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Investigation of leachate quality from the Trail Road Landfill

Ziad Bataineh
Ryerson University

INVESTIGATION OF LEACHATE QUALITY FROM THE TRAIL ROAD LANDFILL

by

Ziad Bataineh
Bachelors of Civil Engineering
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ABSTRACT

Leachate data for the Trail Road sanitary landfill were obtained for stages three (3) and four (4) of the landfill, located in the City of Ottawa, for the period of 10 years from 1996 to 2005. Data included several parameters such as pH, BOD, COD, Ca, Fe, Cl, SO_4, some selected heavy metals such as: Cu, Zn, Pb, and other parameters like Toluene and Vinyl Chloride

Analysis was performed to these data using Microsoft Excel analysis tools. Various graphical and statistical techniques such as Correlation, regression, and contaminant specific analysis were used to characterize leachate from the Trail Road Landfill. The data collected were fitted with trend lines to represent temporal variations. Pearson Product Moment correlation analysis as a multivariate statistical method was later used for identifying linear relationships between the quality of leachate with respect to the water infiltration to the waste, calculated from monthly precipitation data.

Results from this research yielded noteworthy temporal variations of many parameters in leachate over the study period. Also, the effect of many factors like the net water infiltrating waste from precipitation and the methanogenesis of leachate on the behaviour of leachate parameters was noticeable.

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Thank God our Lord, the most Gracious and the most Merciful, for giving me the will and strength to complete this work.

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INTRODUCTION

1.1 Background

Sanitary landfills are still the principal practice for municipal, commercial, institutional and industrial waste disposal. Other methods such as incineration and composting of waste remain as competing technologies in modern world for safe and reliable waste management. Several factors govern the selection of the technology. Environmental and economical considerations are the utmost governing factors in the selection of waste disposal technology. In Canada, landfill disposal of waste is controlled by different regulations that permit waste disposal as long as they constitute no threats to human health and environment surrounding the disposal facility.

Economical considerations and capital cost play imperative rule in the selection of a technology for waste disposal and continue to keep landfills as the most desired disposal technology for different types of waste. Technologies like incineration and composting are believed to cost even more than regular sanitary landfills since they still produce waste that eventually will require landfilling (El-Fadel et al. 2002).

The need for controlled and engineered landfills is the focus of today's research and studies to create a clean and reliable technology. Generation of contaminated leachate and gas from modern landfills are the main concern for both human health and environment. Modern landfills are now designed with gas and leachate collection systems to reduce any risk that might impose on both humans and environment.

1.2 Design and Management of the Trail Road Landfill

The Trail Road landfill is located east of Moodie Drive, north of the Trail Road in the City of Ottawa. The landfill was opened in 1980 and serve as an extension of the former Nepean landfill which operated approximately between 1960 to 1980 and was capped with a low-permeability cover in 1993. The landfill is owned and operated by the City of Ottawa and currently serving as a municipal sanitary landfill accepting non-hazardous waste including residential waste, construction, commercial, institutional, and light industrial waste. A list of materials accepted at the landfill is shown in Table 2.1 in Chapter 2.

The Trail Road Landfill is comprised of four stages. Stages 1 and 2 were fully operational at the inception of the Trail facility and then closed and capped with a low permeability cover in 1988 and 1991, respectively. These initial stages were designed as natural attenuation fill areas and thus do not have engineered bottom liners. Similarly, no bottom liner exists at the Nepean Landfill, where waste was placed directly into a former sand and gravel pit.

Conversely, Stages 3 and 4 of the Trail Road Landfill are contained with clay and geomembrane bottom liner and a leachate collection system. Stage 3 has been closed and completed with an interim cover at the end of 2002. Stage 4 is currently in operation (from 2003 to present). The Trail Road facility also includes a household special waste depot and leaf and yard waste composting facility as shown in Figure 1.1.

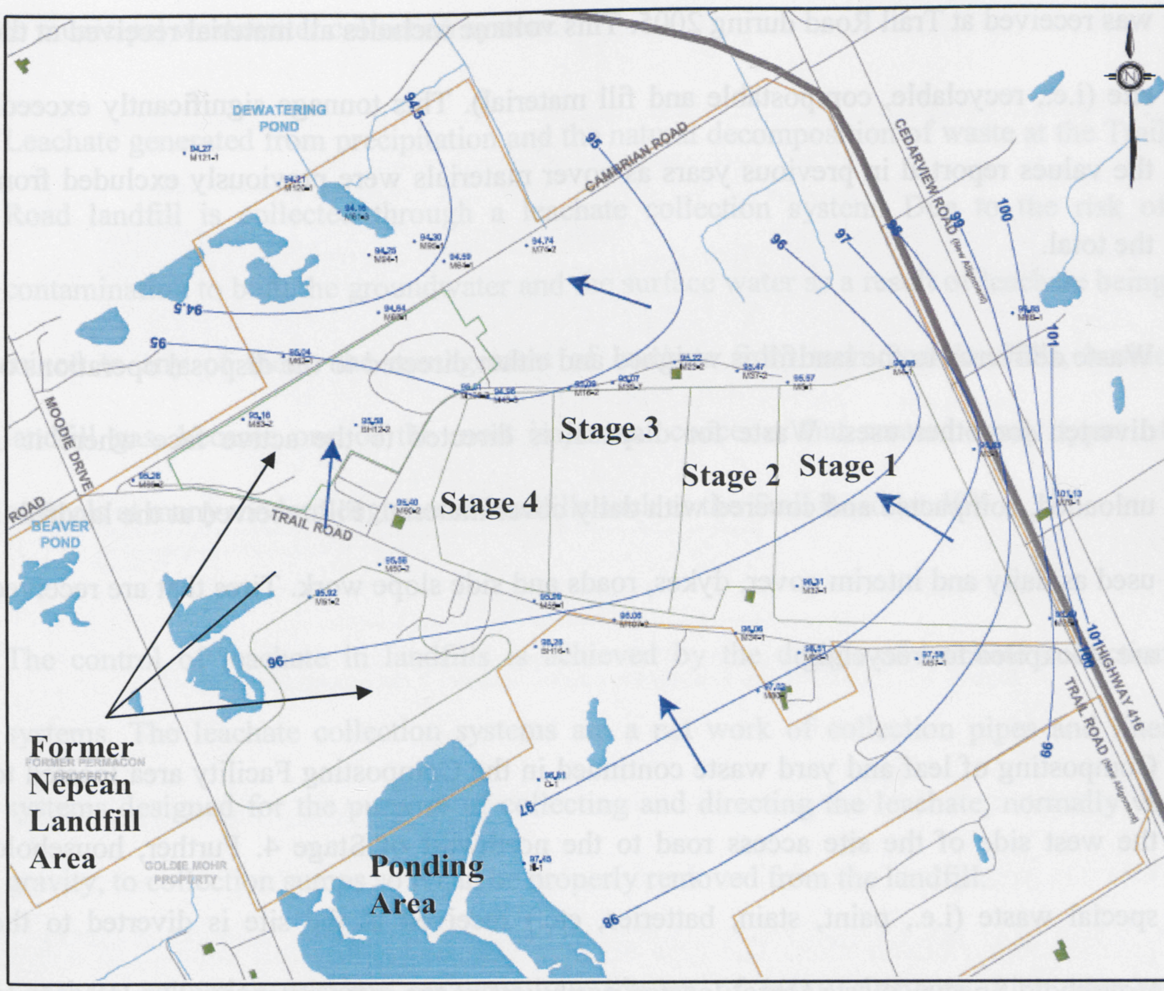

Figure 1.1: The Trail Road Landfill, Source: 2004 Annual Monitoring Report, Dillon Consulting

1.2.1 Trail Road Landfill Operations

In 2005, the majority of waste placement activities at the Trail Road landfill were concentrated in Stage 4. Waste placement in Stage 4 was originally commenced in July of 1999 during which other stages, stage 2 and 3, were active.

Landfilling operations for the Trail Road landfill were performed in accordance with the Trail Road Development and Operations Report, February 1990 submitted to the Ministry of Environment with the Certificate of Approval application. Most of the waste received in 2005 was placed predominantly in Stage 4. Approximately 350,000 tonnes of material was received at Trail Road during 2005. This volume includes all material received at the site (i.e., recyclable, compostable and fill material). This tonnage significantly exceeds the values reported in previous years as cover materials were previously excluded from the total.

Waste delivered to the landfill is weighed and either directed to the disposal operations or diverted for other uses. Waste for disposal is directed to the active face where it is unloaded, compacted and covered with daily cover material. Fill received at the landfill is used as daily and interim cover, dykes, roads and side slope work. Tires that are received are stockpiled for recycling.

Composting of leaf and yard waste continued in the Composting Facility area located to the west side of the site access road to the northwest of Stage 4. Further, household special waste (i.e., paint, stain, batteries, etc.) received at the site is diverted to the Household Special Waste Depot located northwest of the main entrance. The Household Special Waste Depot annual report is provided so local residents can directly deliver their household waste to the landfill.

1.2.2 Management of Leachate at the Trail Road Landfill

The management of leachate is the key to the elimination of the potential for a landfill to pollute underground aquifers. A number of alternatives have been used in modern landfills to manage the leachate collected from the landfill including: (1) leachate recycling, (2) leachate evaporation, (3) treatment followed by disposal, and (4) discharge to municipal wastewater collection system.

Leachate generated from precipitation and the natural decomposition of waste at the Trail Road landfill is collected through a leachate collection system. Due to the risk of contamination to both the groundwater and the surface water as a result of leachate being mixed to any of them, the management of leachate from municipal landfills, beside landfill gas, became one of the most important concerns that created many types of controls at many modern engineered landfills such as the Trail Road landfill.

The control of leachate in landfills is achieved by the design of leachate collection systems. The leachate collection systems are a net work of collection pipes and liner systems designed for the purpose of collecting and directing the leachate, normally via gravity, to collection sumps so it can be properly removed from the landfill.

Leachate collection systems are usually made up of many elements. First element includes the selection of the liner system to be used in the landfill. Second element comprises the development of a suitable grading plan for the landfill that includes the placement of the leachate collection and drainage channels and pipe lines for the removal of leachate. Third and final element is the layout and the design of the leachate removal collection and holding facilities.

The liner system used at the Trail Road landfill comprises of both single composite liner consisting of 600mm of compacted clay liner and an 80mil High Density Polyethylene (HDPE) geomembrane and perforated leachate collection pipes placed in the drainage layer which is usually made up of clear crushed stone or gravel to allow for collection of leachate. The liner system and perforated pipes are similar to the one shown in Figure 1.2 below.

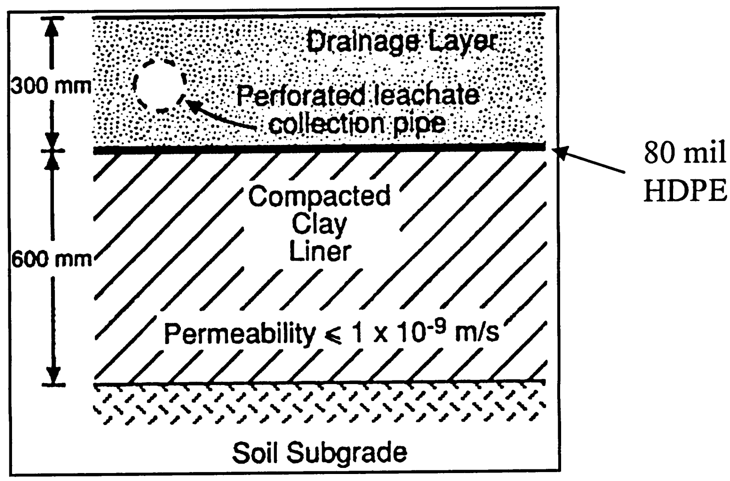

Figure 1.2: Typical Clay Composite Liner, Source: Tchobanoglous et al. 1993.

Liner systems at the Trail Road landfill are used to minimize the infiltration of leachate into the subsurface soils below the buried waste thus eliminating the potential for groundwater contamination. The type of liner system selected will depend, to a large extent, on the topography and the environmental conditions of the landfill site. In areas where groundwater is not encountered, a single liner can be considered enough (Tchobanoglous et al. 1993). Geological conditions for the Trail Road landfill, Annual Monitoring and Operation Report, Dillon Consulting, 2004, reveals shallow aquifer conditions at most areas within the landfill. The liner system is placed above the shallow aquifer to prevent any leachate intrusion to the groundwater below.

The perforated leachate collection pipes at the Trail Road landfill are placed at a slope vary between 2% all the way to 12% depending on the topography and the waste placement at the site. The waste landfilled at the Trail Road landfill is usually placed on the top of the drainage layer and compacted to different thicknesses similar to the one shown in Figure 1.3 below.

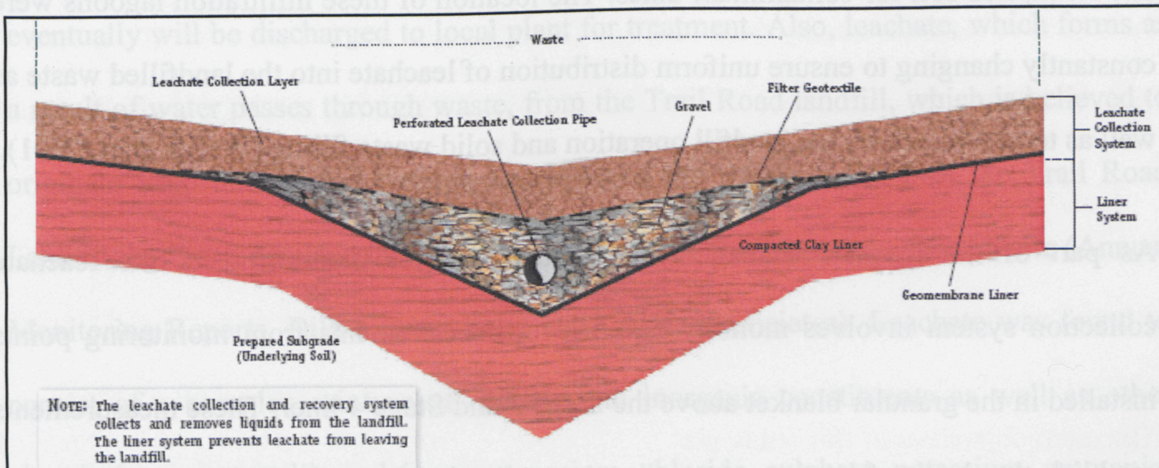

Figure 1.3: Typical Leachate Collection System, Source: Waste Management Website

1.2.2.1 Leachate Recirculation

Leachate is collected from the lined portions of the landfill (Stages 3 and 4) by means of a gravity drainage system beneath the waste material. The drains lead to a collector header that pumps the liquid to a collector manhole. From the collector manhole, a portion of the leachate is recirculated to Stage 4 and the remainder is trucked to the Robert O. Pickard Environmental Centre (ROPEC) for treatment.

Leachate recirculation was carried out at the Trail Road landfill, originally at Stage 3 and continued for the current active Stage 4, to enhance organic biodegradation and to reduce the contaminating life span of the landfill site (Warith et al. 2001). In addition to all that, leachate was also recirculated to defer the leachate treatment and handling for a period of time until better characterization of the leachate was determined. The leachate was withdrawn from the leachate collection system and was pumped back into filtration lagoons. The infiltration lagoons were constructed using a combination of waste and on-site stockpiled soil for contaminant dikes. The location of these infiltration lagoons were constantly changing to ensure uniform distribution of leachate into the landfilled waste as well as to accommodate the landfill operation and solid waste filling (Warith et al. 2001).

As part of the leachate management program, annual monitoring of the leachate collection system involves monthly liquid level measurements from monitoring points installed in the granular blanket above the Stage 3 and Stage 4 liner. These measurements establish the depth of leachate mounding immediately above the liner. These monitors have been installed along the north edge of Stages 3 and 4 (referred to as manholes) and across the centre line of Stage 3 (referred to as cleanouts).

There has been no significant leachate mounding occurring based on the monitoring measurements for manholes. In 2005, the leachate mound was typically only 0.1 to 0.5 m above the liner, consistent with measurements collected in previous years.

1.2.2.2 Leachate Sampling

Leachate samples from the leachate collection system are obtained from the leachate pump stations. Samples are collected daily and quarterly for analysis of a standard suite of parameters including volatile organic priority pollutants, semi-annually for dioxins and furans and once per year for analysis of pesticide compounds and PCBs in accordance with the Trail Road Leachate Discharge Agreement with the City's Sewer Use Program

1.3 Quality of Leachate at the Trail Road Landfill

Quality of leachate from the Trail Road landfill is very important since most of leachate eventually will be discharged to local plant for treatment. Also, leachate, which forms as a result of water passes through waste, from the Trail Road landfill, which is believed to originate from the unlined Nepean Landfill and the stages 1 and 2 of the Trail Road Landfill, has been detected in the groundwater below and around the landfill site (Annual Monitoring Reports, Dillon Consulting, and Golder Associates). Leachate was found to consist of a complex mixture of organic and inorganic constituents as well as other chemical parameters like calcium, magnesium, chloride, sulphate, potassium, ammonia, other nitrogen compounds, dissolved organic carbon, phenols and iron.

Composition of the Leachate in many landfills is generally affected by different factors like:

- The type of waste material put into the landfill
- Landfill conditions include the pH, temperature, moisture, age and climate
- Characteristics of precipitation entering the landfill
- Type of operational procedures at the landfill (Recirculation of leachate back to the landfill, shredding of waste…etc)

The effect of rainfall on the quality of leachate will be introduced and discussed in details in the body of this thesis.

1.4 Objectives

While there are a lot of studies that have been done to report both temporal and spatial variations of leachate quality from landfills (Morris, et al. 2003, Tatsi et al. 2002, Statom et al. 2004, Warith et al. 2001, El-Fadel et al. 2002, Kjeldsen et al. 2002, Kouzeli-Katsiri et al. 1999), it has not been fully investigated due to the variety and abundance of factors, such as waste composition and landfill operation, that affect the forecast of the quality of leachate.

The main objectives of this study are:

1- To investigate the quality of leachate from the Trail Road landfill using leachate data obtained from different operation and monitoring reports for the landfill in previous and recent years;
2- To examine the temporal variations (i.e. the concentration of contaminant over time) for some parameters (both organic and inorganic) in leachate;
3- Attempt to define any possible correlation (using Pearson Moment Type) between selected leachate quality parameters with respect to other factors that might affect the temporal behaviour of the leachate (methanogenesis, high pH, and water infiltrating waste from precipitation).

Following the investigation in this report, the results will be presented and evaluated in conjunction with different studies and investigation that are presented in the literature.

1. 5 Research Methodology

The approach employed in this research to achieve the above stated objectives comprises the following steps:

1. Review the theory and current studies that relate to the quality of leachate from municipal landfills;
2. Identify the factors that generally impact the quality of leachate ;
3. Utilize commercial software (Microsoft Excel) tools to analyze the recorded data for leachate from 1996 to 2005 and to establish remarks concerning behavior of leachate with respect to time and rainfall;
4. Develop a comprehensive approach that is capable of defining the overall quality of leachate from the Trail Road landfill;
5. Provide the readers with an appealing, easy to understand graphical representation of the temporal variation of leachate pollutants over the time period from 1996 to 2005.

1. 6 Thesis Organization

Chapter 2 presents a literature review of research and investigations related to the behavior of solid waste decomposition and quality of leachate from municipal landfills. Chapter 3 describes the data collection and statistical tools used for the analysis of data. Chapter 4 presents the implementation stage of different statistical tools used to analyze the data. Results are presented and discussed in this chapter. Comparison of the results to other studies and field investigation are also made in this chapter. Chapter 5 is the thesis conclusion and recommendations for future research.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Current database for landfill leachates in Canada are not geographically specific; rarely acknowledge the impact of site specific parameters such as age, water balance, composition of waste received, and landfill operations and management on the quality of water leaching out from waste. Analysis of data from lined landfills, like the Trail Road Landfill in Ottawa, was needed to provide useful information that can be used for the design and management of the landfill leachates. The specific objectives of this study, therefore, were to acquire leachate data from the Trail Road Municipal Solid Waste (MSW) landfill (from 1996 to 2005) and analyze these data in an effort to characterize the quality of the Trail Road landfill leachate.

Quality of leachate from municipal landfills is affected by the stabilization of waste. Stabilization of waste proceeds in five chronological and divergent phases (Tchobanoglous et al. 1993). The rate and characteristics of leachate produced and biogas generated from a landfill vary from one phase to another and reflect the microbially mediated processes taking place inside the landfill. The progress toward final stabilization of landfill solid waste is subject to the physical, chemical, and biological factors within the landfill environment, the age and characteristics of landfilled waste, the operational and management controls applied, as well as the site-specific external conditions. Movement through the phases is reflected by significant changes in leachate and gas quality. Non conservative constituents of leachate (primarily organic in nature) tend to decompose and stabilize with time, whereas conservative constituents will remain long after waste stabilization occurs. Conservative constituents include various heavy metals, ammonia, chloride, and sulfide. Metals often are precipitated within the landfill and are infrequently found at high concentrations in leachate, with the exception of iron.

Analysis of leachate from unlined landfills can be unrepresentative on the quality of leachate. Unlined landfills (like former Nepean Landfill, Ottawa and Stages 1 and 2 at the Trail Road Landfill) can produce leachates with much less contaminant concentration. This can be attributed mainly to dilution that occurred from groundwater. Unfortunately, because of the variability in leachate quality, prediction of leachate characteristics as a function of time has been quite difficult. General trends in quality are possible, however these ranges are still large and prediction of the point in time at which each phase begins and ends is not possible as of yet. Current research in landfill management, such as the use of leachate recirculation and other operational procedures like waste baling and shredding, may make it possible to control waste decomposition and consequently make leachate characteristics more predictable. Numerous field investigations and studies (Warith et al. 2001 and El- Fadel et al. 2002, Morris et al. 2003, Katsiri et al. 1999, Kjeldsen, 2002, Mehta et al. 2002, Durmusoglu et al. 2005, Frascari, et al. 2004, Jensen, et al. 1999, Akesson et al. 1997, and Robinson, 2005) reported multiple investigations and long term monitoring for leachate quality from different landfills.

2.2 General

This chapter provides a literature review on the quality of leachate from sanitary landfills based on different pilot scale and field scale studies and investigations. The understanding and the prediction of long-term trends of leachate quality (during landfill operation and after closure) is of great importance in order to evaluate the type of the treatment facility, to assess the potential for contamination of ground and surface waters and an indicator of the type of degradation processes that are occurring in the landfill and consequently of the degree of stabilization achieved, Frascari et al. 2004.

The quality of leachate is mainly defined by the concentration of different contaminants generated as a result from the different chemical, physical and biological processes that take place in the landfill as a result of water leaching out through waste (Kjeldsen, 2002). Leachate often forms when the moisture content within the waste exceeds the field capacity of the waste (Durmusoglu et al. 2005). Soluble organics and insoluble organics are encountered in the waste at the emplacement or simply formed as a result from different chemical, physical and biological processes within the landfill. In order to investigate and evaluate the quality of leachate from a MSW landfill, different factors that influence the formation, composition and behaviour of leachate must be analyzed and reported.

The safe and reliable long-term disposal of solid waste residues, which is defined as the waste that is not recycled, is considered an important component of the integrated solid waste management. Different elements are considered very essential in the planning, design and operation of landfills. These principals include: (1) landfill layout and design;

(2) landfill operation and management; (3) reactions occurring in the landfills; (4) management of landfill gases; (5) management of leachate; (6) environmental monitoring; and (7) landfill closure and post closure care (Tchobanoglous et al. 1993).

Sanitary landfills is still the primary and most economical method for the disposal of municipal refuse and many hazardous wastes despite the fact that it has lost its share in the group of solid waste management technologies to those of recycling, incineration and composting (Katsiri, et al. 1999). However, Economical considerations continue to keep landfills as the most attractive disposal route of municipal solid waste (MSW) while other alternatives like composting, incineration and recycling are considered volume reduction process since they still produce waste fractions (e.g. ashes, slag) which ultimately need to be landfilled (El-Fadel et al. 2002).

Typical waste composition of municipal solid waste at the sanitary landfills includes both organic (like food wastes and yard wastes) and inorganic (like dirt and ashes) components. This composition can play a great role in the reactions that occur in landfills. Biological reactions which represent the decomposition of the organic matter in the waste lead to the evolution of landfill gases and eventually liquids. These type of reactions proceeds aerobically for short period immediately after deposition of waste until the oxygen initially present is depleted. During the aerobic decomposition, CO_2 is the main gas produced. Once the oxygen is consumed, the decomposition becomes anaerobic and organic matter is converted to CO_2 and CH_4, and trace amounts of ammonia and hydrogen sulphide (Kjeldsen et al. 2002).

