A) in distilled water. The pH values were then adjusted to 3.0 by adding a few drops of concentrated HCl to the solution. This adjustment was done for the first two operational conditions with high constituent loadings to achieve more acidic water. The pH of the synthetic AMD was not adjusted to 3.0 during the last two operational conditions with low constituent loadings.

A hydraulic flow rate of 5.0 L/day was set to be pumped to the system for high hydraulic loading and 2.5 L/day for the low hydraulic loadings on a continuous basis.

This corresponds to a surface loading of 299 mm/day and 149 mm/day for the peat and SRB columns. The system was operated under laboratory conditions where the temperature ranged from 19 to 21 °C.

Table 6-2: Elemental Composition of Synthetic AMD

<i>Element</i>	<i>High Conc. (mg/L)</i>	<i>Low Conc. (mg/L)</i>
<i>Fe</i>	200	50
<i>Zn</i>	100	25
<i>Al</i>	90	22.5
<i>Mn</i>	25	6.25
<i>Ni</i>	20	5
<i>Cu</i>	20	5
<i>Cd</i>	6	1.5
<i>K</i>	780	195
<i>Na</i>	460	115
<i>SO₄</i>	5874	1470

6.3 Sampling Procedure and Analysis

The system first was initially operated for a few days with distilled water to achieve the desired hydraulic circulation. During this period, the flow rate was gradually increased from 1.585 L/day to the value of 5.0 L/day (95 mm/day to 299 mm/day for the peat and SRB columns), which was the desired rate for the first operational condition. Sample collection was started exactly one day after feeding the system with synthetic AMD.

To assess the performance of the system and the impact of each component, the influent AMD and the effluent after each component were collected using a 20 mL syringe. Each sample was analyzed for redox potential, dissolved oxygen (DO) concentration and pH. These values were measured using an Orion model 420A redox meter, VWR scientific DO meter model 4000 and a digital Corning pH meter model 340. Samples were then filtered using 0.45µm HV Millipore filter paper and preserved with 2 drops of concentrated HCl. To determine metal concentrations, samples were sent to Caducon Laboratories for ICP analysis. This procedure was repeated twice a week for continuous monitoring of the system.

To measure sulphate concentrations, 10 mL syringes were used to collect samples after each component. Weekly samples were sent to Caducon Laboratories for analysis. Following the Standard Methods for Water and Wastewater Quality (Clesceri et al., 1989), alkalinity and/or acidity of the samples after each port were determined. Alkalinity and acidity tests were conducted once per week. The system was operated for a total of approximately 14 months with varying hydraulic and constituent loadings.

6.4 Results and Discussion

Initially the combined system operated under high constituent loading and high flow rate condition for 95 days, followed with 128, 83, 79 days of operation under high constituent-low flow, low constituent-low flow and low constituent-high flow conditions, respectively (Table 6-1). Different operational condition periods are distinguished with dash lines on the presented figures. A complete data set based on the system components and operational conditions is presented in Appendix C.

Champagne (2001) reported 14% reduction in flow rate when the system was operated under high constituent loading and flow rate of 1.585 L/day. This reduction in flow, which was attributed to evaporative losses, resulted in an increase in the metal concentrations. Due to the similar operational conditions in this study, the same correction factor was applied to each constituent concentration during all the operational conditions. This adjustment was only conducted to calculate the sulphate removal and percentage of cumulative metal removal over cumulative loading.

6.4.1 Conceptual Model

Each operational condition represents expected seasonal variations in AMD strength and discharge. In this combined passive treatment system, each component was designed to partially mitigate the acidic water, remove dissolved metals and establish the required conditions (such as pH, DO concentration, etc.) as the solution migrated through the various components. After passing the AMD through all the components, it is expected to have a neutral drainage with a considerable increase in alkalinity.

The first component consisted of the oxidation and sedimentation tanks. It was designed to remove excess dissolved metals, especially iron, out of the solution by precipitation. This metal removal can help the performance of the system, specifically the ALD from armoring in the presence of high metal concentrations. It is expected to obtain consistent metal removal results in all the operational conditions after passing the AMD through this stage. In other words, variation in flow rate and constituent loading should not have a significant impact on the performance of this component.

Based on Table 5-1, the adsorption capacity of the peat utilized in this

investigation was higher for metal ions such as Cu, Fe, and Al when compared to Zn, Cd, Ni and Mn at the operational pH level. Hence, it is expected that metal breakthrough would be observed in the peat biofilter in the same relative order. In addition, a multi-component metal ion solution such as AMD will result in competitive adsorption and subsequently lower metal adsorption onto the peat. As the sorption sites on the peat matrix are limited, more strongly charged cations could displace weaker ions resulting in the possibility of metal cations with weaker bonds leaching out of the peat. Therefore, it can be expected that metal breakthrough in the peat biofilter would occur faster compared to feeding the column with individual metal solutions.

By moving from the second to the third operational conditions (from high constituent-low flow to low constituent-low flow) metal desorption in the peat biofilter was expected due to a significant drop in the AMD constituent concentrations.

Based on equilibrium theory, decreasing the concentration of dissolved metals in the solution results in the establishment of a new equilibrium condition between the AMD and peat biofilter as an adsorbent. As the adsorption capacity of the peat is limited, it is expected that the peat would gradually be saturated during the first two operational conditions with high constituent concentrations. By decreasing the influent concentrations and establishment of new equilibrium conditions, desorption of metals from peat back to the solution is expected.

Other metal removal mechanisms such as precipitation may occur in the peat biofilter column. Precipitation of dissolved metals can be observed under appropriate pH and/or redox conditions. There is also a potential for biological activity that would lead to consumption of dissolved oxygen and create anaerobic conditions for the SRB columns.

As described by Champagne (2001), sulphate reducing bacteria activities in lower parts of the peat column, where anaerobic conditions may be established, could be another alternative for metal removal in this stage. An amendment layer on top of the peat biofilter was designed to provide a source of carbon for these aerobic bacteria and to prevent them from biodegrading the peat matrix.

The next step was the SRB component, which required anaerobic conditions for activity. Establishment of anaerobic conditions was expected to occur during the peat biofilter column by aerobic bacteria. In the SRB stage, bacterial activity consumes one to two moles of hydrogen ions per mole of sulphate and produces hydrogen sulphide and alkalinity. Hydrogen sulphide then reacts with metal cations and produces metal sulphides that, due to low solubility, will precipitate out of the solution (Equations 3-3 to 3-9).

In this combined system, two SRB columns were employed to ensure that there would not be any significant metal breakthrough during this stage within the course of study. The enlarged SRB stage was employed to remove dissolved metals from the solution and increase the alkalinity of the drainage. Sorption onto the mushroom compost surface could be another mechanism for metal removal in this stage.

To ensure adequate alkalinity and pH conditions of the effluent, the ALD stage was designed. In this stage, alkalinity is added through the dissolution of limestone. Anaerobic conditions are required to limit precipitation and armoring of the ALD. It can be expected that during the operation time, the efficiency of this stage may be gradually reduced due to the consumption and/or unpreventable armoring of the limestone.

6.4.2 Effluent Concentrations

Dissolved oxygen, redox potential, pH, acidity, alkalinity and sulphate concentration variations are presented in Figures 6-2 to 6-7. In these figures, different operational conditions are defined with dash lines. Overall, the dissolved oxygen concentration of the solution had no considerable change after the oxidation and sedimentation tanks. However, as was expected, this value decreased significantly through the peat biofilter column (Figure 6-2). By reducing dissolved oxygen, the AMD approached anaerobic conditions prior to reaching the sulphate reducing bacteria (SRB) and anoxic limestone drain (ALD) stages for which the establishments of anaerobic conditions were essential. This reduction suggested some bacterial activity in the peat biofilter leading to the consumption of dissolved oxygen.

Redox measurements indicated that SRB columns and ALD were operating under anaerobic conditions (Figure 6-3). It can also be said that no sulphate reducing bacteria activity occurred in the peat biofilter stage as the redox potential value was much higher than required (Takai et al., 1966). The average redox potential after the first SRB increased gradually from -76.9 mV during the first steady state condition to -36.0 , 14.8 and 99.4 mV for the following operational conditions (Table 6-7 to 6-10) resulting a gradual reduction in the SRB activity. This phenomenon was consistent with the dissolved oxygen results presented in Figure 6-2. The decreased SRB activity was connected with the increased dissolved oxygen concentration entering the first SRB column from the peat biofilter. Gradually consumption of the amendment layer on top of the peat column may have caused the carbon source to become depleted resulting in dissolved oxygen consumption in this stage (Figure 6-2 and 6-3).

Figure 6-2: Dissolved Oxygen Concentration as a Function of Volumetric Loading and System Component

Figure 6-3: Redox Potential as a Function of Volumetric Loading and System Component

Figure 6-4: pH as a Function of Volumetric Loading and System Component

Figure 6-5: Acidity as a Function of Volumetric Loading and System Component

Figure 6-6: Alkalinity as a Function of Volumetric Loading and System Component

Figure 6-7: Sulphate Removal as a Function of Volumetric Loading and System Component

Redox potential decreased slightly during all the operational conditions after the second SRB column. The ALD stage did not show any significant change in the redox potential value of the solution.

According to Figure 6-4, the pH remained relatively constant during all the operational conditions. It can be seen in Figure 6-4 that there was a slight increase in the influent pH at the beginning of the third condition. This increase was due to lack of pH adjustment for the final two conditions. A similar increase can be seen for the following components including oxidation and sedimentation tanks.

The pH level reduced slightly during the third and fourth operational conditions after oxidation and sedimentation tanks. Based on theory, Fe^{2+} reacts with oxygen and hydrogen ions to produce Fe^{3+} . Subsequently ferric iron reacts with water and produces ferric hydroxide that precipitates out of solution. The increase in H^+ ions associated with the precipitation of ferric hydroxide could be the reason for the slight drop in pH at the oxidation and sedimentation tanks during the final two operational conditions (Equations 3-1 and 3-2). As the influent pH level during the first two operational conditions was lower compared to the last two conditions, iron hydroxide precipitation and consequently pH reduction were not significant.

The peat biofilter decreased the pH level of the solution during the last two operational conditions. In this stage, the adsorption of metal cations onto the peat matrix caused hydrogen ions to release into solution and reduce the pH of the AMD. This reduction in the last two operational conditions was noticeable in comparison to the first two conditions. In addition, the higher pH values entering the column may have increased the precipitation of ferric hydroxide also causing a reduction in pH.

By passing the AMD through the first SRB, pH increased significantly during all the operational conditions. Referring to Equations 3-3 to 3-9, SRB successfully reduced sulphate and generated alkalinity that resulted in an increase of the pH of the AMD. As can be seen in Figure 6-4, the pH of the solution approached neutral values after passing through the second SRB and ALD columns.

With the exception of the variability during the first few days of the first operational condition, which was due to some hydraulic problems in the columns, the acidity of the solution was generally constant for each component during each operational condition (Figure 6-5). The acidity of the solution was reduced to zero after passing through the first SRB column. As expected, the acidity of the AMD was much lower for last two operational conditions with lower constituent concentrations.

Figure 6-6 presents the alkalinity of the AMD after each stage of the combined system. Overall, no alkalinity was noticed before the first SRB column. The increase in alkalinity was the result of sulphate reduction, as illustrated by sulphate removal (Figure 6-7), redox potential (Figure 6-3) and low DO concentration (Figure 6-2). The alkalinity of the system gradually decreased during the third and fourth operational conditions, which was consistent with the increase in dissolved oxygen concentration and redox potential values. All of these graphs (Figures 6-2, 6-3 and 6-6) indicate that the SRB activity decreased in the first SRB column during the latter two conditions. This could partially be attributed to the lower consumption of dissolved oxygen in the peat biofilter and consequently lower SRB activity in the following stages during the last two operational conditions.

In spite of this reduction in SRB activity, most of the sulphate removal occurred

in the first SRB column (Figure 6-7). The average sulphate-loading rate for each operating condition was 22020 mg/day for the first, 11720 mg/day for the second, 2648 mg/day for the third, and 6085 mg/day for the fourth operational condition. Sulphate removal was computed using the following equation.

$$Q (S_0 - S_e) \quad (6-1)$$

Where, the hydraulic loading is represented by Q (L/day), influent concentration by S_0 (mg/L) and the measured effluent sulphate concentration as S_e (mg/L). As can be seen in Figure 6-7, sulphate removal in the first SRB column increased gradually during the first two operational conditions, indicating an increase in the SRB activity at this time. This sulphate removal decreased significantly at the beginning of the third operational condition. That could be partially due to the lower sulphate loading into the system and consequently lower removal in the system components, and partially due to the fact that by exhausting the amendment layer on top of the peat, bacterial activity reduced in the peat, and therefore the DO concentration of AMD increased before entering the first SRB column. This gradual reduction in the SRB activity resulted in a reduction in sulphate removal (figure 6-7) and alkalinity generation (Figure 6-6) during the last two operational conditions. The average influent sulphate concentration during each operational condition as well as sulphate concentration after each system component can be found in Appendices A and E as well as Table 6-3.

6.4.3 Metal Removal and System Components

The average and standard deviation of metal concentrations as well as sulphate concentration during each operational condition can be found in Table 6-3. Overall, it can be said that the constituent loading concentrations were relatively constant during the course of the study. Figure 6-8 represents the concentration of dissolved heavy metals in the influent during the experiment as a function of volumetric loading. As can be seen in this figure, there are two gaps in the plotted results during the first and second operational conditions. The first perturbation was caused by the displacement of the whole system to a new location and the second one was a hydraulic problem in the peat column, resulting from a clog in the tubing partially due to the gas pressure generated by microbial activities in the SRB stage under low flow rate condition.

Generally, precipitation is a method of causing dissolved contaminants to settle out as a solid precipitate. The oxidation tank, as mentioned in previous sections, was designed to generate metal hydroxides, particularly ferric hydroxide that would precipitate out of solution within this column and the settling tank. Metal concentrations and cumulative removal of metals after the oxidation column are presented in Figures 6-9 and 6-10. The percentage cumulative removal over cumulative loading is employed to illustrate the removal trends that would be difficult to observe in a plot of metal concentration with time due to system variability.

As expected, iron oxidation and subsequently precipitation occurred in the oxidation column (Figure 6-10). In this column, Fe^{2+} reacts with oxygen to produce Fe^{3+} , which after hydrolysis produces ferric hydroxide and acidity as hydrogen ions. The yellowish ferric hydroxide precipitate seen on the rocks in the oxidation tank supported

Table 6-3: Average Concentration of Heavy Metals and Sulphate in Synthetic AMD

<i>Element</i>	<i>1st Operational Condition (mg/L)</i>		<i>2nd Operational Condition (mg/L)</i>		<i>3rd Operational Condition (mg/L)</i>		<i>4th Operational Condition (mg/L)</i>	
	<i>Ave.</i>	<i>St. Dev.</i>	<i>Ave.</i>	<i>St. Dev.</i>	<i>Ave.</i>	<i>St. Dev.</i>	<i>Ave.</i>	<i>St. Dev.</i>
<i>Fe</i>	190.6	7.7	191.7	9.2	48.5	1.3	48.6	1.0
<i>Zn</i>	98.6	6.0	97.7	3.1	25.2	3.6	26.7	0.9
<i>Al</i>	90.4	3.7	92.7	3.2	21.9	0.5	21.9	1.0
<i>Mn</i>	25.3	1.0	26.6	1.1	6.8	0.2	6.7	0.2
<i>Ni</i>	19.4	0.7	19.9	1.0	5.2	0.2	5.1	0.1
<i>Cu</i>	19.4	0.8	19.2	0.9	4.9	0.1	4.7	0.1
<i>Cd</i>	6.9	0.5	7.3	0.3	1.8	0.1	1.8	0.1
<i>Sulphate</i>	4404	758	4688	320	1059	130	1217	148

Figure 6-8: Influent Concentration as a Function of Volumetric Loading

Figure 6-9: Metal Concentration after Oxidation Column

Figure 6-10: Cumulative Removal after the Oxidation Column

this assumption. pH reduction occurred during the third and fourth operational conditions where influent pH was higher (Figure 6-4). Slight removal of the other metals was noted through the oxidation column as well.

The sedimentation tank was the next component that allowed the metal hydroxides produced during the oxidation step to precipitate out of solution. Metal concentration and cumulative retention results after the sedimentation tank can be found in Figures 6-11 and 6-12. Reduction in pH (Figure 6-4) and iron hydroxide precipitation was also noted in this column.

Metal concentrations entering the sedimentation tank decreased gradually at the beginning of the third operational condition (Figure 6-11). Similar trend can be seen in the cumulative metal removal (Figure 6-12) during the first days of the first condition. These gradual reductions were attributed to the hydraulic retention time of the sedimentation tank and the time required to change the concentration of AMD in this tank.

Peat biofilter has the ability to remove metals from solution via cationic exchange. In order to compare the actual adsorbed mass with the expected value, a mass balance calculation was conducted using the single metal equilibrium isotherm (Table 6-4). The actual and expected metal mass removals presented in this table, reflect the cumulative metal retentions in the peat biofilter at the end of each operational condition. Columns in Table 6-4 can be defined as:

$A = (\sum C_{in} \times Q_{in}) \times \Delta t$; Total metal mass (mg) that entered the peat column during each operational condition.