As a result of numerous investigations and studies (El- Fadel et al. 2002, Morris et al. 2003, Katsiri et al. 1999, Kjeldsen, 2002. Mehta et al. 2002, Durmusoglu et al. 2005, Frascari et al. 2004, Jensen et al. 1999 and Robinson, 2005), it was noted that different chemical reactions, like dissolution and suspension of landfill materials and biological conversion products in the liquid percolating through the waste, evaporation and vaporization of chemical compounds and water into the evolving landfill gas, sorption of volatile and semivolatile organic compounds into the landfill material, dehalogenation and decomposition of organic compounds, and oxidation-reduction reactions affecting metals and the solubility of metal salts, are not exactly defined and the interrelationships of these chemical reactions within the landfill are not well understood. The dissolution of biological conversion products and other compounds, particularly of organic compounds, into leachate is of special importance because these materials can be transported out of the landfill with the leachate. Other important chemical reactions include those between certain organic compounds and clay liners, which may alter the structure and permeability of the liner material.

Landfills can vary in terms of the waste they ultimately receive. Sanitary landfills, like the Trail Road landfill, are the type of landfills that receive municipal waste. This type of waste generally delivered as commingled MSW. In few cases, these types of landfills accept sludge from wastewater treatment plants and limited amounts on nonhazardous industrial waste. Municipal landfills use native soil as intermediate and final cover depending on the type of soil at the site.

The Trail Road sanitary landfill is designed (stages 3 and 4) with clay liner underneath deposited waste cells, leachate collection and gas collection or flaring systems. The landfill is designed to receive different types of wastes (as shown in Table 2.1) ranges from residential and commercial waste to compost materials.

Table 2.1: Materials Accepted at the Trail Road Landfill, Source: City of Ottawa, 2006

Waste Type Received at The Trail Road Landfill	
Residential waste	Contaminated soils
Commercial waste	Car Tires
Demolition & construction waste	Truck Tires
Commercial brush and yard waste	Farm Waste
Residential brush and yard waste	Compost – commercial rate
Large residential brush and sod	Compost – pick-up or legal load
Clean fill	Compost – car load
Asphalt	Cardboard
Mixed brush	Asbestos
Mattresses	Stumps

2.3 Leachate Quality

2.3.1 General

Leachate, which produced when rainwater infiltrates through the mass of the waste, is considered as a foreseeable consequence for waste disposal in landfills. In most landfills, leachate is composed of the liquid that has entered the landfills from external sources, such as surface drainage, precipitation, groundwater and water from underground springs and liquid produced from the decomposition of the waste itself. Since leachate may contain high concentrations of organic and inorganic materials including toxic compounds and heavy metals, the need to understand the formation mechanisms of leachate and the characterization of leachate quality has become very important in order to ensure proper leachate management that will minimize any potential adverse impacts that will result from waste disposal activities.

Within a landfill, and as water percolates through the landfill waste, contaminants are leached from the solid waste a complex sequence of physically, chemically, and biologically mediated events occurs. As a consequence of these processes, refuse is either degraded or transformed. Mechanisms of contaminant removal include leaching of naturally soluble materials, leaching of soluble biodegradation products of complex organic molecules, leaching of soluble products of chemical reaction, and washout of fines and colloids. The characteristics of the leachate produced are highly variable, depending on the composition of the solid waste, precipitation rate, site hydrology, compaction, cover design, waste age, sampling procedures, and interaction of leachate with the environment, and landfill design and operation (Reinhart et al.1998).

It is often considered difficult to forecast the quality of leachate from municipal landfills due to a variety of different influencing factors such as waste composition and landfill operations. Therefore, the quality of leachate from landfills can be generally analyzed from the temporal trends that certain pollutants, organic or inorganic, in leachate precede over a time period during or after the landfilling activity has taken place. Difficulty in predicting the quality of leachate arises also from the fact that different chemical and biological processes, like hydrolysis, adsorption, biodegradation, speciation, dissolution, dilution, ion exchange, re-dox, contact time, partitioning, precipitation, gas and heat generation and transport, take a place within the waste mass it self at emplacement in the landfill. A lot of soluble organic and inorganic compounds in leachate are a result to the aforementioned processes. E-Fadel et al. 2002 presented a model that predicted the concentration of contaminants in leachate as a function of leachate production. The model did not account for the internal dynamics of leachate such as slow and fast leaching effects on the solubilization of contaminants. This would be almost impossible to establish a model for predicting the quality of the leachate from either the production quantities or based on previous trends that certain contaminants preceded over time.

2.3.2 Factors Affecting Leachate Quality

It has been demonstrated that large variations in leachate quality exists for different landfills, but also at different locations at the same landfill (Tatsi et al. 2002). The variation in leachate quality can be attributed to many interacting factors such as the composition and depth of waste, the availability of moisture and oxygen, climate conditions, landfill design and operation, and waste age.

Durmusoglu et al. 2005, reported variable behaviour for different measured pollutants in leachate for time period of 30 months as a result of change in climate and age of the landfill. As a result, temporal variation trends presented in his study were not quite representative of the quality of the leachate from the landfill. Trends in leachate quality rather are more representative for longer time period of monitoring and analysis.

Frascari et al. 2004, for an intensive 10-years monitoring and analysis study, reported that the concentration of the chemical oxygen demand (COD) were found increasing in the landfill leachate during methanogenic conditions. Almost all field and laboratory scale studies reported decrease in the organic content, measured by the biochemical oxygen demand (BOD) and COD, for landfill during methanogenic phases (Durmusoglu et al. 2005, Warith et al. 2001).

2.3.2.1 Waste Composition

The composition of municipal waste plays a great role in the variation of leachate characteristics. The waste composition of refuse determines the extent of biological activity within the landfill. Municipal waste, food and garden wastes, and crop and animal residues contribute to the organic material in leachate. Inorganic constituents in leachate are often derived from ash wastes and construction and demolition debris. Field investigations found that increased quantities of paper in solid waste resulted in a decreased rate of waste decomposition. Lignin, the primary component of paper, is resistant to anaerobic decomposition which is the primary means of degradation in landfills. Due to the variability of solid waste, only general assumptions can be made about the relationship between waste composition and leachate quality (Reinhart et al. 1998).

Weber et al. 2002, found that most of pollutants in leachate are inorganic ions, mostly sulfate and calcium, for landfill cells that was filled with land-disposed residential construction waste. Akesson et al. 1997 reported different leachate quality, for test cells constructed and monitored for a period of five months, due to different biochemical conditions encountered at different locations within the waste mass.

2.3.2.2 Depth of Waste

Municipal landfills with deep fills usually produce leachate with higher contaminant concentration. It is obvious that deeper fills require more water to reach saturation, require a longer time for decomposition, and distribute the leached material over a longer period of time. Water entering the fill will travel down through the waste. As the water percolates through the landfill, it contacts the refuse and leaches chemicals from the waste. Deep landfills offer greater contact 4 times between the liquid and solid phases which increases leachate strength (Reinhart et al. 1998).

2.3.2.3 Moisture Availability

Water is the most significant factor influencing waste stabilization and leachate quality. Increase in moisture content within waste mass, either by rainfall addition or leachate recirculation, has been demonstrated repeatedly to have a stimulating effect on solid waste biodegradation (Katsiri et al. 1999). Higher moisture content within waste has been proven to improve leachate quality, especially in terms of organic strength, measured by BOD and COD. Numerous investigations, Chan et al. 2002, Warith et al. 2001, Mehta et al. 2002, Chanthikul et al. 2004, Al-Yousfi et al. 1998, reported improved leachate quality as a result to enhanced biodegradation conditions for waste as a result of leachate recirculation back to the waste.

Moisture within the landfill serves as a reactant in the hydrolysis reactions, transports nutrients and enzymes, dissolves metabolites, provides pH buffering, dilutes inhibitory compounds, exposes surface area to microbial attack, and controls microbial cell swelling (Reinhart et al. 1998). High moisture flow rates can flush soluble organics and microbial cells out of the landfill and in such cases microbial activity plays a lesser role in determining leachate quality. Also, high moisture application rates can remove the majority of waste contaminants early in the life of the fill. Under low flow rate conditions, anaerobic microbial activity is the significant factor governing leachate organic strength. The quantity of moisture is important because it directly affects stabilization rates within the landfill. Katsiri et al. 1999 noted the important role of moisture in supporting the biodegradation rate. It was found that an increase of moisture content increases the rate of biodegradation by a factor of 4-10. Relatively dry landfills (i.e. 20 to 40 percent water) have very slow stabilization rates because there is only a small quantity of moisture to support biological degradation. Recommended moisture content reported in the literature ranges from a minimum of 25 percent (wet basis) to optimum levels of 40 to 70 percent (Reinhart et al. 1998). Tatsi et al. 2002, reported that during wet season (spring/winter) rainwater percolating through refuse beds extracted, dissolved and solubilized several constituents producing larger volumes of diluted leachate. Also, during dry season (summer), the concentration of certain pollution parameters (like COD, BOD, TP, NH3, TKN, and Color) were higher.

2.3.2.4 Oxygen Availability

The quantity of free oxygen in a landfill utters to some extent the type of decomposition (i.e. anaerobic or aerobic). Aerobic decomposition occurs during initial placement of waste, also called initial adjustment, while oxygen is available (Kjeldsen et al. 2002). Aerobic degradation may continue to occur at, and just below, the surface of the fill. Chemicals released as a result of aerobic decomposition differ greatly from those produced during anaerobic degradation (Tchobanoglous et al. 1993, Kjeldsen et al. 2002). During aerobic decomposition, microorganisms degrade organic matter to CO_2, H_2O, and partially degraded residual organics, producing considerable heat. High concentrations of organic acids, ammonia, hydrogen, carbon dioxide, methane, and water are produced during anaerobic degradation. Phase changes occur in the fill as a result of reductions in the quantity of oxygen in the landfill. For instance, a transitional phase takes place when oxygen is depleted and anaerobic conditions develop. Representation of waste stabilization phases is discussed in details in the following sections.

2.3.2.5 Temperature

Landfill temperature has been shown to fluctuate with seasonal ambient temperature variations at landfill sites. Temperature affects bacterial growth and chemical reactions within the landfill. Each microorganism possesses an optimum growth temperature, and any deviation from that temperature will decrease growth due to enzyme deactivation and cell wall rupture. Different types of bacteria, hydrolytic and fermentative bacteria, acetogenic bacteria and methanogens bacteria exist at different temperature during waste decomposition (Kjeldsen et al. 2002).

Solubility of many salts (e.g. $Ca_3(PO_4)_2$ and NaCl) increases with temperature. However, a number of compounds in leachate, such as $CaCO_3$ and $CaSO_4$, show a decrease in solubility with increasing temperature (Reinhart et al. 1998).

2.3.2.6 Codisposal with WWTP Sludge

Codisposal of municipal solid waste and sludge from municipal wastewater treatment plants (WWTP) can have a significant impact on leachate quality. Codisposal can accelerate leachate formation and the rate of biological stabilization through the addition of moisture, microbes, and nutrients provided by the sludge. Sludge codisposal with municipal solid waste (or with leachate when employing recirculation) has been found to increase the rate of refuse decomposition rate by 10 times (El- Fadel et al. 2004). Also, the rate if solubilization of organic load was found to increase slightly by 1to 2 times. This is mainly attributed to the fact that sludge from WWTP controls pH (increases pH) in the neutral region and provides an aqueous environment that is more attractive to microorganisms. With the exception of a more acidic leachate with higher biochemical oxygen demand (BOD) concentrations, the chemical composition of leachate does not appear to change significantly with the codisposal of MSW and WWTP sludge (Reinhart et al. 1998).

2.3.2.7 Codisposal with Incineration Ash

Several solid residuals are usually produced by combustion facilities. These solids include bottom ash, fly ash and scrubber products. Bottom ash is completely or partially combusted material that passes through or is discharged from the combustion grate. Fly ash is the term for particulate matter captured from flue gas by the air pollution control system; it could include scrubber residue, bag house dust, and what is shaken from precipitators. Management of combustion solids is very important due to concerns with landfilling of the ash in municipal landfills. These concerns arise from the fact that ashes may leach out into the groundwater. Therefore, bottom ash and fly ash are often managed together and disposed in lined MSW landfills or in double-lined monofills devoted solely to the dispose of ash. Ash monofills are specially designed to reduce the ability of heavy metals to migrate from the ash into the environment. Monofills are often co-located with MSW incinerators or existing landfills to reduce transportation distances and siting difficulties.

Incinerator ash can contain concentrations of heavy metals such as lead, cadmium, mercury, arsenic, copper, and zinc, which originate from plastics, colored printing inks, batteries, certain rubber products, and hazardous waste from households and small industrial generators. Organic compounds such as dioxins and furans have also been detected in incinerator ash.

Many researches have reported that leachate from MSW landfills codisposing ash is similar to those ones accepting MSW only. In general, these researchers found no obvious difference between the metal content in leachates from codisposal sites and from municipal sites. This observation suggested that the neutral pH of MSW leachates does not promote leaching of metals from municipal waste combustion ashes. Also, there was no clear difference in the number or the detected levels of organic compounds between the leachates collected from the codisposal sites and the municipal disposal sites.

Leachates generated and collected from landfills codisposing ashes did not generate detectable semi-volatile compounds. Table 2.2 shows values of several conventional parameters in MSW leachates and in codisposal site leachates (Reinhart et al. 1998).

Table 2.2: Comparison of parameters in MSW and codisposal site leachates (Source: Reinhart et al. 1998)

Type of Leachate	pH, (Units)	Ammonia-N, (mg/l)	TOC*, (mg/l)
MSW Leachates	6.98 - 7.8	53 - 580	138 - 2680
Codisposal Site Leachates	7.2 - 7.3	160 - 410	436 - 1310

*** TOC: Refers to Total Organic Carbon**

2.3.2.8 Processing of Waste

Processing of MSW (like baling, shredding and composting) can have a great impact on the quality of leachate produced at a landfill. Robinson et al. 2005, reported that leachate from waste that have been mechanical sorted had a very high polluting potential. This is due to the fact that the fine organic fraction residues that result from the sorting process can produce a very strong leachate at high moisture content levels. On the other hand, biological pre-treatment of such waste, using composting, produced a leachate with much lower pollutant concentration. In other field studies, it was found that pre-sorting of waste, to remove bulky items, and shredding of waste before landfilling can improve the quality of leachate (El-Fadel et al. 2002). Baling of waste was found to reduce the moisture content due to the fact that portion of moisture is squeeze out during baling and the increased waste density. Advantage of waste baling comes from the idea of reducing the cumulative organic leaching due to longer biological treatment time inside the bale itself. It was also found that other contaminants, like heavy metals, are not affected by the biological treatment inside the bale. Baling of waste before filling was also found to produce large volumes of dilute leachate and waste required a longer period to stabilize compared to unbaled wastes. Baling can enhance leachate production by decreasing the elapsed time before leaching, reducing the moisture-retention ability of the waste, and by increasing the overall volume of the leachate produced.

Unlike Fadel, other researches reported that leachate from shredded waste is more highly contaminated during early stages of waste stabilization and less contaminated during later phases than leachate from unshredded waste (Reinhart et al. 1998). Research also agreed that leachate from shredded fills has significantly higher concentrations of pollutants than leachate from unshredded landfills. This higher strength leachate was attributed to increased surface area and, consequently, increased rates of biodegradation in shredded waste landfills. However, once the field capacity of the shredded or baled refuse is reached, the cumulative mass of pollutant removal per kg of solid waste will be the same regardless of the type of waste processing.

2.3.2.9 Age of Landfill

Quality of leachate is also influenced by the length of time which has elapsed since the waste was placed in the landfill. Generally, the concentration of many contaminants in leachate decreases with time as described in Table 2.3 below and in many literatures and research. Organic loading (described by BOD and COD) have been reported decreasing over time (Tatsi et al. 2002). Other parameters that describe the biodegradation process within the waste, like pH levels, generally increase towards the alkaline values when the waste is older. This can be considered as an indication of more stabilized waste.

Table 2.3: Typical composition of leachate for new and old landfills (Source: G.Tchobanoglous et al. 1993)

Constituent	New landfill (less than 2 years)	Mature landfill (greater than 10 years)
BOD_5	2,000-30,000	100-200
TOC	1,500-6,000	80-100
COD	3,000-60,000	100-500
TSS	200-2,000	100-400
Organic-N	10-800	80-120
Ammonia-N	10-800	20-40
Nitrate	5-40	5-10
Total-P	5-100	5-10
Ortho-P	4-80	4-8
Calcium	200-3,000	100-400
Magnesium	50-1,500	50-200
Potassium	200-1,000	50-400
Sodium	200-2,500	100-200
Chloride	200-3,000	100-400
Sulfate	50-1,000	20-50
Total Iron	50-1,200	20-200

2.3.2.10 Operation and Management Procedure

Operational and management procedures, such as waste pre-treatment and leachate recirculation, can also affect the formation of such a liquid. Examples on management measures that used are the recirculation of leachate collected back into the waste mass, composting, shredding and baling of waste. Different studies and investigations (El-Fadel et al. 2002, Warith et al. 2001, Reinhart et al. 1998) are described in the sections above.

2.4 Composition of Leachate

Leachate composition is primarily a function of the age of the landfill and the degree of waste stabilization. Leachate formation is usually an indication of increased moisture content which is associated with the biochemical processes in sanitary landfills. Formation and chemical composition of leachate is usually influenced by many factors. Climatic and hydrological factors like rainfall and initial moisture content can contribute widely to the formation of leachate in landfill. Composition of leachate mainly depends on the water percolating through solid waste undergoing decomposition. It is anticipated that both biological materials and chemical constituents will be leached into the solution. It is worth mentioning that composition of leachate, for example the one presented in Table 2.3 above, may vary for different landfills under different operational procedures and waste conditions. It is always considered almost impossible to set a standard values for contaminants in leachate from landfills.

2.4.1 Waste Stabilization

Decomposition of solid wastes in landfills is essentially due to microbial processes and therefore, the production of biogas and leachate are both directly related to the activity of microorganisms (Tatsi et al. 2002). Numerous landfill investigation studies have suggested that the stabilization of waste proceeds in five sequential and distinct phases (Kjeldsen et al. 2002, Reinhart et al. 1998, Tchobanoglous et al. 1993). The rate and characteristics of waste produced and leachate generated from a landfill vary from one phase to another and reflect the microbially mediated processes taking place inside the landfill. The rate of progress through these stages is dependent on the physical, chemical, and microbiological conditions developed within the landfill with time. The phases experienced by degrading wastes are shown in Figure 2.2 and described below

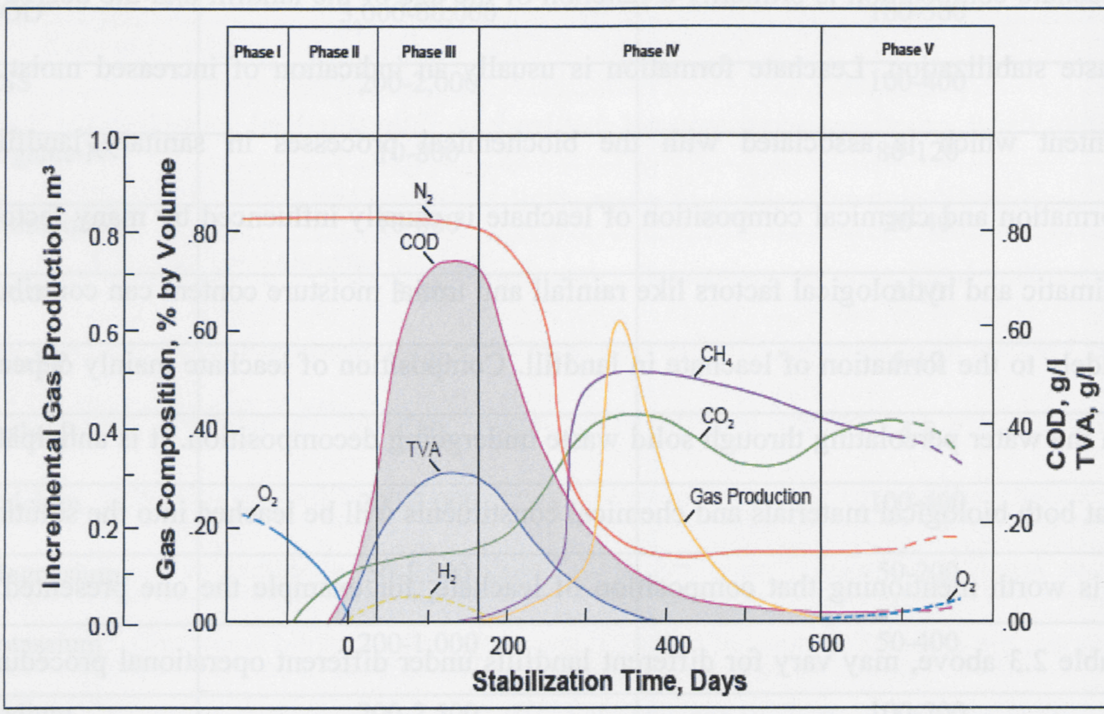

Figure 2.2: General trends in gas and leachate quality development. Figure is modified, Source: Kjeldsen et al. 2002.

2.4.1.1 Stage I: Initial Adjustment Phase

This phase starts once oxygen is depleted and it is characterized by the aerobic decomposition of the organic component in the MSW. This kind of decomposition occurs under aerobic conditions due to the air amounts trapped within the landfill. The principal source for aerobic and anaerobic microorganisms is the soil material used for daily and final cover. Other sources of microorganisms can be recycled leachate and digested sludge.

This phase is associated with initial placement of solid waste and accumulation of moisture within landfills. An acclimation period (or initial lag time) is observed until sufficient moisture develops and supports an active microbial community. Preliminary changes in environmental components occur in order to create favorable conditions for biochemical decomposition. During this first stage of decomposition, aerobic microorganisms degrade the organic materials to CO_2, H_2O, and partially degraded residual organics; producing considerable heat. Since only a finite quantity of oxygen is buried within the waste, and there are limitations on air transport into the landfill, aerobic decomposition is responsible for only a small portion of biodegradation within the landfill. Any leachate produced during this initial phase is most likely a result of moisture squeezed out of the waste during compaction and cell construction. Leachate formed during this phase is characterized by the entrainment of particulate matter, dissolution of highly soluble salts initially present in the landfill, and the presence of relatively small amounts of organic species from aerobic degradation

2.4.1.2 Stage II: Transition Phase

In the transition phase, the field capacity is often exceeded, and a transformation from an aerobic to an anaerobic environment occurs, as evidenced by the depletion of oxygen trapped within the landfill media. Once the available oxygen is depleted, anaerobic conditions begin to develop. This stage is called Transition Phase. During this stage, and as the landfill becomes anaerobic, nitrate and sulfate, which serve as electron acceptors, in the biological conversion reactions, are often reduced to nitrogen gas and hydrogen sulfide. As the waste undergoes anaerobic conditions, the microorganisms, which is responsible for the conversion of the organic material to methane and carbon dioxide, began the process of converting complex organics to organic acids. The pH of leachate formed starts to drop due to the presence of organic acids and the effect of the elevated concentration of carbon dioxide within the landfill. By the end of this phase, measurable concentrations of COD (480 to 18000 mg/L) and volatile organic acids (VOA) (100 to 3000 mg/L) can be detected in the leachate.

2.4.1.3 Stage III: Acid Phase

Third stage, Acid Phase, is characterized by accelerated production of organic acids and lesser amounts of hydrogen gas. Cellulose and hemicellulose are the major biodegradable constituents. Biodegradation of the biodegradable content is carried out by three types of bacteria: (1) hydrolytic and fermentative bacteria (2) acetogenic bacteria (3) methanogens bacteria.

During this phase, BOD and COD reported to be the highest and the BOD/COD is above 0.4 with pH is acidic (less than 7). The pH of the leachate will often drop to 5 or below due to presence of organic acids and high CO_2 concentration. This stage involves two-step process. First step involves the enzyme-mediated transformation (hydrolysis) of the higher molecular mass compounds (like lipids and proteins) into compounds suitable for use by microorganisms as source of energy and cell carbon. Second step in the process (acidogenesis) involves the microbial conversion of compounds resulting from step one into lower molecular mass intermediate compounds as typified by acetic acid

(CH3COOH) and small concentrations of fluvic and other more complex organic acids. The principal gas produced during this stage, Acid Phase, is CO_2. The microorganisms involved in this conversion, described collectively as nonmethanogenic, consists of facultative and obligate anaerobic bacteria and known as acidogens or acid formers.