Figure 6-11: Metal Concentration after the Sedimentation Column

Figure 6-12: Cumulative Removal after the Sedimentation Column

Table 6-4: Theoretical and Actual Metal Removal at the Peat Column

Metals		Total M _{In} mg	Total M _{Out} mg	Ave. M Conc. mg/L	q _s mmol /g	b L/ mmol	Atomic Weight g/mol	q _s mg/g	b L/mg	q _e mg/g	Expect. Sorp. mg	M Aqu. mg	Actual Remov. mg	Actual/ Expect. Ratio
		A	B	C	D	E	F	G	H	I	J	K	L	N
1st Operational Conditions	Fe	86764	28633	46.2	0.21	2.65	55.847	11.73	0.05	10.50	14570	372	57759	3.96
	Al	42793	32839	68.6	0.21	4.85	26.982	5.67	0.18	5.33	7398	553	9401	1.27
	Zn	46629	43335	88.4	0.13	1.37	65.39	8.50	0.02	5.70	7902	713	2581	0.33
	Mn	12005	11767	24	0.08	2.07	54.938	4.40	0.04	2.13	2958	194	45	0.02
	Ni	9298	8557	17.4	0.12	1.46	58.693	7.04	0.02	2.28	3159	140	601	0.19
	Cu	9126	5961	11.8	0.35	0.44	63.546	22.24	0.01	2.59	3588	95	3070	0.86
	Cd	3261	3005	6.2	0.12	0.59	112.41	13.49	0.01	0.46	645	50	206	0.32
2nd Operational Conditions	Fe	141369	39499	44.9	0.21	2.65	55.847	11.73	0.05	10.43	14472	362	101508	7.01
	Al	72292	54550	79.7	0.21	4.85	26.982	5.67	0.18	5.35	7418	643	17099	2.31
	Zn	77969	74373	97.1	0.13	1.37	65.39	8.50	0.02	5.73	7953	783	2813	0.35
	Mn	20482	20132	26.4	0.08	2.07	54.938	4.40	0.04	2.21	3070	213	137	0.04
	Ni	15652	14785	19.4	0.12	1.46	58.693	7.04	0.02	2.35	3257	156	711	0.22
	Cu	15175	10291	15.8	0.35	0.44	63.546	22.24	0.01	2.60	3604	127	4757	1.32
	Cd	5582	5404	7.3	0.12	0.59	112.41	13.49	0.01	0.50	700	59	119	0.17
3rd Operational Conditions	Fe	152959	41221	4.8	0.21	2.65	55.847	11.73	0.05	7.95	11035	39	111699	10.12
	Al	78584	60869	19.9	0.21	4.85	26.982	5.67	0.18	4.61	6402	160	17555	2.74
	Zn	85441	83641	31.6	0.13	1.37	65.39	8.50	0.02	3.31	4598	255	1545	0.34
	Mn	22512	22624	8.6	0.08	2.07	54.938	4.40	0.04	1.00	1385	69	-	-
	Ni	17199	16607	6.2	0.12	1.46	58.693	7.04	0.02	0.91	1269	50	542	0.43
	Cu	16570	12116	6.5	0.35	0.44	63.546	22.24	0.01	0.80	1112	52	4402	3.96
	Cd	6130	6067	2.3	0.12	0.59	112.41	13.49	0.01	0.15	204	19	44	0.22
4th Operational Conditions	Fe	169951	41366	0.4	0.21	2.65	55.847	11.73	0.05	7.87	10920	3	128582	11.77
	Al	87129	68098	18.5	0.21	4.85	26.982	5.67	0.18	4.51	6252	149	18882	3.02
	Zn	96165	94558	27.6	0.13	1.37	65.39	8.50	0.02	3.07	4261	223	1384	0.32
	Mn	25161	25341	6.9	0.08	2.07	54.938	4.40	0.04	0.89	1229	56	-	-
	Ni	19246	18679	5.2	0.12	1.46	58.693	7.04	0.02	0.81	1119	42	525	0.47
	Cu	18456	13773	4.2	0.35	0.44	63.546	22.24	0.01	0.70	973	34	4649	4.78
	Cd	6858	6812	1.9	0.12	0.59	112.41	13.49	0.01	0.13	175	15	31	0.18

$B = (\sum C_{out} \times Q_{out}) \times \Delta t$; Total metal mass (mg) that exited the peat column during each operational condition.

C = The average effluent concentration (mg/L) in the peat column during each operational condition.

$D = q_s$ (mmol/g), Langmuir adsorption isotherm constant at pH = 3.0 (Table 5-1).

$E = b$ (L/mmol), Langmuir adsorption isotherm constant at pH = 3.0 (Table 5-1).

F = Atomic weight of metals (g/mol).

$G = (D \times F)$; q_s (mg/g), Langmuir adsorption isotherm constant.

$H = (E / F)$; b (L/mg), Langmuir adsorption isotherm constant.

I = Equilibrium amount of metal adsorbed per unit weight of peat (mg/g) based on Equation (5-1).

$J = (I) \times (\text{Mass of peat in the column})$; expected total metal mass adsorbed (mg) during each operational condition.

$K = (\text{Volume of the peat}) \times (\text{Porosity}) \times (C)$; mass of metals in the aqueous phase in the peat column.

$L = (A - B - K)$; actual metal removal in the peat column (mg).

$N = (L / K)$; Ratio of the actual to expected metal removal based on the single ion equilibrium isotherm.

The mass balance calculations were conducted based on the following parameters:

Volume of the peat = 9.375 L.; (0.146 m x 0.56 m).

Assumed dry density of the peat = 148 g/L, (Shibchurn, 2001).

Assumed porosity = 0.86, (Shibchurn, 2001).

Average pH of the AMD in the peat column = 3.0

Since the first two conditions operated under high constituent concentrations and the final two conditions under low constituent concentrations, the ideal expected total metal mass adsorption under similar constituent loadings should be in the same range (Table 6-4, column J). The slight difference in the expected sorption under similar constituent loadings was due to different hydraulic flow rates as well as inevitable fluctuations in the influent metal concentrations (Table 6-3) and consequently differences in the average metal loadings during each operational condition.

Figures 6-13 to 6-16 compare the actual with the expected metal mass retentions onto the peat biofilter at the end of each operational condition based on Table 6-4. As can be seen, the actual retentions were much higher than expected (based on the single species isotherm) for Fe and Al during all the operational conditions and for Cu during the latter three conditions. This higher removal indicated existence of some other removal mechanism within the peat biofilter. Furthermore, the differences in the actual to the expected metal removal values could be attributed to the competitive metal sorption occurring within this stage. In this competition, those metal ions with stronger bonds were retained by the peat biofilter and more mobile ions released back into solution.

According to Champagne (2001), metal adsorption onto the peat can occur in different ways based on bond strength and the fractions of peat to which metals were bound. These fractions can be divided into water extractable fraction, exchangeable fraction, oxide-bound fraction, organic matter-bound fraction and/or residual metal fraction. High retention values for iron, copper and aluminum were reported by Champagne (2001) as they were generally bound to the organic matter fraction (strong bonds), where low retention was determined for zinc, manganese, nickel and cadmium, as

Figure 6-13: Expected and Actual Metal Removal at the Peat Column at the End of the First Operational Condition

Figure 6-14: Expected and Actual Metal Removal at the Peat Column at the End of the Second Operational Condition

Figure 6-15: Expected and Actual Metal Removal at the Peat Column at the End of the Third Operational Condition

Figure 6-16: Expected and Actual Metal Removal at the Peat Column at the End of the Fourth Operational Condition

they were associated with the exchangeable fraction of peat.

The actual to expected removal ratio for Fe was 3.96, 7.01, 10.12, 11.77; for Al was 1.27, 2.31, 2.74, 3.02 and for Cu was 0.86, 1.32, 3.96, 4.78 during different conditions (Figures 6-13 to 6-16). Overall, this ratio was less than 50% for metals such as Zn, Mn, Ni and Cd during all the operational conditions. These trends were consistent with what was reported by Champagne (2001).

The metal concentrations and cumulative removal for the peat biofilter are presented in Figures 6-17 and 6-18, respectively. As mentioned earlier, two hydraulic problems within the columns during the first and second operational conditions resulted in slight fluctuations in metal concentrations.

Adsorption was observed for a short time for all the metals after passing through the peat column. Subsequently, due to the limited number of adsorption sites in the peat matrix and metal ion competitions in the multi-ion solution (AMD), metals gradually started to breakthrough the peat column. Breakthrough was defined as the point where the cumulative metal removal reached 90% of the cumulative metal mass loaded into the system (Figure 6-18). This definition was selected to eliminate the impact of effluent concentration variability. Competition between metal ions in the AMD solution caused those adsorbed metals with lower positive charges and weaker bonds to gradually release back into solution (Figures 6-17 and 6-18).

The order of breakthrough in this study was $\text{Cu} > \text{Al} > \text{Cd} > \text{Zn} > \text{Ni} > \text{Mn}$ (Figure 6-18). It was consistent with the equilibrium test results, as the metals with the lower q_s values broke through the peat column first (Table 5-1).

Figure 6-17: Metal Concentration after the Peat Biofilter Column

Figure 6-18: Cumulative Removal after the Peat biofilter Column

The order of breakthrough reported by Champagne (2001) was Al > Ni > Cd > Zn > Mn. As can be seen, the breakthrough orders for Al, Cd, Zn and Mn were consistent in both studies. In addition, the cumulative iron removal increased significantly during both investigations. This increase may be attributed to other removal mechanisms like precipitation. As mentioned before, under appropriate pH conditions, iron can precipitate as iron hydroxide.

Champagne (2001) reported SRB activity as a secondary metal removal mechanism in the peat biofilter stage under similar operational conditions. However, the DO and redox results presented in Figures 6-2 and 6-3 indicate that some dissolved oxygen remained and positive redox potentials exist (more than 150 mV) which indicate no SRB activity occurred in this column. Sulphate concentration results (Figure 6-7) were also consistent with this reasoning, as no significant sulphate concentration reductions were observed in the peat column in this study.

To compare the breakthrough time for each metal with the reported results by Champagne (2001), the approximate total mass loadings of each metal to the peat biofilter prior to breakthrough were calculated (Table 6-5). In this study, all metal breakthroughs occurred during the first operational condition with high constituent loading and high flow rate (5.0 L/day or 299 mm/day). The results reported by Champagne (2001) represent metal breakthroughs using a different source of peat under the same constituent concentration loading (high constituent) but with a lower flow rate (1.585 L/day or 95 mm/day).

Table 6-5 indicates that the amount of metal adsorption before saturation of the peat was much lower in this investigation in comparison to that reported by Champagne

(2001). This result can be attributed to the different source and consequently different physical structure of the peat utilized in these investigations. The peat utilized by Champagne (2001) was composed of finer particles in comparison to the peat used in this study. Therefore, there might be less opportunity for metal cations to contact with adsorption sites in the peat matrix. It also could be partially due to the higher hydraulic flow rate in this study, as it was more than three times higher than what was reported by Champagne (2001). All of these conditions could result in less contact between the dissolved metals in the AMD and the potential adsorption sites in the peat, leading to the lower metal adsorption. As presented in Table 6-5, the ratios of metal mass introduced into the peat column prior to saturation were in a range of 3.3 to 4.1 for Mn, Zn, Cd and Ni where this ratio was much higher for Al (6.4).

Table 6-5: Comparison of Metal Mass Fed to the Peat Column before Breakthrough

<i>Metals</i>	<i>This Investigation Metal Mass (mg)</i>	<i>Reported by Champagne Metal Mass (mg)</i>	<i>Ratio of Metal Mass</i>
<i>Mn</i>	625	2055	3.3
<i>Zn</i>	2500	9179	3.7
<i>Cd</i>	150	575	3.8
<i>Ni</i>	500	2055	4.1
<i>Al</i>	4500	28852	6.4
<i>Fe</i>	-	-	-
<i>Cu</i>	3100	-	-

As expected, metal desorption occurred at the beginning of the third operational condition where high constituent loading changed to low constituent loading. With the establishment of a new equilibrium condition in the peat biofilter during the third operational condition, the excess amounts of metal mass, which had previously been

retained onto the peat, released back to solution. A slight drop in the cumulative metal removal at the beginning of the third operational condition in Figure 6-18, supports metal desorption in this stage.

Other evidence of metal desorption can be inferred from the total mass adsorbed before and after the change in the constituent loadings (Table 6-4). For example, for Zn, Mn, Ni, Cu and Cd the total metal mass adsorbed decreased during the second and third operational conditions, from 2813 mg to 1545 mg for zinc, 137 mg to zero for manganese, 711 mg to 542 mg for nickel, 4757 mg to 4402 mg for copper and 119 mg to 44 mg for cadmium.

Figures 6-19 to 6-22 represent the metal concentration and percentage of cumulative removal over cumulative loading through the first and second SRB columns. Dissolved oxygen consumption in the peat biofilter aided in generating anaerobic conditions for the sulphate reducing bacteria columns for which the establishments of anaerobic conditions were essential.

Low dissolved oxygen concentrations as well as low redox potential presented in Figures 6-2 and 6-3 supports the establishment of anaerobic conditions in these SRB columns. Furthermore, the sulphate removal results presented in Figure 6-7 provide additional support for SRB activity and concur with the results presented in Figures 6-19 and 6-20.

In the SRB stage, metals were expected to react with hydrogen sulphide produced by sulphate reducing bacteria and precipitate out of the solution as metal sulphides (Equations 3-3 to 3-8). With the exception of manganese, (Figures 6-19 and 6-20) all the metals were removed completely after passing through the first SRB column for the first

Figure 6-19: Metal Concentration after the First SRB Column

Figure 6-20: Cumulative Removal after the First SRB Column

Figure 6-21: Metal Concentration after the Second SRB Column

Figure 6-22: Cumulative Removal after the Second SRB Column

few days during the first operational condition. Following manganese, other metals gradually broke through in sequence of iron, nickel and zinc.

Alkalinity generation is a by-product of SRB activity (Equations 3-3 to 3-6) and this corresponds to a significant increase in pH (Figure 6-4). Reduction of acidity and generation of alkalinity were noticeable at this stage (Figures 6-5 and 6-6).

Figure 6-20 shows a negative cumulative removal for manganese after the first SRB column. This negative value indicated a higher cumulative mass of manganese exited the column than cumulative mass that entered the column. It was anticipated that this excess manganese was present in an adsorbed phase prior to the start of this work. The SRB columns as well as ALD column were the same columns that were used by Champagne (2001) for her experiments because the metals had not reached to the level of breakthrough in the previous study.

As sorption onto the surface of the mushroom compost was reported as a secondary removal mechanism for this stage by Champagne (2001), it may be possible that the manganese was subsequently desorbed due to competitive metal sorption during this study. In other words, that portion of the adsorbed metals with weaker bonds was leached back into the solution.

To have a better idea about this excess Mn, cumulative mass of each metal after each system component was calculated and the results were tabulated (Appendix D). Table 6-6 represents a summary of these results with regards to the cumulative excess manganese exiting from the SRB columns within the course of study.

As can be seen in Table 6-6, cumulative mass of manganese exited from the first SRB was greater than cumulative mass of manganese loaded into the system during all

the operational conditions. This excess mass was also noticed for the second SRB column during the last two operational conditions. The total manganese desorption in this study was 8.90 g through the SRB1 and 3.64 g through the second SRB column. These excess metal masses were less than the total manganese (11.49 g) that was loaded to the system by Champagne (2001) during her investigations. Therefore, it is possible the excess manganese observed in this study was released from what was retained from the previous experiments. It must be noted that no manganese breakthrough was reported by Champagne (2001) through the SRB columns.

Table 6-6: Cumulative Mass of Manganese Exiting from the SRB Columns

<i>Operational Condition</i>	<i>Cumulative Mass Entered System (g)</i>	<i>Cumulative Mass Exited SRB1 (g)</i>	<i>Cumulative Excess Mass SRB1 (g)</i>	<i>Cumulative Mass Exited SRB2 (g)</i>	<i>Cumulative Excess Mass SRB2 (g)</i>
<i>First</i>	11.996	17.057	5.06	4.134	
<i>Second</i>	20.357	27.301	6.94	19.491	
<i>Third</i>	22.011	30.535	8.52	24.299	2.29
<i>Fourth</i>	24.636	33.532	8.90	28.274	3.64

As can be seen in Figure 6-21 and 6-22, manganese broke through the second SRB column near the end of the first operational condition. This delay could be due to the hydraulic and residency time of the system as well as the adsorption capacity of the mushroom compost in the second SRB column.

Figures 6-23 and 6-24 show the effluent concentrations and percentage of cumulative metal removal over cumulative loading through the ALD column, respectively. As mentioned previously, the purpose of the ALD component was to

Figure 6-23: Metal Concentration after the ALD Column

Figure 6-24: Cumulative Removal after the ALD Column

increase the alkalinity of the solution. No significant changes were noted by comparing these two figures with the similar figures for the second SRB column. Similarly, no significant changes in pH and alkalinity of the solution were observed during this stage.

It can be said that the combined system without the ALD stage was adequately able to treat the AMD and no further increase in pH and alkalinity via dissolution of CaCO_3 was required or chemically favored during the ALD stage.

Tables 6-7 to 6-10 represent the average and standard deviation of the measured parameters of the AMD after each system component, during the steady state period at each operational condition. The last two weeks of each operational condition was designated as steady state conditions as most of the measured parameters including dissolved oxygen, pH, redox potential, acidity, alkalinity, sulphate and different dissolved metal concentrations reached a relatively constant value (Appendix C).

The system reached steady state conditions after loading 405 L AMD into the system during the first operational condition. This cumulative loading was determined equal to 753 L, 1010 L and 1348 L for the second, third and fourth operational conditions, respectively.

As indicated in the Tables 6-7 to 6-10, the combined passive system was able to treat AMD and remove dissolved metals by more than 99% for Al, Cd, Cu, Fe, Ni and Zn during the first operational condition (high flow and high concentration). Metal removal during the second operational condition (low flow and high constituent loadings) was more than 99% for Al, Cd, Cu, Ni, Zn and 98% for Fe. The same removal percentage was noted for Al, Cd, Cu, Ni and Zn during the third operational condition (low flow and low constituent loadings). In this condition, iron removal was more than 95%. During the last

Table 6-7: Effluent Concentration during the Steady State Period after Each System Component – First Operational Condition

Parameters		System Components					
		Oxid.	Sed.	Peat	SRB1	SRB2	ALD
DO (mg/L)	Ave.	3.3	3.1	1.1	0.6	0.9	1.0
	St. Dev.	0.23	0.25	0.28	0.09	0.22	0.39
Redox (mV)	Ave.	359.5	369.6	377.7	-76.9	-42.6	-51.6
	St. Dev.	15.06	7.72	7.67	19.70	19.52	16.91
PH	Ave.	3.1	3.1	2.9	6.6	6.7	6.8
	St. Dev.	0.12	0.09	0.08	0.07	0.04	0.01
Acidity (mg/L CaCO ₃)	Ave.	1167	1158	943	0	0	0
	St. Dev.	14	14	70	0	0	0
Alkalinity (mg/L CaCO ₃)	Ave.	0	0	0	297	388	390
	St. Dev.	0	0	0	26	34	36
Sulphate (mg/L)	Ave.	4833	4930	4953	3280	2960	2887
	St. Dev.	67	62	81	61	26	85
Al (mg/L)	Ave.	86.9	87.8	89.2	1.1	0.5	0.6
	St. Dev.	1.95	1.67	1.78	0.22	0.11	0.06
Al (Cum Ret. %)	Ave.	-1.0	0.5	25.8	99.4	99.8	99.7
	St. Dev.	0.05	0.15	2.05	0.06	0.03	0.03
Cd (mg/L)	Ave.	6.5	6.5	6.5	0.0	0.0	0.0
	St. Dev.	0.15	0.09	0.14	0.00	0.00	0.00
Cd (Cum Ret. %)	Ave.	-0.7	-0.1	8.4	99.8	99.8	99.9
	St. Dev.	0.03	0.13	0.74	0.00	0.00	0.00
Cu (mg/L)	Ave.	18.3	18.5	18.9	0.0	0.0	0.0
	St. Dev.	0.30	0.20	2.44	0.04	0.01	0.01
Cu (Cum Ret. %)	Ave.	-0.6	0.7	38.8	99.8	99.9	99.9
	St. Dev.	0.06	0.12	3.53	0.01	0.00	0.00
Fe (mg/L)	Ave.	177.8	176.3	23.8	81.5	0.3	0.3
	St. Dev.	2.22	3.30	14.17	2.65	0.06	0.04
Fe (Cum Ret. %)	Ave.	2.6	4.0	67.1	82.0	99.9	99.9
	St. Dev.	0.15	0.08	1.09	1.81	0.00	0.01
Mn (mg/L)	Ave.	24.4	24.7	24.8	34.9	35.7	34.4
	St. Dev.	0.51	0.52	0.53	1.27	8.00	8.06
Mn (Cum Ret. %)	Ave.	-1.6	-0.2	2.0	-42.8	76.4	77.3
	St. Dev.	0.07	0.10	0.27	0.20	9.44	9.19
Ni (mg/L)	Ave.	19.4	19.6	19.3	0.2	0.0	0.0
	St. Dev.	0.41	0.35	0.33	0.41	0.00	0.00
Ni (Cum Ret. %)	Ave.	-1.2	-0.3	8.3	99.7	99.9	99.9
	St. Dev.	0.04	0.10	0.62	0.08	0.00	0.00
Zn (mg/L)	Ave.	90.9	91.6	90.6	0.4	0.3	0.1
	St. Dev.	1.19	1.34	1.59	0.17	0.00	0.06
Zn (Cum Ret. %))	Ave.	-1.1	0.1	7.6	99.7	99.8	99.8
	St. Dev.	0.02	0.13	0.56	0.06	0.04	0.10