Leachate produced during this stage is characterized by high BOD_5 and COD due to dissolution of organic acids in leachate. Also, due to low pH during this stage, many inorganic constituents, mainly heavy metals, will be solubilized. Many essential nutrients are expected to be removed from the system during this stage as well.

The decrease in pH values is usually accompanied by metal species mobilization resulting in a chemically aggressive leachate. Also, a decrease in the sorptive capacity of the refuse is seen during this phase. The high concentrations of BOD, COD and specific conductance occur during the acid formation phase. Viable biomass growth associated with the acid formers (acidogenic bacteria), and rapid consumption of substrate and nutrients are the predominant features of this phase.

2.4.1.4 Stage IV: Methane Fermentation

Transition from the acid formation phase to the methane fermentation phase occurs in the range of 4 to 10 years after waste placement and may continue over a period of several years. Methane fermentation stage occurs when measurable quantities of methane are produced.

During this phase, pH become neutralized and a second group of microorganisms, which known as methane formers (also known as methanogens), convert the acetic acid and hydrogen gas formed by the acid formers in the acid phase to methane (CH_4) and carbon dioxide (CO_2). These microorganisms are strict anaerobic and called methanogenic. For example, sulfate and nitrate are reduced to sulfides and ammonia, respectively. COD and BOD concentrations decline since much of these materials are converted to gas. The pH within the landfill during this stage usually rises to neutral values due to the fact that acids and hydrogen gas produced by acid formers have been converted to CH_4 and CO_2. pH of leachate during this stage will rise, controlled by bicarbonate buffering system, and the concentration of BOD_5 and COD will be reduced. With such higher pH values, fewer inorganic constituents can remain in solution and as a result, the concentration of heavy metals in leachate will be reduced. Heavy metals are removed by complexation and precipitation. Methanogens work relatively slowly but efficiently over many years decomposing any remaining degradable organics.

2.4.1.5 Stage V: Maturation Phase

Final stage, Maturation Phase, occurs after the readily available biodegradable organic material has been converted to CH_4 and CO_2. The rate of landfill gas generation diminishes significantly during this stage because of most of the available nutrients have been removed with the leachate during previous stages and the substrate that remain in landfill is slowly biodegradable. During maturation phase, leachate will often contain fluvic acids which are considered difficult to process further biologically.

2.5 Organic Compounds

Higher proportions of organic materials existing in fresh leachate are biodegradable and can be removed by biological processes. Parameters like BOD and COD are usually used to measure the organic content in leachate. Higher values of COD and BOD are expected for fresh leachate than older leachate (Tatsi et al. 2002, Kjeldsen et al. 2002, Statom et al. 2004, Katsiri et al. 1999). The rate of biodegradation of organic matter in the waste controls the overall stabilization process in the landfill (Katsiri et al. 1999). Most organic and inorganic contaminants follow the trend of decreasing concentration with increasing leachate age and stability (Tatsi et al. 2002). A decline in BOD concentrations can be considered as an indication for advanced state of degradation and can be attributed to a combination of reduction in organic contaminants available for leaching and the increased biodegradation of organic compounds. A constant decrease in COD is also expected as degradation of organic matter continues. As shown in Table 2.3, leachates from old refuse have lower BOD and COD values.

2.5.1 Organic Indicator Ratios

The biodegradability of leachate usually varies with time. Ratios like BOD_5/COD, etc. may reflect the composition of organic matter in leachate and they are, in turn, related to the age of leachate, and hence the degree of stabilization (Tatsi et al. 2002, Kjeldsen et al. 2002, Statom et al. 2004). Changes in the biodegradability can be measured by the BOD_5/COD ratio as BOD_5 is a direct measurement of the treatability of wastewater by the application of biological processes. Due to their biodegradability nature, organic compounds, which contributes to COD, decreases more rapidly than inorganic ones with increasing age of leachate. Therefore, the observed decrease in BOD_5/COD ratio represents a more complete oxidation of organic carbon, corresponding to higher (positive) oxidation conditions; hence, it becomes less readily available as an energy source for microbial growth. The main organic compounds in old leachate were reported as refractory, non-biodegradable, such as humic substances (Tatsi et al. 2002).

BOD_5/COD ratio tends to decrease as the age of leachate increases, varying from 0.5 for relatively fresh leachate to 0.2 for an older (more stabilized) one (Tatsi et al. 2002, Statom et al. 2004). For most cases, this ratio will be in the range of 0.5 or greater. Generally, ratios in the range of 0.4 to 0.6 are taken as an indication that organic matter in the leachate is readily biodegradable. The ratio of BOD_5/COD is expected to be in the range of 0.05 to 0.2 for mature more stable landfills. The BOD_5/COD ratio drops because leachate from mature landfills typically contains humic and fluvic acids, which are not readily biodegradable (Tchobanoglous et al. 1993). Overall, landfill stability can be classified based on the BOD/COD ratio. Table 2.4 below shows classification of landfill stabilization in relation to the BOD/COD ratio as published by the Solid Waste Management of North America (SWANA).

Table 2.4: Landfill Stability by SWANA. Source: El-Fadel, et al. 2002

BOD/COD ratio	**Significance**
> 0.5	Young, unstable landfill
0.1 – 0.5	Moderately stable landfill
< 0.1	Old stable landfill

The knowledge of the BOD_5/COD ratio helps in the design for leachate treatment system. For example, one would design a leachate treatment system for new landfills different from a system for old landfill. This also would implicate different financial strains on the choice for the best method for the management of leachate. Low BOD_5/COD ratio of old leachate indicates that the treatment of such leachate may require an extra chemically aided post treatment system or appropriate preliminary treatment.

Other ratios like COD/TOC are useful in studying the organic matter in leachate. The ratio of COD to TOC is considered valuable in studying the composition of organic matter in leachate. The COD to TOC ratio tends to decrease as the landfill ages. This ratio varied from 3.3 for a relatively young landfill to 1.16 for an old landfill (Reinhart et al. 1998). The maximum possible COD/TOC for several organic compounds is 4.0, and can be as low as 1.3 for organics containing carboxyl groups. A decrease in this ratio reflects a more oxidized state of the organic carbon which becomes less readily available as an energy source for microbial growth.

Other ratio, like VOA/TOC, is also important in defining the composition of the organic matter within the leachate. The ratio of the VOA as a percent of TOC represents the biodegradable portion of the organic matter. For example, knowing that the VOA's represent the readily biodegradable portion of the organic matter, a decrease in the ratio of carbon present in free volatile acids to TOC supports the decrease in BOD/COD ratio (Reinhart et al. 1998).

2.6 Inorganic Compounds

A range of heavy metals are commonly found in landfill leachates including zinc, copper, cadmium, lead, nickel, chromium, and mercury. These metals are either soluble components of the refuse or are products of physical processes such as corrosion and complexation (Kjeldsen et al. 2002). Heavy metal concentrations in leachate usually do not follow patterns of organic indicators such as COD or BOD, nutrients, or major ions. Heavy metal release is a function of characteristics of the leachate such as pH, flow rate, and the concentration of complexing agents (Reinhart et al. 1998). Metal solubility generally decreases with increasing pH (Abduli et al. 2003, Kjeldsen et al. 2002). In addition, the hydrogen ion concentration will indirectly influence metal solubility by its impact on such processes as the dissociation of an acid to yield a precipitant anion and reduction-oxidation reactions. With time, moderate to high molecular weight humic-like substances are formed from waste organic matter in a process similar to soil humification. These substances tend to form strong complexes with heavy metals. Tatsi et al. 2002 reported that fresh leachate showed higher degree of metal stabilization, due to lower pH values caused by the biological production of organic (fatty) acids. Also, as the landfill age increased, the consequent increase in pH values caused a certain decrease in metal solubility. Moreover, it was brought into being that the lower concentration of metals in stabilized leachates is mainly due to adsorption and precipitation reactions (by co-existing sulfide, carbonate or hydroxide anions), which, in turn, are enhanced by the gradual increase in oxidation reduction potential (ORP) values with increasing age of landfill (Jensen et al. 1999, Abduli et al. 2003).

Conductivity, measured in mS/cm, can be used as a gross indicator of the total concentration of dissolved inorganic matter or ions present in leachate. The primary metal species contributing to specific conductance are calcium, magnesium, sodium, and potassium. In general, specific conductance decreases with time as a result of the eventual depletion of soluble inorganic materials within the waste.

2.6 Leachate Management

Leachate management is now considered one of the greatest problems associated with the environmentally sound operation of sanitary landfills because these liquid wastes can cause a considerable pollution problem by contacting the surface soil, ground or surface waters. This problem is even worse in places where landfills operate without an appropriate impermeable bottom liner or an effective collection and subsequent treatment system (Tatsi et al. 2002). The management of leachate is the basic key to avoid any potential pollution threat to underground aquifers and as a result, the contamination of groundwater. Over the previous years, many methods have been used to manage the leachate collected at municipal landfills. These methods included leachate recycling, evaporation, treatment followed by disposal and discharge to municipal wastewater collection system.

Leachate Recycling is considered a very effective method in leachate treatment especially at the early stages of the landfill operation. It includes the collection of leachate throughout the landfill or at defined locations at the landfill, like collection lagoons constructed at the working face, and pumped it back into the waste. The benefits of leachate recycling back to the landfill have been reported to attenuate the concentration of BOD, COD, TDS, nutrients and heavy metals (Morris et al. 2003, Warith et al. 2001, Mehta et al. 2002). Katsiri et al. 1999 reported the decrease in organic mass, COD, due to the increase in the organic decomposition that resulted from the recirculation back to the waste. A decrease of 2 kgms of the organic mass was reported after 500 days of recirculation back to the waste. Warith et al. 2001, also reported a decrease in the organic load, measured as BOD and COD, due to the acceleration happened in the decomposition of organic waste after recirculation was implemented. Another advantage of leachate recycling is that recycling promotes the recovery of landfill gas that contains methane (CH4) as a result of the conversion of organics to CO2 and CH4. It always recommended that landfills using recirculation to have gas collection or flaring system since generation of gases is greater.

Leachate Evaporation is considered one of the simplest methods to manage leachate at municipal landfills. Evaporation of leachate can be achieved using lined leachate evaporation ponds during the warm months of summer. The only disadvantage of this method is the odour gases that may accumulate under the surface cover. Different methods, like the use of compost and or soil filter, can be used to manage odours from evaporation ponds. *Leachate Treatment* can be used as an alternative method whenever recirculation or evaporation is not implemented or is not feasible at the landfill. Different physical, chemical and biological treatment options, like using activated sludge, are used for treatment of leachate. Other management options include the direct discharge of leachate to municipal treatment plants. This option might require pre-treatment in case of strong leachate from landfill.

Chapter 3

METHODOLOGY

3.1 General

Leachate quality data for the Trail Road landfill were obtained from two sources. First source is the annual monitoring reports for the Trail Road landfill completed by different engineering consulting companies. These reports prepared to the Ontario Ministry of Environment as a requirement under the current Certificate of Approval for the landfill operation. Annual reports were completed by Golder Associates and Dillon Consulting. The second source is the City of Ottawa database. Data analysis was performed using Microsoft Excel tools. In addition, this research employed analysis of data obtained from previous studies and field investigations to provide comparison with the Trail Road landfill leachate quality data.

Meteorological data (total precipitation and average temperature), which represent the meteorological conditions of the landfill, were obtained from Environment Canada database for the City of Ottawa MacDonald-Carter International Airport Meteorological Station.

In order to calculate the net precipitation infiltration to the waste, evapotranspiration (total water loss from free water evaporation, plant transpiration and soil moisture evaporation) can be estimated using different methods such as, Blaney-Criddle, Penman-Monteth, Penman & Blaney (1956) and Thornthwaite and Mather (1957). For the purpose of this investigation, and due to the lack of many parameters required for the estimation of evapotranspiration, the Thornthwaite and Mather method was selected to calculate the evapotranspiration because the equation is based on the assumption that Potential Evapotranspiration was dependent only upon meteorological conditions (like monthly temperature) and ignored the effect of vegetative density and maturity.

Other methods, like Blaney-Criddle, Penman-Monteth, Penman & Blaney, require many information, such as Humidity, Vapour pressure, Heat Flux...etc, which are not available for the weather station that represents the weather conditions for the Trail Road landfill.

3.2 Data Selection and Organization

Data for leachate from the Trail Road landfill were acquired for the time period from 1996 to 2005. Data represent leachate quality obtained from both Stage3 and Stage 4 at the Trail Road landfill. Leachate data were selected for different organic and inorganic parameters.

The data selected for this research were primarily chosen for two reasons. First, some of the data selected have been previously investigated for similar landfill leachate in different research and studies. For example, Statom et al. 2004 and Morris et al. 2003 investigated wide range of organic and inorganic compounds in leachate from similar engineered sanitary landfills and concluded many findings. Although, their findings might have different interpretations, the general trend of analysis in this study was completed based on a multiple findings from variety of field and laboratory studies used for this work. Second reason for the parameters selection was to use the investigations between many factors (like water balance and pH) that many of the previous studies used in their investigation to establish the behaviour of many parameters in leachate over time. For example, Tatsi et al. 2002, investigated possible correlation between the parameters themselves and with water balance while Statom et al. 2004, established temporal linear trends for many of these parameters in an effort to establish direct linear relationship between parameters with respect to time and methanogenesis (high pH levels) so parameter behaviour in the future can be predicted. Table 3.1 below shows some of the studies that investigated similar parameters that used in this thesis.

Table 3.1: Example of Similar Landfills Studies

Reference Study	Similar Parameters Investigated	Landfill Type	Analysis Type
Tatsi et al. 2002	pH, BOD, COD, SO_4^{2-}, Cl^-, Fe, Cu, Zn, Pb	MSW Landfill	Pearson Moment Correlation, Water Balance, Leachate Recirculation Effect, Temporal Trends
Statom et al.2004	pH, BOD, COD, SO_4^{2-}, Cl^-, Fe, Cu, Zn, Pb, Ca	MSW Landfill	Temporal Trends, Water Balance, Pearson Moment Correlation
Morris et al. 2003	pH, BOD, COD, SO_4^{2-}, Cl^-, Fe, Cu, Zn, Pb, Ca, Toluene	MSW landfill, MSW Test Cells	Water Balance, Leachate Recirculation Effect, Temporal Trends
Warith et al. 2001	pH, BOD, COD, Cl-	Same Landfill	Water Balance, Temporal Trends
Kjeldsen et al. 2002	pH, BOD, COD, SO_4^{2-}, Cl^-, Fe, Cu, Zn, Pb, Ca, Toluene, Vinyl Chloride	Multiple MSW Landfills in USA	Pearson Moment Correlation, Water Balance, Leachate Recirculation Effect, Temporal Trends

Data were organized in four groups for the purpose of the thesis analysis. First group contains pollutants from dissolved organics matter, in which, indicators like Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) can be used to represent the strength of such pollutants in leachate. Second group contains inorganic macrocomponents like Calcium (Ca), Iron (Fe), Chloride (Cl), and Sulfates (SO_4). Third group contains heavy metals like Zinc (Zn), Lead (Pb), and Copper (Cu). Fourth group contains pollutants from all other compounds such as Toluene and micro-organic compounds like Vinyl Chloride.

Data for all the above-mentioned parameters were collected and organized in tables shown in Appendix A. Data were not reported and missing for some pollutants during specific time periods. Additional data for leachate pH were also acquired.

Meteorological data that describes the landfill conditions were acquired and organized in tables as shown in Appendix B. For these data, the amount of net water filtration (and runoff) was calculated. Amount of water evapotranspiration was calculated using Thornthwaite and Mather formula.

3.3 Chronological Data Analysis

In order to identify trends in all selected organic and inorganic parameters levels, a plot of each parameter versus age of the landfill was developed. Selected parameters within the leachate in the landfill were used to create the graphs.

Leachate parameters were investigated with respect to amount of net water infiltrated to the waste (assuming all precipitation infiltrated the waste and no runoff occurred) after evapotranspiration was subtracted from the amount of precipitation reported for each month.

Using the meteorological data available from Environment Canada for Ottawa McDonald-Carter International Airport Station and using the Thornthwaite and Mather formula (Alkaeed et al. 2006, Palmer et al. 1958), Potential Evapotranspiration, which is defined as the amount of water that could be evaporated and transpired if there was sufficient water available for the use of vegetation, was calculated using the following formula:

$$E = 1.6\left(\frac{10T}{I}\right)^{a}$$

Where:

E = monthly potential Evapotranspiration (cm).

T = mean monthly temperature (C).

I = a heat index for a given area which is the sum of 12 monthly index values i.

i is derived from mean monthly temperatures using the following formula:

$$i = \left(\frac{T}{5}\right)^{1.514}$$

a= an empirically derived exponent which is a function of I,

$$a = 6.75*10^{-7}I^{3} - 7.71*10^{-5}I^{2} + 1.79*10^{-2}I + 0.49$$

Calculated values for evapotranspiration and net water infiltration to the waste are presented in Appendix B.

Linear regression for leachate parameters was performed to identify temporal trends in all selected organic and inorganic parameters. Linear regression was selected in attempt to identify linear relationship for parameter concentration over time. The data were fitted into linear trend line and the regression value was estimated for each trend line. The regression value, R^2, is considered a measurement of the degree of how the selected linear trend fit the data. Linear trend is defined as in the following equation:

$$y = mx + b$$

Where, y = represents the concentration value for the parameter at any time

m = slope of the linear trend for the fitted data

b = is the intercept value for the parameter concentration (y-axis)

x = is the value for time (x-axis)

Correlation, Pearson Product Moment Correlation, which describes the degree of relationship between two variables, was performed to investigate possible linear relationships between different parameters with respect to two effects. First, the leachate parameters were investigated with respect to the effect of the net water infiltrated to the waste in attempt to define a direct relationship between the two. Secondly, the leachate parameters were investigated with respect to the effect of pH levels. Correlation results are presented in the results and discussion chapter.

The following equation describes the Pearson Product Moment Correlation used to estimate the correlation between any two parameters:

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

Where,

r = correlation value (-1.0 to 1.0)

n = expected number of x and y pairs

x = parameter 1

y = parameter 2

The correlation is 1 in the case of an increasing linear relationship, −1 in the case of a decreasing linear relationship, and some value in between in all other cases, indicating the degree of linear dependence between the variables. The closer the coefficient is to either −1 or 1, the stronger the correlation between the variables.

Results for correlation between all leachate parameters with respect to water infiltration and pH levels are presented in results and discussion chapter.

3.4 Data Comparison

Results from both the data collected and the analysis performed were compared to other studies and investigations reported in the literature. General trend in all organic and inorganic parameters concentration were compared to similar data from other studies. The results obtained for correlation and regression were also compared to other findings from studies.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

Presented in this chapter are the results of statistical and graphical analyses of the leachate from stages 3 and 4 in the Trail Road MSW landfill. Data for leachate are for 10 years period (from 1996 to 2005) are presented to identify temporal trends for different pollutants and to determine the effects of climate, region or location, and waste characteristics on quality of leachate. The leachate quality data presented in this section is part of data collected regularly at the Trail Road landfill as part of its monitoring program.

The results are presented in two scenarios. First scenario is to identify the temporal trends for the pollutants over the sampling period (1996-2005) and to identify long-term trends in the pollutant over time. The second scenario is to present the effect of rainfall infiltration on leachate quality parameters.

Due to the relatively high variability of the data and possible influence of other monitoring conditions, the evaluation of long-term temporal trends in pollutant concentration is investigated based on the slope of the linear regression between time (period from 1996 to 2005) and concentration of pollutant. The slope of the linear regression between pollutant concentration and time is used to define the trends as increasing, decreasing or stable.

4. 1.1 Dissolved Organic Matter:

A- Temporal variation:

Data for BOD and COD, which can be used as indicators of the organic content in leachate, are presented in Figures 4.1 and 4.2.