Table 6-8: Effluent Concentration during the Steady State Period after Each System Component – Second Operational Condition

Parameters		System Components					
		Oxid.	Sed.	Peat	SRB1	SRB2	ALD
<i>DO (mg/L)</i>	<i>Ave.</i>	4.6	3.7	1.1	1.1	0.8	0.9
	<i>St. Dev.</i>	0.19	0.21	0.18	0.22	0.04	0.17
<i>Redox (mV)</i>	<i>Ave.</i>	381.6	377.9	378.0	-36.0	-80.7	-76.6
	<i>St. Dev.</i>	3.19	3.87	16.63	11.43	4.29	6.31
<i>PH</i>	<i>Ave.</i>	3.1	3.1	3.0	6.4	6.6	6.7
	<i>St. Dev.</i>	0.05	0.04	0.03	0.03	0.04	0.08
<i>Acidity (mg/L CaCO₃)</i>	<i>Ave.</i>	1188	1175	950	0	0	0
	<i>St. Dev.</i>	53	35	0	0	0	0
<i>Alkalinity (mg/L CaCO₃)</i>	<i>Ave.</i>	0	0	0	250	400	388
	<i>St. Dev.</i>	0	0	0	0	0	18
<i>Sulphate (mg/L)</i>	<i>Ave.</i>	5183	5147	5077	3353	2997	3043
	<i>St. Dev.</i>	112	118	80	157	189	144
<i>Al (mg/L)</i>	<i>Ave.</i>	91.2	90.9	80.4	0.0	0.0	0.0
	<i>St. Dev.</i>	1.40	0.98	5.12	0.00	0.00	0.00
<i>Al (Cum Ret. %)</i>	<i>Ave.</i>	-0.6	0.0	25.1	99.3	99.8	99.8
	<i>St. Dev.</i>	0.04	0.08	0.43	0.02	0.01	0.01
<i>Cd (mg/L)</i>	<i>Ave.</i>	7.0	7.0	7.3	0.0	0.0	0.0
	<i>St. Dev.</i>	0.17	0.13	0.35	0.02	0.00	0.01
<i>Cd (Cum Ret. %)</i>	<i>Ave.</i>	-0.9	-0.7	2.6	99.8	99.8	99.8
	<i>St. Dev.</i>	0.02	0.09	0.07	0.01	0.00	0.00
<i>Cu (mg/L)</i>	<i>Ave.</i>	18.8	18.6	14.9	0.0	0.0	0.0
	<i>St. Dev.</i>	0.52	0.23	0.15	0.01	0.00	0.01
<i>Cu (Cum Ret. %)</i>	<i>Ave.</i>	0.1	0.6	33.0	99.8	99.9	99.9
	<i>St. Dev.</i>	0.04	0.10	0.29	0.00	0.00	0.00
<i>Fe (mg/L)</i>	<i>Ave.</i>	171.0	164.7	33.4	80.4	31.1	29.8
	<i>St. Dev.</i>	10.82	6.51	18.25	4.01	3.70	7.99
<i>Fe (Cum Ret. %)</i>	<i>Ave.</i>	4.8	6.2	73.7	75.5	98.2	98.2
	<i>St. Dev.</i>	0.27	0.38	0.18	0.42	0.43	0.45
<i>Mn (mg/L)</i>	<i>Ave.</i>	26.8	26.7	27.0	33.7	35.4	35.6
	<i>St. Dev.</i>	0.81	0.26	0.64	2.25	1.27	1.38
<i>Mn (Cum Ret. %)</i>	<i>Ave.</i>	0.2	-0.7	1.1	-34.6	5.5	6.6
	<i>St. Dev.</i>	0.05	0.03	0.02	0.45	1.14	1.23
<i>Ni (mg/L)</i>	<i>Ave.</i>	21.2	20.9	21.6	17.1	0.0	0.0
	<i>St. Dev.</i>	0.61	0.21	0.65	0.49	0.00	0.03
<i>Ni (Cum Ret. %)</i>	<i>Ave.</i>	-1.0	-0.9	4.9	84.9	99.8	99.9
	<i>St. Dev.</i>	0.01	0.11	0.12	2.01	0.00	0.01
<i>Zn (mg/L)</i>	<i>Ave.</i>	99.7	99.1	102.6	33.5	0.1	0.2
	<i>St. Dev.</i>	1.47	0.55	5.61	3.99	0.01	0.18
<i>Zn (Cum Ret. %)</i>	<i>Ave.</i>	-0.9	-0.6	4.2	96.2	99.8	99.8
	<i>St. Dev.</i>	0.02	0.07	0.08	0.92	0.00	0.00

Table 6-9: Effluent Concentration during the Steady State Period after Each System Component – Third Operational Condition

Parameters		System Components					
		Oxid.	Sed.	Peat	SRB1	SRB2	ALD
<i>DO (mg/L)</i>	<i>Ave.</i>	4.4	4.5	1.8	1.9	1.3	1.5
	<i>St. Dev.</i>	0.31	0.19	0.32	0.42	0.06	0.12
<i>Redox (mV)</i>	<i>Ave.</i>	358.4	367.7	463.7	14.8	-56.7	-52.9
	<i>St. Dev.</i>	20.18	14.82	56.98	17.46	18.65	9.31
<i>PH</i>	<i>Ave.</i>	3.7	3.6	3.0	6.6	6.8	6.8
	<i>St. Dev.</i>	0.04	0.04	0.01	0.05	0.07	0.06
<i>Acidity (mg/L CaCO₃)</i>	<i>Ave.</i>	260	270	208	0	0	0
	<i>St. Dev.</i>	14	0	11	0	0	0
<i>Alkalinity (mg/L CaCO₃)</i>	<i>Ave.</i>	0	0	0	150	270	260
	<i>St. Dev.</i>	0	0	0	7	14	21
<i>Sulphate (mg/L)</i>	<i>Ave.</i>	1203	1270	1263	887	950	953
	<i>St. Dev.</i>	64	46	67	99	304	301
<i>Al (mg/L)</i>	<i>Ave.</i>	20.2	20.7	8.0	0.3	0.1	0.1
	<i>St. Dev.</i>	0.35	0.38	0.78	0.06	0.04	0.05
<i>Al (Cum Ret. %)</i>	<i>Ave.</i>	-0.1	-1.2	21.5	99.2	99.7	99.7
	<i>St. Dev.</i>	0.02	0.01	0.16	0.00	0.00	0.00
<i>Cd (mg/L)</i>	<i>Ave.</i>	1.6	1.7	1.6	0.0	0.0	0.0
	<i>St. Dev.</i>	0.07	0.08	0.67	0.01	0.00	0.00
<i>Cd (Cum Ret. %)</i>	<i>Ave.</i>	-0.9	-2.3	-1.2	99.7	99.8	99.8
	<i>St. Dev.</i>	0.00	0.00	0.08	0.00	0.00	0.00
<i>Cu (mg/L)</i>	<i>Ave.</i>	4.6	4.7	3.0	0.0	0.0	0.0
	<i>St. Dev.</i>	0.11	0.11	0.29	0.01	0.00	0.00
<i>Cu (Cum Ret. %)</i>	<i>Ave.</i>	0.5	-0.7	26.4	99.8	99.9	99.9
	<i>St. Dev.</i>	0.01	0.00	0.05	0.00	0.00	0.00
<i>Fe (mg/L)</i>	<i>Ave.</i>	40.4	40.4	3.1	9.3	13.1	8.4
	<i>St. Dev.</i>	2.25	1.93	4.69	1.72	6.95	0.42
<i>Fe (Cum Ret. %)</i>	<i>Ave.</i>	6.1	6.2	74.6	73.5	95.5	95.8
	<i>St. Dev.</i>	0.04	0.03	0.10	0.03	0.06	0.05
<i>Mn (mg/L)</i>	<i>Ave.</i>	6.5	6.6	6.8	7.9	15.3	15.3
	<i>St. Dev.</i>	0.04	0.13	1.73	0.34	5.40	5.31
<i>Mn (Cum Ret. %)</i>	<i>Ave.</i>	0.1	-2.3	-2.7	-38.8	-10.1	-9.0
	<i>St. Dev.</i>	0.01	0.01	0.06	0.10	0.31	0.31
<i>Ni (mg/L)</i>	<i>Ave.</i>	4.9	5.1	4.0	4.3	0.1	0.0
	<i>St. Dev.</i>	0.02	0.09	1.59	0.18	0.01	0.01
<i>Ni (Cum Ret. %)</i>	<i>Ave.</i>	-0.9	-2.4	1.1	74.0	99.8	99.8
	<i>St. Dev.</i>	0.01	0.01	0.09	0.23	0.00	0.00
<i>Zn (mg/L)</i>	<i>Ave.</i>	25.3	26.1	23.7	14.1	0.1	0.1
	<i>St. Dev.</i>	0.40	0.62	9.13	0.52	0.03	0.02
<i>Zn (Cum Ret. %)</i>	<i>Ave.</i>	-0.8	-2.3	-0.1	89.8	99.7	99.8
	<i>St. Dev.</i>	0.01	0.01	0.06	0.19	0.00	0.00

Table 6-10: Effluent Concentration during the Steady State Period after Each System Component – Fourth Operational Condition

Parameters		System Components					
		Oxid.	Sed.	Peat	SRB1	SRB2	ALD
<i>DO (mg/L)</i>	<i>Ave.</i>	4.8	4.6	3.2	2.2	1.8	1.9
	<i>St. Dev.</i>	0.82	0.23	0.39	0.35	0.25	0.13
<i>Redox (mV)</i>	<i>Ave.</i>	361.5	372.6	437.9	99.4	-60.7	-38.8
	<i>St. Dev.</i>	28.89	23.96	32.95	20.97	14.73	15.27
<i>PH</i>	<i>Ave.</i>	3.9	3.7	3.1	6.6	6.9	7.0
	<i>St. Dev.</i>	0.03	0.09	0.03	0.02	0.01	0.03
<i>Acidity (mg/L CaCO₃)</i>	<i>Ave.</i>	258	263	235	0	0	0
	<i>St. Dev.</i>	11	4	0	0	0	0
<i>Alkalinity (mg/L CaCO₃)</i>	<i>Ave.</i>	0	0	0	115	149	151
	<i>St. Dev.</i>	0	0	0	0	4	6
<i>Sulphate (mg/L)</i>	<i>Ave.</i>	1318	1353	1423	783	708	705
	<i>St. Dev.</i>	97	95	73	19	15	6
<i>Al (mg/L)</i>	<i>Ave.</i>	21.4	21.4	20.1	0.2	0.0	0.0
	<i>St. Dev.</i>	1.09	1.30	1.61	0.09	0.01	0.03
<i>Al (Cum Ret. %)</i>	<i>Ave.</i>	0.3	-1.0	21.2	99.2	99.7	99.7
	<i>St. Dev.</i>	0.02	0.04	0.11	0.00	0.00	0.00
<i>Cd (mg/L)</i>	<i>Ave.</i>	1.8	1.8	2.0	0.1	0.0	0.0
	<i>St. Dev.</i>	0.09	0.02	0.16	0.12	0.07	0.07
<i>Cd (Cum Ret. %)</i>	<i>Ave.</i>	-0.8	-2.4	-1.6	99.6	99.7	99.7
	<i>St. Dev.</i>	0.02	0.03	0.09	0.07	0.04	0.04
<i>Cu (mg/L)</i>	<i>Ave.</i>	4.6	4.6	4.4	0.0	0.0	0.0
	<i>St. Dev.</i>	0.13	0.06	0.17	0.02	0.01	0.02
<i>Cu (Cum Ret. %)</i>	<i>Ave.</i>	0.6	-0.7	25.1	99.7	99.8	99.8
	<i>St. Dev.</i>	0.02	0.03	0.17	0.00	0.00	0.00
<i>Fe (mg/L)</i>	<i>Ave.</i>	42.5	44.1	0.3	2.7	6.8	8.0
	<i>St. Dev.</i>	1.18	1.21	0.11	0.19	1.39	1.40
<i>Fe (Cum Ret. %)</i>	<i>Ave.</i>	6.4	6.8	77.0	75.2	94.2	94.6
	<i>St. Dev.</i>	0.06	0.02	0.23	0.20	0.07	0.12
<i>Mn (mg/L)</i>	<i>Ave.</i>	6.7	6.7	6.8	7.7	8.3	8.1
	<i>St. Dev.</i>	0.35	0.35	0.45	0.14	0.59	0.45
<i>Mn (Cum Ret. %)</i>	<i>Ave.</i>	0.1	-2.2	-2.9	-36.3	-14.7	-13.5
	<i>St. Dev.</i>	0.01	0.02	0.02	0.18	0.08	0.08
<i>Ni (mg/L)</i>	<i>Ave.</i>	5.0	5.0	5.1	6.2	0.0	0.1
	<i>St. Dev.</i>	0.06	0.04	0.30	0.30	0.02	0.03
<i>Ni (Cum Ret. %)</i>	<i>Ave.</i>	-0.8	-2.4	0.6	66.6	99.7	95.6
	<i>St. Dev.</i>	0.01	0.02	0.02	0.93	0.00	0.03
<i>Zn (mg/L)</i>	<i>Ave.</i>	25.8	25.9	26.6	24.7	0.2	0.2
	<i>St. Dev.</i>	0.50	0.48	1.57	1.66	0.11	0.06
<i>Zn (Cum Ret. %)</i>	<i>Ave.</i>	-0.7	-2.3	-0.6	83.3	99.7	99.7
	<i>St. Dev.</i>	0.02	0.03	0.03	0.83	0.00	0.01

operational condition (high flow and low constituent loadings) Al, Cd, Cu, Fe, and Zn were removed by more than 99% and iron and nickel removal was approximately 95%.

Manganese removal reduced significantly from 77% during the first operational condition to 7% during the second condition. No manganese removal was noticed during the last two conditions. Effluent concentration of metals including copper, nickel and zinc met the Canadian MMLER metal constituent limits of 0.6 mg/L, 1.0 mg/L and 1.0 mg/L, respectively (Kilborn, 1996). Based on Tables 6-7 to 6-10, figures in Appendix E represent the effluent concentrations of AMD during the steady state period after each system component.

To have a better idea about the overall performance of the system components during the course of this study, the total mass of all the metals introduced into the system and cumulative metal removals after each component were calculated (Figure 6-25).

As can be seen, total cumulative metal removal was about 16% for the oxidation and sedimentation tanks. This number increased up to 46% for the peat column, 80% for the first SRB and 92% for the second SRB and ALD stage. It can be concluded that peat biofilter and first SRB column had the greatest role in the mitigation of synthetic AMD among all the other system components.

Overall it can be said that the performance of the combined passive treatment system was adequate for the remediation of acid mine drainage. The system successfully neutralized the pH and increased the alkalinity of the solution. Sulphate and dissolved metals concentrations were also reduced significantly during the experimental time of more than one year under different hydraulic and constituent loadings.

Figure 6-25: Overall Metal removal

7 CONCLUSION AND RECOMMENDATIONS

7.1 Summary and Conclusion

Passive treatment is an appropriate alternative to the conventional active chemical treatment of acid mine drainage for removing metals and acidity over a long-term period. A combined passive treatment system was designed by Champagne (2001) for mitigation of a moderate strength AMD under Canadian climatic conditions. This system consisted of four passive treatment components including: oxidation/sedimentation for excess metal removal; peat biofilter for heavy metal sorption and establishment of anaerobic conditions; sulphate reducing bacteria for sulphate reduction and increase in the alkalinity of the solution; and anoxic limestone drain for alkalinity addition. This investigation was conducted to evaluate the performance of this combined system under different hydraulic and constituent loadings as a simulation for seasonal fluctuations in flow rate and dissolved metal concentrations. Since this study used a new peat for the peat biofilter column, two other studies were undertaken including: 1) Physical/chemical characterization of the utilized peat; 2) Equilibrium test to evaluate the sorption capacity of the peat at different pH levels.

In terms of elemental ion composition and exchangeable fraction, it was found that in comparison to the total amount of metals supplied as synthetic AMD to the system, the extractable mass of heavy metal ions from the peat biofilter was negligible (< 0.01%). The peat utilized had an average CEC of 153.3 (meq/100 g) that represents a moderate ion adsorption capacity. According to ASTM D4427-92, this peat was

classified as low ash content ($< 5\%$), moderate fiber content (fibric H1-H3 Von Post Scale) and highly acidic ($\text{pH} < 4.5$) in both water and calcium chloride solution.

Equilibrium test results showed a significant increase in the adsorption capacity of the metals onto the peat with increasing pH value of the solution. At a pH of 3.2, the relative single metal sorption capacity order was found to be: $\text{Cu} > \text{Fe} > \text{Al} > \text{Mn} > \text{Zn} > \text{Ni}$ while at a pH of 3.0 the relative order was $\text{Cu} > \text{Fe} \approx \text{Al} > \text{Zn} > \text{Ni} > \text{Mn}$ and at a pH of 2.8 the order was: $\text{Cu} > \text{Fe} > \text{Al} > \text{Cd} > \text{Zn} > \text{Mn}$.

The combined passive treatment system was operated under four different combinations of hydraulic and constituent loadings to examine the efficiency of the system under seasonal variations in AMD strength and discharged. To evaluate the efficiency of the bench-scale combined system and its components, parameters such as dissolved oxygen, redox potential, pH, alkalinity, acidity, sulphate and metal concentrations were regularly measured.

Oxidation and sedimentation tanks mainly removed the excess iron by precipitating it out of the solution. The peat biofilter adsorbed significant amounts of metal ions during the first operational condition. Gradually the metals started to break through. The order of breakthrough was consistent with equilibrium test results with $\text{Cu} > \text{Al} > \text{Cd} > \text{Zn} > \text{Ni} > \text{Mn}$ at a pH of 3.0 which was the natural pH of the peat. In the peat biofilter column, effluent iron concentrations did not follow the expected trend for adsorption that was followed for the other metals. It appeared that iron removal was due to other removal mechanisms such as precipitation during this stage. By changing the operational conditions from the high constituent concentration to low constituent concentration, new equilibrium conditions between the peat and AMD were established and some metals

including Zn, Mn, Ni, Cu and Cd desorbed back to the solution. However, these metals, with the exception of Mn, were subsequently removed in the SRB stage. The establishment of anaerobic conditions throughout the peat biofilter was another goal that was achieved by microbial activity at this stage. The SRB stage reduced the acidity of the solution completely and consequently increased the alkalinity of the drainage, and sulphate concentrations were reduced as expected. During the experiment, metals such as manganese, iron, nickel and zinc gradually broke through the first SRB column. Within the second SRB column, breakthrough of Mn was also noted. No further changes in the characteristics of the synthetic acid mine drainage were observed through the anoxic limestone drain stage during all the operational conditions.