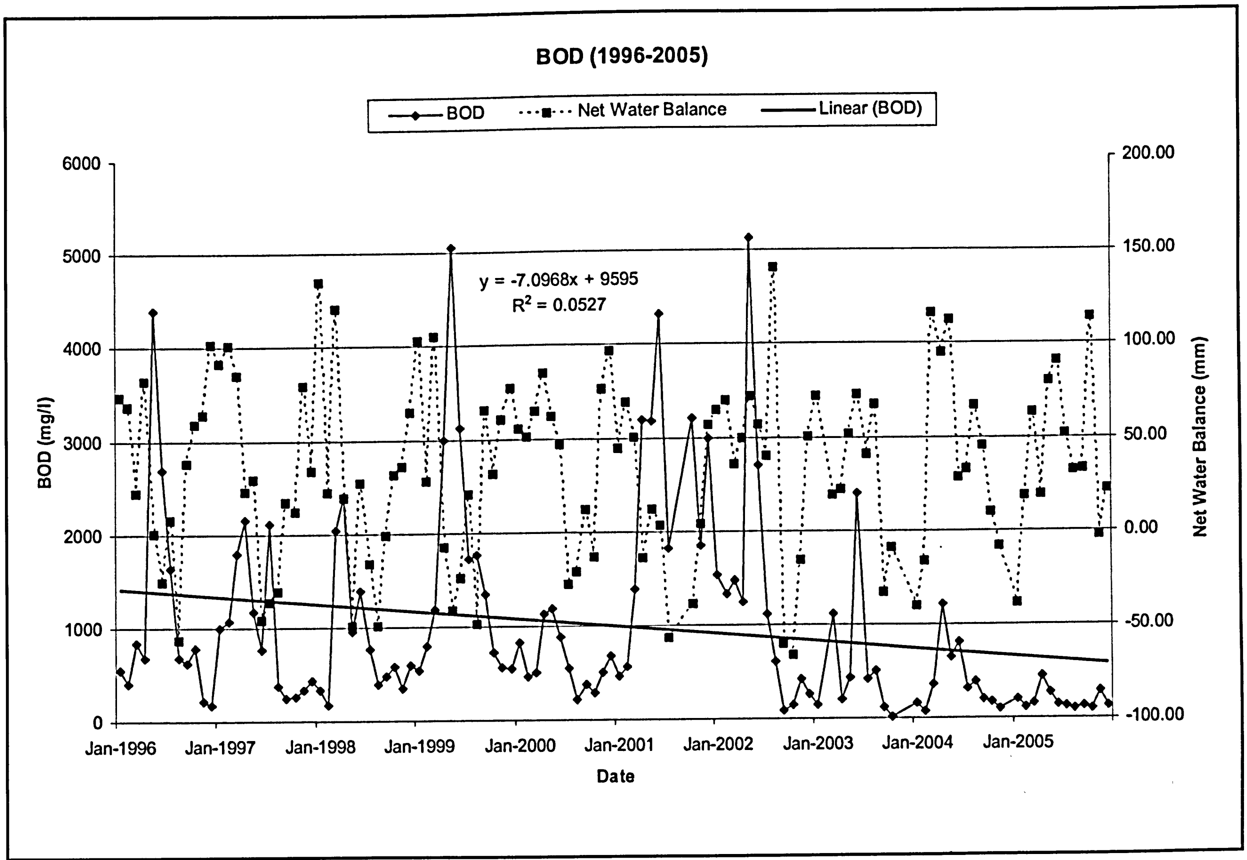

Figure 4.1: Changes in BOD Concentration over time

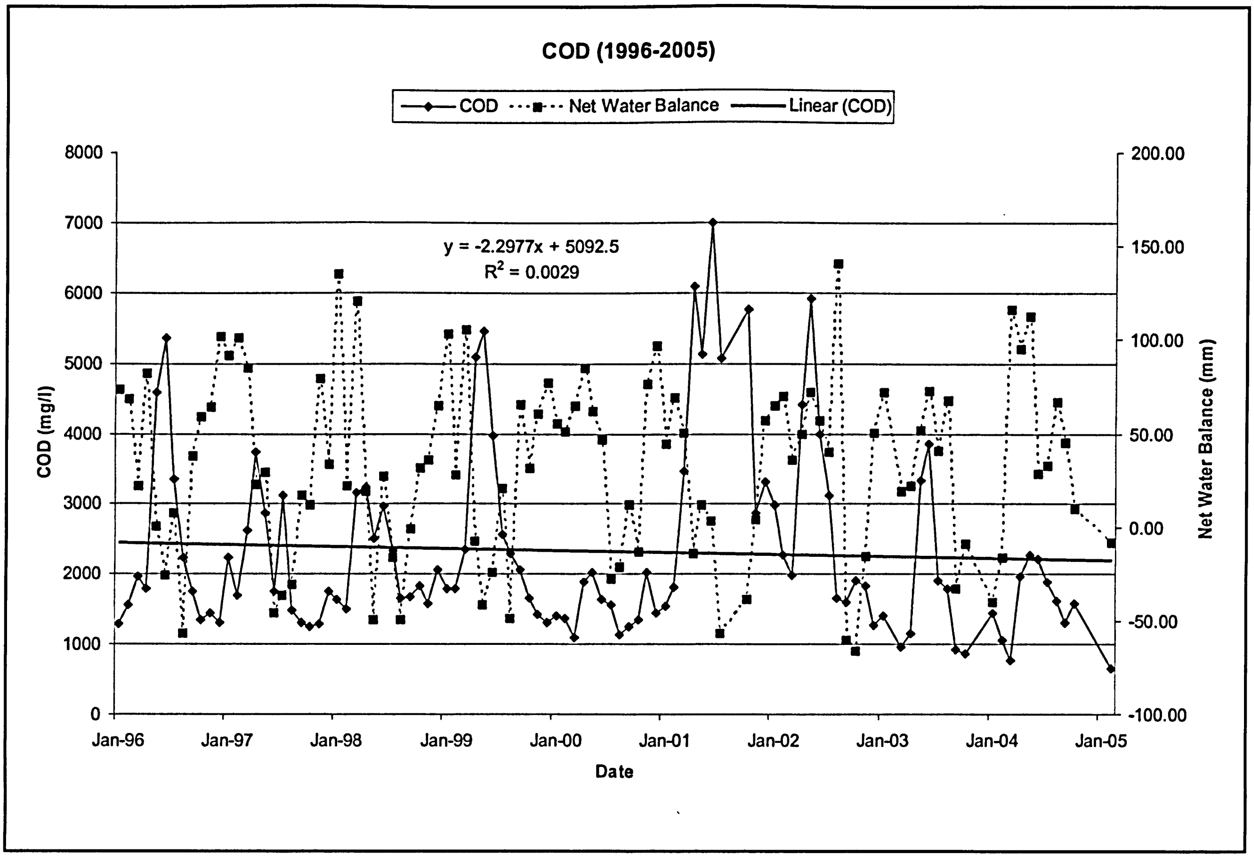

Figure 4.2: Changes in COD Concentration over time

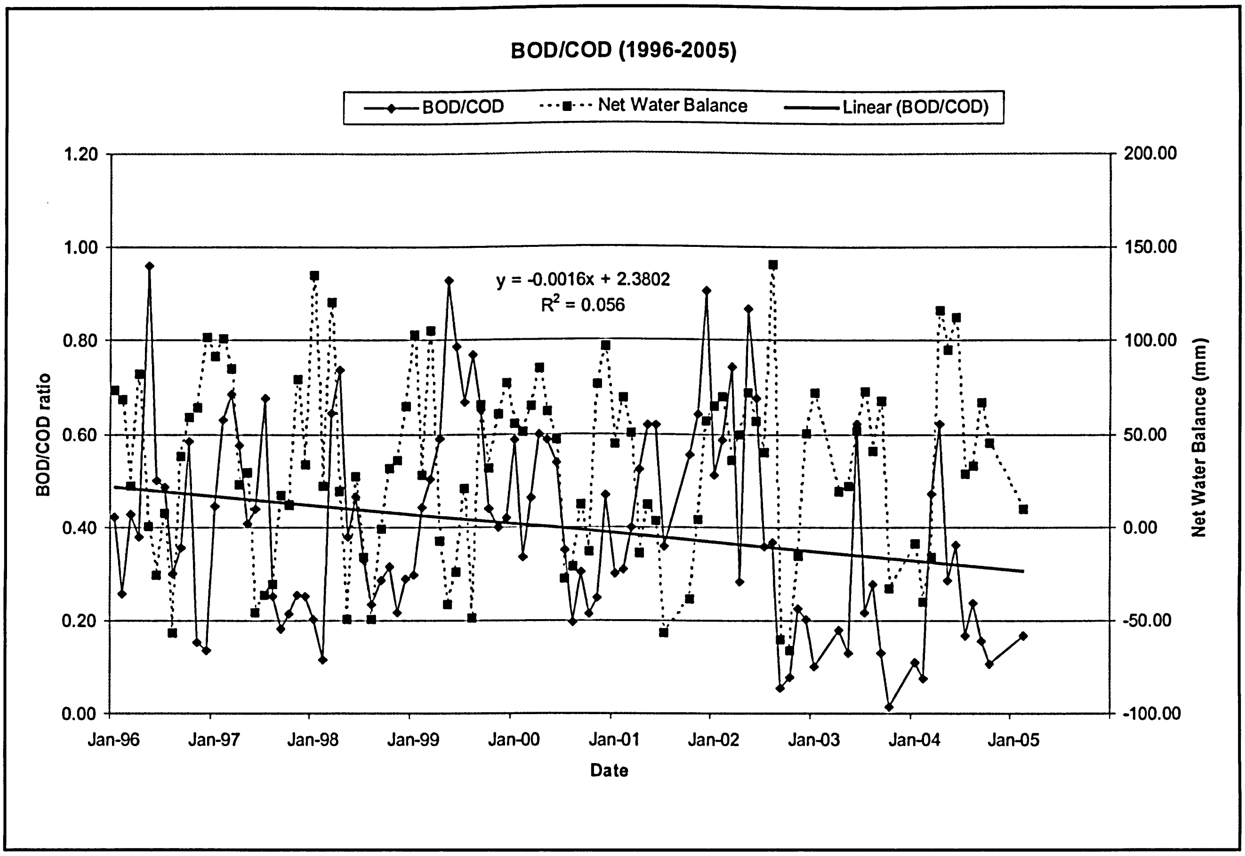

Figure 4.3: Changes in BOD/COD ratio over time

As can be noted in Figures 4.1, 4.2 and 4.3, a decreasing trend in BOD, COD and BOD/COD concentration/ ratio was noted over the past 10 years since leachate was first re-circulated back to stages 3 (1991 to 2003) and 4 (2003 to present) in the landfill. BOD concentration decreased from 1140mg/l (average for the year of 1996) to 183 mg/l (average of the year 2005). The end value (average BOD for the year 2005) of BOD, 183mg/l indicates that continuing addition of leachate back into the waste through recirculation, along with water infiltration into the waste, had enhanced the biodegradation process within the waste. The end value of BOD concentration in 2005, average of 183 mg/l, represents leachate in stable methanogenic conditions. Many data reported in literature from both field studies and laboratory scale studies (Christensen et al. 2000, Kjeldsen et al. 2002, Morris et al. 2003, Fadel et al. 2001, Warith et al. 2001, Statom et al. 2003, Tatsi and Zouboulis, 2002, Kouzeli et al. 1999, Akesson and Nilsson, 1997) reported similar values for BOD and COD concentrations during stable methanogenic conditions.

Similarly, a decreasing trend in COD concentration was noted over the 10 years period. COD concentration decreased from 2334mg/l (average for the year of 1996) to 660 mg/l (average of the year 2005). The decrease in BOD and COD also confirms the decrease in BOD/COD ratio. BOD/COD ratio decreased from 0.41 (average for the year of 1996) to 0.17 (average of the year 2005) over the 10 year's period. This indicates that the landfill is experiencing stable methanogenic conditions.

To define the long-term temporal trend in the BOD, COD and BOD/COD concentration/ratio, a linear regression between time (period from 1996 to 2005) and concentration of pollutant (measured by BOD and COD) was carried out for the data to establish a linear relationship between concentration of pollutant with respect to time. Although the regression value (R^2) was too low for BOD, COD and BOD/COD data (0.052, 0.003 and 0.056 respectively); indicating poor linear relationship, the slope of the linear regression is a negative value (inverse relationship) indicating that the BOD, COD and BOD/COD concentration/ratio generally decreasing over time. Since the R^2 value is very low and can not be considered reliable, a long-term future prediction of BOD, COD and BOD/COD concentration/ratio is quite not feasible for such R^2 value. The estimated BOD, COD and BOD/COD values for the trend line are far compared to the measured one.

B- Effect of Rainfall Infiltration:

The effect of rainfall was investigated to determine if a correlation between rainfall infiltrated the waste mass and organic content exist. A positive relationship between the net water balance, which represents the net rain water infiltrated into the waste, and the pollutant concentration is shown in Figures 4.1, 4.2 and 4.3. Correlation results for water infiltration with regard to BOD, COD and BOD/COD ratio were -0.129, -0.22 and -0.020 respectively. The correlation results all show an inverse relationship. This means that the higher the net water infiltrated to the waste, the lower the pollutant concentration. For example, for BOD, for the winter of the year 1996, the net water infiltrated was 101.8mm while the BOD concentration was 176mg/l. On the other hand, during spring of the year 1999, the BOD concentration was 5060mg/l while the net water infiltrated to the waste was negative value of -41.mm (no water infiltrated to waste). This explains the reduction in the biodegradable organic compounds and the increase of microbiological activities due to the increase in the solid-waste moisture content due to higher water infiltrated to waste in addition to leachate recirculation back to waste. The same relationship was also evident for COD concentration and BOD/COD ratio with net water infiltrated. For example, in Figure 4.2, for the spring of the year 1996, the net water infiltrated was negative -25.72mm (no water infiltrated to waste) while the COD concentration was 5366mg/l. On the other hand, during winter of 2004, the COD concentration was 765mg/l while the net water infiltrated to the waste was 67.2mm. In Figure 4.3, the correlation between BOD/COD ratio and water infiltration was also inverse one. For example, for the spring of the year 1996, the net water infiltrated was 0.56mm while the BOD/COD ratio was 0.96. On the other hand, during the fall of 2003, the BOD/COD ratio was below 0.1 (0.01) for a recorded water infiltration of 116.28 mm.

4. 1.2 Inorganic macrocomponents

A- Temporal Variation:

Data for Calcium (Ca), Iron (Fe), Chloride (Cl), and Sulfates (SO_4) are presented in Figures 4.4, 4.5, 4.6 and 4.7 below. Also, the pH conditions during the 10 years period are also presented. Due to neutral pH values during the time period, leachate from the Trail Road landfill can be considered under methanogenic conditions. The pH profile, shown on Figures 4.4 and 4.5, shows stable methanogenic conditions. pH values ranged from 6.28 to 8.11 with an average of 7.4 (near neutral) over the 10 years time period. Also, as shown in Figure 4.4, lower calcium concentrations are expected in the methanogenic phase due to higher pH values

Figure 4.4 shows that the concentration of calcium increased slightly over time. During the year 1996, the calcium concentration was approximately 179 mg/l while it reached a concentration of 222 mg/l during the year 2005. The increasing trend of calcium, evident by the linear regression slope of 0.095, in leachate from the Trail Road landfill is consistent with other field data. For example, R.A. Statom et al. 2004, reported increasing concentration of calcium for a lined MSW cell, in engineered landfill with leachate collection system, after 6 years of sampling.

Values range for calcium in the leachate, 18mg/l minimum to 310 mg/l maximum, provides that leachate from stages three and four is under stable methanogenic conditions. This is consistent with data from other literature. Kjeldsen et al. 2002, reported calcium range of 20-600 mg/l for calcium in leachate in stable methanogenic phase and 10-2500 mg/l in the acidic phase. Tatsi et al. 2002, reported calcium range of 3.8 to 138 mg/l for calcium in leachate during stable methanogenic conditions.

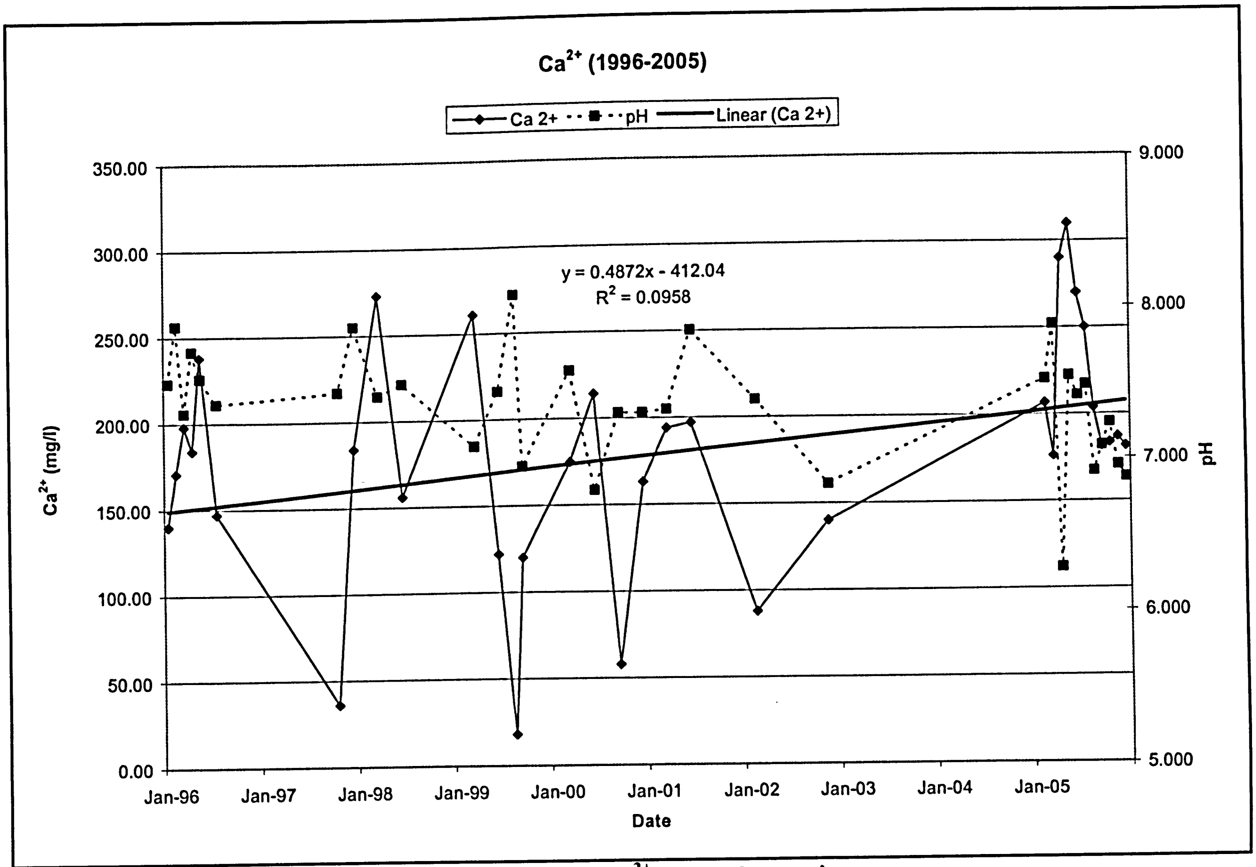

Figure 4.4: Changes in Ca^{2+} and pH over time

Figure 4.5 shows that the concentration of iron had slightly increase over the 10 years period. The iron concentration increased from approximately 7.8mg/l in 1996 to 9.4 mg/l in 2005. This increase is also supported by the findings from Statom et al. 2004 study. Christensen et al. 2001, reported iron concentration from 3 to 280 mg/l in their literature for multiple new landfills in the methanogenic phase. Tatsi et al. 2002, reported an average of 6.5 mg/l for iron in leachate during stable methanogenic conditions. In addition, since the leachate resembles methanogenic conditions, the iron concentrations are lower due to higher pH values (Kjeldsen et al. 2002). The pH during the period of 1996 to 2005 was neutral (around 7.4).

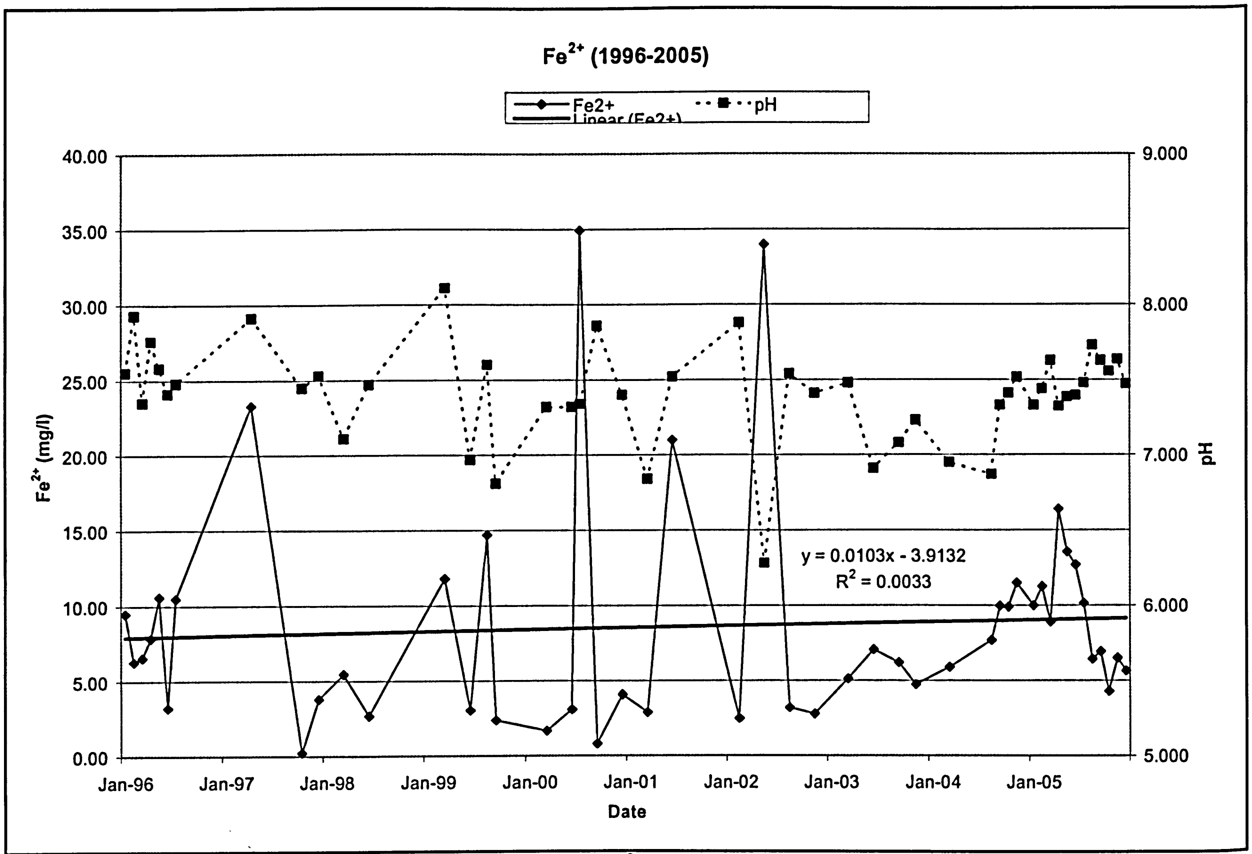

Figure 4.5: Changes in Fe^{2+} and pH over time

Figure 4.6 shows the relationship of sulfate over time. Although the sulfate concentration is slightly increasing during the 10 years period, evident by the regression slope, concentrations are considered lower since leachate exhibits methanogenic conditions. Sulfate concentration range, 0.7 to 287 mg/l, provides that leachate is under methanogenic conditions. This is consistent with data reported in other literature. Kjeldsen et al. 2002, reported sulfate concentration range of (10 to 420 mg/l) during methanogenic phase. Sulfate concentrations in methanogenic phase are expected to be lower due to microbial reduction of sulfate to sulfide. Lower concentration for calcium, iron and sulfate in the methanogenic phase is due to enhanced precipitation and sorption as a result of higher pH.

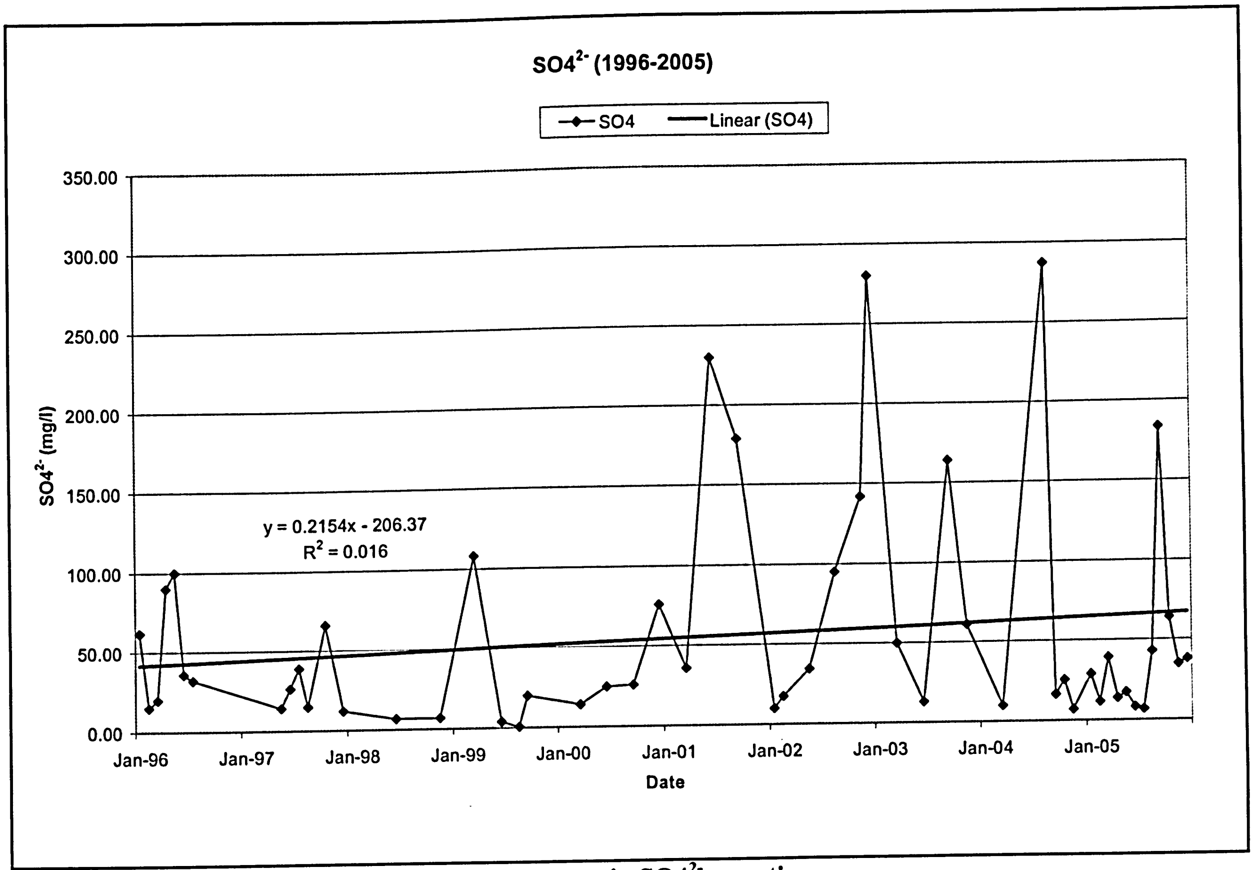

Figure 4.6: Changes in SO4^{2-} over time

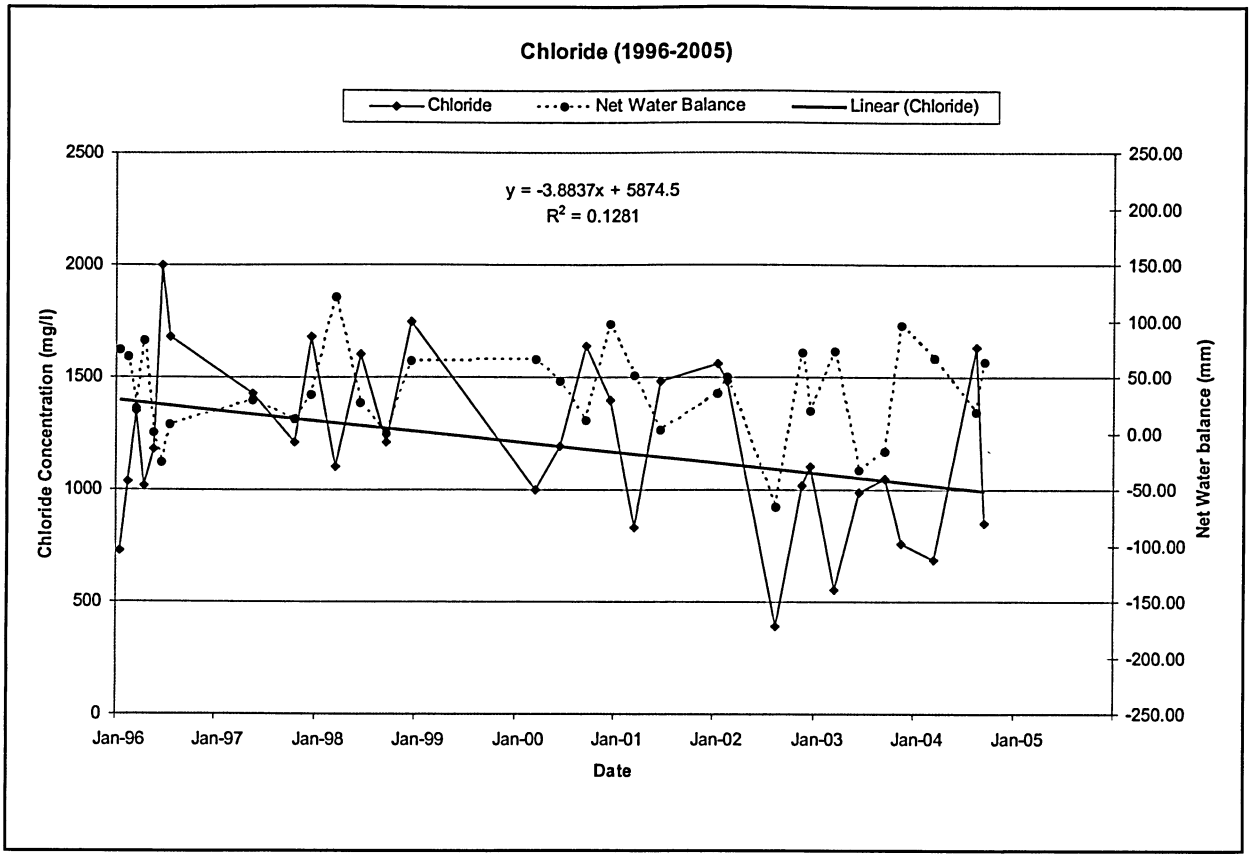

Figure 4.7: Changes in Cl^- over time

Figure 4.7 shows the concentration of chloride over time. Although the chloride concentration is slightly increasing during the 10 years period, evident by the regression slope, overall concentration is considered lower due to higher solubility of chloride from waste in water as a result from both leachate re-circulation back and water infiltrated to the waste. Chloride concentration values ranged from 390 to 2000 mg/l, with an average of 1205 mg/l, provides that leachate is under methanogenic conditions. This is consistent with other literature. Kjeldsen et al. 2002, reported, for different literature data, an average chloride concentration of 2120 mg/l during methanogenic phase.