Overall, the combined passive treatment system was able to mitigate adequately the synthetic acid mine drainage under variable operational conditions. The initial drainage with low pH and high acidity of the AMD was successfully treated to a neutralized effluent with adequate alkalinity. Sulphate concentrations and dissolved metals were reduced significantly within the combined system. With the exception of manganese, cumulative metal removals were found to be more than 95% during all the operational conditions. This combined system was successfully able to mitigate synthetic AMD to meet the Canadian MMLER metal constituent limits during the 14-months experimental period.

7.2 Recommendations

Mining industry is continuously developing and it can be expected that new technologies will make it more profitable to mine low-grade ores. This trend could lead

to production of more mining waste and tailings resulting in more AMD generation. Consistent investigations and new engineering methods are required to minimize the impacts of this inevitable water contamination.

In this study, the following recommendations can be suggested that may help to improve the overall efficiency of this combined passive treatment system for remediation of Canadian acid mine drainage:

- Exploration of alternative removal mechanisms for dissolved manganese.
- Designing a more efficient oxidation system to enhance the removal of iron and manganese through the oxidation/sedimentation stage.
- Increasing the pH level of AMD before entering the oxidation/sedimentation stage to enhance the precipitation of dissolved metals in the oxidation/sedimentation stage.
- Estimation of required peat biofilter replacement period or enlargement of the peat biomass to prevent metal breakthrough.
- Determination of the other metal removal mechanisms through the peat biofilter stage.
- Preparation of a valve in the SRB stage to release the excess gas pressure. This can enhance the AMD hydraulic flow during the low flow rate conditions.
- Investigation of potential vegetation and plants as an alternative treatment component or to enhance the performance of the system components during the warm seasons. This also could reduce the rate of water evaporation throughout the open stages.

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APPENDIX A

Synthetic Acid Mine Drainage Recipe

SYNTHETIC AMD RECIPE FOR VARIOUS BATCH SOLUTIONS

Element	High Conc. (mg/L)	Low Conc. (mg/L)	Metal Salt	High conc. (g/L)	Low conc. (g/L)
Fe	200	50	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	0.996	0.249
Zn	100	25	$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	0.440	0.110
Al	90	22.5	$\text{Al}_2(\text{SO}_4)_3 \cdot 16\text{H}_2\text{O}$	1.051	0.263
Mn	25	6.25	$\text{MnSO}_4 \cdot \text{H}_2\text{O}$	0.077	0.019
Ni	20	5	$\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$	0.090	0.023
Cu	20	5	CuSO_4	0.050	0.013
Cd	6	1.5	$3\text{CdSO}_4 \cdot 8\text{H}_2\text{O}$	0.014	0.004
K	780	195	K_2SO_4	1.739	0.435
Na	460	115	Na_2SO_4	1.417	0.354

APPENDIX B

Peat Characterization - Raw Data

PEAT ELEMENTAL COMPOSITION ($\mu\text{g/g}$)

Date Performed: Jan-22-2002

Location Performed: Seprotech Laboratory

Theory: Identifies the total metal ions that exist in peat whether mobile or not.

Sample Name	Ca	Cd	Co	Cr	Cu	Fe	Mg	Mn	Ni	Pb	Zn	As	K	Na	P	Se
A	7500	2	12	30	56	7340	4280	394	50	2100	98	154	4020	494000	1222	1
B	9280	2	26	42	72	7460	5200	438	56	1500	136	112	3320	542000	1104	0
C	8400	2	10	32	46	5480	5000	116	32	160	80	7	5640	562000	810	1
Ave.	8393	2	16	35	58	6760	4827	316	46	1253	105	91	4327	532667	1045	0
St. Dev.	890	0	9	6	13	1110	484	175	12	993	29	76	1190	34948	212	0

PEAT EXTRACTABLE IONS ($\mu\text{g/g}$)

Date Performed: Jan-22-2002

Location Performed: Carleton University

Theory: Identifies the metal ions, which may be displaced by solution.

Sample Name	Ca	Cd	Co	Cr	Cu	Fe	Mg	Mn	Ni	Pb	Zn	As	K	Na	P	Se
A	1300	7	ND	ND	ND	253	1011	ND	ND	ND	17	6	4160	748	87	ND
A	1239	7	ND	ND	ND	ND	1041	ND	ND	ND	17					
B	1044	ND	ND	ND	ND	ND	832	ND	ND	ND	18	4	2278	541	318	ND
B	1037	ND	ND	ND	ND	213	829	ND	ND	ND	16					
C	1246	ND	ND	ND	ND	ND	1090	ND	ND	ND	24	7	2118	703	328	ND
C	1384	3	ND	ND	ND	266	1068	4	ND	ND	ND					
Ave.	1208	5	ND	ND	ND	244	978	ND	ND	ND	18	6	2852	664	244	ND
St. Dev.	140	2	ND	ND	ND	27	118	ND	ND	ND	3	1	1136	109	137	ND

ND = Not Detected

CATION EXCHANGE CAPACITY

Date Performed: Jan-15-2002

Location Performed: Carleton University

Theory: HCl remove cation and replace H^+ . The adsorbed H^+ then replaced by Ba^{2+} .

NaOH neutralizes acetic acid.

$$CEC \text{ (meq / 100g)} = \frac{(\forall N)100}{M_p}$$

Where the cation exchange capacity is given as meq/100 g of oven-dried peat, $\forall$ is the volume of NaOH titrated (mL), N is the normality of the NaOH solution and M_p is the mass of the peat specimen (g).

Sample	NaOH (mL)	CEC (meq/100g)
1	7.4	148
2	8.3	166
3	7.3	146
Ave	7.7	153.3
St. Dev.	0.55	11.02

Note: NaOH= 0.1 N and M=0.5 g.

MOISTURE CONTENT

Date Performed: Jan-15-2002

Location Performed: Carleton University

Theory: Dried at 90°C for 48 hours.

$$\text{Moisture (\%)} = \frac{A - B}{B} 100$$

Where the moisture content is expressed on dry mass basis, A is the initial mass of the air-dried peat specimen (g) and B is the sample mass remaining after drying at 90°C (g).

Sample	Dish (g)	(A)	Dish + Sample (g)	Dried Dish + Sample (g)	(B)	(A-B)	(A-B)/(B)x100
		Peat (g)			Dried Sample (g)	Moisture (g)	Moisture (%)
1	63.7092	12.0007	75.7099	74.7462	11.0370	0.9637	8.7315
2	59.1487	11.9999	71.1486	70.1557	11.0070	0.9929	9.0206
3	58.7118	12.0001	70.7119	69.7642	11.0524	0.9477	8.5746
4	62.8116	12.0007	74.8123	73.8619	11.0503	0.9504	8.6007
5	58.9609	11.9999	70.9608	70.0027	11.0418	0.9581	8.6770
6	59.4785	12.0003	71.4788	70.4891	11.0106	0.9897	8.9886
7	62.5683	12.0001	74.5684	73.6135	11.0452	0.9549	8.6454
8	57.4092	12.0005	69.4097	68.4598	11.0506	0.9499	8.5959
Ave.					11.0369	0.9634	8.7293
St. Dev.					0.0181	0.0180	0.1773

ASH AND ORGANIC MATTER CONTENT

Date Performed: Apr-13-2002

Location Performed: Carleton University

Theory: Dried at 90°C for 48 hours. Placed in oven and heated to 440°C for 2 hours.

$$\text{Ash (\%)} = \frac{D}{B}100$$

$$\text{Organic Matter (\%)} = \frac{(B - D)}{B}100$$

Both values were reported on an oven-dried mass basis; where D is the mass of ashes remaining after ignition (g) and B is the sample mass remaining after drying at 90°C (g).

Sample	Burned Dish + Sample (g)	Dish (g)	(D)	(B)	(D)/(B)x100	(B-D)/(B)x100
			Ash Mass (g)	Dried Sample (g)	Ash (%)	OM (%)
1	60.6287	60.5058	0.1229	9.0399	1.36	98.64
2	57.6206	57.4630	0.1576	9.0645	1.74	98.26
3	59.5087	59.4092	0.0995	9.0752	1.10	98.90
4	66.8972	66.7835	0.1137	9.0662	1.25	98.75
5	63.8670	63.7172	0.1498	9.0571	1.65	98.35
6	64.5866	64.4745	0.1121	9.0586	1.24	98.76
Ave.			0.1259	9.0603	1.3900	98.6100
St. Dev.			0.0229	0.0119	0.2530	0.2530

APPENDIX C

Combined Passive Treatment System Test

Raw Data

DISSOLVED OXYGEN (mg/L) - 1st OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
27-Apr-01	70	5	4.35	4.42	4.14	2.01	0.16	0.07	0.13
1-May-01	74	25	3.39	3.97	3.85	2.62	0.69	0.21	1.64
4-May-01	77	40	2.94	2.64	2.87	1.21	0.25	0.16	0.84
7-May-01	80	55	3.97	4.52	4.17	1.58	0.52	0.16	1.37
10-May-01	83	70	2.90	2.78	2.65	0.95	0.20	0.11	0.24
14-May-01	87	90	2.91	3.49	3.58	0.82	0.28	0.13	0.16
17-May-01	90	105	3.98	3.83	3.83	1.35	0.84	0.19	0.38
21-May-01	94	125	3.74	3.61	3.21	0.95	0.29	0.12	0.29
24-May-01	97	140	3.39	2.68	2.97	1.03	0.50	0.14	0.26
28-May-01	101	160	3.65	3.42	3.55	1.70	0.46	0.21	0.24
31-May-01	104	175	4.04	3.80	3.23	1.30	0.92	0.25	0.43
4-Jun-01	108	195	4.69	4.47	4.37	1.93	1.50	0.83	0.74
7-Jun-01	111	210	2.37	2.19	1.67	0.73	0.57	0.06	0.09
11-Jun-01	115	230	4.57	3.57	4.00	1.56	0.85	0.43	0.19
14-Jun-01	118	245	3.81	3.89	3.06	0.90	0.53	0.12	0.11
18-Jun-01	122	265	3.67	3.15	2.70	0.95	0.51	0.08	0.09
21-Jun-01	125	280	3.23	3.53	2.95	1.15	0.70	0.22	0.30
2-Jul-01	136	335	3.89	4.00	3.41	1.11	0.96	0.30	0.54
5-Jul-01	139	350	3.41	3.37	2.93	0.82	0.63	0.26	0.51
9-Jul-01	143	370	3.73	3.79	3.44	1.16	0.78	0.44	0.65
12-Jul-01	146	385	4.19	3.85	3.53	0.81	0.57	0.60	0.66
16-Jul-01	150	405	3.48	3.24	2.80	0.80	0.60	0.66	0.69
19-Jul-01	153	420	3.06	3.15	3.06	1.14	0.60	0.80	0.80
26-Jul-01	160	455	5.71	6.95	6.50	3.37	1.97	2.89	2.55
30-Jul-01	164	475	3.68	3.59	3.29	1.35	0.45	1.09	1.41

DISSOLVED OXYGEN (mg/L) – 2nd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
6-Aug-01	171	493	3.95	3.71	3.34	1.44	0.69	0.75	1.34
9-Aug-01	174	500	4.05	4.05	3.46	1.35	0.80	0.68	1.35
13-Aug-01	178	510	4.15	3.90	3.36	1.14	0.95	0.62	1.29
16-Aug-01	181	518	3.04	3.75	3.20	1.07	0.81	0.60	0.87
20-Aug-01	185	528	3.36	3.40	3.24	0.72	0.52	0.77	0.98
20-Sep-01	216	605	4.14	4.05	3.82	1.09	0.90	0.88	1.22
26-Sep-01	222	620	4.10	3.95	3.29	1.16	0.80	0.93	1.23
4-Oct-01	230	640	2.89	3.06	2.91	0.71	0.63	0.52	1.15
8-Oct-01	234	650	3.04	3.56	2.96	1.46	1.02	0.64	1.27
12-Oct-01	238	660	3.17	3.19	2.67	1.62	0.84	0.74	0.75
15-Oct-01	241	668	3.24	3.29	2.76	0.97	0.69	0.55	0.95
19-Oct-01	245	678	3.06	3.16	2.95	0.97	0.82	0.50	0.68
22-Oct-01	248	685	3.23	3.75	3.30	1.62	0.69	0.48	0.75
26-Oct-01	252	695	3.50	3.13	3.18	1.60	0.67	0.89	1.00
30-Oct-01	256	705	4.34	4.05	4.50	2.62	1.50	1.45	1.68
2-Nov-01	259	713	4.35	4.77	4.41	1.12	1.13	0.93	1.19
9-Nov-01	266	730	4.16	4.46	4.13	1.43	1.07	0.90	0.95
18-Nov-01	275	753	4.07	4.47	3.55	0.92	0.86	0.82	0.70
24-Nov-01	281	768	3.60	4.44	3.54	1.03	1.01	0.76	1.03
5-Dec-01	292	795	4.20	4.79	3.91	1.27	1.30	0.75	0.92

DISSOLVED OXYGEN (mg/L) – 3rd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
19-Dec-01	306	830	4.19	4.57	3.74	1.20	1.05	0.65	0.68
24-Dec-01	311	843	3.89	4.42	3.56	1.26	1.14	0.65	0.73
28-Dec-01	315	853	4.60	4.69	4.03	1.19	1.70	1.50	0.95
5-Jan-02	323	873	4.30	4.40	4.27	1.46	1.17	0.70	0.65
10-Jan-02	328	885	4.24	4.00	4.12	1.72	0.83	1.38	0.88
16-Jan-02	334	900	4.17	4.13	4.16	2.86	1.24	0.80	0.85
18-Jan-02	336	905	4.76	4.30	4.30	1.48	1.01	0.73	0.93
22-Jan-02	340	915	4.76	4.49	4.62	2.75	1.16	0.98	1.02
30-Jan-02	348	935	4.43	4.13	4.70	2.45	1.16	0.94	0.80
4-Feb-02	353	948	4.41	4.40	4.68	2.63	1.20	1.08	1.30
7-Feb-02	356	955	4.40	4.73	4.64	2.92	1.36	1.23	1.78
13-Feb-02	362	970	4.22	4.63	4.40	3.02	1.82	1.58	1.52
20-Feb-02	369	988	4.44	5.20	4.38	3.39	1.96	1.60	1.86
25-Feb-02	374	1000	4.55	4.64	4.41	1.86	1.96	1.50	2.39
1-Mar-02	378	1010	4.78	4.48	4.67	1.46	1.40	1.27	1.57
7-Mar-02	384	1025	4.17	4.05	4.29	2.00	2.23	1.18	1.35
12-Mar-02	389	1038	4.56	4.65	4.53	2.02	1.97	1.30	1.53

DISSOLVED OXYGEN (mg/L) – 4th OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
25-Mar-02	402	1103	4.58	4.20	4.30	1.46	1.94	1.59	1.31
28-Mar-02	405	1118	4.72	4.33	4.60	2.96	1.80	1.56	1.75
2-Apr-02	410	1143	4.78	4.45	4.90	3.51	1.94	2.15	1.70
5-Apr-02	413	1158	4.65	4.89	4.70	3.05	1.80	1.62	1.93
11-Apr-02	419	1188	4.55	4.50	4.58	2.60	1.72	1.61	1.66
16-Apr-02	424	1213	4.95	4.70	4.65	3.80	1.93	1.85	1.88
24-Apr-02	432	1253	4.68	4.49	4.63	1.87	1.76	1.60	2.13
30-Apr-02	438	1283	4.46	4.50	4.47	2.80	1.80	1.48	1.85
6-May-02	444	1313	4.57	4.28	4.48	2.45	1.96	1.80	1.81
13-May-02	451	1348	4.64	5.91	4.94	2.83	1.83	1.88	2.13
17-May-02	455	1368	4.59	4.46	4.50	3.69	2.67	2.00	1.91
23-May-02	461	1398	4.55	4.65	4.49	3.34	2.19	1.80	1.88
30-May-02	468	1433	4.53	4.00	4.48	2.97	2.10	1.43	1.85

REDOX (mV) - 1st OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
5-Jul-01	139	350	360.8	372.5	373.1	356	-36	46.7	27.8
9-Jul-01	143	370	366.3	372.3	364.9	412.1	-69.5	-68.2	-69.1
12-Jul-01	146	385	355.8	372.5	372.3	408.7	-56.8	-37.6	-20.2
16-Jul-01	150	405	365	364.4	368.3	375.5	-91.1	-45.5	-50.8
19-Jul-01	153	420	348.2	357.5	368.5	388.8	-93.4	-55.9	-63.3
26-Jul-01	160	455	352	340	361.5	371.3	-51.1	-14.2	-27.9
30-Jul-01	164	475	362.6	376	380.1	375	-71.9	-54.9	-64.2

REDOX (mV) - 2nd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
6-Aug-01	171	493	358.4	330.6	370.1	392.4	-73	-67.8	-44.5
9-Aug-01	174	500	362.4	361.4	325.3	392.1	-37.6	-81.7	-27.9
13-Aug-01	178	510	366.4	380.7	314	348.7	-59.2	-82	-45.5
16-Aug-01	181	518	357.7	333.4	327.4	357.9	-54.1	-85.5	-59.5
20-Aug-01	185	528	339.5	328.2	318.5	347.5	-9.3	-48.9	-14.8
20-Sep-01	216	605	346.8	363.8	359.5	433.7	27.3	-51.3	102.1
26-Sep-01	222	620	370.1	364.4	344.4	453.6	-55	-40	-40
4-Oct-01	230	640	336.6	352.2	347.8	387	6.2	75.5	58
8-Oct-01	234	650	319.7	328.3	307.3	329	-11.9	-45.4	-2.7
12-Oct-01	238	660	346.6	362.8	348.3	361.4	-27.9	-53.4	-39.1
15-Oct-01	241	668	333	329.1	310.6	321.7	-27.4	-47.2	-15.3
19-Oct-01	245	678	313.5	324.5	318.1	320	-13.7	-49.6	-32.1
22-Oct-01	248	685	363.5	362.6	354.6	395.2	11.2	16.2	-0.4
26-Oct-01	252	695	361.1	371.8	370.3	488.1	-21.1	-20.1	-25.1
30-Oct-01	256	705	371.8	372.9	368.1	469.6	-27	-49.1	-52.2
2-Nov-01	259	713	367.1	364.1	369.1	464	-7	-52.5	-60.3
9-Nov-01	266	730	368.2	383.2	381.1	355.2	-53.1	-71.1	-54.5
18-Nov-01	275	753	374.5	382.2	380.1	397.1	-43.3	-79.1	-79
24-Nov-01	281	768	373.5	384.5	380.1	366.5	-41.8	-77.5	-81.3
5-Dec-01	292	795	367	378.2	373.4	370.5	-22.8	-85.6	-69.4