Concentration values for chloride are expected to be lower at lower moisture content. Statom et al. reported chloride concentration average of approximately 850 mg/l for landfill cell without recirculation. Again, chloride concentrations in methanogenic phase are expected to be lower due to solubility of chloride from fresh waste. Chloride concentration for leachate from the Trail Road landfill showed an average of 1206 mg/l. this indicates that higher chloride was leached out from waste due to higher moisture content.

Since the R^2 values for the linear regression for calcium (0.095), iron (0.003), chloride (0.128) and sulfate (0.016) are very low, and can not be considered reliable, a long-term future prediction of calcium, iron, chloride and sulfate concentration is considered not feasible for such R^2 value.

B- Effect of Rainfall Infiltration:

Correlation analysis results performed for calcium shows that there is fairly a positive correlation (0.307) between calcium and water infiltrated. This concludes, for some extent, that higher calcium concentrations are expected for higher moisture content resulted from more water infiltrated through the waste. In our special case, recirculation of leachate back to the waste, with more water being infiltrated, higher moisture content is added to the waste. This will accelerate waste decomposition toward stable methanogenic conditions in which over all lower calcium concentrations (<310 mg/l) are expected at such conditions. This is consistent with literature reported by Kjeldsen et al. 2002, where calcium concentrations were lower for methanogenic conditions (average 60 mg/l).

Correlation results for iron with respect to water infiltration showed an inverse relation between water infiltrated and iron concentration (-0.144). Despite the fact that the regression value is somehow small, the overall iron concentration are smaller for methanogenic conditions due to higher pH values (average pH=7.4)

Correlation between chloride and net water balance revealed inverse relationship. Although the regression value was small (-0.188), chloride concentration is consistent with other literature that reported the lower chloride concentration during methanogenic phase.

As for the sulfate, the correlation between sulfate and water infiltration showed a very small inverse dependant relationship (correlation value of -0.040). This concludes that no direct relationship between sulfate and water infiltrated. Previous literatures (Kjeldsen et al. 2002) suggested that overall sulfate concentration is lower during methanogenic phase due to microbial reduction of sulfate to sulfide and over all washout by leaching.

4.1.3 Heavy Metals

A- Temporal Variation:

Data for Zinc (Zn), Lead (Pb), and Copper (Cu) are presented in Figures 4.8, 4.9 and 4.10. Figure 4.8 shows the concentration of zinc over time. The concentration of zinc decreased from approximately 1.1mg/l in 1996 to 0.46 mg/l in 2005, with an average of 0.56 mg/l, over time period of 10 years. Concentration values for zinc are consistent with other literature for leachate in stable methanogenic conditions. Christensen et al. 2001, reported average value of 0.6 mg/l for zinc concentration in leachate from 20 German landfills in methanogenic phases.

Tatsi et al. 2002, reported zinc concentration between 0.07 to 0.2 mg/l for methanogenic leachate with an average of 0.13 mg/l. Jensen et al. 1999, reported zinc concentration within the range of 0.085 to 5.310 mg/l for three (3) Danish landfills in operation.

Different processes, like sorption and precipitation, are the reason for low heavy metal concentration in methanogenic phase since such mechanisms prevent mobilization of metals (Kjeldsen et al. 2002, Durmusoglu et al. 2005, Jensen et al. 1999). Abduli et al. 2003, in a field study, reported lower heavy metals concentration during methanogenic phases due to high pH values. For the same study, a big portion of heavy metals was found to be adsorbed or precipitated to suspended solids during methanogenic phase. Durmusoglu et al. 2005, reported decrease in zinc concentration over 30 months monitoring of data for active landfill in Turkey.

The R^2 value for the linear regression for zinc concentration over time is very low (0.058) and can not be considered reliable. A long-term future prediction of zinc concentration is considered not feasible for such R^2 value. The estimated zinc values for the trend line are far compared to the measured one.

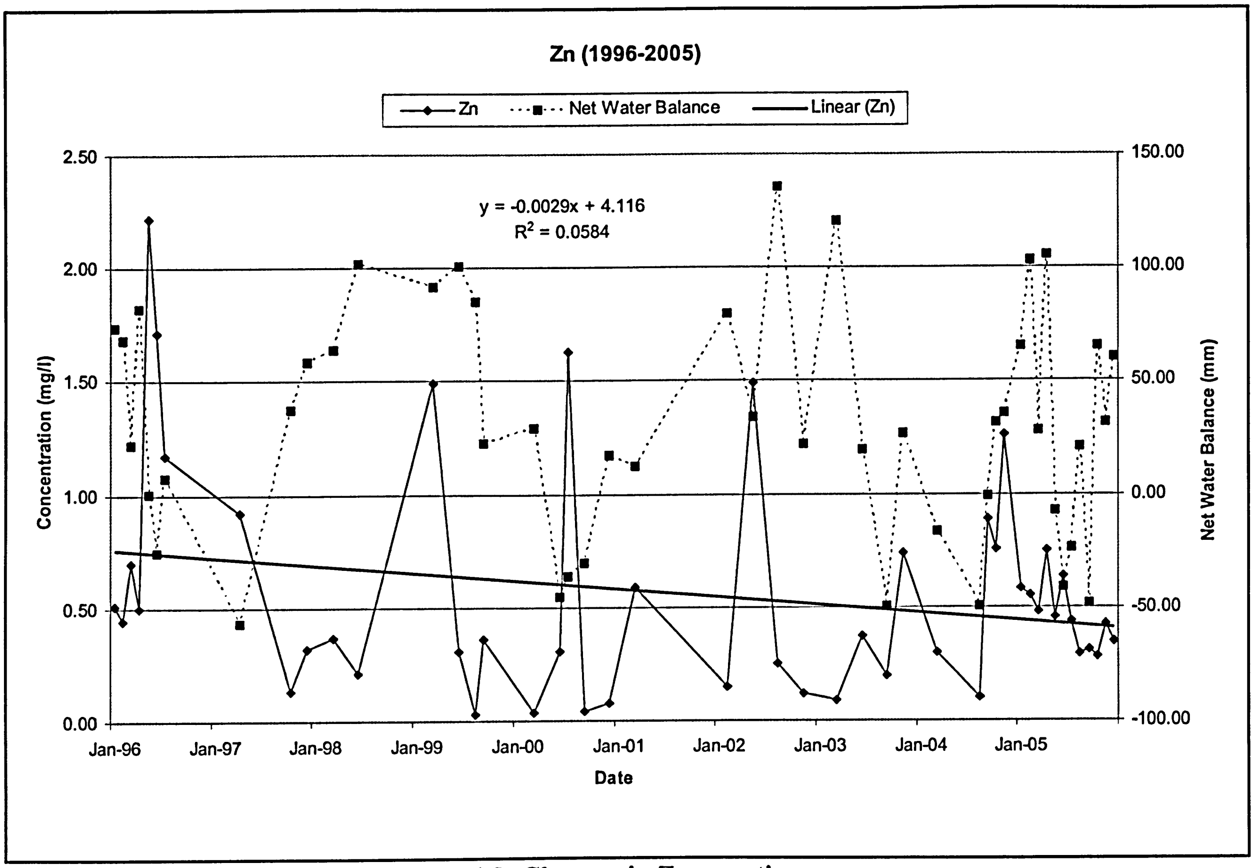

Figure 4.8: Changes in Zn over time

Figure 4.9 shows the concentration of lead over time. The concentration of lead, over time period of 10 years, exhibited variable trends of decreasing and increasing. For example, during the years of 1998 and 1999 was constant 0.03 mg/l. during the years of 2002 and 2005, the concentration was constant of 0.02 mg/l. In general, the lead concentration ranged from 0.1 mg/l (maximum value) to 0.01 mg/l (minimum value) with an average of 0.03 mg/l. Concentration values for lead are consistent with other literature for leachate in stable methanogenic conditions. Christensen et al. 2001, reported average value of 0.09 mg/l for landfills in methanogenic conditions. Jensen et al. 1999, reported lead concentration range of 0 to 0.016 for three (3) Danish landfills in operation. Overall, lower lead concentration is expected during methanogenic phases (Abduli et al. 2003).

The R^2 value for the linear regression for lead concentration over time is very low (0.034) and can not be considered reliable. A long-term future prediction of lead concentration is considered not feasible for such R^2 value.

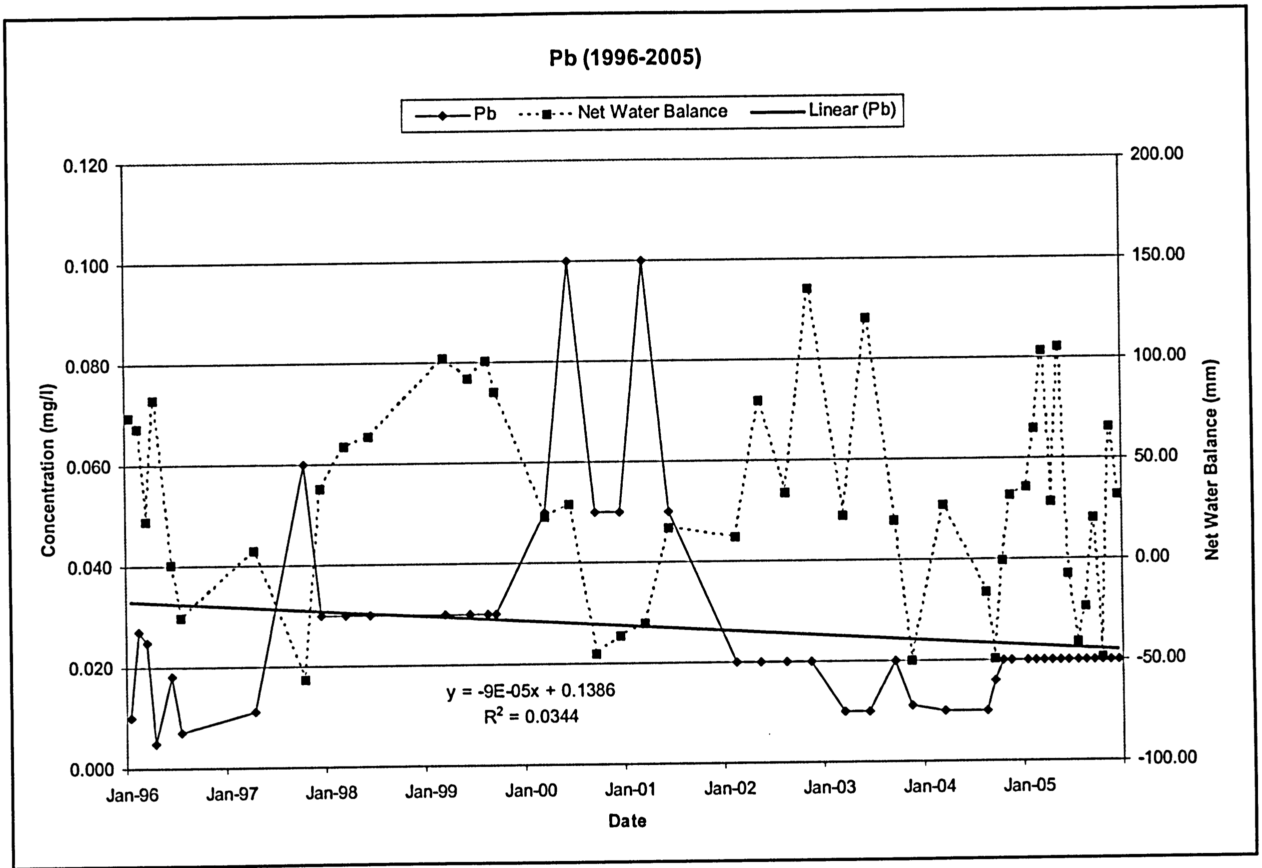

Figure 4.9: Changes in Pb over time

Figure 4.10 shows the concentration of copper over time. The concentration of copper increased from approximately 0.06mg/l in 1996 to 0.14 mg/l in 2005, with an average of 0.165 mg/l, over time period of 10 years. Concentration values for copper are consistent with other literature for leachate in stable methanogenic conditions. Tatsi et al. 2002, reported average value of 0.35 mg/l for copper concentration for stable methanogenic leachate. Jensen et al. 1999, reported copper concentration range of 0.002 to 0.034 for three (3) Danish landfills in operation.

The R^2 value for the linear regression for copper concentration over time is very low (0.1041) and can not be considered reliable. A long-term future prediction of copper concentration is considered not feasible for such R^2 value.

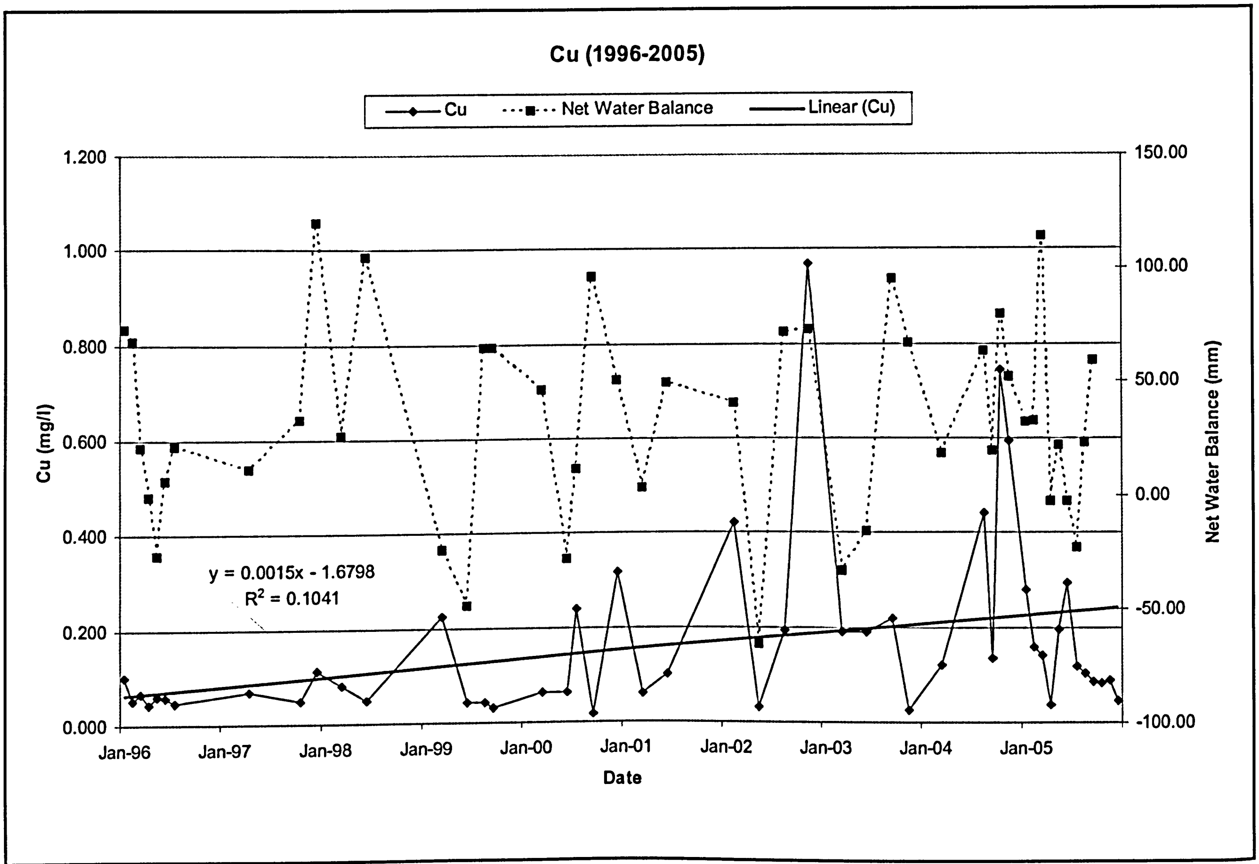

Figure 4.10: Changes in Cu over time

<u>B- Effect of Rainfall Infiltration:</u>

Correlation analysis results performed for zinc shows that there is a very small inverse correlation (-0.037) between zinc and water infiltrated to waste. Correlation analysis results performed for lead shows that there is a very small positive correlation (0.04) between lead and water infiltrated to waste. Correlation analysis results performed for copper shows that there is a very small positive correlation (0.097) between copper and water infiltrated to waste. Having such a very small values for correlation between heavy metals and water infiltration, then the effect of moisture content on concentration of heavy metals in waste during methanogenic phases is minimal. This supports findings from different studies (Kjeldsen et al. 2002, Durmusoglu et al. 2005, Abduli et al. 2003) that the heavy metals concentrations are reduced due to different chemical processes, like sorption and precipitation, during methanogenic due to high pH values.

4. 1.4 Other Compounds

<u>A- Temporal Variation:</u>

Data for Toluene and Vinyl Chloride are presented in Figures 4.11 and 4.12.

Figure 4.11 shows the concentration of toluene over time. The concentration of toluene slightly decreased from approximately 64.5 μg/l in 1996 to 55.7 μg/l in 2005, with an average of 48.9 μg/l, over time period of 10 years. Since the decrease is so small, stable conditions can be claimed for toluene concentration over the time period.

Concentration values for toluene are consistent with other literature for leachate in stable methanogenic conditions. Morris et al. 2003, reported average value of 30μg/l for toluene concentration in leachate from controlled landfill site using leachate recirculation. Other field studies, Reinhart et al. 1998, reported an average of 22.4μg/l for old lined landfills in stable methanogenic conditions. This value is a little lower than our results due to the fact that leachate at the Trail Road landfill still receiving waste (i.e. in operation).

The R^2 value for the linear regression for toluene concentration over time is very low (0.008), a long-term future prediction of toluene concentration is considered not feasible.

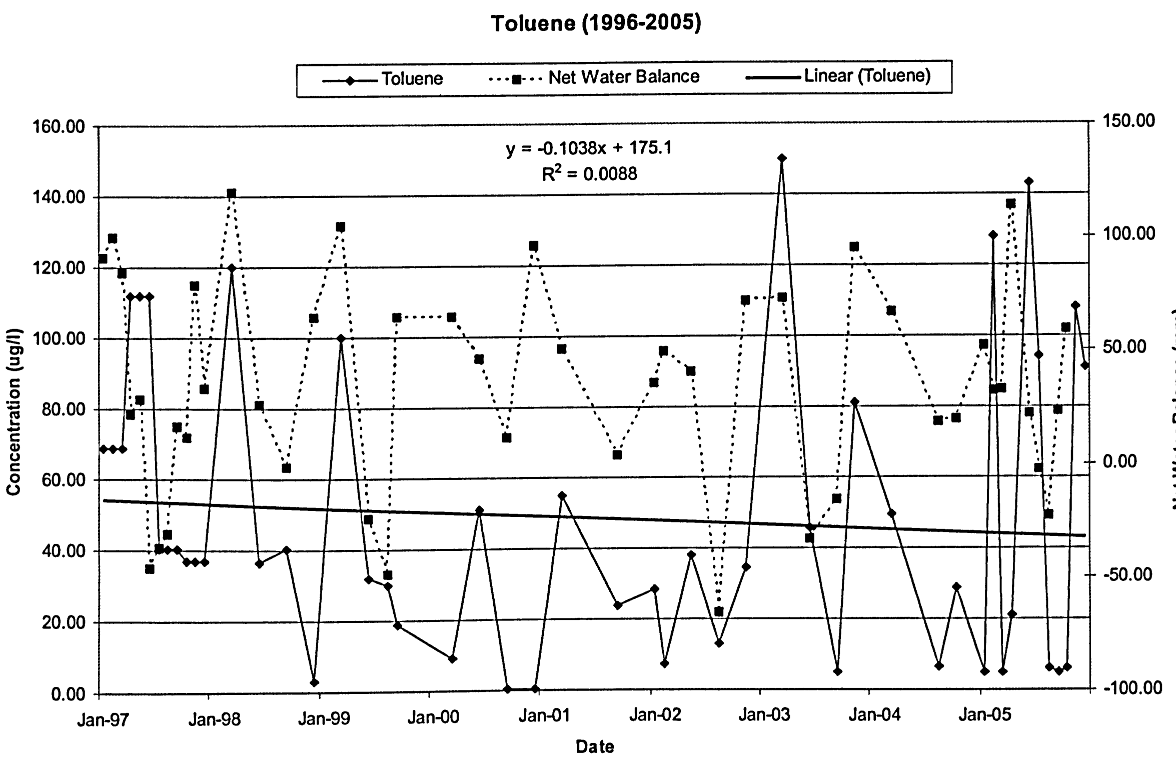

Figure 4.11: Changes in Toluene over time

Figure 4.12 shows the concentration of vinyl chloride over time. The concentration of vinyl chloride slightly increased from approximately 1.90 μg/l in 1996 to 2.0 μg/l in 2005, with an average of 2.06 μg/l, over time period of 10 years. Since the increase is so small, stable conditions can be claimed for vinyl chloride concentration over the time period.

Concentration values for toluene are consistent with other literature for leachate in stable methanogenic conditions. Reinhart et al. 1998, reported an average of 4.07 μg/l for lined landfills in methanogenic conditions.

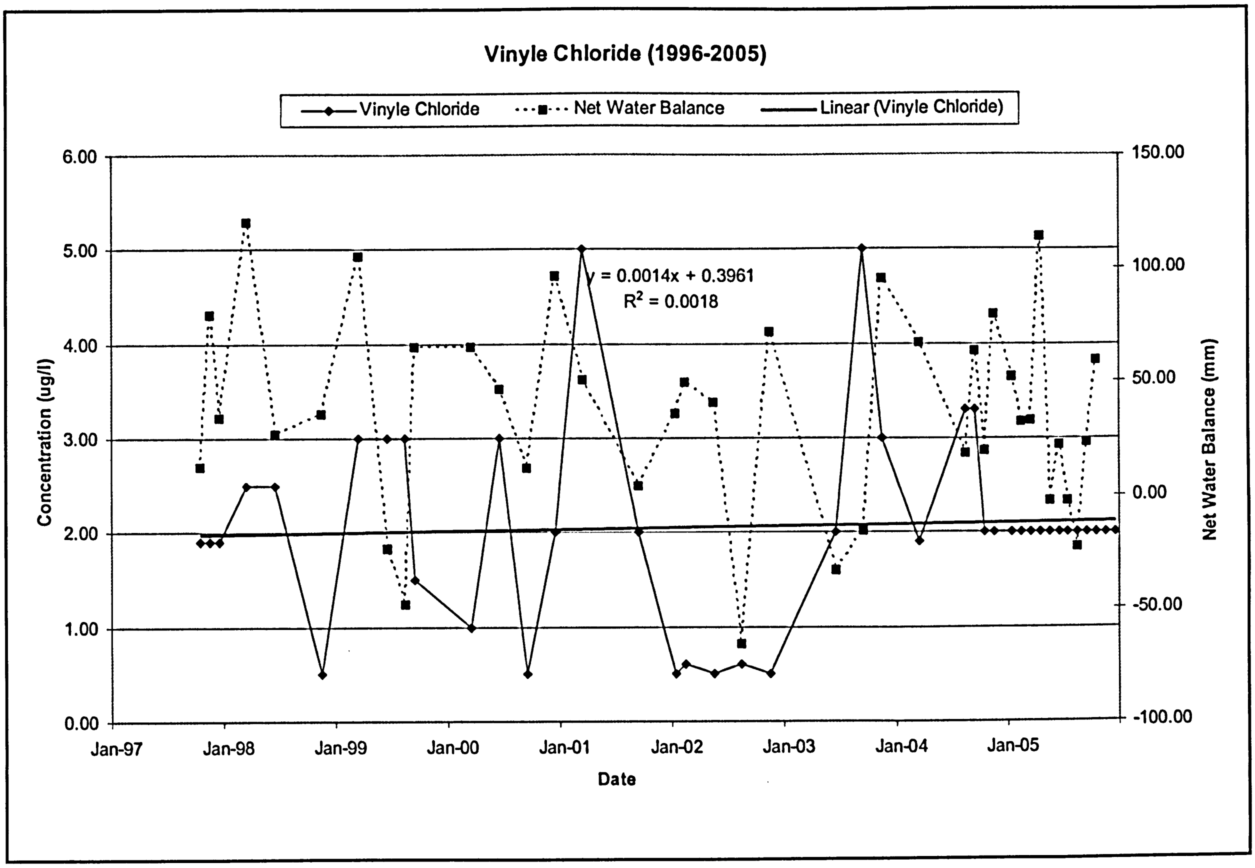

Figure 4.12: Changes in Vinyl Chloride over time

B- Effect of Rainfall Infiltration:

Correlation analysis results performed for toluene shows that there is a small positive correlation (0.16) between toluene and water infiltrated to waste. Toluene is a man-made aromatic hydrocarbon produced mostly from petroleum. This chemical intermediate is the predominant feedstock in benzene production and a key octane-boosting component for gasoline blending. Toluene is also used as a raw material in the production of other chemicals (*e.g.*, toluene diisocyanate and benzoic acid) and as a solvent in paints and coatings, inks, adhesives, and pharmaceuticals (EPA, 1994). Since toluene is slightly soluble in water, then there would be no direct correlation between toluene and water infiltration except for the part that increasing moisture content may increase the flushing of toluene in leachate.

On the other hand, despite the fact that vinyl chloride is also slightly soluble in water, correlation analysis results performed for vinyl chloride shows that there is a very small inverse correlation (-0.009) between vinyl chloride and water infiltrated to waste. Under such small correlation value, -0.009, there is no correlation can be claimed for vinyl chloride with regard to water infiltration.

4.2 Summary of Discussion

The data for the Trail Road Landfill leachate was collected and analyzed for different organic and inorganic parameters for the time period from 1996 to 2005. Analysis of data included statistical tools using Microsoft Excel to investigate both temporal variation of data over the time period and correlation of all pollutants concentration with regard to seasonal variation (i.e. rainfall infiltration to waste). Data and analysis are presented in Tables 4.1, 4.2 and 4.3.

Data were not specifically analyzed for leachate recirculation since a previous study, by M. Warith, 2001, was carried for the same leachate from 1991 to 2000. Only general observation for pollutant behaviour for the last ten years of data was introduced.

Table 4.1: Leachate Composition for the Trail Road landfill

Parameter	Trail Road (1996 to 2005)				Trail Road In 2005	
	Average	Range	Standard Deviation	Sewer By-Law Limit	Average	Range
pH	7.4	6.28-8.11	0.33	5.5-9.5	7.5	7.32-7.63
BOD (mg/l)	1007.2	13-5128	1076.36	300	183	101-450
COD (mg/l)	2326.9	660-6990	1320.77	---	660	---*
BOD/COD	0.4	0.01-0.93	0.21	---	0.17	---*
Cl (mg/l)	1205.9	390-2000	377.75	1500	---*	---*
SO4 (mg/l)	55.91	0.7-287	67.77	1500	40.9	14-183.5
Fe(mg/l)	8.62	0.23-34.95	7.23	50	9.4	4.3-16.4
Zn (mg/l)	0.56	0.03-2.22	0.49	3	0.46	0.285-0.75
Cu (mg/l)	0.165	0.016-0.97	0.188	3	0.136	0.038-0.29
Pb (mg/l)	0.027	0.005-0.1	0.019	5	0.02	0.02**
Ca (mg/l)	179.27	18-310	66.62	---	221.77	176-310
Toluene(μg/l)	48.88	0.5-150	41.14	---	55.67	5-143
Vinyl Chloride(μg/l)	2.06	0.5-5.0	1.03	---	2	2**

** Constant value over the whole year
---* Missing
--- Not Determined

Pearson type correlation analysis was performed to indicate possible relationships between different pollutants in leachate with regard to the rainfall infiltration and methanogenesis (neutral pH conditions). Results are presented in Table 4.2. The most noteworthy is the acceptable correlation found between the following parameters:

1. (BOD, COD) and pH,
2. (BOD, COD) and NWB,
3. Chloride and (pH, NWB),
4. BOD/COD and pH,
5. Fe and (NWB, pH).

Table 4.2: Pearson Type Correlation Results for the Trail Road Landfill

Parameter 1	Parameter 2	Parameter 3	Correlation (1 and 2)	Correlation (1 and 3)
BOD	NWB	pH	-0.129	-0.445
COD	NWB	pH	-0.218	-0.315
BOD/COD	NWB	pH	0.020	-0.387
Chloride	NWB	pH	-0.188	0.369
Ca	NWB	pH	0.307	-0.067
Fe	NWB	pH	-0.144	-0.255
Zn	NWB	pH	-0.037	-0.04
Pb	NWB	pH	0.040	0.013
Cu	NWB	pH	0.097	0.079
SO4	NWB	pH	-0.040	0.008
Toluene	NWB	pH	0.160	-0.163
Vinyl Chloride	NWB	pH	-0.009	-0.223

Table 4.3: Leachate Composition for Different Landfills

Parameter	Acid Phase (*)		Methanogenic Phase (*)		Thessaloniki Landfill, Greece (+)	
	Average	Range	Average	Range	Fresh	Stabilized
pH	6.1	4.5-7.5	8	7.5-9	4.9-6.7	7.3-8.8
BOD (mg/l)	13000	4000 -40000	180	20-250	9500-80795	50-4200
COD (mg/l)	22000	6000 -60000	3000	500-4500	44000-115000	685-15000
BOD/COD	0.58	†	0.06	†	†	†
Cl (mg/l)	†	†	†	†	580-10100	1162-9209
SO4 (mg/l)	500	70 -1750	80	10-420	400-2500	55-500
Fe(mg/l)	†	†	†	†	146-160	0.11-25
Zn (mg/l)	5	0.1 -120	0.03-4	†	1.2-36	0.07-0.2
Cu (mg/l)	†	†	†	†	0.18-6	0.1-0.53
Pb (mg/l)	†	†	†	†	0.23-2.1	< DL
Ca (mg/l)	1200	10- 2500	60	20-600	1727	3324
Toluene(μg/l)	86.6~	†	22.3~	†	†	†
Vinyl Chloride(μg/l)	530~	†	4.07~	†	†	†

~ Debra and Reinhart, 1998
(*) Kjeldsen et al. 2002
< DL Less than detection limit
(+) Tatsi and Zouboulis, 2002
† Not reported

Organic Content:

A decline in the organic content, measured by BOD and COD, was noted for leachate from the Trail Road landfill. BOD concentration decreased from 1140mg/l (average for 1996) to 183 mg/l (average for 2005). COD concentration decreased from 2334mg/l (average for 1996) to 660 mg/l (average for 2005). The ratio of BOD/COD decreased from 0.41 (average for 1996) to 0.17 (average for 2005) over the same period. End values for BOD, COD and BOD/COD ratio indicate that the leachate is within the stable methanogenic conditions. End values (2005 values) are consistent with other research (both field and laboratory scale studies) as indicated in Tables 4.1 and 4.3. Therefore, the end values for BOD, COD and BOD/COD in 2005 represent stable methanogenic conditions.

It is evident that moisture addition, using recirculation of leachate back to waste and rainfall infiltration to the waste, had accelerated the biodegradation of organic content within the waste, due to increased microbial activities within the waste, to a shorter time span than of which the waste would degrade under normal conditions. Different parameters, like BOD/COD ratio and pH levels, which describe the age of the landfill and the stabilization of waste, are approximately 0.17 and 7.5 respectively for the year 2005. These values represent stable conditions and older landfill. Tchobanoglous et al. 1993, provided that average value for pH for mature landfills (more than 10 years old) is within the range of 6.6 to 7.5. Kjeldsen et al. 2002, in a comparison made for different leachate from different literature, reported average of BOD/COD ratio of 0.11 to 0.24 for landfills that are 20-30 years old.

Correlation results for BOD and COD showed an inverse relationship with regard to moisture content and pH levels. The higher the moisture content and pH levels, the lower are the organic content. Results for correlation are shown in Table 4.2.

Inorganic Content:

Inorganic pollutants, like Ca^{2+}, Fe, Cl^- and SO_4, found in the Trail Road landfill leachate generally have lower concentrations since the leachate exhibit stable methanogenic conditions. This can be clearly seen when values for The Trail Road landfill are compared to other results reported by other studies in Tables 4.1 and 4.2.

Within the stable methanogenic phase, the concentration of inorganic pollutants exhibited different trends. The results are shown in Table 4.4 below.

Table 4.4: Inorganic Leachate Composition for the Trail Road Landfill

Parameter	Trend	Linear Regression Factor (R^2)
Ca^{2+}	Increasing	0.0958
Fe	Slightly Increasing	0.0033
Cl^-	Decreasing	0.1281
SO_4	Increasing	0.016

Decreasing trend for chloride is mainly due to continuous washout and removal of chloride from organic waste as a result of continuous leachate recirculation in addition to more water infiltration from rainfall. This is consistent with other research data (Kjeldsen et al. 2002). Increasing trend for calcium is due to increased moisture content and higher pH values, evident by correlation, and is consistent with other literature (Kjeldsen et al. 2002, Tatsi et al. 2002, Statom et al. 2004). The slight increasing trend for iron can be attributed also to moisture content and higher pH values as seen in correlation results in

Table 4.3. This is also consistent with other research data (Christensen, 2001, Tatsi et al. 2002, Statom et al. 2004).

Increasing trend for sulfate is also minimal and no correlation was found with either moisture content or pH levels. Overall decrease in the concentration is a result of biological transformation of sulfate to sulfide (Kjeldsen et al. 2002).

Heavy Metals:

Heavy metals, like Zn, Pb, and Cu, found in the Trail Road landfill leachate generally have lower concentrations since the leachate exhibit stable methanogenic conditions. This can be clearly seen when values for heavy metals in leachate from the Trail Road landfill are compared to other results reported by other studies in Tables 4.1 and 4.2.

Due to high pH levels (near neutral), different processes, like sorption and precipitation, are the reason for low heavy metal concentration in methanogenic phase since such mechanisms prevent mobilization of metals (Kjeldsen et al. 2002, Durmusoglu et al. 2005, Jensen et al. 1999).

Within the stable methanogenic phase, the concentration of heavy metals exhibited different trends. The results are shown in Table 4.5 below.

Table 4.5: Heavy Metals in Leachate from the Trail Road Landfill

Parameter	Trend	Linear Regression Factor (R^2)
Zn	Slightly Decreasing	0.058
Pb	Slightly Decreasing	0.034
Cu	Increasing	0.104

Decreasing trends for zinc and lead and increasing trend for copper are all minimal and no correlation was found with either moisture content or pH levels. Overall, lower concentration for heavy metals was found. Decrease in zinc concentration is consistent with findings from Durmusoglu et al. 2005 and Lo et al. 1996. Decrease in lead and increase in copper concentration is not consistent with results from Durmusoglu et al. 2005. Since the linear regression factor, R^2, was low for all zinc, lead and copper, the trend reported for such metals in leachate from the Trail Road is not quite representative and care should be exercised when forecasting long term concentration for such metals. For example, based on a 12-years data, Statom et al. 2004, reported that all zinc, lead and copper were below detection limit and no significant trend was noted.

<u>Toluene and Vinyl Chloride:</u>

Toluene and vinyl chloride found in the Trail Road landfill leachate generally have lower concentrations since the leachate exhibit stable methanogenic conditions. This can be clearly seen when values for toluene and vinyl chloride in leachate from the Trail Road landfill are compared to other results reported by other studies in Tables 4.1 and 4.2. Within the stable methanogenic phase, the concentration of toluene and vinyl chloride exhibited different trends. The results are shown in Table 4.6 below.

Table 4.6: Toluene and Vinyl Chloride in Leachate from the Trail Road Landfill

Parameter	**Trend**	**Linear Regression Factor (R^2)**
Toluene	Stable	0.008
Vinyl Chloride	Stable	0.001

Stable trends for toluene and vinyl chloride can be noticed. Correlation results for toluene show that positive relation between toluene and moisture content and inverse relation with respect to pH levels. This means that toluene has exhibited stable conditions at both higher moisture content and methanogenic conditions.

Vinyl chloride correlation results show an inverse relation with respect to pH levels. This could mean that vinyl chloride is stable during methanogenic conditions.

Chapter 5

CONCLUSION AND SUGGESTIONS FOR FUTURE STUDIES

5.1 General

Leachate parameters from the Trail Road landfill were acquired and examined for two primary objectives. First, the temporal variation of all leachate parameters was investigated to study the behavior of parameter concentration over time. Secondly, the effect of other factors like methanogenesis, high pH, and the net water infiltrating waste from precipitation on the behavior of leachate parameters was also examined using Pearson Moment Type correlation.

Most of leachate parameters investigated in this study showed decline in parameter concentration over time. This was evident by the temporal variation of leachate parameters over the ten years study period. Also, the effect of the net water, that infiltrated waste, and the effect of methanogenesis, high pH levels, of leachate on the concentration of parameters in leachate during the ten years study period were noticed.

5.1.1 Temporal Trends

The data from the Trail Road landfill yielded temporal trends for most leachate parameters analyzed in this study. The effects of water addition to the waste, through leachate recirculation back into the waste mass and water infiltration from precipitation, and the high pH levels of the leachate were found to be the primary reasons for the variation in the temporal trends established for all parameters. For example, decreasing trends were noted for BOD, COD, BOD/COD ratio, chloride, zinc and lead while increasing trends were noted for calcium, iron, sulfate and copper. However, only pH, toluene and vinyl chloride exhibited stable trends.

The long term trends are consistent with different field and laboratory scale studies for leachate noted in other landfills that are undergoing stable methanogenic conditions.

5.1.2 Correlation Analysis

Based on the results from the correlation analysis of the leachate parameters with regard to both precipitation infiltration to the waste mass and the methanogenesis of the leachate, it appears that noteworthy relationship existed between the leachate parameters, such as BOD, COD, chloride and calcium, and the amount of precipitation infiltrated the waste. Also, since the leachate from the Trail Road landfill exhibits stable methanogenic conditions, evident by pH levels, it was noted that the composition of leachate is dependable on the decomposition stage of the waste. BOD, COD, iron and chloride showed relevant correlation with the methanogenesis of leachate. During the time period from 1996 to 2005, organic content, heavy metals and toluene and vinyl chloride concentration were consistent with other studies for waste degradation during methanogenic conditions.

5.2 Future Research

Based on the results from this study, the following topics are recommended for future studies on the quality of leachate from the Trail Road landfill:

1. In future studies, the net water balance from precipitation to the waste should be adjusted to account for surface runoff so more precise water quantities added to the waste can be calculated.
2. To solely account for the effect of net water balance on the quality of leachate from the Trail Road landfill, specific waste samples should be collected and monitored under no effect of recirculation of leachate back to the waste.
3. Behavior of heavy metals from the Trail Road landfill leachate should be further investigated. Samples collected for leachate from the Trail Road landfill should be filtered when analyzing for heavy metals to account for the effect of processes like dissolution in water and adsorption to suspended colloids and particles on the results obtained.
4. Since former Nepean landfill was constructed without using engineered liners, the effect of leachate from the former Nepean landfill should be accounted for when analyzing the quality of leachate from the Trail Road landfill.
5. Research should be extended to beyond stable methanogenic conditions. Possible decomposition might occur even after final cover is placed at the landfill.

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APPENDICES

APPENDIX A

Daily and Monthly Leachate Data

1. **Biochemical oxygen demand (BOD)**
2. **Chemical oxygen demand (COD)**
3. **pH**
4. **Chloride (Cl)**
5. **Calcium (Ca^{2+})**
6. **Sulfate (SO_4-)**
7. **Zinc (Zn)**
8. **Vinyl Chloride**
9. **Toluene**
10. **Copper (Cu)**
11. **Lead (Pb)**
12. **Iron (Fe)**

Notes:

- Data were obtained from the annual monitoring reports done by Golder Associates and Dillon Consulting and the City of Ottawa for the years between 1996 and 2005
- †: Denotes that data were not measured or reported

1. BOD Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
25/1/96	548	24/1/97	1130	5/1/98	700	4/1/99	230	4/1/00	680
22/2/96	332	27/1/97	860	12/1/98	143	11/1/99	300	10/1/00	810
23/2/96	430	3/2/97	330	19/1/98	310	27/1/99	1070	17/1/00	960
24/2/96	400	10/2/97	290	26/1/98	168	2/2/99	1030	24/1/00	790
25/2/96	440	28/2/97	2600	2/2/98	150	8/2/99	1020	31/1/00	910
3/3/96	770	3/3/97	1830	9/2/98	106	15/2/99	720	7/2/00	260
4/3/96	480	9/3/97	1750	16/2/98	88	22/2/99	400	15/2/00	580
12/3/96	1230	17/3/97	1640	23/2/98	350	3/3/99	1830	23/2/00	650
13/3/96	970	24/3/97	1060	2/3/98	1570	8/3/99	430	28/2/00	340
19/3/96	750	31/3/97	2700	9/3/98	2400	15/3/99	840	6/3/00	570
19/4/96	684	1/4/97	2700	16/3/98	520	22/3/99	1630	13/3/00	610
17/5/96	4400	7/4/97	1120	23/3/98	3900	5/4/99	1370	20/3/00	320
20/6/96	2685	14/4/97	2400	30/3/98	1810	12/4/99	1430	27/3/00	510
23/7/96	1573	28/4/97	2400	6/4/98	1240	19/4/99	6200	3/4/00	1080
31/7/96	1700	5/5/97	1140	13/4/98	4200	3/5/99	5800	10/4/00	1060
6/8/96	1270	12/5/97	2700	20/4/98	1840	11/5/99	4900	17/4/00	790
12/8/96	460	20/5/97	2000	27/4/98	2300	20/5/99	4100	25/4/00	1580
19/8/96	440	23/5/97	610	4/5/98	1130	25/5/99	5500	1/5/00	550
26/8/96	530	26/5/97	300	11/5/98	1440	31/5/99	5000	8/5/00	1570
3/9/96	580	27/5/97	270	19/5/98	750	9/6/99	4900	15/5/00	1630
16/9/96	200	2/6/97	800	25/5/98	490	14/6/99	2900	22/5/00	1380
23/9/96	290	9/6/97	260	1/6/98	800	21/6/99	2000	29/5/00	810
30/9/96	1420	16/6/97	161	8/6/98	460	28/6/99	2700	5/6/00	1000
7/10/96	1900	23/6/97	640	15/6/98	1780	5/7/99	2500	12/6/00	460
14/10/96	650	30/6/97	2000	22/6/98	1180	12/7/99	2100	19/6/00	730
21/10/96	400	2/7/97	2400	29/6/98	2700	19/7/99	1010	26/6/00	1340
28/10/96	196	7/7/97	4300	6/7/98	1430	26/7/99	1250	3/7/00	370
4/11/96	124	21/7/97	1170	13/7/98	1130	3/8/99	360	6/7/00	440
11/11/96	320	28/7/97	600	20/7/98	820	9/8/99	520	7/7/00	410
9/12/96	176	5/8/97	600	27/7/98	360	16/8/99	3354	10/7/00	440
		11/8/97	300	4/8/98	350	31/8/99	2800	17/7/00	460
		18/8/97	300	10/8/98	260	7/9/99	340	24/7/00	300
		25/8/97	300	17/8/98	520	13/9/99	1060	31/7/00	1410
		2/9/97	150	24/8/98	320	20/9/99	2200	7/8/00	220
		8/9/97	300	31/8/98	490	27/9/99	1800	14/8/00	150
		15/9/97	300	8/9/98	470	4/10/99	830	21/8/00	300
		22/9/97	155	28/9/98	490	12/10/99	730	5/9/00	300
		29/9/97	300	5/10/98	430	18/10/99	540	12/9/00	660
		6/10/97	210	13/10/98	650	25/10/99	810	18/9/00	240
		14/10/97	150	19/10/98	1000	15/11/99	560	25/9/00	310
		20/10/97	178	26/10/98	220	22/11/99	920	2/10/00	300
		28/10/97	530	9/11/98	280	29/11/99	220	10/10/00	400
		3/11/97	660	16/11/98	490	6/12/99	490	16/10/00	400

		10/11/97	182	23/11/98	198	13/12/99	440	23/10/00	220
		17/11/97	150	30/11/98	400	21/12/99	400	30/10/00	111
		8/12/97	540	7/12/98	1140	28/12/99	870	6/11/00	500
		15/12/97	510	14/12/98	950	28/12/99	870	4/12/00	1790
		22/12/97	400	21/12/98	370			11/12/00	340
		29/12/97	310	28/12/98	310			18/12/00	280
				29/12/98	230			26/12/00	290

BOD Data: (Continued)