REDOX (mV) – 3rd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
19-Dec-01	306	830	347.00	368.60	373.60	375.90	21.90	-82.30	-73.50
24-Dec-01	311	843	300.00	338.50	349.50	389.30	2.20	-69.40	-62.00
28-Dec-01	315	853	314.50	344.00	348.00	378.50	-12.50	-40.50	-68.50
5-Jan-02	323	873	315.40	324.70	357.90	438.20	29.30	-78.60	-76.70
10-Jan-02	328	885	311.80	339.20	325.70	368.80	50.70	-36.40	-42.20
16-Jan-02	334	900	296.10	344.10	376.20	435.00	22.60	-82.30	-76.10
18-Jan-02	336	905	341.80	346.00	355.20	455.00	-15.30	-72.60	-46.50
22-Jan-02	340	915	352.60	362.00	376.00	430.00	-0.70	-49.10	-32.00
30-Jan-02	348	935	305.00	343.00	352.00	370.00	-6.20	-36.00	-60.30
4-Feb-02	353	948	343.20	368.50	336.50	404.40	57.90	-58.60	-41.00
7-Feb-02	356	955	349.00	380.00	366.10	379.00	33.30	-74.20	-14.30
13-Feb-02	362	970	286.00	339.00	373.40	477.90	-0.50	-78.60	-70.50
20-Feb-02	369	988	353.00	370.50	351.00	435.00	-8.60	-86.00	-72.40
25-Feb-02	374	1000	331.80	345.20	348.30	407.00	10.00	-68.70	-30.90
1-Mar-02	378	1010	341.50	359.60	361.90	398.30	-2.30	-75.30	-44.30
7-Mar-02	384	1025	301.60	337.70	356.60	490.50	14.00	-56.90	-62.80
12-Mar-02	389	1038	346.70	378.00	384.50	502.40	32.60	-38.00	-51.70

REDOX (mV) – 4th OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
25-Mar-02	402	1103	352.20	366.60	385.10	461.50	76.90	-43.90	-11.40
28-Mar-02	405	1118	345.90	348.00	361.60	474.00	19.60	-72.10	-57.30
2-Apr-02	410	1143	347.20	365.40	368.10	426.50	36.00	-50.70	-54.40
5-Apr-02	413	1158	324.00	340.00	353.10	436.50	15.30	-77.30	-51.90
11-Apr-02	419	1188	301.50	338.30	339.10	485.70	17.80	-85.10	-78.80
16-Apr-02	424	1213	303.50	327.40	336.40	472.40	51.10	-56.00	-30.10
24-Apr-02	432	1253	324.40	343.00	345.00	430.00	23.90	-77.40	-60.90
30-Apr-02	438	1283	340.00	372.20	393.50	420.00	52.00	-78.90	-51.10
6-May-02	444	1313	342.30	347.70	358.60	486.30	45.10	-85.20	-71.40
13-May-02	451	1348	365.60	394.10	394.00	410.00	123.20	-51.30	-27.50
17-May-02	455	1368	353.70	377.00	391.90	418.00	100.20	-45.60	-24.10
23-May-02	461	1398	324.80	333.00	346.50	483.50	72.10	-77.30	-55.10
30-May-02	468	1433	330.20	341.80	358.10	439.90	102.10	-68.40	-48.30

pH - 1st OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
27-Apr-01	70	5	3.1	3.21	3.38	3.55	7.24	7.44	7.58
1-May-01	74	25	3.02	3.28	3.21	2.92	7.09	7.4	7.5
4-May-01	77	40	2.99	3.21	3.13	2.57	7.26	7.42	7.31
7-May-01	80	55	2.93	3.21	3.32	2.75	7.12	7.33	7.39
10-May-01	83	70	2.9	3.15	3.11	2.49	7.04	7.16	7.24
14-May-01	87	90	2.86	3.05	3	2.7	6.85	7.15	7.21
17-May-01	90	105	2.99	3.18	3.1	2.99	6.88	7.24	7.24
21-May-01	94	125	3.03	3.23	3.24	2.86	6.8	7.13	7.15
24-May-01	97	140	2.94	3.07	3.06	2.89	6.71	7.12	7.21
28-May-01	101	160	3.05	3.27	3.19	2.9	6.76	7.06	7.11
31-May-01	104	175	3.04	3.2	3.18	2.87	6.62	7.1	7.04
4-Jun-01	108	195	3.09	3.27	3.17	3.02	6.68	7.06	7.1
7-Jun-01	111	210	2.95	3.13	3.13	3.04	6.6	7	7.06
11-Jun-01	115	230	2.94	3.11	3.07	3.03	6.51	6.94	7.07
14-Jun-01	118	245	3.13	3.2	3.11	3.02	6.42	6.87	7.06
18-Jun-01	122	265	2.94	3.1	3.13	2.94	6.46	6.97	7
21-Jun-01	125	280	3.15	3.31	3.19	2.96	6.58	6.93	7
2-Jul-01	136	335	2.92	3.01	3.12	2.93	6.38	6.74	6.88
5-Jul-01	139	350	3.04	3.18	3.22	2.95	6.47	6.84	6.82
9-Jul-01	143	370	3.09	3.13	3.15	2.9	6.52	6.85	6.92
12-Jul-01	146	385	3.01	3.18	3.11	2.91	6.66	6.9	6.9
16-Jul-01	150	405	3.08	3.11	3.12	2.97	6.61	6.72	6.78
19-Jul-01	153	420	2.96	3.04	3.05	2.9	6.6	6.8	6.79
26-Jul-01	160	455	3.13	3.21	3.17	2.91	6.46	6.73	6.76
30-Jul-01	164	475	2.86	2.93	2.96	2.79	6.53	6.73	6.77

pH - 2nd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
6-Aug-01	171	493	3.04	3.19	3.07	2.89	6.59	6.74	6.9
9-Aug-01	174	500	2.96	3.11	3.14	2.81	6.51	7.05	6.75
13-Aug-01	178	510	3.06	3.19	3.22	2.94	6.66	6.82	6.81
16-Aug-01	181	518	3.03	3.18	3.25	2.92	6.59	6.79	6.82
20-Aug-01	185	528	3	3.13	3.13	2.91	6.4	6.72	6.71
20-Sep-01	216	605	2.91	2.95	2.93	2.94	6.7	6.81	6.79
26-Sep-01	222	620	2.92	3.03	3.03	2.86	6.77	6.78	6.89
4-Oct-01	230	640	3.15	3.19	3.19	2.91	6.75	6.74	6.88
8-Oct-01	234	650	3.17	3.3	3.22	3	6.67	6.76	6.8
12-Oct-01	238	660	3.07	3.14	3.2	2.98	6.56	6.76	6.8
15-Oct-01	241	668	2.87	2.98	2.98	2.85	6.51	6.73	6.8
19-Oct-01	245	678	3.07	3.2	3.17	2.89	6.7	6.75	6.77
22-Oct-01	248	685	3.15	3.22	3.22	3	6.59	6.73	6.92
26-Oct-01	252	695	3.12	3.19	3.23	3.02	6.51	6.78	6.9
30-Oct-01	256	705	3.05	3.12	3.23	2.96	6.48	6.69	6.76
2-Nov-01	259	713	2.99	3.1	3.11	2.89	6.37	6.62	6.68
9-Nov-01	266	730	3.02	3.12	3.13	2.92	6.46	6.7	6.72
18-Nov-01	275	753	2.98	3.06	3.08	2.97	6.43	6.59	6.7
24-Nov-01	281	768	3	3.11	3.09	3.01	6.42	6.65	6.71
5-Dec-01	292	795	2.86	3.01	3.01	2.96	6.37	6.58	6.57

pH - 3rd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
19-Dec-01	306	830	4.02	3.72	3.35	2.91	6.24	6.51	6.55
24-Dec-01	311	843	4.12	3.84	3.56	3.22	6.56	6.65	6.66
28-Dec-01	315	853	4.17	3.89	3.65	3.13	6.55	6.87	6.79
5-Jan-02	323	873	4.16	3.97	3.74	3.16	6.70	6.85	6.87
10-Jan-02	328	885	4.10	3.85	3.65	3.16	6.65	6.86	6.87
16-Jan-02	334	900	4.23	3.94	3.70	3.23	6.65	6.87	6.88
18-Jan-02	336	905	4.09	3.80	3.55	3.00	6.69	6.84	6.82
22-Jan-02	340	915	4.09	3.80	3.56	2.99	6.67	6.83	6.81
30-Jan-02	348	935	4.09	3.80	3.56	2.97	6.65	6.83	6.80
4-Feb-02	353	948	3.99	3.81	3.60	3.00	6.66	6.82	6.87
7-Feb-02	356	955	4.00	3.73	3.61	3.08	6.63	6.85	6.89
13-Feb-02	362	970	3.96	3.63	3.48	2.96	6.58	6.80	6.82
20-Feb-02	369	988	3.89	3.82	3.67	3.03	6.61	6.84	6.85
25-Feb-02	374	1000	3.99	3.84	3.69	2.97	6.49	6.81	6.88
1-Mar-02	378	1010	3.98	3.72	3.58	3.01	6.55	6.70	6.75
7-Mar-02	384	1025	3.85	3.66	3.61	3.01	6.59	6.74	6.80
12-Mar-02	389	1038	3.99	3.74	3.65	3.02	6.65	6.84	6.87

pH - 4th OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
25-Mar-02	402	1103	3.99	3.95	3.75	2.94	6.57	6.88	6.83
28-Mar-02	405	1118	3.94	3.89	3.78	3.00	6.63	6.84	6.87
2-Apr-02	410	1143	3.96	3.77	3.74	2.92	6.64	6.84	6.83
5-Apr-02	413	1158	4.07	3.83	3.74	2.94	6.58	6.90	6.87
11-Apr-02	419	1188	4.15	3.84	3.81	2.97	6.59	6.83	6.89
16-Apr-02	424	1213	4.10	3.99	3.88	3.04	6.68	6.97	6.96
24-Apr-02	432	1253	3.98	3.75	3.71	2.93	6.66	6.96	6.89
30-Apr-02	438	1283	4.13	3.83	3.62	3.04	6.64	6.87	6.94
6-May-02	444	1313	4.08	3.90	3.76	3.14	6.57	6.94	6.89
13-May-02	451	1348	4.04	3.92	3.70	3.04	6.53	6.93	6.94
17-May-02	455	1368	4.05	3.91	3.69	3.03	6.54	6.91	6.92
23-May-02	461	1398	4.04	3.96	3.87	3.10	6.55	6.91	7.00
30-May-02	468	1433	4.04	3.89	3.70	3.07	6.58	6.92	6.96

ACIDITY (mg/L) as CaCO₃ - 1st OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
27-Apr-01	70	5	1436	1500	738	372	0	0	0
1-May-01	74	25	1375	1225	1275	380	0	0	0
7-May-01	80	55	1450	1600	1500	990	0	0	0
14-May-01	87	90	1700	1680	1050	375	0	0	0
21-May-01	94	125	1700	1675	1700	1325	0	0	0
28-May-01	101	160	1800	1775	1765	1250	100	0	0
4-Jun-01	108	195	1200	1150	1200	925	0	0	0
11-Jun-01	115	230	1275	1175	1200	975	0	0	0
18-Jun-01	122	265	1275	1250	1175	1000	0	0	0
2-Jul-01	136	335	1250	1225	1200	965	50	0	0
9-Jul-01	143	370	1200	1175	1210	900	0	0	0
16-Jul-01	150	405	1175	1175	1150	865	25	0	0
26-Jul-01	160	455	1175	1150	1150	1000	0	0	0
30-Jul-01	164	475	1225	1175	1175	965	0	0	0

ACIDITY (mg/L) as CaCO₃ - 2nd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
6-Aug-01	171	493	1150	1080	1100	925	0	0	0
13-Aug-01	178	510	1200	1125	1090	1000	0	0	0
8-Oct-01	234	650	1200	1175	1175	925	0	0	0
15-Oct-01	241	668	1225	1175	1175	825	0	0	0
22-Oct-01	248	685	1225	1175	1200	925	0	0	0
30-Oct-01	256	705	1250	1200	1175	925	0	0	0
9-Nov-01	266	730	1250	1150	1150	950	200	0	0
12-Nov-01	269	738	1250	1150	1150	950	75	0	0
28-Nov-01	285	778	1250	1150	1150	950	0	0	0
5-Dec-01	292	795	1325	1225	1200	950	0	0	0

ACIDITY (mg/L) as CaCO₃ - 3rd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
20-Dec-01	307	833	275	260	800	650	0	0	0
28-Dec-01	315	853	300	275	325	275	0	0	0
5-Jan-02	323	873	330	275	300	250	0	0	0
10-Jan-02	328	885	330	275	325	270	0	0	0
16-Jan-02	334	900	295	275	280	225	0	0	0
30-Jan-02	348	935	295	250	270	250	0	0	0
4-Feb-02	353	948	275	250	270	225	0	0	0
13-Feb-02	362	970	270	250	270	240	0	0	0
20-Feb-02	369	988	270	270	290	250	0	0	0
25-Feb-02	374	1000	270	260	280	245	0	0	0
1-Mar-02	378	1010	270	250	270	215	0	0	0
12-Mar-02	389	1038	280	270	270	200	0	0	0

ACIDITY (mg/L) as CaCO₃ - 4th OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
25-Mar-02	402	1103	275	255	250	225	0	0	0
30-Mar-02	407	1128	275	250	255	230	0	0	0
5-Apr-02	413	1158	275	250	260	235	0	0	0
12-Apr-02	420	1193	280	255	260	235	0	0	0
18-Apr-02	426	1223	275	250	260	235	0	0	0
26-Apr-02	434	1263	250	255	255	350	0	0	0
1-May-02	439	1288	275	255	260	230	0	0	0
13-May-02	451	1348	275	265	265	235	0	0	0
23-May-02	461	1398	275	250	260	235	0	0	0

ALKALINITY (mg/L) as CaCO₃ - 1st OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
27-Apr-01	70	5	1436	1500	738	372	0	0	0
1-May-01	74	25	0	0	0	0	130	170	150
7-May-01	80	55	0	0	0	0	340	330	340
14-May-01	87	90	0	0	0	0	425	500	500
21-May-01	94	125	0	0	0	0	275	375	390
28-May-01	101	160	0	0	0	0	360	475	475
4-Jun-01	108	195	0	0	0	0	350	450	475
11-Jun-01	115	230	0	0	0	0	325	475	475
18-Jun-01	122	265	0	0	0	0	375	480	500
2-Jul-01	136	335	0	0	0	0	125	475	475
9-Jul-01	143	370	0	0	0	0	290	425	425
16-Jul-01	150	405	0	0	0	0	275	350	350
26-Jul-01	160	455	0	0	0	0	325	415	420
30-Jul-01	164	475	0	0	0	0	290	400	400

ALKALINITY (mg/L) as CaCO₃ - 2nd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
6-Aug-01	171	493	0	0	0	0	375	470	475
13-Aug-01	178	510	0	0	0	0	375	525	525
8-Oct-01	234	650	0	0	0	0	150	275	300
15-Oct-01	241	668	0	0	0	0	300	375	350
22-Oct-01	248	685	0	0	0	0	250	350	350
30-Oct-01	256	705	0	0	0	0	250	350	350
9-Nov-01	266	730	0	0	0	0	250	400	400
12-Nov-01	269	738	0	0	0	0	250	400	400
28-Nov-01	285	778	0	0	0	0	250	400	400
5-Dec-01	292	795	0	0	0	0	250	400	375

ALKALINITY (mg/L) as CaCO₃ - 3rd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
20-Dec-01	307	833	0	0	0	0	225	375	350
28-Dec-01	315	853	0	0	0	0	190	375	375
5-Jan-02	323	873	0	0	0	0	150	300	275
10-Jan-02	328	885	0	0	0	0	150	275	275
16-Jan-02	334	900	0	0	0	0	150	300	300
30-Jan-02	348	935	0	0	0	0	150	285	260
4-Feb-02	353	948	0	0	0	0	190	290	275
13-Feb-02	362	970	0	0	0	0	190	335	345
20-Feb-02	369	988	0	0	0	0	210	400	385
25-Feb-02	374	1000	0	0	0	0	150	285	300
1-Mar-02	378	1010	0	0	0	0	155	280	275
12-Mar-02	389	1038	0	0	0	0	145	260	245

ALKALINITY (mg/L) as CaCO₃ - 4th OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
25-Mar-02	402	1103	0	0	0	0	125	240	215
30-Mar-02	407	1128	0	0	0	0	120	210	195
5-Apr-02	413	1158	0	0	0	0	120	182	182
12-Apr-02	420	1193	0	0	0	0	110	174	165
18-Apr-02	426	1223	0	0	0	0	115	167	167
26-Apr-02	434	1263	0	0	0	0	115	170	164
1-May-02	439	1288	0	0	0	0	110	158	154
13-May-02	451	1348	0	0	0	0	115	152	156
23-May-02	461	1398	0	0	0	0	115	146	146

SULPHATE (mg/L) - 1st OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
30-Apr-01	73	20	3710	4220	4100	3390	1620	760	730
4-May-01	77	40	3870	3940	4050	3760	2870	2660	2620
7-May-01	80	55	4140	4210	4230	4200	2860	2770	2730
14-May-01	87	90	4300	4410	4450	4440	3230	3090	3090
21-May-01	94	125	4290	4410	4360	4500	3260	3130	3080
28-May-01	101	160	3690	3720	3900	3840	3120	2970	2960
4-Jun-01	108	195	3880	3750	3940	3850	3050	2940	2940
11-Jun-01	115	230	4040	4090	4100	4030	3100	2920	2890
18-Jun-01	122	265	4230	4320	4080	4110	3100	2960	2930
2-Jul-01	136	335	6700	4880	4950	4770	3410	3110	3080
9-Jul-01	143	370	4550	4700	5020	6390	3130	2990	2930
16-Jul-01	150	405	4690	4790	4880	4860	3210	2970	2790
26-Jul-01	160	455	4790	4800	5000	5000	3320	2930	2920
30-Jul-01	164	475	4780	4910	4910	5000	3310	2980	2950

SULPHATE (mg/L) - 2nd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
6-Aug-01	171	493	4020	4040	4290	4520	3220	2880	2960
13-Aug-01	178	510	4550	4490	4550	4750	3350	3100	3090
20-Aug-01	185	528	4460	4300	4610	4720	3150	2960	2940
26-Sep-01	222	620	4380	4410	4530	4380	3160	2890	2940
4-Oct-01	230	640	4640	4700	4730	4680	2950	2880	2770
12-Oct-01	238	660	4460	4550	4670	4650	3130	2940	2980
19-Oct-01	245	678	4650	4720	4810	4770	3290	2950	2910
26-Oct-01	252	695	4850	4900	4920	4700	3320	2980	2960
2-Nov-01	259	713	4760	4850	4960	4940	3440	2940	3000
9-Nov-01	266	730	5030	4960	5090	5400	3470	2970	2960
18-Nov-01	275	753	5010	5060	5010	5000	3300	3210	3210
24-Nov-01	281	768	5160	5210	5210	5160	3230	2930	2960
5-Dec-01	292	795	4980	5280	5220	5070	3530	2850	2960