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
2/1/01	330	2/1/02	1600	6/1/03	131	5/1/04	140	4/1/05	370
8/1/01	390	8/1/02	1680	22/1/03	150	15/1/04	300	11/1/05	122
15/1/01	200	16/1/02	1220	5/3/03	150	29/1/04	35	17/1/05	164
22/1/01	230	24/1/02	1580	19/3/03	150	3/2/04	29	24/1/05	137
29/1/01	1160	30/1/02	1560	24/3/03	35	11/2/04	73	2/2/05	112
7/2/01	270	5/2/02	2000	7/4/03	75	24/2/04	134	15/2/05	92
12/2/01	240	13/2/02	480	16/4/03	56	3/3/04	590	25/2/05	130
19/2/01	1250	19/2/02	2200	22/4/03	130	9/3/04	41	4/3/05	200
26/2/01	480	27/2/02	660	30/4/03	570	19/3/04	66	11/3/05	102
5/3/01	1490	5/3/02	850	14/5/03	730	23/3/04	37	30/3/05	270
26/3/01	1280	13/3/02	1080	22/5/03	116	31/3/04	1070	31/3/05	42
2/4/01	2900	19/3/02	2500	28/5/03	440	16/4/04	193	11/4/05	320
9/4/01	280	3/4/02	920	9/6/03	2600	19/4/04	2000	15/4/05	670
16/4/01	3900	10/4/02	430	11/6/03	2200	29/4/04	1470	21/4/05	430
23/4/01	4800	16/4/02	2400	2/7/03	75	3/5/04	260	29/4/05	380
30/4/01	4100	2/5/02	7200	9/7/03	790	13/5/04	710	5/5/05	220
7/5/01	2700	8/5/02	1540	17/7/03	170	14/5/04	138	20/5/05	460
14/5/01	790	14/5/02	3300	28/7/03	99	25/5/04	980	25/5/05	250
22/5/01	5700	21/5/02	6600	31/7/03	930	27/5/04	1160	27/5/05	161
23/5/01	2100	30/5/02	7000	5/8/03	79	1/6/04	1240	3/6/05	138
30/5/01	4600	5/6/02	3400	14/8/03	1140	8/6/04	1780	10/6/05	108
6/6/01	4200	13/6/02	2500	26/8/03	280	10/6/04	1640	16/6/05	38
13/6/01	3800	19/6/02	2100	2/9/03	163	11/6/04	250	23/6/05	300
19/6/01	5900	25/6/02	2800	9/9/03	65	14/6/04	280	30/6/05	139
27/6/01	3400	3/7/02	230	16/9/03	191	15/6/04	860	11/7/05	109
4/7/01	300	9/7/02	2100	23/9/03	26	16/6/04	1080	18/7/05	176
11/7/01	3500	23/7/02	650	30/9/03	154	18/6/04	460	20/7/05	130
17/7/01	1650	31/7/02	1480	7/10/03	13	21/6/04	450	25/7/05	84
10/10/01	1310	8/8/02	1240			22/6/04	960	3/8/05	104
17/10/01	4900	14/8/02	320			23/6/04	570	15/8/05	98
24/10/01	3400	20/8/02	260			24/6/04	970	6/9/05	330
14/11/01	500	11/9/02	150			25/6/04	690	12/9/05	79

20/11/01	3200	19/9/02	75			28/6/04	710	16/9/05	60
5/12/01	3500	25/9/02	42			29/6/04	440	22/9/05	79
7/12/01	3200	17/10/02	151			30/6/04	480	30/9/05	67
12/12/01	2100	31/10/02	150			2/7/04	480	6/10/05	65
19/12/01	3200	8/11/02	1120			19/7/04	153	14/10/05	96
		14/11/02	140			6/8/04	162	24/10/05	200
		20/11/02	320			10/8/04	151	28/10/05	36
		26/11/02	75			11/8/04	129	7/11/05	850
		4/12/02	75			12/8/04	129	10/11/05	230
		10/12/02	150			13/8/04	260	16/11/05	93
		18/12/02	550			14/8/04	146	23/11/05	230
						17/8/04	560	30/11/05	34
						18/8/04	640	8/12/05	250
						19/8/04	750	21/12/05	75
						20/8/04	330	28/12/05	81
						23/8/04	290		
						25/8/04	650		
						26/8/04	710		
						27/8/04	580		
						30/8/04	300		
						7/9/04	163		
						9/9/04	200		
						13/9/04	163		
						14/9/04	111		
						15/9/04	55		
						16/9/04	47		
						17/9/04	450		
						27/9/04	360		
						28/9/04	290		
						4/10/04	109		
						12/10/04	179		
						19/10/04	280		
						25/10/04	117		
						2/11/04	169		
						3/11/04	60		
						8/11/04	101		
						15/11/04	71		
						22/11/04	97		

2. COD Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
25/1/96	1300	24/1/97	2100	2/1/98	1650	4/1/99	1670	4/1/00	1890
22/2/96	1096	25/1/97	2600	3/1/98	1680	5/1/99	1560	5/1/00	890
23/2/96	1330	27/1/97	1960	5/1/98	1750	6/1/99	1500	6/1/00	840
24/2/96	790	28/1/97	2200	6/1/98	1310	7/1/99	1680	7/1/00	1490
25/2/96	1170	29/1/97	1990	7/1/98	1860	8/1/99	1700	10/1/00	2100
26/2/96	1980	30/1/97	2800	12/1/98	1300	11/1/99	1550	11/1/00	830
27/2/96	2200	31/1/97	1950	13/1/98	1620	12/1/99	1570	12/1/00	910
28/2/96	2000	1/2/97	1760	14/1/98	1690	13/1/99	1520	13/1/00	730
29/2/96	1900	3/2/97	1850	15/1/98	1550	18/1/99	1640	14/1/00	1310
1/3/96	1860	4/2/97	1650	16/1/98	1520	19/1/99	2000	17/1/00	2300
2/3/96	2200	5/2/97	1890	19/1/98	1600	20/1/99	1320	18/1/00	1380
3/3/96	2200	6/2/97	1840	20/1/98	1670	21/1/99	1520	19/1/00	1400
4/3/96	1640	7/2/97	1690	21/1/98	1800	22/1/99	1620	20/1/00	1400
5/3/96	1500	8/2/97	1710	22/1/98	1480	23/1/99	1770	21/1/00	1140
6/3/96	1860	10/2/97	1800	23/1/98	1800	26/1/99	1880	24/1/00	2200
7/3/96	1810	11/2/97	1790	26/1/98	1670	27/1/99	1880	25/1/00	1320
9/3/96	2400	12/2/97	1780	27/1/98	1780	28/1/99	2400	26/1/00	1260
10/3/96	1700	13/2/97	1900	28/1/98	1730	29/1/99	2300	27/1/00	1250
12/3/96	2500	14/2/97	1870	29/1/98	1630	30/1/99	3100	28/1/00	1070
13/3/96	2300	15/2/97	1830	30/1/98	1630	2/2/99	1530	31/1/00	2600
14/3/96	1630	18/2/97	2300	2/2/98	1590	3/2/99	1760	1/2/00	1390
15/3/96	1560	19/2/97	990	3/2/98	1490	4/2/99	2800	2/2/00	1340
19/3/96	2381	20/2/97	650	4/2/98	1560	5/2/99	2300	3/2/00	1240
19/4/96	1800	21/2/97	910	5/2/98	1670	8/2/99	2300	4/2/00	940
17/5/96	4580	22/2/97	740	6/2/98	1540	10/2/99	1500	7/2/00	1430
20/6/96	5366	24/2/97	1000	9/2/98	1520	11/2/99	1590	8/2/00	870
23/7/96	3182	25/2/97	1290	11/2/98	1400	12/2/99	2000	15/2/00	2300
25/7/96	3300	26/2/97	1740	12/2/98	1580	13/2/99	2600	16/2/00	1950
31/7/96	3600	27/2/97	1400	16/2/98	1430	15/2/99	1960	17/2/00	1470
2/8/96	1840	28/2/97	4700	17/2/98	1560	16/2/99	1420	18/2/00	1560
6/8/96	2700	1/3/97	1440	18/2/98	1430	17/2/99	1350	23/2/00	2900
7/8/96	2800	3/3/97	3100	19/2/98	1430	18/2/99	1340	24/2/00	1320
8/8/96	3300	4/3/97	4200	20/2/98	1370	19/2/99	1280	25/2/00	460
9/8/96	3000	5/3/97	1890	21/2/98	1060	22/2/99	1840	26/2/00	780
10/8/96	2600	6/3/97	1970	23/2/98	1300	23/2/99	1290	28/2/00	980
12/8/96	1730	7/3/97	1530	24/2/98	1360	24/2/99	1530	29/2/00	980
14/8/96	2450	8/3/97	2400	25/2/98	1510	26/2/99	1860	1/3/00	660
15/8/96	2200	9/3/97	3500	26/2/98	1700	3/3/99	3600	2/3/00	990
16/8/96	2900	11/3/97	2600	27/2/98	2000	4/3/99	2800	3/3/00	1160
19/8/96	1240	13/3/97	3000	2/3/98	3100	5/3/99	1940	6/3/00	1560
20/8/96	1950	14/3/97	2400	3/3/98	3400	8/3/99	1500	7/3/00	760
21/8/96	1740	15/3/97	3100	4/3/98	3800	9/3/99	1580	8/3/00	1460
22/8/96	1880	17/3/97	3200	5/3/98	3500	10/3/99	1700	9/3/00	580

23/8/96	1820	18/3/97	2500	6/3/98	3500	11/3/99	1270	10/3/00	430
26/8/96	1320	20/3/97	2600	7/3/98	2700	12/3/99	1690	13/3/00	1620
27/8/96	2100	21/3/97	2600	8/3/98	3100	13/3/99	1580	14/3/00	1230
28/8/96	2300	22/3/97	2500	9/3/98	4200	15/3/99	2400	15/3/00	1180
29/8/96	1780	24/3/97	2600	10/3/98	3800	16/3/99	1900	16/3/00	1210
30/8/96	3100	25/3/97	2500	11/3/98	2700	17/3/99	2200	17/3/00	380
3/9/96	2300	26/3/97	1890	12/3/98	2300	18/3/99	2700	20/3/00	1400
4/9/96	2100	27/3/97	2400	13/3/98	2500	19/3/99	2100	21/3/00	1420
5/9/96	4100	29/3/97	2300	15/3/98	1720	20/3/99	1830	22/3/00	1290
6/9/96	2600	31/3/97	4100	16/3/98	1650	22/3/99	2600	23/3/00	660
7/9/96	1920	1/4/97	2300	18/3/98	1940	23/3/99	3000	24/3/00	1500
9/9/96	1870	2/4/97	3900	19/3/98	2900	24/3/99	2700	27/3/00	1210
10/9/96	1360	3/4/97	4000	23/3/98	6300	25/3/99	2800	28/3/00	1460
11/9/96	1370	7/4/97	3200	24/3/98	4800	26/3/99	2700	29/3/00	1080
12/9/96	1590	8/4/97	2600	25/3/98	1770	27/3/99	3100	30/3/00	710
13/9/96	1180	9/4/97	2200	26/3/98	1560	29/3/99	2900	31/3/00	1130
16/9/96	980	10/4/97	3000	27/3/98	3300	30/3/99	3200	3/4/00	1970
17/9/96	1460	11/4/97	3000	28/3/98	5100	31/3/99	2500	4/4/00	2000
18/9/96	1380	14/4/97	3500	30/3/98	3000	1/4/99	2800	5/4/00	2100
19/9/96	1550	15/4/97	4600	1/4/98	2600	2/4/99	2300	6/4/00	2100
20/9/96	1370	16/4/97	4900	3/4/98	4900	3/4/99	2400	7/4/00	1180
21/9/96	1590	17/4/97	5500	6/4/98	2300	4/4/99	2500	8/4/00	2100
23/9/96	1410	18/4/97	5400	7/4/98	2100	5/4/99	2600	10/4/00	1720
24/9/96	1450	21/4/97	4700	8/4/98	2300	6/4/99	1890	11/4/00	1770
25/9/96	1480	22/4/97	4800	9/4/98	1790	7/4/99	2800	12/4/00	1840
26/9/96	1580	23/4/97	3300	13/4/98	6400	8/4/99	2000	13/4/00	1990
27/9/96	1420	25/4/97	3000	14/4/98	2800	9/4/99	2300	14/4/00	2200
28/9/96	1810	28/4/97	3300	15/4/98	2100	10/4/99	1860	15/4/00	1440
30/9/96	2465	29/4/97	3900	17/4/98	1400	11/4/99	2400	17/4/00	1240
2/10/96	1700	30/4/97	3800	20/4/98	3400	12/4/99	2500	18/4/00	2200
3/10/96	1440	1/5/97	3400	21/4/98	3900	13/4/99	9200	19/4/00	1260
4/10/96	1410	2/5/97	3300	22/4/98	3300	14/4/99	10200	20/4/00	2100
5/10/96	1520	3/5/97	2352	23/4/98	4300	15/4/99	10200	21/4/00	2000
7/10/96	2550	5/5/97	3484	24/4/98	2500	16/4/99	8400	25/4/00	2600
9/10/96	1810	6/5/97	3900	27/4/98	4300	19/4/99	9400	26/4/00	1360
10/10/96	1450	7/5/97	3400	28/4/98	4000	20/4/99	5900	27/4/00	3300
11/10/96	1460	8/5/97	3300	29/4/98	3800	21/4/99	6200	28/4/00	1200
12/10/96	1330	9/5/97	3500	30/4/98	3400	22/4/99	6400	1/5/00	1620
14/10/96	1630	12/5/97	4300	1/5/98	3500	23/4/99	5800	2/5/00	1100
15/10/96	1330	13/5/97	3700	4/5/98	2800	26/4/99	10100	3/5/00	1720
16/10/96	1160	14/5/97	3200	5/5/98	2800	27/4/99	6800	4/5/00	1490
17/10/96	1330	15/5/97	3500	6/5/98	3500	28/4/99	5300	5/5/00	1430
18/10/96	1380	16/5/97	3600	7/5/98	2100	3/5/99	9200	8/5/00	2900
19/10/96	1310	20/5/97	4000	8/5/98	3000	4/5/99	4100	9/5/00	1770
21/10/96	1280	21/5/97	2200	11/5/98	3100	5/5/99	4300	10/5/00	1130
22/10/96	840	22/5/97	2100	13/5/98	3300	6/5/99	4700	11/5/00	1970
23/10/96	1340	23/5/97	2000	14/5/98	1770	11/5/99	7800	12/5/00	2400

24/10/96	1150	26/5/97	1550	15/5/98	2700	12/5/99	4100	13/5/00	2500
25/10/96	1150	27/5/97	1500	19/5/98	2500	13/5/99	4000	15/5/00	2800
26/10/96	810	28/5/97	1660	20/5/98	1780	14/5/99	6700	16/5/00	3700
28/10/96	1060	29/5/97	1580	21/5/98	1920	20/5/99	7800	17/5/00	1900
29/10/96	1030	30/5/97	1630	22/5/98	1940	21/5/99	4400	18/5/00	1680
30/10/96	1060	2/6/97	2100	25/5/98	2400	25/5/99	6800	19/5/00	3900
31/10/96	1155	3/6/97	1680	26/5/98	1820	26/5/99	2000	22/5/00	3100
2/11/96	1300	4/6/97	1560	28/5/98	2000	27/5/99	6700	23/5/00	2400
4/11/96	2100	5/6/97	1500	29/5/98	2300	28/5/99	2400	24/5/00	1360
5/11/96	1450	6/6/97	1480	1/6/98	2800	31/5/99	6800	25/5/00	1330
6/11/96	2000	9/6/97	1460	2/6/98	2100	1/6/99	2200	26/5/00	1480
7/11/96	1790	10/6/97	1580	3/6/98	1910	2/6/99	4000	29/5/00	2000
8/11/96	1620	11/6/97	1470	4/6/98	1820	3/6/99	3200	30/5/00	1570
9/11/96	1410	12/6/97	1380	6/6/98	1850	9/6/99	8600	31/5/00	1330
11/11/96	810	16/6/97	1110	8/6/98	2200	10/6/99	2700	1/6/00	3000
12/11/96	970	17/6/97	1600	9/6/98	2000	11/6/99	1710	2/6/00	2300
13/11/96	1040	18/6/97	1220	10/6/98	1900	14/6/99	5100	5/6/00	2500
14/11/96	1080	19/6/97	1430	11/6/98	1750	15/6/99	2500	6/6/00	1540
15/11/96	1105	20/6/97	1510	12/6/98	1980	17/6/99	4300	7/6/00	1940
18/11/96	1810	23/6/97	1610	15/6/98	4000	18/6/99	1970	8/6/00	1040
19/11/96	1170	24/6/97	1768	16/6/98	4500	21/6/99	4600	9/6/00	1630
20/11/96	1200	25/6/97	2200	17/6/98	4200	25/6/99	9300	12/6/00	850
21/11/96	2000	26/6/97	2100	18/6/98	3800	28/6/99	4900	13/6/00	1360
22/11/96	1520	27/6/97	2504	19/6/98	4200	29/6/99	1950	14/6/00	2100
23/11/96	1320	30/6/97	3872	22/6/98	5000	30/6/99	2500	15/6/00	960
25/11/96	1700	2/7/97	4700	23/6/98	3000	5/7/99	4600	16/6/00	1400
26/11/96	1320	4/7/97	6900	24/6/98	2400	6/7/99	6200	19/6/00	1830
27/11/96	1170	7/7/97	6400	25/6/98	3000	7/7/99	3400	20/6/00	1820
28/11/96	1420	8/7/97	5200	26/6/98	3000	8/7/99	1610	21/6/00	1150
29/11/96	1650	9/7/97	4900	29/6/98	4800	9/7/99	2300	22/6/00	1650
30/11/96	1520	10/7/97	3700	30/6/98	3200	12/7/99	3700	23/6/00	1670
2/12/96	1470	11/7/97	3900	2/7/98	3950	16/7/99	3200	26/6/00	2300
3/12/96	1560	14/7/97	3600	3/7/98	2700	19/7/99	2070	27/6/00	1300
4/12/96	1210	15/7/97	1870	6/7/98	3300	20/7/99	2500	28/6/00	1320
5/12/96	1190	16/7/97	1970	7/7/98	2300	21/7/99	2500	29/6/00	1370
6/12/96	570	17/7/97	2700	8/7/98	5400	22/7/99	1370	30/6/00	1090
9/12/96	1670	18/7/97	3200	9/7/98	2000	23/7/99	1610	3/7/00	1340
10/12/96	1340	21/7/97	2600	10/7/98	2200	26/7/99	2500	4/7/00	910
11/12/96	1180	22/7/97	2100	13/7/98	2800	27/7/99	1940	5/7/00	3600
12/12/96	1210	23/7/97	2000	14/7/98	1760	28/7/99	1340	6/7/00	1720
13/12/96	1280	24/7/97	1710	15/7/98	2600	29/7/99	1740	7/7/00	2500
16/12/96	1460	25/7/97	1790	17/7/98	2600	30/7/99	1150	10/7/00	1580
17/12/96	1620	28/7/97	1744	20/7/98	2400	3/8/99	1910	11/7/00	1040
18/12/96	810	29/7/97	1650	21/7/98	1890	4/8/99	1820	12/7/00	1920
19/12/96	970	30/7/97	1580	22/7/98	1770	5/8/99	1590	13/7/00	1420
20/12/96	1210	31/7/97	1470	23/7/98	1500	6/8/99	1420	14/7/00	1260
23/12/96	1870	1/8/97	2700	24/7/98	1420	9/8/99	1330	17/7/00	1610

24/12/96	1620	5/8/97	1700	27/7/98	1860	10/8/99	1260	18/7/00	2100
30/12/96	1160	7/8/97	1470	28/7/98	1520	11/8/99	1360	19/7/00	1180
31/12/96	1430	8/8/97	1410	29/7/98	1340	12/8/99	1450	20/7/00	1400
		11/8/97	1420	30/7/98	1670	13/8/99	1280	21/7/00	1440
		12/8/97	1470	31/7/98	2000	16/8/99	5300	24/7/00	1290
		13/8/97	2400	4/8/98	1840	17/8/99	1520	25/7/00	1400
		14/8/97	1200	5/8/98	1370	18/8/99	3500	26/7/00	1060
		15/8/97	1250	7/8/98	1490	19/8/99	2500	27/7/00	650
		18/8/97	1160	10/8/98	1120	20/8/99	2800	28/7/00	950
		19/8/97	1300	11/8/98	1540	31/8/99	5300	31/7/00	2500
		20/8/97	1260	12/8/98	1860	1/9/99	1770	1/8/00	980
		21/8/97	1670	13/8/98	1450	7/9/99	790	2/8/00	4000
		25/8/97	1080	14/8/98	1450	8/9/99	1440	3/8/00	970
		26/8/97	1220	17/8/98	2100	9/9/99	1590	4/8/00	1080
		28/8/97	1330	18/8/98	1590	10/9/99	1210	7/8/00	1400
		29/8/97	1332	19/8/98	1510	11/9/99	1150	8/8/00	910
		2/9/97	1280	20/8/98	1440	13/9/99	2400	9/8/00	660
		3/9/97	1300	21/8/98	1540	14/9/99	1200	10/8/00	740
		4/9/97	1400	24/8/98	1930	15/9/99	1720	11/8/00	930
		5/9/97	1280	25/8/98	1630	16/9/99	1500	14/8/00	840
		8/9/97	1220	26/8/98	2000	17/9/99	1380	15/8/00	880
		9/9/97	1440	27/8/98	1870	18/9/99	2900	16/8/00	990
		10/9/97	2400	28/8/98	1860	20/9/99	4100	17/8/00	860
		11/9/97	2600	31/8/98	1900	21/9/99	1730	18/8/00	980
		12/9/97	1640	1/9/98	1540	22/9/99	2100	21/8/00	1190
		15/9/97	1130	3/9/98	1530	23/9/99	2700	22/8/00	1040
		16/9/97	1230	4/9/98	1600	24/9/99	1640	23/8/00	1340
		17/9/97	1230	8/9/98	1840	27/9/99	3600	24/8/00	1430
		18/9/97	1050	9/9/98	1710	28/9/99	3500	25/8/00	900
		19/9/97	1050	10/9/98	1700	30/9/99	3000	28/8/00	860
		22/9/97	880	15/9/98	1740	1/10/99	1060	29/8/00	850
		23/9/97	1010	16/9/98	1680	4/10/99	2000	31/8/00	1090
		24/9/97	1080	17/9/98	1800	5/10/99	1570	1/9/00	830
		25/9/97	1190	18/9/98	1650	6/10/99	1450	5/9/00	1290
		26/9/97	1140	21/9/98	1670	7/10/99	1400	6/9/00	800
		29/9/97	1170	22/9/98	1540	8/10/99	1400	7/9/00	810
		30/9/97	930	23/9/98	1580	12/10/99	2600	8/9/00	980
		1/10/97	1140	24/9/98	1600	13/10/99	1700	12/9/00	2200
		2/10/97	1170	28/9/98	1810	14/10/99	1400	13/9/00	1040
		3/10/97	1120	29/9/98	1880	15/10/99	1030	14/9/00	770
		6/10/97	1200	30/9/98	1720	16/10/99	1400	15/9/00	3300
		7/10/97	1210	1/10/98	1760	18/10/99	1600	18/9/00	550
		8/10/97	1540	2/10/98	2100	19/10/99	1400	19/9/00	530
		9/10/97	1200	5/10/98	1840	20/10/99	1280	20/9/00	1300
		10/10/97	1210	6/10/98	1660	21/10/99	220	21/9/00	1400
		14/10/97	1220	7/10/98	1520	22/10/99	220	22/9/00	1130
		15/10/97	1290	8/10/98	1420	25/10/99	4400	25/9/00	1460

		16/10/97	1330	9/10/98	2600	26/10/99	1220	26/9/00	1300
		17/10/97	1220	13/10/98	2100	27/10/99	2200	29/9/00	1450
		20/10/97	1230	15/10/98	3100	28/10/99	2500	2/10/00	1510
		21/10/97	1250	16/10/98	2200	29/10/99	2700	3/10/00	1450
		22/10/97	1290	17/10/98	2000	4/11/99	600	10/10/00	1710
		23/10/97	1230	19/10/98	2500	5/11/99	1000	11/10/00	1640
		24/10/97	1290	20/10/98	2200	6/11/99	1400	12/10/00	1480
		28/10/97	1490	21/10/98	1510	11/11/99	1260	13/10/00	760
		29/10/97	1220	22/10/98	1320	12/11/99	1280	16/10/00	1930
		30/10/97	1250	23/10/98	1450	15/11/99	2100	17/10/00	1320
		3/11/97	1380	26/10/98	1540	16/11/99	1530	18/10/00	770
		4/11/97	1100	27/10/98	1400	19/11/99	1850	19/10/00	1040
		5/11/97	1140	28/10/98	1520	22/11/99	2900	20/10/00	1270
		6/11/97	1170	29/10/98	1460	23/11/99	1670	23/10/00	1540
		7/11/97	1210	30/10/98	1260	24/11/99	1590	24/10/00	1290
		10/11/97	1160	2/11/98	1950	29/11/99	590	26/10/00	1070
		11/11/97	1350	3/11/98	1640	30/11/99	750	27/10/00	1120
		12/11/97	1210	4/11/98	1400	1/12/99	1040	30/10/00	1420
		14/11/97	1160	5/11/98	1440	2/12/99	1310	31/10/00	1460
		17/11/97	1210	6/11/98	1560	3/12/99	1160	1/11/00	800
		18/11/97	1270	9/11/98	1510	6/12/99	1320	2/11/00	1400
		19/11/97	1470	10/11/98	1540	7/12/99	1100	3/11/00	800
		20/11/97	1290	11/11/98	1830	8/12/99	830	6/11/00	1880
		21/11/97	1380	12/11/98	1700	9/12/99	1110	27/11/00	3100
		24/11/97	1330	13/11/98	1400	10/12/99	1150	28/11/00	4700
		25/11/97	1630	16/11/98	1650	13/12/99	1140	29/11/00	1260
		26/11/97	1620	17/11/98	1640	14/12/99	1180	30/11/00	2200
		27/11/97	1270	18/11/98	1420	15/12/99	1400	1/12/00	1130
		28/11/97	1230	19/11/98	1810	16/12/99	1550	4/12/00	3400
		2/12/97	1820	20/11/98	1380	17/12/99	1300	5/12/00	1640
		3/12/97	1660	23/11/98	1580	20/12/99	1220	6/12/00	1570
		4/12/97	1850	24/11/98	1490	21/12/99	1380	7/12/00	1340
		5/12/97	1860	25/11/98	1400	22/12/99	1370	8/12/00	1250
		8/12/97	1880	26/11/98	1510	23/12/99	1470	11/12/00	1730
		9/12/97	1660	27/11/98	1620	24/12/99	1360	13/12/00	1720
		10/12/97	1720	30/11/98	1600	28/12/99	2300	14/12/00	1310
		11/12/97	1930	1/12/98	1770	29/12/99	1500	15/12/00	1260
		12/12/97	1930	2/12/98	1610			18/12/00	870
		15/12/97	2100	3/12/98	1520			19/12/00	1280
		16/12/97	1920	4/12/98	1580			20/12/00	1190
		17/12/97	1700	7/12/98	2300			21/12/00	1170
		18/12/97	1680	8/12/98	3200			22/12/00	1080
		19/12/97	1670	9/12/98	3100			26/12/00	1380
		22/12/97	1740	10/12/98	2800			27/12/00	1180
		23/12/97	1440	11/12/98	3600				
		24/12/97	1460	14/12/98	2700				
		26/12/97	1720	15/12/98	2200				