SULPHATE (mg/L) - 3rd OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
19-Dec-01	306	830	1140	1220	2650	4270	3240	3040	3050
24-Dec-01	311	843	1070	1240	2330	1670	1600	2680	2720
28-Dec-01	315	853	1160	1300	1840	1550	980	1180	1280
5-Jan-02	323	873	1220	1340	1510	1540	870	830	840
10-Jan-02	328	885	1060	1210	1390	1460	830	850	860
16-Jan-02	334	900	1130	1200	1330	1390	800	760	740
18-Jan-02	336	905	1130	1190	1400	1440	810	740	750
22-Jan-02	340	915	1200	1290	1370	1440	790	720	730
30-Jan-02	348	935	810	1070	1240	1320	820	710	730
4-Feb-02	353	948	980	1320	1280	1230	860	740	740
7-Feb-02	356	955	910	1160	1180	1240	870	730	730
13-Feb-02	362	970	840	990	1060	1240	870	730	730
20-Feb-02	369	988	1070	1140	1330	1400	960	660	670
25-Feb-02	374	1000	1100	1230	1200	1920	1600	990	970
1-Mar-02	378	1010	870	1130	1220	1230	1000	1300	1300
7-Mar-02	384	1025	1120	1240	1280	1220	840	800	800
12-Mar-02	389	1038	1190	1240	1310	1340	820	750	760

SULPHATE (mg/L) - 4th OPERATIONAL CONDITION

Date	Day	V. Load.	Port						
		(L)	Influ.	Oxi.	Sed.	Peat	SRB1	SRB2	ALD
25-Mar-02	402	1103	1050	1210	1290	1390	810	750	740
28-Mar-02	405	1118	1270	1330	1390	1430	770	730	730
2-Apr-02	410	1143	1310	1370	1430	1490	800	730	730
5-Apr-02	413	1158	1100	1200	1280	1325	780	730	740
11-Apr-02	419	1188	910	1000	1080	1020	760	720	750
16-Apr-02	424	1213	1060	1120	1200	1300	770	730	740
24-Apr-02	432	1253	1390	1160	1280	1310	790	720	720
30-Apr-02	438	1283	1360	1400	1440	1460	890	860	850
6-May-02	444	1313	1320	1340	1410	1470	760	760	760
13-May-02	451	1348	1350	1440	1450	1480	770	730	700
17-May-02	455	1368	1160	1210	1230	1320	770	700	700
23-May-02	461	1398	1240	1280	1330	1420	780	700	710
30-May-02	468	1433	1300	1340	1400	1470	810	700	710

Influent Metal Concentration (mg/L) - 1st OPERATIONAL CONDITION

Date	Day	V.	Influent						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	94.7	7.46	20.1	200	27	20.1	108
30-Apr-01	73	20	82.7	6.25	18.6	176	23.6	17.4	94.1
4-May-01	77	40	88.3	6.7	19.7	185	25.5	18.9	101
7-May-01	80	55	91.7	7.01	19.8	193	26.2	19.2	104
10-May-01	83	70	97.8	7.33	21.1	205	27.9	20.3	109
14-May-01	87	90	93.7	7.08	19.7	200	25.7	20.1	100
17-May-01	90	105	92.9	7	19.1	193	25.1	19.3	98.4
21-May-01	94	125	90	6.73	18.4	189	24.1	18.6	95.5
24-May-01	97	140	91.1	6.71	18.8	189	24.7	19.2	97.5
28-May-01	101	160	90.9	6.84	20	192	25.3	19.1	99.1
31-May-01	104	175	90.2	6.97	19.8	192	25.7	19.1	98.7
4-Jun-01	108	195	89.2	6.93	19.7	190	25.3	18.9	98.4
7-Jun-01	111	210	90.4	7.87	19.8	192	25.4	19.1	99.6
11-Jun-01	115	230	94.3	8.2	20.6	194	26.5	19.8	104
14-Jun-01	118	245	92.8	7.28	20.2	195	26.3	19	102
18-Jun-01	122	265	84.3	7.02	18.7	170	24.9	19.3	95.4
21-Jun-01	125	280	91.1	6.45	19.8	190	26.1	19.7	111
2-Jul-01	136	335	95.6	6.83	19.7	197	25.1	20.9	103
5-Jul-01	139	350	92.4	6.94	19.5	197	25.4	20.4	98.7
9-Jul-01	143	370	86.1	6.28	18.3	185	24	19.1	91.2
12-Jul-01	146	385	91.3	6.74	19.5	200	25.8	20.5	95.8
16-Jul-01	150	405	87	6.5	18.5	187	24.2	19.3	90.4
19-Jul-01	153	420	85.7	6.35	18.2	187	24.2	19	88.8
26-Jul-01	160	455	85.9	6.3	18.2	185	24	19.1	88.8
30-Jul-01	164	475	88.9	6.53	18.7	182	25.2	19.8	91.9

Influent Metal Concentration (mg/L) - 2nd OPERATIONAL CONDITION

Date	Day	V.	Influent						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	91.1	7.4	18.5	182	25.1	18.8	98.4
9-Aug-01	174	500	95.5	7.72	18.6	183	26.5	19.5	101
13-Aug-01	178	510	96.1	7.75	17.2	167	27.1	19.5	102
16-Aug-01	181	518	90.9	7.15	18.5	185	25.7	18.7	95.5
20-Aug-01	185	528	94.7	7.49	18.5	187	26.3	19.5	98
20-Sep-01	216	605	88.5	6.86	18.7	181	24.8	18	91.7
26-Sep-01	222	620	90.7	6.98	18.7	183	24.9	18.5	93.2
4-Oct-01	230	640	94.2	7.44	19.5	192	26.4	19.2	97
8-Oct-01	234	650	87.8	7.06	18.1	196	25.8	20	93
12-Oct-01	238	660	87.9	7.08	19.2	192	26.1	19.6	93.6
15-Oct-01	241	668	90.3	7.11	19.7	196	26.7	20.1	96.2
19-Oct-01	245	678	92.1	7.19	19.8	198	27.7	20.3	97.7
22-Oct-01	248	685	93.5	7.24	20	197	27.4	20.4	98.4
26-Oct-01	252	695	95.4	7.42	20.3	195	28.2	20.9	101
30-Oct-01	256	705	94.1	7.4	20	198	27.7	20.4	98.7
2-Nov-01	259	713	93.6	7.22	19.7	196	26.9	20.1	97.6
9-Nov-01	266	730	101	7.73	20.9	201	29.1	21.3	103
18-Nov-01	275	753	90.7	6.84	18.7	203	26.1	20.5	98.1
24-Nov-01	281	768	91.8	6.99	18.9	198	26.4	20.9	99.7
5-Dec-01	292	795	93.5	7.22	19.6	203	27.2	21.8	101

Influent Metal Concentration (mg/L) - 3rd OPERATIONAL CONDITION

Date	Day	V.	Influent						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	21.4	1.91	4.7	49.6	7	5.17	16.1
24-Dec-01	311	843	22.2	1.92	5	50.3	7.16	5.39	15.8
28-Dec-01	315	853	22	1.89	5.02	50.1	7.08	5.42	24.1
5-Jan-02	323	873	21.9	2	5.09	49.4	6.99	4.97	27.3
10-Jan-02	328	885	21.8	1.78	4.99	48.3	6.72	5.07	26.6
16-Jan-02	334	900	21.8	1.81	4.85	48.3	6.89	5.13	26.1
18-Jan-02	336	905	22.6	1.89	4.9	49.1	6.65	5.26	26.4
22-Jan-02	340	915	21.9	1.86	4.81	47.1	6.53	5.17	25.9
30-Jan-02	348	935	21.4	1.77	4.67	48.7	6.48	5.14	26.1
4-Feb-02	353	948	22.5	1.88	4.92	49.4	6.92	5.36	27.4
7-Feb-02	356	955	22	1.86	4.88	47.4	6.92	5.34	27.4
13-Feb-02	362	970	22.3	1.83	4.84	48.5	6.73	5.25	27.2
20-Feb-02	369	988	22.7	1.87	4.97	47.7	6.99	5.42	27.8
25-Feb-02	374	1000	22.6	1.83	4.92	49.6	6.96	5.33	27.4
1-Mar-02	378	1010	21.2	1.66	4.6	47.2	6.33	4.89	24.9
7-Mar-02	384	1025	20.9	1.67	4.61	45.4	6.6	4.98	25.4
12-Mar-02	389	1038	21.4	1.54	4.77	48.3	6.63	4.98	25.8

Influent Metal Concentration (mg/L) - 4th OPERATIONAL CONDITION

Date	Day	V.	Influent						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	21.3	1.72	4.76	48.1	6.66	5.06	26.4
28-Mar-02	405	1118	20.8	1.7	4.65	46.6	6.86	5.18	26.8
2-Apr-02	410	1143	21.7	1.8	4.76	48.7	6.77	5.26	27.4
5-Apr-02	413	1158	21.1	1.77	4.69	46.7	6.82	5.09	26.5
11-Apr-02	419	1188	21.3	1.78	4.71	49.3	6.51	5.02	28.6
16-Apr-02	424	1213	21.2	1.82	4.71	48.5	6.46	4.97	28
24-Apr-02	432	1253	22.9	1.94	5.02	48.7	6.61	5.25	27
30-Apr-02	438	1283	22.9	1.76	4.71	49.6	6.46	5.07	25.8
6-May-02	444	1313	22.8	1.77	4.66	49.2	6.45	5.09	26.3
13-May-02	451	1348	22.8	1.77	4.63	49	7.31	5.07	25.9
17-May-02	455	1368	23.4	1.84	4.78	49.9	6.67	5.06	26
23-May-02	461	1398	20.4	1.86	4.65	49.5	6.42	4.96	25.8
30-May-02	468	1433	21.5	1.82	4.78	48.5	6.5	5.02	26.2

Metal Concentration after Oxidation Column (mg/L) - 1st

OPERATIONAL CONDITION

Date	Day	V.	Oxidation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	93.2	7.29	20	195	26.8	19.8	107
30-Apr-01	73	20	90.7	6.76	20	192	26.2	19.3	104
4-May-01	77	40	87.8	6.69	19.6	183	25.5	18.9	101
7-May-01	80	55	91.9	7.03	19.6	190	26.2	19.3	104
10-May-01	83	70	99.7	7.42	21.3	205	28.5	20.7	111
14-May-01	87	90	93.8	7.03	19.4	195	25.6	19.9	99.6
17-May-01	90	105	94.6	7.12	19.3	188	25.4	19.6	99.6
21-May-01	94	125	92.3	6.99	19.5	193	25.7	19.7	99.5
24-May-01	97	140	92.5	6.78	18.7	182	25	19.3	98
28-May-01	101	160	91.1	6.88	20	187	25.5	19.1	98.9
31-May-01	104	175	91.7	7.13	20	188	25.7	19.2	99.8
4-Jun-01	108	195	91.8	7.13	20.1	187	26	19.3	100
7-Jun-01	111	210	91.6	7.95	20	189	25.8	19.2	100
11-Jun-01	115	230	94.2	8.21	20.4	186	26.6	19.9	104
14-Jun-01	118	245	93.7	7.32	20.3	189	26.7	19.8	103
18-Jun-01	122	265	89.2	7.16	19.5	170	26	19.6	97.6
21-Jun-01	125	280	91.2	6.49	19.7	182	26.4	19.7	111
2-Jul-01	136	335	94.1	6.61	19.6	184	25.3	20.9	103
5-Jul-01	139	350	93.2	7	19.6	192	25.8	20.7	99.9
9-Jul-01	143	370	86.7	6.35	18.3	178	24.4	19.3	91.8
12-Jul-01	146	385	91.6	6.76	19.4	193	25.8	20.5	95.8
16-Jul-01	150	405	87	6.52	18.4	180	24.2	19.4	90.8
19-Jul-01	153	420	84.8	6.29	18	179	23.9	18.9	90.8
26-Jul-01	160	455	86.4	6.37	18.2	175	24.4	19.3	89.5
30-Jul-01	164	475	89.5	6.62	18.7	177	25.1	19.9	92.4

Metal Concentration after Oxidation Column (mg/L) - 2nd
OPERATIONAL CONDITION

Date	Day	V.	Oxidation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	89.5	7.45	17.9	153	25.3	18.6	97.5
9-Aug-01	174	500	93.4	7.68	18	154	26.4	19.5	101
13-Aug-01	178	510	95.9	7.81	17	147	4.84	20	103
16-Aug-01	181	518	91.1	7.31	18.2	157	25.6	18.8	96.3
20-Aug-01	185	528	91.4	7.47	17.7	146	26.4	19.3	97.5
20-Sep-01	216	605	89.8	7.01	18.4	180	24.5	18.1	92.1
26-Sep-01	222	620	92.2	7.11	18.9	183	25.2	18.9	95.8
4-Oct-01	230	640	94.7	7.54	19.5	185	26.3	19.3	97.3
8-Oct-01	234	650	90.8	7.34	18.7	189	27.4	20.3	96.7
12-Oct-01	238	660	87.2	7.06	18.9	177	25.8	19.5	93.3
15-Oct-01	241	668	91.6	7.21	19.7	185	27.1	20.5	97.6
19-Oct-01	245	678	90.8	7.23	19.5	178	27.4	20.5	98
22-Oct-01	248	685	94	7.34	19.9	181	27.8	20.8	100
26-Oct-01	252	695	96.1	7.46	20.2	180	28.1	21	101
30-Oct-01	256	705	93.7	7.36	20	178	28.3	20.9	101
2-Nov-01	259	713	93.3	7.27	19.4	177	27.2	20.3	98.1
9-Nov-01	266	730	99.3	7.73	20.4	171	28.8	21.4	104
18-Nov-01	275	753	90.1	6.91	18.5	174	26.1	20.7	98.1
24-Nov-01	281	768	90.8	6.99	18.5	159	26.7	21.1	100
5-Dec-01	292	795	92.8	7.24	19.4	180	27.7	21.9	101

Metal Concentration after Oxidation Column (mg/L) - 3rd
OPERATIONAL CONDITION

Date	Day	V.	Oxidation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	20.2	1.96	4.47	40.2	7.18	5.27	16.1
24-Dec-01	311	843	20.5	1.91	4.74	40.2	7.13	5.29	15.8
28-Dec-01	315	853	21	1.91	4.92	42.9	7.15	5.47	24.5
5-Jan-02	323	873	20.5	2.02	4.9	42.3	7.04	5	27.6
10-Jan-02	328	885	20.5	1.81	4.84	39.9	6.76	5.11	26.8
16-Jan-02	334	900	20.5	1.84	4.7	38.5	6.73	5.13	26.2
18-Jan-02	336	905	20.6	1.88	4.63	41	6.65	5.22	26.3
22-Jan-02	340	915	20.8	1.89	4.68	39	6.67	5.27	26.4
30-Jan-02	348	935	19.3	1.77	4.29	35.2	6.66	5.05	25.7
4-Feb-02	353	948	20.5	1.87	4.59	36.1	6.83	5.29	26.9
7-Feb-02	356	955	20.8	1.88	4.71	34.5	6.91	5.38	27.5
13-Feb-02	362	970	18.9	1.82	4.49	33.6	6.76	5.19	26.7
20-Feb-02	369	988	21.1	1.9	4.76	40.9	7	5.41	28.1
25-Feb-02	374	1000	20.9	1.83	4.65	42.5	6.97	5.34	28
1-Mar-02	378	1010	20.2	1.68	4.5	41.7	6.44	4.93	25.1
7-Mar-02	384	1025	19.8	1.67	4.52	37.8	6.45	4.93	25.1
12-Mar-02	389	1038	20.5	1.56	4.7	41.7	6.51	4.96	25.8

Metal Concentration after Oxidation Column (mg/L) - 4th
OPERATIONAL CONDITION

Date	Day	V.	Oxidation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	19.9	1.71	4.55	43.5	6.81	5	26.4
28-Mar-02	405	1118	21.1	1.81	4.77	45.5	6.66	5.29	27.6
2-Apr-02	410	1143	21.1	1.79	4.72	43.8	6.66	5.2	27
5-Apr-02	413	1158	20.7	1.79	4.77	45.3	6.59	5.17	27
11-Apr-02	419	1188	20	1.76	4.58	44.5	6.52	4.96	28.2
16-Apr-02	424	1213	20.6	1.85	4.65	45.9	6.54	5.05	28.4
24-Apr-02	432	1253	22.9	1.94	5.02	44.3	6.52	5.22	27
30-Apr-02	438	1283	22.6	1.8	4.78	45.7	6.5	5.15	26.3
6-May-02	444	1313	22.2	1.81	4.67	45.5	6.51	5.13	26.3
13-May-02	451	1348	21.4	1.74	4.45	41.6	7.25	4.96	25.7
17-May-02	455	1368	22.9	1.82	4.66	41.6	6.63	5.05	25.9
23-May-02	461	1398	20.5	1.95	4.49	42.6	6.46	4.93	25.1
30-May-02	468	1433	20.7	1.82	4.73	44.1	6.63	5.05	26.3

Metal Concentration after Sedimentation Column (mg/L) - 1st
OPERATIONAL CONDITION

Date	Day	V.	Sedimentation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	45.4	3.54	9.87	96.7	13.1	9.67	53.7
30-Apr-01	73	20	89	6.89	19.1	188	25.6	18.9	102
4-May-01	77	40	86.7	6.67	19.4	180	25.1	18.5	100
7-May-01	80	55	91.4	6.94	19.9	188	26.1	19.2	104
10-May-01	83	70	90.8	6.94	19.4	191	25.4	19.8	98.3
14-May-01	87	90	93.2	7.03	19.4	193	25.6	19.8	99.5
17-May-01	90	105	92.6	6.94	18.9	186	25.1	19.4	98.4
21-May-01	94	125	91.2	7	19.9	197	26.2	20.5	102
24-May-01	97	140	91.6	6.74	18.6	181	24.5	19	96.8
28-May-01	101	160	90.6	6.95	19.8	180	25.7	19.3	99.8
31-May-01	104	175	90.2	6.98	19.7	184	25.4	19	98.7
4-Jun-01	108	195	91.6	7.1	19.9	186	25.9	19.3	100
7-Jun-01	111	210	91.1	7.78	19.8	186	25.6	19	100
11-Jun-01	115	230	92.7	8.07	20.1	185	26.3	19.5	102
14-Jun-01	118	245	93	7.42	20.4	189	26.7	19.9	104
18-Jun-01	122	265	87.1	7	19.1	172	25.5	19.3	97
21-Jun-01	125	280	92.1	6.82	19.8	181	26.5	19.8	109
2-Jul-01	136	335	93.3	6.73	19.5	186	25.2	20.8	103
5-Jul-01	139	350	89	6.69	18.7	181	24.4	19.7	95.2
9-Jul-01	143	370	90.9	6.82	19	180	25.4	20.2	96.2
12-Jul-01	146	385	92.8	6.83	19.6	194	26.2	20.8	96.9
16-Jul-01	150	405	86.7	6.5	18.4	180	24.2	19.4	90.7
19-Jul-01	153	420	87	6.49	18.4	177	24.5	19.4	92.2
26-Jul-01	160	455	87.3	6.44	18.4	176	24.5	19.4	90.2
30-Jul-01	164	475	90.3	6.64	18.8	172	25.4	20.1	93.1

Metal Concentration after Sedimentation Column (mg/L) - 2nd
OPERATIONAL CONDITION

Date	Day	V.	Sedimentation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	92.3	7.48	18.8	155	26	19.2	101
9-Aug-01	174	500	95.9	7.8	19.2	156	27	19.9	103
13-Aug-01	178	510	91.5	7.53	17.4	141	26.1	18.8	97.8
16-Aug-01	181	518	92.9	7.51	18	153	26.4	19.2	98.4
20-Aug-01	185	528	94.9	7.61	18.4	155	27.1	19.7	98.8
20-Sep-01	216	605	89.8	7.01	18.4	177	25.1	18.6	94.2
26-Sep-01	222	620	91	7.13	18.6	170	25.9	19	96
4-Oct-01	230	640	95.1	7.47	19.6	181	26.5	19.6	98.8
8-Oct-01	234	650	89.9	7.26	18.9	185	26.7	20	95.3
12-Oct-01	238	660	92.1	7.45	19.8	186	27.7	20.8	98.9
15-Oct-01	241	668	91.5	7.24	19.6	181	27.2	20.4	97.6
19-Oct-01	245	678	91.7	7.26	19.6	178	27.4	20.5	98.3
22-Oct-01	248	685	92.9	7.3	19.7	178	27.6	20.5	99
26-Oct-01	252	695	94	7.36	19.8	176	27.7	20.6	99.9
30-Oct-01	256	705	98	7.56	20.1	177	27.9	20.9	101
2-Nov-01	259	713	95.3	7.38	19.7	176	27.6	20.5	99.4
9-Nov-01	266	730	98	7.56	20.1	168	28.3	21.1	102
18-Nov-01	275	753	92	7.19	18.7	171	26.6	21	99.7
24-Nov-01	281	768	90.3	6.93	18.3	158	26.5	20.7	98.7
5-Dec-01	292	795	90.3	7.01	18.7	165	27	21.1	98.8

Metal Concentration after Sedimentation Column (mg/L) - 3rd
OPERATIONAL CONDITION

Date	Day	V.	Sedimentation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	34.4	3.03	7.42	65.3	11.4	8.36	34.5
24-Dec-01	311	843	30	2.57	6.68	56.8	9.61	7.43	27.5
28-Dec-01	315	853	28.4	2.45	6.36	55.3	9.28	7.04	32.2
5-Jan-02	323	873	25.5	2.38	5.83	50	8.16	5.98	32.1
10-Jan-02	328	885	26.3	2.29	5.98	47.7	8.4	6.36	33.1
16-Jan-02	334	900	31.3	2.6	6.8	53.6	9.58	7.41	37.6
18-Jan-02	336	905	31.4	2.64	6.76	54.5	9.65	7.51	37.7
22-Jan-02	340	915	24.1	2.12	5.35	43.8	7.6	5.96	29.9
30-Jan-02	348	935	22.1	1.98	4.96	40.6	7.19	5.65	28.7
4-Feb-02	353	948	22.6	1.99	5.03	41.1	7.29	5.69	28.9
7-Feb-02	356	955	22.1	2.02	5.04	36.8	7.38	5.75	29.4
13-Feb-02	362	970	22.8	2.04	5.08	35.8	7.54	5.86	29.9
20-Feb-02	369	988	25.1	2.2	5.44	42.7	8.06	6.26	31.9
25-Feb-02	374	1000	22	1.93	4.91	43	7.14	5.5	28.2
1-Mar-02	378	1010	20.9	1.76	4.66	41.5	6.68	5.16	26.3
7-Mar-02	384	1025	20.3	1.69	4.57	38.2	6.49	4.99	25.4
12-Mar-02	389	1038	21	1.6	4.78	41.6	6.74	5.11	26.6

Metal Concentration after Sedimentation Column (mg/L) - 4th
OPERATIONAL CONDITION

Date	Day	V.	Sedimentation						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	21.5	1.85	4.9	43.8	6.78	5.34	27.9
28-Mar-02	405	1118	22.3	1.87	5.03	44.2	6.96	5.44	28.3
2-Apr-02	410	1143	22	1.87	4.89	43.8	6.89	5.42	28.2
5-Apr-02	413	1158	21.6	1.87	4.87	43.4	6.87	5.38	28
11-Apr-02	419	1188	20.7	1.82	4.69	44.5	6.74	5.13	29.1
16-Apr-02	424	1213	21.3	1.88	4.79	44.3	6.71	5.19	29.1
24-Apr-02	432	1253	22.9	1.96	5.03	38.3	6.66	5.24	27
30-Apr-02	438	1283	22.4	1.81	4.74	41.3	6.53	5.2	26.6
6-May-02	444	1313	21.4	1.76	4.54	41	6.38	5.04	25.8
13-May-02	451	1348	22.3	1.79	4.64	42.8	7.17	5.06	25.9
17-May-02	455	1368	22.7	1.82	4.6	43.4	6.69	5	25.6
23-May-02	461	1398	20	1.84	4.57	45.5	6.36	4.97	25.4
30-May-02	468	1433	20.6	1.82	4.71	44.6	6.54	5.03	26.5

Metal Concentration after Peat biofilter Column (mg/L) - 1st
OPERATIONAL CONDITION

Date	Day	V.	Peat Biofilter						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	0.17	0.01	0.13	0.13	0.08	0.02	0.09
30-Apr-01	73	20	4.18	0.1	0.12	1.01	13.4	0.13	3.34
4-May-01	77	40	31.9	6.65	0.04	1.27	25.2	19.8	102
7-May-01	80	55	60.5	6.45	0.15	12	24.7	18.4	97.3
10-May-01	83	70	47.5	5.4	0.88	120	22	17.3	81
14-May-01	87	90	17	4	1.46	187	26.4	13.8	70.4
17-May-01	90	105	15.6	6.12	1.59	121	29.3	19.6	105
21-May-01	94	125	52.1	6.9	3.5	125	24.5	20.7	97
24-May-01	97	140	54.4	7.55	3.95	23	27.1	19.6	107
28-May-01	101	160	87.7	6.93	7.13	1.4	25.4	18.6	95.6
31-May-01	104	175	104	6.96	11.6	1.5	25.7	18.8	98
4-Jun-01	108	195	104	7.27	17.7	1.8	26.2	19.3	101
7-Jun-01	111	210	105	7.32	21.6	1.25	26.2	19.1	100
11-Jun-01	115	230	108	8.06	25.7	11.4	26.2	19.2	102
14-Jun-01	118	245	113	8.03	27.3	5.1	26.4	19.5	103
18-Jun-01	122	265	89.8	6.9	24.5	47.9	24.8	18.2	93.2
21-Jun-01	125	280	97.1	7.11	24	76	26.1	19.4	103
2-Jul-01	136	335	40.1	5.63	11.7	207	24.7	17.2	92.2
5-Jul-01	139	350	48.2	7.04	10.8	89	25.9	20.1	104
9-Jul-01	143	370	79	7.16	11.9	12.1	25.7	20.4	99
12-Jul-01	146	385	98.2	6.76	14	15.8	25.9	20	93.9
16-Jul-01	150	405	86.6	6.36	15.7	20.2	24.5	18.9	89.4
19-Jul-01	153	420	90.2	6.59	18.7	11.5	24.7	19.2	91.6
26-Jul-01	160	455	89.5	6.45	21.6	44.2	24.5	19.2	89.1
30-Jul-01	164	475	90.5	6.66	19.4	19.1	25.6	19.7	92.3

Metal Concentration after Peat biofilter Column (mg/L) - 2nd
OPERATIONAL CONDITION

Date	Day	V.	Peat Biofilter						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	89.4	7.36	19.9	18.8	26.7	18.1	105
9-Aug-01	174	500	78.4	7.1	18.6	29.4	25.3	17.7	102
13-Aug-01	178	510	62.7	6.08	14.4	159	23.2	15.8	82.6
16-Aug-01	181	518	54.3	5.37	12.4	208	22.6	14.1	73.3
20-Aug-01	185	528	43.4	4.67	10.7	238	21.5	12	63.8
20-Sep-01	216	605	24.1	8.19	6.89	3.68	24.4	18.2	91
26-Sep-01	222	620	62.3	8.25	6.81	2.28	27	19.9	105
4-Oct-01	230	640	81.5	7.79	7.63	15.3	26.8	20.5	103
8-Oct-01	234	650	89.8	7.37	11.7	0.6	26.9	20.2	97.1
12-Oct-01	238	660	94.1	7.63	17.8	3.71	27	20.5	98.5
15-Oct-01	241	668	88.9	7.51	18.4	1.78	27.5	20.2	98.5
19-Oct-01	245	678	96.7	7.85	19.5	0.87	27.6	21.2	102
22-Oct-01	248	685	102	7.58	21.7	0.54	28.1	20.8	102
26-Oct-01	252	695	100	7.55	21.2	0.44	27.8	20.5	101
30-Oct-01	256	705	101	7.75	21.3	1.14	28.7	21.1	104
2-Nov-01	259	713	105	8	21.6	1.28	28.7	21.4	105
9-Nov-01	266	730	79	7.15	20.5	114	28.1	21.1	100
18-Nov-01	275	753	74.8	7.7	14.9	13.4	27.7	22.3	109
24-Nov-01	281	768	81.7	7.26	14.8	49.2	26.5	21.6	100
5-Dec-01	292	795	84.8	7.01	15.1	37.5	26.7	21	98.7

Metal Concentration after Peat biofilter Column (mg/L) - 3rd
OPERATIONAL CONDITION

Date	Day	V.	Peat Biofilter						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	86.2	7.29	17.6	32.8	27	20.3	104
24-Dec-01	311	843	12.9	2.32	5.69	14.8	8.72	6.67	32.9
28-Dec-01	315	853	14.2	2.49	6.23	11.8	8.05	6.94	29.4
5-Jan-02	323	873	17.4	2.02	6.74	0.98	7.61	5.48	24.5
10-Jan-02	328	885	19	2.02	7.1	0.27	7.53	5.5	25.6
16-Jan-02	334	900	17.1	1.9	6.77	0.31	7.08	5.07	26.1
18-Jan-02	336	905	17	1.92	6.68	0.46	7.12	5.09	26.5
22-Jan-02	340	915	16	1.84	6.41	0.55	6.88	4.97	26.2
30-Jan-02	348	935	17.9	2	6.66	0.2	7.21	5.49	27.8
4-Feb-02	353	948	17.4	1.92	6.24	0.22	6.91	5.25	26.9
7-Feb-02	356	955	17.2	1.95	6.22	0.32	7.29	5.38	27.7
13-Feb-02	362	970	17	1.95	5.88	0.36	7.27	5.34	27.5
20-Feb-02	369	988	18.7	2.07	6.34	1.79	7.69	5.71	29.5
25-Feb-02	374	1000	26.3	2.33	6.71	7.44	8.74	6.65	31.6
1-Mar-02	378	1010	8.68	1.12	3.31	8.54	4.88	3.23	15.8
7-Mar-02	384	1025	7.14	1.23	2.73	0.46	7.49	2.99	21.6
12-Mar-02	389	1038	8.16	2.33	3.04	0.39	8.14	5.85	33.7

Metal Concentration after Peat biofilter Column (mg/L) - 4th
OPERATIONAL CONDITION

Date	Day	V.	Peat Biofilter						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	15	1.97	4.1	0.55	7.28	5.82	30
28-Mar-02	405	1118	16.1	1.99	4.09	0.37	7.19	5.82	29.5
2-Apr-02	410	1143	17	1.84	4.25	0.35	6.96	5.38	28.1
5-Apr-02	413	1158	18.4	1.89	4.28	0.29	6.96	5.42	28.3
11-Apr-02	419	1188	17.7	1.79	4.08	0.26	6.73	5.07	29.3
16-Apr-02	424	1213	19.9	1.84	4.18	0.65	6.78	5.15	29.2
24-Apr-02	432	1253	22.6	1.95	4.6	0.25	7.18	5.56	28.5
30-Apr-02	438	1283	16.9	1.63	3.89	0.27	6.4	4.53	23.3
6-May-02	444	1313	16.2	1.69	3.7	0.55	6.81	4.61	25.8
13-May-02	451	1348	20.9	1.9	4.24	0.32	6.64	5.34	27.8
17-May-02	455	1368	21.7	1.96	4.6	0.33	7.42	5.45	27.9
23-May-02	461	1398	19.7	2.2	4.24	0.1	6.44	4.81	24.7
30-May-02	468	1433	18	1.82	4.37	0.3	6.53	4.96	25.8

Metal Concentration after First SRB Column (mg/L) - 1st
OPERATIONAL CONDITION

Date	Day	V.	SRB-1						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	0.9	0.01	0.01	0.2	0.01	0.02	0.04
30-Apr-01	73	20	0.84	0.02	0.02	0.36	15.3	0.02	0.08
4-May-01	77	40	1.1	0.02	0.02	0.23	14.8	0.08	0.24
7-May-01	80	55	1.24	0.02	0.01	0.2	15.5	0.08	0.28
10-May-01	83	70	0.6	0.02	0.03	0.31	16.9	0.06	0.34
14-May-01	87	90	0.32	0.01	0.01	0.18	21.7	0.04	0.01
17-May-01	90	105	0.59	0.02	0.03	0.69	25.2	0.09	0.26
21-May-01	94	125	0.87	0.01	0.01	0.48	29.6	0.02	0.02
24-May-01	97	140	0.01	0.01	0.03	1.52	40.4	0.06	0.16
28-May-01	101	160	0.01	0.01	0.01	8.23	43.9	0.02	0.2
31-May-01	104	175	0.14	0.01	0.04	18.2	44.2	0.04	0.3
4-Jun-01	108	195	0.09	0.02	0.05	25.9	42.3	0.04	0.3
7-Jun-01	111	210	0.14	0.02	0.07	35.2	41.4	0.02	0.25
11-Jun-01	115	230	0.03	0.01	0.06	35.7	44.2	0.02	0.21
14-Jun-01	118	245	0.01	0.02	0.06	43.1	45.8	0.02	0.21
18-Jun-01	122	265	0.01	0.02	0.08	41	44	0.04	0.31
21-Jun-01	125	280	0.02	0.02	0.09	47.4	45.9	0.07	0.58
2-Jul-01	136	335	0.56	0.01	0.01	57	48.8	0.04	0.04
5-Jul-01	139	350	0.72	0.01	0.02	53	45.3	0.02	0.27
9-Jul-01	143	370	1.05	0.01	0.04	55.1	38.2	0.11	0.53
12-Jul-01	146	385	1.22	0.01	0.02	85.7	42.5	0.02	0.06
16-Jul-01	150	405	0.93	0.01	0.01	85	36.7	0.02	0.24
19-Jul-01	153	420	0.97	0.01	0.01	80.9	34.5	0.07	2.73
26-Jul-01	160	455	1.29	0.01	0.02	81.5	33.8	0.02	0.5
30-Jul-01	164	475	1.35	0.01	0.1	78.6	34.4	0.85	0.57

Metal Concentration after First SRB Column (mg/L) - 2nd
OPERATIONAL CONDITION

Date	Day	V.	SRB-1						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	0.87	0.02	0.12	88.9	39.8	0.68	0.93
9-Aug-01	174	500	0.68	0.02	0.09	92.2	41.2	0.93	0.74
13-Aug-01	178	510	0.61	0.01	0.01	89.5	40.5	1.55	1.14
16-Aug-01	181	518	0.4	0.01	0.01	89.7	39.6	1.08	0.26
20-Aug-01	185	528	0.52	0.01	0.01	86.1	38.5	1.18	0.44
20-Sep-01	216	605	0.96	0.01	0.01	36.4	22.1	2.78	3.33
26-Sep-01	222	620	0.55	0.06	0.06	43.5	26.6	3.24	4.08
4-Oct-01	230	640	0.96	0.01	0.01	50.5	27.9	19.9	3.46
8-Oct-01	234	650	1.14	0.04	0.09	61.3	31.6	4.65	4.48
12-Oct-01	238	660	0.43	0.01	0.01	75.5	36	6.05	5.23
15-Oct-01	241	668	0.58	0.01	0.01	83.3	37.6	6.61	6.01
19-Oct-01	245	678	0.71	0.03	0.07	78.4	37.6	8.03	6.98
22-Oct-01	248	685	0.6	0.01	0.01	86.5	39.2	8.89	8.65
26-Oct-01	252	695	0.88	0.01	0.02	93.4	38.4	10.3	12.8
30-Oct-01	256	705	0.94	0.01	0.01	88.9	37.6	11.2	14.8
2-Nov-01	259	713	0.96	0.01	0.01	0.2	36.8	11	12.4
9-Nov-01	266	730	0.01	0.01	0.01	0.53	36.5	12.4	15.3
18-Nov-01	275	753	0.01	0.01	0.01	83.8	35.9	16.9	30.9
24-Nov-01	281	768	0.01	0.05	0.02	81.5	33.9	16.8	31.5
5-Dec-01	292	795	0.01	0.01	0.01	76	31.4	17.7	38.1

Metal Concentration after First SRB Column (mg/L) - 3rd
OPERATIONAL CONDITION

Date	Day	V.	SRB-1						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	0.03	0.02	0.06	65.4	31.6	16.5	44.8
24-Dec-01	311	843	0.04	0.01	0.04	26.2	14.9	7.52	21.7
28-Dec-01	315	853	0.01	0.01	0.03	17.1	11.3	6.15	17.2
5-Jan-02	323	873	0.23	0.01	0.05	16.3	10.6	5.63	16.2
10-Jan-02	328	885	0.87	0.02	0.04	17.7	10.2	5.39	15.7
16-Jan-02	334	900	0.86	0.01	0.04	15	9.21	4.99	14.7
18-Jan-02	336	905	0.9	0.02	0.06	14.6	9.1	4.85	14.3
22-Jan-02	340	915	0.77	0.02	0.05	13.9	8.75	4.62	13.5
30-Jan-02	348	935	0.86	0.01	0.01	13	9.08	5	13.9
4-Feb-02	353	948	0.11	0.02	0.03	13.5	9.75	5.29	15.2
7-Feb-02	356	955	0.03	0.02	0.04	15.1	9.84	5.26	15.3
13-Feb-02	362	970	0.17	0.01	0.04	15.3	10.3	5.37	15.6
20-Feb-02	369	988	1.12	0.05	0.12	15.4	11.4	6.36	18.3
25-Feb-02	374	1000	0.25	0.01	0.04	21.1	15.5	8.61	27.2
1-Mar-02	378	1010	0.3	0.01	0.03	11.2	8.24	4.47	14.7
7-Mar-02	384	1025	0.24	0.01	0.02	8.88	7.7	4.15	13.8
12-Mar-02	389	1038	0.35	0.02	0.04	7.85	7.61	4.15	13.8

Metal Concentration after First SRB Column (mg/L) - 4th
OPERATIONAL CONDITION

Date	Day	V.	SRB-1						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	0.01	0.01	0.04	5.8	6.91	4.29	14.9
28-Mar-02	405	1118	0.7	0.07	0.2	7.04	6.68	3.99	14.3
2-Apr-02	410	1143	0.14	0.01	0.03	5.42	6.9	3.69	12.9
5-Apr-02	413	1158	0.13	0.01	0.02	5.39	7.75	4.52	16.5
11-Apr-02	419	1188	0.06	0.02	0.07	4.24	7.5	4.49	17.9
16-Apr-02	424	1213	0.02	0.01	0.05	3.8	7.79	4.96	21
24-Apr-02	432	1253	0.2	0.02	0.1	4.36	8.26	5.72	21.8
30-Apr-02	438	1283	0.27	0.01	0.05	3.54	8.1	5.84	22.5
6-May-02	444	1313	0.11	0.01	0.03	3.2	7.92	5.85	22.7
13-May-02	451	1348	0.27	0.01	0.04	2.93	7.87	6.01	24.2
17-May-02	455	1368	0.32	0.01	0.01	2.66	7.56	5.9	22.8
23-May-02	461	1398	0.25	0.25	0.01	2.49	7.63	6.28	24.9
30-May-02	468	1433	0.12	0.02	0.01	2.58	7.77	6.57	26.8

Metal Concentration after Second SRB Column (mg/L) - 1st
OPERATIONAL CONDITION

Date	Day	V.	SRB-2						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	1.37	0.03	0.03	0.54	0.2	0.06	0.25
30-Apr-01	73	20	1.66	0.02	0.02	0.24	0.33	0.02	0.07
4-May-01	77	40	0.01	0.01	0.01	0.11	0.7	0.02	0.01
7-May-01	80	55	0.15	0.01	0.01	0.12	0.61	0.02	0.02
10-May-01	83	70	0.16	0.01	0.01	0.18	0.54	0.02	0.04
14-May-01	87	90	0.39	0.01	0.01	0.07	0.56	0.02	0.01
17-May-01	90	105	0.43	0.01	0.01	0.2	0.62	0.02	0.02
21-May-01	94	125	0.64	0.01	0.02	0.12	0.63	0.02	0.01
24-May-01	97	140	0.01	0.01	0.03	0.32	0.67	0.04	0.16
28-May-01	101	160	0.01	0.01	0.01	0.1	0.7	0.02	0.16
31-May-01	104	175	0.01	0.01	0.01	0.18	0.7	0.02	0.06
4-Jun-01	108	195	0.01	0.01	0.01	0.2	0.71	0.02	0.08
7-Jun-01	111	210	0.01	0.01	0.02	0.2	0.81	0.02	0.13
11-Jun-01	115	230	0.01	0.01	0.01	0.2	0.81	0.02	0.18
14-Jun-01	118	245	0.01	0.01	0.01	0.22	0.7	0.02	0.12
18-Jun-01	122	265	0.01	0.01	0.01	0.2	0.91	0.02	0.12
21-Jun-01	125	280	0.01	0.05	0.05	0.81	1.4	0.22	1.8
2-Jul-01	136	335	0.01	0.01	0.02	0.5	2.75	0.02	0.2
5-Jul-01	139	350	0.01	0.01	0.01	0.23	5.06	0.02	0.09
9-Jul-01	143	370	0.01	0.01	0.02	0.23	8.82	0.02	0.22
12-Jul-01	146	385	0.24	0.01	0.02	0.65	17.8	0.02	0.1
16-Jul-01	150	405	0.37	0.01	0.02	0.25	28	0.02	0.28
19-Jul-01	153	420	0.62	0.01	0.01	0.32	30.8	0.02	2.18
26-Jul-01	160	455	0.6	0.01	0.02	0.31	37.9	0.02	0.34
30-Jul-01	164	475	0.53	0.01	0.01	0.4	45.9	0.02	0.29

Metal Concentration after Second SRB Column (mg/L) - 2nd
OPERATIONAL CONDITION

Date	Day	V.	SRB-2						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	0.01	0.01	0.01	0.8	48.6	0.02	0.22
9-Aug-01	174	500	0.01	0.01	0.01	0.39	50	0.02	0.17
13-Aug-01	178	510	0.01	0.01	0.01	0.48	53.6	0.02	0.91
16-Aug-01	181	518	0.01	0.01	0.01	0.58	54.2	0.02	0.15
20-Aug-01	185	528	0.16	0.01	0.01	0.39	50.7	0.02	0.15
20-Sep-01	216	605	0.01	0.01	0.01	1.84	69.1	0.02	0.01
26-Sep-01	222	620	0.91	0.06	0.18	3.83	54.7	0.16	1.11
4-Oct-01	230	640	0.11	0.01	0.01	5.55	41.9	0.02	0.09
8-Oct-01	234	650	0.59	0.02	0.07	8.33	41.1	0.09	0.61
12-Oct-01	238	660	0.01	0.01	0.01	0.73	40.3	0.02	0.01
15-Oct-01	241	668	0.01	0.01	0.01	9.62	41.1	0.02	0.01
19-Oct-01	245	678	0.01	0.01	0.01	15.8	40.2	0.02	0.04
22-Oct-01	248	685	0.01	0.01	0.01	21.6	38	0.02	0.02
26-Oct-01	252	695	0.02	0.01	0.01	15.2	40.1	0.02	0.05
30-Oct-01	256	705	0.21	0.01	0.01	20.1	36.3	0.02	0.09
2-Nov-01	259	713	0.48	0.01	0.01	3.92	34.5	0.02	0.01
9-Nov-01	266	730	0.01	0.01	0.01	3.69	29.6	0.07	0.25
18-Nov-01	275	753	0.01	0.01	0.01	29.7	35.2	0.02	0.06
24-Nov-01	281	768	0.01	0.01	0.01	28.3	34.3	0.02	0.07
5-Dec-01	292	795	0.01	0.01	0.01	35.3	36.8	0.02	0.06

Metal Concentration after Second SRB Column (mg/L) - 3rd
OPERATIONAL CONDITION

Date	Day	V.	SRB-2						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	0.52	0.01	0.01	39.5	41.7	0.03	0.09
24-Dec-01	311	843	0.02	0.01	0.03	32.6	35	0.03	0.24
28-Dec-01	315	853	0.24	0.01	0.04	5.79	14.7	0.04	0.17
5-Jan-02	323	873	0.16	0.01	0.05	10.9	13.3	0.09	0.38
10-Jan-02	328	885	0.95	0.03	0.09	12.6	15.7	0.12	0.45
16-Jan-02	334	900	0.79	0.01	0.03	11.5	15	0.04	0.1
18-Jan-02	336	905	0.76	0.01	0.02	12.2	14.8	0.06	0.17
22-Jan-02	340	915	0.85	0.01	0.03	10.7	14.4	0.06	0.17
30-Jan-02	348	935	0.26	0.01	0.01	6.33	13.8	0.03	0.08
4-Feb-02	353	948	0.12	0.05	0.06	12.9	15.3	0.19	0.88
7-Feb-02	356	955	0.01	0.01	0.02	9.92	14.9	0.15	0.42
13-Feb-02	362	970	0.06	0.01	0.01	11.9	15.3	0.04	0.09
20-Feb-02	369	988	0.01	0.01	0.02	8.27	14.5	0.06	0.22
25-Feb-02	374	1000	0.33	0.01	0.01	15.4	19.7	0.09	0.33
1-Mar-02	378	1010	0.01	0.01	0.01	21.1	21.5	0.06	0.12
7-Mar-02	384	1025	0.08	0.01	0.01	9.09	12.3	0.05	0.11
12-Mar-02	389	1038	0.08	0.01	0.01	9.03	12	0.06	0.16

Metal Concentration after Second SRB Column (mg/L) - 4th
OPERATIONAL CONDITION

Date	Day	V.	SRB-2						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	0.01	0.01	0.03	9.77	11.9	0.05	0.18
28-Mar-02	405	1118	0.01	0.01	0.02	9.38	11.5	0.04	0.13
2-Apr-02	410	1143	0.01	0.01	0.01	8.15	11.2	0.05	0.16
5-Apr-02	413	1158	0.01	0.01	0.01	10.3	11.3	0.04	0.14
11-Apr-02	419	1188	0.01	0.01	0.06	9.56	10.2	0.04	0.31
16-Apr-02	424	1213	0.01	0.01	0.02	8.08	9.95	0.02	0.16
24-Apr-02	432	1253	0.01	0.01	0.09	11.7	10.3	0.03	0.1
30-Apr-02	438	1283	0.01	0.01	0.05	10.7	11.3	0.05	0.15
6-May-02	444	1313	0.01	0.01	0.03	7.94	9.45	0.07	0.37
13-May-02	451	1348	0.01	0.01	0.01	7.31	8.87	0.08	0.31
17-May-02	455	1368	0.01	0.01	0.03	8.43	8.69	0.04	0.09
23-May-02	461	1398	0.02	0.14	0.02	5.21	7.67	0.04	0.1
30-May-02	468	1433	0.01	0.01	0.01	6.2	7.89	0.03	0.11

**Metal Concentration after ALD Column (mg/L) - 1st OPERATIONAL
CONDITION**

Date	Day	V.	ALD						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
27-Apr-01	70	5	1.16	0.01	0.01	0.07	0.13	0.02	0.02
30-Apr-01	73	20	1.48	0.01	0.01	0.08	0.31	0.02	0.02
4-May-01	77	40	0.01	0.01	0.01	0.08	0.67	0.02	0.01
7-May-01	80	55	0.08	0.01	0.01	0.13	0.59	0.02	0.03
10-May-01	83	70	0.22	0.01	0.01	0.07	0.54	0.02	0.01
14-May-01	87	90	0.53	0.01	0.01	0.05	0.54	0.02	0.01
17-May-01	90	105	0.63	0.01	0.01	0.13	0.58	0.02	0.01
21-May-01	94	125	0.68	0.01	0.01	0.24	0.6	0.02	0.08
24-May-01	97	140	0.01	0.01	0.01	0.08	0.57	0.02	0.01
28-May-01	101	160	0.01	0.01	0.01	0.08	0.6	0.02	0.01
31-May-01	104	175	0.01	0.01	0.01	0.08	0.64	0.02	0.01
4-Jun-01	108	195	0.01	0.01	0.01	0.1	0.7	0.02	0.01
7-Jun-01	111	210	0.01	0.01	0.01	0.1	0.69	0.02	0.01
11-Jun-01	115	230	0.01	0.01	0.01	0.13	0.78	0.02	0.01
14-Jun-01	118	245	0.01	0.01	0.01	0.07	0.78	0.02	0.01
18-Jun-01	122	265	0.01	0.01	0.01	0.14	0.88	0.02	0.01
21-Jun-01	125	280	0.01	0.01	0.01	0.15	1.05	0.02	0.02
2-Jul-01	136	335	0.01	0.01	0.02	0.26	2.65	0.04	0.26
5-Jul-01	139	350	0.01	0.01	0.02	0.22	5.15	0.02	0.02
9-Jul-01	143	370	0.11	0.01	0.01	0.17	9.09	0.02	0.04
12-Jul-01	146	385	0.36	0.01	0.01	0.26	16.8	0.02	0.03
16-Jul-01	150	405	0.58	0.01	0.01	0.28	26.5	0.02	0.01
19-Jul-01	153	420	0.67	0.01	0.01	0.28	29.7	0.02	5.87
26-Jul-01	160	455	0.56	0.01	0.01	0.32	36.9	0.02	0.07
30-Jul-01	164	475	0.54	0.01	0.02	0.37	44.6	0.02	0.12

**Metal Concentration after ALD Column (mg/L) - 2nd OPERATIONAL
CONDITION**

Date	Day	V.	ALD						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
6-Aug-01	171	493	0.01	0.01	0.01	0.44	46.8	0.02	0.41
9-Aug-01	174	500	0.01	0.01	0.01	0.58	51.3	0.02	0.14
13-Aug-01	178	510	0.01	0.01	0.01	0.4	52.5	0.02	0.4
16-Aug-01	181	518	0.01	0.01	0.01	0.43	52.2	0.02	0.05
20-Aug-01	185	528	0.01	0.01	0.01	0.34	48.9	0.02	0.05
20-Sep-01	216	605	0.01	0.01	0.01	3.85	69.4	0.02	0.04
26-Sep-01	222	620	0.88	0.06	0.17	3.17	54.3	0.16	1.07
4-Oct-01	230	640	0.61	0.01	0.01	3.54	41.6	0.02	0.13
8-Oct-01	234	650	0.05	0.01	0.01	6.39	41.5	0.02	0.09
12-Oct-01	238	660	0.01	0.01	0.01	9.24	39.7	0.02	0.04
15-Oct-01	241	668	0.01	0.01	0.01	11.6	39.5	0.02	0.01
19-Oct-01	245	678	0.01	0.01	0.01	11.2	40	0.02	0.03
22-Oct-01	248	685	0.01	0.01	0.01	13.5	39.6	0.02	0.02
26-Oct-01	252	695	0.02	0.01	0.01	17	37.4	0.02	0.14
30-Oct-01	256	705	0.25	0.01	0.01	17.7	36.3	0.02	0.05
2-Nov-01	259	713	0.44	0.01	0.01	1.42	33.5	0.02	0.01
9-Nov-01	266	730	0.01	0.01	0.01	6.18	30.8	0.02	0.04
18-Nov-01	275	753	0.01	0.01	0.01	26.3	34.6	0.02	0.1
24-Nov-01	281	768	0.01	0.01	0.01	24.1	35.1	0.02	0.04
5-Dec-01	292	795	0.01	0.02	0.03	38.9	37.2	0.08	0.37

Metal Concentration after ALD Column (mg/L) - 3rd OPERATIONAL CONDITION

Date	Day	V.	ALD						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
19-Dec-01	306	830	0.35	0.01	0.01	37.1	41.6	0.02	0.06
24-Dec-01	311	843	0.01	0.01	0.02	30.9	35.3	0.02	0.12
28-Dec-01	315	853	0.01	0.01	0.01	8.04	15.2	0.03	0.07
5-Jan-02	323	873	0.25	0.01	0.02	9.09	13	0.05	0.31
10-Jan-02	328	885	0.81	0.01	0.02	11.5	15.7	0.04	0.14
16-Jan-02	334	900	0.78	0.01	0.04	10.7	14.9	0.03	0.07
18-Jan-02	336	905	0.83	0.01	0.02	11.9	14.7	0.03	0.08
22-Jan-02	340	915	0.84	0.01	0.02	9.9	14.4	0.03	0.08
30-Jan-02	348	935	0.01	0.01	0.01	8.25	13.4	0.02	0.04
4-Feb-02	353	948	0.01	0.01	0.02	7.64	14.3	0.06	0.21
7-Feb-02	356	955	0.01	0.01	0.03	5.79	14.2	0.03	0.1
13-Feb-02	362	970	0.04	0.01	0.01	9.42	14.9	0.02	0.06
20-Feb-02	369	988	0.01	0.01	0.02	6.66	14.2	0.03	0.08
25-Feb-02	374	1000	0.33	0.01	0.02	7	18.8	0.05	0.13
1-Mar-02	378	1010	0.01	0.01	0.01	16.4	21.4	0.03	0.04
7-Mar-02	384	1025	0.08	0.01	0.01	8.7	12.3	0.03	0.07
12-Mar-02	389	1038	0.11	0.01	0.01	8.11	12.1	0.02	0.08

Metal Concentration after ALD Column (mg/L) - 4th OPERATIONAL CONDITION

Date	Day	V.	ALD						
		Loading							
		(L)	Al	Cd	Cu	Fe	Mn	Ni	Zn
25-Mar-02	402	1103	0.01	0.01	0.04	8.93	12	11.9	0.14
28-Mar-02	405	1118	0.01	0.01	0.03	7.64	11.3	0.03	0.13
2-Apr-02	410	1143	0.01	0.01	0.03	8.13	11	0.04	0.11
5-Apr-02	413	1158	0.01	0.01	0.01	8.65	11.2	0.02	0.06
11-Apr-02	419	1188	0.01	0.01	0.03	6.99	10.4	0.02	0.34
16-Apr-02	424	1213	0.01	0.01	0.03	8.44	9.87	0.02	0.11
24-Apr-02	432	1253	0.01	0.01	0.1	7.98	9.73	0.02	0.04
30-Apr-02	438	1283	0.01	0.01	0.04	8.7	11.2	0.04	0.16
6-May-02	444	1313	0.01	0.01	0.02	8.12	9.5	0.03	0.13
13-May-02	451	1348	0.01	0.01	0.02	6.78	8.57	0.05	0.17
17-May-02	455	1368	0.01	0.01	0.06	7.87	8.45	0.02	0.17
23-May-02	461	1398	0.02	0.14	0.01	7.24	7.69	0.09	0.3
30-May-02	468	1433	0.07	0.01	0.03	9.95	7.8	0.05	0.21

APPENDIX D

Cumulative Metal Mass after Each Component

Cumulative Metal Mass after Each Component

Parameters		Metals						
		Al (mg)	Cd (mg)	Cu (mg)	Fe (mg)	Mn (mg)	Ni (mg)	Zn (mg)
1st Condition	Load	42944	3253	9180	90425	11966	9260	46615
	Oxidation	43342	3275	9232	87975	12143	9367	47098
	Sediment	42793	3261	9126	86764	12005	9298	46629
	Peat	32839	3005	5961	28633	11767	8557	43335
	SRB1	293	6	16	18096	17057	36	155
	SRB2	118	6	8	134	4134	13	123
	ALD	128	5	6	83	3998	11	114
2nd Condition	Load	72357	5548	15287	151368	20357	15535	77570
	Oxidation	72758	5594	15263	143645	20330	15688	78232
	Sediment	72292	5582	15175	141369	20482	15652	77969
	Peat	54550	5404	10291	39499	20132	14785	74373
	SRB1	488	12	24	37712	27301	2690	3712
	SRB2	150	10	14	3468	19491	23	176
	ALD	163	9	12	3468	19293	21	166
3rd Condition	Load	77655	5992	16461	163152	22011	16791	83492
	Oxidation	77683	6043	16385	153171	21992	16945	84163
	Sediment	78584	6130	16570	152959	22512	17199	85441
	Peat	60869	6067	12116	41221	22624	16607	83641
	SRB1	585	16	35	43132	30535	4412	8674
	SRB2	224	13	20	7370	24299	39	231
	ALD	222	11	16	6923	24049	28	191
4th Condition	Load	86297	6701	18335	182395	24636	18798	94011
	Oxidation	86053	6757	18229	170556	24622	18948	94678
	Sediment	87129	6858	18456	169951	25161	19246	96165
	Peat	68098	6812	13773	41366	25341	18679	94558
	SRB1	651	29	53	44751	33532	6496	16705
	SRB2	228	21	33	10818	28274	57	303
	ALD	229	19	31	10156	27983	43	255

APPENDIX E

Effluent Concentration during the Steady State Period after Each System Component

DO Concentration during the Steady State Period

Redox Potential during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD

pH during the Steady State Period

Acidity during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD

Alkalinity during the Steady State Period

Sulphate Concentration during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD

Al Concentration during the Steady State Period

Cd Concentration during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD

Cu Concentration during the Steady State Period

Fe Concentration during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD

Mn Concentration during the Steady State Period

Ni Concentration during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD

Zn Concentration during the Steady State Period

In the X axis, numbers represent the AMD concentrations after each system component, including:

1) Influent, 2) Oxidation, 3) Sedimentation, 4) Peat Biofilter, 5) First SRB, 6) Second SRB, 7) ALD