		29/12/97	1820	17/12/98	2200				
		30/12/97	1740	18/12/98	1520				
		31/12/97	1570	21/12/98	1780				
				22/12/98	1400				
				23/12/98	1580				
				28/12/98	1830				
				29/12/98	1730				
				30/12/98	1380				
				31/12/98	1490				

COD Data: (Continued)

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
2/1/01	1420	2/1/02	3600	6/1/03	1880	5/1/04	850	1/2/05	660
3/1/01	1390	4/1/02	5400	10/1/03	1500	6/1/04	800		
4/1/01	1520	7/1/02	5000	16/1/03	1290	8/1/04	8300		
5/1/01	1480	8/1/02	3700	20/1/03	1350	9/1/04	770		
8/1/01	1860	10/1/02	3500	22/1/03	1020	12/1/04	770		
9/1/01	1350	14/1/02	2000	24/1/03	1440	15/1/04	870		
10/1/01	1340	16/1/02	2900	5/3/03	1400	20/1/04	870		
11/1/01	1190	18/1/02	1460	7/3/03	1400	22/1/04	670		
12/1/01	1290	22/1/02	1380	12/3/03	1420	26/1/04	680		
15/1/01	1730	24/1/02	3600	17/3/03	1370	29/1/04	670		
16/1/01	1460	28/1/02	1680	19/3/03	1090	30/1/04	620		
17/1/01	1470	30/1/02	1700	20/3/03	850	4/2/04	610		
18/1/01	1080	1/2/02	1740	21/3/03	730	5/2/04	1400		
19/1/01	1290	4/2/02	1740	24/3/03	460	6/2/04	650		
22/1/01	1840	5/2/02	4500	27/3/03	340	10/2/04	1610		
23/1/01	1330	7/2/02	1760	28/3/03	590	11/2/04	1310		
29/1/01	2800	13/2/02	1440	4/4/03	930	16/2/04	1580		
31/1/01	1880	15/2/02	1560	7/4/03	420	17/2/04	860		
1/2/01	1670	18/2/02	2400	10/4/03	550	18/2/04	820		
2/2/01	1500	19/2/02	4300	14/4/03	920	20/2/04	880		
7/2/01	1910	21/2/02	1560	16/4/03	570	24/2/04	1130		
8/2/01	1520	25/2/02	2000	22/4/03	1130	26/2/04	910		
9/2/01	1500	27/2/02	1970	25/4/03	1710	27/2/04	1000		
12/2/01	730	1/3/02	1130	28/4/03	1830	1/3/04	850		
13/2/01	880	4/3/02	990	30/4/03	2400	3/3/04	880		
14/2/01	1410	5/3/02	1580	2/5/03	6000	5/3/04	1190		
15/2/01	1230	7/3/02	870	6/5/03	4600	8/3/04	340		
16/2/01	1210	11/3/02	1520	8/5/03	750	9/3/04	174		
19/2/01	2700	13/3/02	3200	12/5/03	7400	10/3/04	510		
20/2/01	2800	15/3/02	1760	14/5/03	1780	12/3/04	760		

21/2/01	3200	18/3/02	3300	20/5/03	3100	15/3/04	700		
22/2/01	2900	19/3/02	4900	22/5/03	770	16/3/04	600		
23/2/01	2700	25/3/02	860	28/5/03	3500	19/3/04	650		
26/2/01	1690	26/3/02	1920	30/5/03	2100	23/3/04	600		
27/2/01	1350	27/3/02	1820	2/6/03	4100	25/3/04	800		
28/2/01	1690	2/4/02	5400	9/6/03	4600	31/3/04	1890		
2/3/01	3000	3/4/02	1810	11/6/03	4000	7/4/04	600		
5/3/01	3700	8/4/02	2700	13/6/03	3500	13/4/04	770		
6/3/01	3200	10/4/02	5400	16/6/03	3100	16/4/04	1590		
7/3/01	3500	12/4/02	4400	2/7/03	1190	19/4/04	2800		
8/3/01	2600	15/4/02	6300	7/7/03	1360	22/4/04	3400		
9/3/01	3000	16/4/02	4100	9/7/03	2300	26/4/04	2700		
22/3/01	2300	18/4/02	3800	14/7/03	1140	29/4/04	1880		
23/3/01	2400	22/4/02	3900	17/7/03	1080	3/5/04	1860		
24/3/01	2700	24/4/02	3500	23/7/03	3200	5/5/04	1870		
26/3/01	2700	29/4/02	7300	28/7/03	980	6/5/04	2700		
27/3/01	4400	2/5/02	12700	30/7/03	3800	10/5/04	2600		
28/3/01	4300	6/5/02	1380	31/7/03	2100	13/5/04	2100		
29/3/01	4100	8/5/02	2600	1/8/03	1300	14/5/04	2500		
30/3/01	4600	10/5/02	780	5/8/03	1040	18/5/04	2300		
31/3/01	5600	13/5/02	3900	12/8/03	2300	26/5/04	2500		
1/4/01	4200	14/5/02	5500	14/8/03	2300	27/5/04	2100		
2/4/01	4300	16/5/02	8600	18/8/03	1190	1/6/04	3010		
4/4/01	2600	21/5/02	6000	26/8/03	1540	2/6/04	2900		
5/4/01	4800	24/5/02	9800	28/8/03	3500	4/6/04	620		
6/4/01	900	27/5/02	970	29/8/03	1230	7/6/04	2840		
7/4/01	5600	30/5/02	12800	2/9/03	1410	8/6/04	2500		
9/4/01	920	3/6/02	4500	3/9/03	1330	9/6/04	2900		
10/4/01	5300	5/6/02	5900	4/9/03	1170	10/6/04	2000		
11/4/01	4900	10/6/02	2800	5/9/03	810	11/6/04	2140		
12/4/01	4900	13/6/02	4200	9/9/03	1060	14/6/04	2100		
13/4/01	7600	17/6/02	3200	10/9/03	910	15/6/04	2400		
16/4/01	6900	19/6/02	2900	11/9/03	820	16/6/04	2500		
18/4/01	9500	21/6/02	3500	12/9/03	280	22/6/04	2500		
19/4/01	9400	24/6/02	5200	16/9/03	1360	23/6/04	1740		
20/4/01	11200	25/6/02	4600	17/9/03	650	24/6/04	2400		
23/4/01	9500	27/6/02	3100	18/9/03	410	25/6/04	1930		
24/4/01	8800	2/7/02	3300	19/9/03	210	28/6/04	2200		
25/4/01	7300	3/7/02	1020	23/9/03	750	29/6/04	1520		
26/4/01	5700	5/7/02	7600	24/9/03	950	30/6/04	1680		
27/4/01	6300	7/7/02	3400	25/9/03	950	2/7/04	1910		
30/4/01	7300	9/7/02	3500	26/9/03	830	19/7/04	1860		
1/5/01	3400	11/7/02	3100	30/9/03	1830	5/8/04	2300		
2/5/01	2600	15/7/02	1590	1/10/03	830	10/8/04	2000		
3/5/01	2500	17/7/02	1490	2/10/03	820	11/8/04	1100		
4/5/01	3100	19/7/02	4600	3/10/03	800	12/8/04	1430		
7/5/01	4300	23/7/02	3000	7/10/03	770	13/8/04	1410		

8/5/01	5900	25/7/02	1960	8/10/03	1120	16/8/04	1820		
9/5/01	6000	29/7/02	3300			17/8/04	2000		
10/5/01	5800	31/7/02	2700			18/8/04	1550		
11/5/01	6400	2/8/02	1460			19/8/04	1570		
14/5/01	2400	6/8/02	2500			20/8/04	1270		
15/5/01	8600	8/8/02	3100			23/8/04	1760		
16/5/01	6600	12/8/02	1690			24/8/04	1700		
17/5/01	5400	14/8/02	860			25/8/04	1570		
18/5/01	7100	16/8/02	1330			26/8/04	1630		
22/5/01	8700	18/8/02	3700			27/8/04	1870		
23/5/01	7400	20/8/02	1010			30/8/04	1540		
24/5/01	6800	22/8/02	100			31/8/04	1150		
25/5/01	2400	24/8/02	1000			1/9/04	1140		
28/5/01	4100	28/8/02	1980			2/9/04	1900		
29/5/01	4100	30/8/02	1140			3/9/04	1510		
30/5/01	4800	3/9/02	1730			7/9/04	2300		
31/5/01	4600	5/9/02	1010			8/9/04	1870		
1/6/01	4000	9/9/02	2400			13/9/04	1680		
4/6/01	7500	11/9/02	1120			14/9/04	900		
5/6/01	5800	13/9/02	1220			15/9/04	620		
6/6/01	6300	16/9/02	1180			16/9/04	660		
7/6/01	6700	19/9/02	1080			17/9/04	1050		
8/6/01	5700	21/9/02	3400			27/9/04	850		
11/6/01	6700	25/9/02	1230			12/10/04	1580		
12/6/01	7200	17/10/02	1190						
13/6/01	7200	21/10/02	3200						
14/6/01	8400	31/10/02	1340						
15/6/01	8100	4/11/02	3100						
18/6/01	6200	8/11/02	3200						
19/6/01	9100	12/11/02	1870						
20/6/01	6800	14/11/02	1480						
21/6/01	6900	18/11/02	1500						
25/6/01	8700	20/11/02	1460						
26/6/01	7100	22/11/02	1910						
27/6/01	6900	25/11/02	1560						
28/6/01	6100	26/11/02	810						
29/6/01	8400	28/11/02	1420						
3/7/01	5700	2/12/02	910						
4/7/01	5200	4/12/02	800						
5/7/01	2600	9/12/02	1050						
6/7/01	9200	10/12/02	1100						
9/7/01	1320	12/12/02	1380						
10/7/01	2200	16/12/02	1310						
11/7/01	6600	18/12/02	2300						
12/7/01	1340	20/12/02	1380						
13/7/01	6400	23/12/02	1190						
16/7/01	6200								

17/7/01	7100								
18/7/01	7000								
10/10/01	4000								
11/10/01	9000								
12/10/01	3100								
15/10/01	3400								
16/10/01	6600								
17/10/01	3600								
18/10/01	7700								
19/10/01	3300								
22/10/01	8900								
23/10/01	8100								
24/10/01	5600								
25/10/01	5900								
26/10/01	8400								
29/10/01	5100								
30/10/01	3700								
31/10/01	2100								
13/11/01	4400								
14/11/01	1890								
15/11/01	1820								
16/11/01	1670								
19/11/01	8300								
20/11/01	1780								
22/11/01	1660								
23/11/01	1670								
26/11/01	6300								
27/11/01	1680								
28/11/01	1790								
29/11/01	3000								
30/11/01	1450								
4/12/01	1510								
5/12/01	3800								
6/12/01	2000								
7/12/01	2000								
10/12/01	6000								
11/12/01	1890								
12/12/01	5600								
13/12/01	5400								
14/12/01	5000								
17/12/01	3800								
18/12/01	1070								
19/12/01	3800								
20/12/01	810								
21/12/01	3400								
27/12/01	5580								
28/12/01	1404								

3. Average Monthly BOD Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	548	January	995	January	331	January	534	January	830
February	400.5	February	1073	February	174	February	793	February	458
March	840	March	1796	March	2040	March	1183	March	503
April	684	April	2155	April	2395	April	3000	April	1128
May	4400	May	1170	May	953	May	5060	May	1188
June	2685	June	773	June	1384	June	3125	June	883
July	1636.5	July	2118	July	770	July	1715	July	547
August	675	August	375	August	388	August	1759	August	223
September	622.5	September	241	September	480	September	1350	September	378
October	786.5	October	267	October	575	October	728	October	286
November	222	November	331	November	342	November	567	November	500
December	176	December	440	December	600	December	550	December	675

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	462	January	1528	January	141	January	158	January	198
February	560	February	1335	February	†	February	79	February	111
March	1385	March	1477	March	1112	March	361	March	154
April	3196	April	1250	April	208	April	1221	April	450
May	3178	May	5128	May	429	May	650	May	273
June	4325	June	2700	June	2400	June	804	June	145
July	1817	July	1115	July	413	July	317	July	125
August	†	August	607	August	500	August	386	August	101
September	†	September	89	September	120	September	204	September	123
October	3203	October	151	October	13	October	171	October	99
November	1850	November	414	November	†	November	99.6	November	287
December	3000	December	258	December	†	December	†	December	135

†: Denotes missing data

4. Average Monthly COD Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	1300	January	2229	January	1636	January	1799	January	1416
February	1558.25	February	1700	February	1500	February	1792	February	1369
March	1967.2	March	2623	March	3159	March	2345	March	1090
April	1800	April	3745	April	3242	April	5094	April	1889
May	4580	May	2871	May	2513	May	5453	May	2024
June	5366	June	1757	June	2974	June	3969	June	1642
July	3360.6	July	3128	July	2333	July	2572	July	1565
August	2237.5	August	1493	August	1658	August	2289	August	1133
September	1753.7	September	1317	September	1682	September	2071	September	1244
October	1347.4	October	1255	October	1832	October	1655	October	1340
November	1436.5	November	1294	November	1575	November	1425	November	2018
December	1306.8	December	1756	December	2065	December	1310	December	1441

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	1540	January	2993	January	1413	January	1443	January	†
February	1811	February	2270	February	†	February	1063	February	660
March	3473	March	1988	March	965	March	765	March	†
April	6091	April	4419	April	1162	April	1963	April	†
May	5136	May	5912	May	3333	May	2281	May	†
June	6990	June	3990	June	3860	June	2216	June	†
July	5072	July	3120	July	1906	July	1885	July	†
August	†	August	1656	August	1800	August	1628	August	†
September	†	September	1597	September	925	September	1316	September	†
October	5760	October	1910	October	868	October	1580	October	†
November	2878	November	1831	November	†	November	†	November	†
December	3317	December	1269	December	†	December	†	December	†

†: Denotes missing data

5. Average BOD/COD Data:

1996		1997		1998		1999		2000	
Date	value	Date	value	Date	value	Date	value	Date	value
January	0.42	January	0.45	January	0.20	January	0.30	January	0.59
February	0.26	February	0.63	February	0.12	February	0.44	February	0.33
March	0.43	March	0.68	March	0.65	March	0.50	March	0.46
April	0.38	April	0.58	April	0.74	April	0.59	April	0.60
May	0.96	May	0.41	May	0.38	May	0.93	May	0.59
June	0.50	June	0.44	June	0.47	June	0.79	June	0.54
July	0.49	July	0.68	July	0.33	July	0.67	July	0.35
August	0.30	August	0.25	August	0.23	August	0.77	August	0.20
September	0.35	September	0.18	September	0.29	September	0.65	September	0.30
October	0.58	October	0.21	October	0.31	October	0.44	October	0.21
November	0.15	November	0.26	November	0.22	November	0.40	November	0.25
December	0.13	December	0.25	December	0.29	December	0.42	December	0.47

2001		2002		2003		2004		2005	
Date	value	Date	value	Date	value	Date	value	Date	value
January	0.30	January	0.51	January	0.10	January	0.11	January	†
February	0.31	February	0.59	February	†	February	0.07	February	0.20
March	0.40	March	0.74	March	†	March	0.47	March	†
April	0.52	April	0.28	April	0.18	April	0.62	April	†
May	0.62	May	0.87	May	0.13	May	0.28	May	†
June	0.62	June	0.68	June	0.62	June	0.36	June	†
July	0.36	July	0.36	July	0.22	July	0.17	July	†
August	†	August	0.37	August	0.28	August	0.24	August	†
September	†	September	0.06	September	0.13	September	0.16	September	†
October	0.56	October	0.08	October	0.01	October	0.11	October	†
November	0.64	November	0.23	November	†	November	†	November	†
December	0.90	December	0.20	December	†	December	†	December	†

†: Denotes missing data

6. Average Monthly pH Data:

1996		1997		1998		1999		2000	
Date	value	Date	value	Date	value	Date	value	Date	value
January	7.55	January	†	January	†	January	†	January	†
February	7.93	February	†	February	†	February	†	February	†
March	7.35	March	†	March	7.11	March	6.97	March	7.32
April	7.76	April	†	April	†	April	†	April	†
May	7.58	May	7.91	May	†	May	†	May	†
June	7.41	June	†	June	7.47	June	7.6	June	7.34
July	7.48	July	†	July	†	July	†	July	7.86
August	†	August	†	August	†	August	6.81	August	†
September	†	September	†	September	†	September	7.32	September	†
October	†	October	7.45	October	†	October	†	October	†
November	†	November	†	November	8.11	November	†	November	†
December	†	December	7.53	December	†	December	†	December	†

2001		2002		2003		2004		2005	
Date	value	Date	value	Date	value	Date	value	Date	value
January	7.40	January	7.52	January	†	January	†	January	7.330
February	†	February	7.88	February	†	February	†	February	7.440
March	†	March	†	March	6.91	March	6.870	March	7.628
April	6.84	April	†	April	†	April	†	April	7.323
May	†	May	6.28	May	†	May	†	May	7.386
June	†	June	†	June	7.08	June	†	June	7.396
July	†	July	†	July	†	July	†	July	7.478
August	†	August	7.54	August	†	August	†	August	7.730
September	†	September	†	September	7.23	September	7.33	September	7.628
October	†	October	†	October	†	October	7.41	October	7.556
November	†	November	7.41	November	6.95	November	†	November	7.634
December	†	December	7.48	December	†	December	†	December	7.473

†: Denotes missing data

7. Average Monthly Chloride (Cl) Date:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	731	January	†	January	†	January	†	January	†
February	1036	February	†	February	†	February	†	February	†
March	1350	March	†	March	1100	March	†	March	1000
April	1020	April	†	April	†	April	†	April	†
May	1180	May	1430	May	†	May	†	May	†
June	2000	June	†	June	1600	June	†	June	1190
July	1679	July	†	July	†	July	†	July	†
August	†	August	†	August	†	August	†	August	†
September	†	September	†	September	1210	September	†	September	1640
October	†	October	1210	October	†	October	†	October	†
November	†	November	†	November	†	November	†	November	†
December	†	December	1680	December	1750	December	†	December	1400

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	†	January	1560	January	†	January	†	January	†
February	†	February	1480	February	†	February	†	February	†
March	830	March	†	March	556	March	688	March	†
April	†	April	†	April	†	April	†	April	†
May	†	May	146	May	†	May	†	May	†
June	1480	June	†	June	989	June	†	June	†
July	†	July	†	July	†	July	†	July	†
August	†	August	390	August	†	August	1630	August	†
September	†	September	†	September	1050	September	851	September	†
October	†	October	†	October	†	October	†	October	†
November	†	November	1020	November	760	November	†	November	†
December	†	December	1100	December	†	December	†	December	†

†: Denotes missing data

8. Average Monthly Calcium Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	140.00	January	†	January	†	January	†	January	†
February	170.75	February	†	February	†	February	†	February	†
March	197.80	March	†	March	273.00	March	261.00	March	175.00
April	184.00	April	†	April	†	April	†	April	†
May	238.00	May	†	May	†	May	†	May	†
June	431.00	June	†	June	156.00	June	122.00	June	214.00
July	147.00	July	†	July	†	July	†	July	†
August	†	August	†	August	†	August	18.00	August	†
September	†	September	†	September	†	September	120.00	September	57.90
October	†	October	36.00	October	†	October	†	October	†
November	†	November	†	November	†	November	†	November	†
December	†	December	184.00	December	†	December	†	December	163.00

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	†	January	†	January	†	January	†	January	†
February	†	February	88.00	February	†	February	†	February	206.50
March	194.00	March	†	March	†	March	†	March	176.00
April	†	April	†	April	†	April	†	April	290.00
May	†	May	410.00	May	†	May	†	May	310.00
June	197.00	June	†	June	†	June	†	June	270.00
July	†	July	†	July	†	July	†	July	250.00
August	†	August	†	August	†	August	†	August	203.50
September	†	September	†	September	†	September	0.01	September	181.50
October	†	October	†	October	†	October	0.01	October	183.50
November	†	November	140.00	November	†	November	0.01	November	187.00
December	†	December	†	December	†	December	†	December	181.50

†: Denotes missing data

9. Average Monthly Sulfate Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	62.0	January	†	January	†	January	†	January	†
February	15.0	February	†	February	†	February	†	February	†
March	20.0	March	†	March	†	March	108.0	March	14.0
April	90.0	April	†	April	†	April	†	April	†
May	100.0	May	14.20	May	†	May	†	May	†
June	36.0	June	26.31	June	6.60	June	4.00	June	25.0
July	32.0	July	38.92	July	†	July	†	July	†
August	†	August	14.90	August	†	August	0.70	August	†
September	†	September		September	†	September	20.0	September	26.0
October	†	October	66.0	October	†	October	†	October	†
November	†	November		November	6.90	November	†	November	†
December	†	December	12.0	December	†	December	†	December	76.0

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	36.0	January	10.00	January	†	January	†	January	29
February	†	February	17.50	February	†	February	†	February	11.8
March	†	March	†	March	50.0	March	10.0	March	39.5
April	†	April	†	April	†	April	†	April	14
May	†	May	34.50	May	†	May	†	May	17.5
June	230.0	June	†	June	13.0	June	†	June	8.35
July	†	July	†	July	†	July	†	July	6.95
August	†	August	95.00	August	†	August	287.0	August	43
September	179.0	September	†	September	164.0	September	16.6	September	183.5
October	†	October	†	October	†	October	25.5	October	64.2
November	†	November	142.00	November	61.0	November	7	November	35
December	†	December	280.00	December	†	December	†	December	38

†: Denotes missing data

10. Average Monthly Zinc Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	0.51	January	†	January	†	January	†	January	†
February	0.44	February	†	February	†	February	†	February	†
March	0.70	March	†	March	0.37	March	1.49	March	0.04
April	0.50	April	0.92	April	†	April	†	April	†
May	2.22	May	†	May	†	May	†	May	†
June	1.71	June	†	June	†	June	0.30	June	0.30
July	1.17	July	†	July	†	July	†	July	1.63
August	†	August	†	August	†	August	0.03	August	†
September	†	September	†	September	0.21	September	0.36	September	0.04
October	†	October	0.13	October	†	October	†	October	†
November	†	November	†	November	†	November	†	November	†
December	†	December	0.32	December	†	December	†	December	0.08

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	†	January	†	January	†	January	†	January	0.585
February	†	February	0.15	February	†	February	†	February	0.555
March	0.590	March	†	March	0.089	March	0.30	March	0.480
April	†	April	†	April	†	April	†	April	0.750
May	†	May	1.49	May	†	May	†	May	0.455
June	4.60	June	†	June	0.37	June	†	June	0.640
July	†	July	†	July	†	July	†	July	0.440
August	†	August	0.25	August	†	August	0.10	August	0.295
September	†	September	†	September	0.20	September	0.89	September	0.315
October	†	October	†	October	†	October	0.76	October	0.285
November	†	November	0.12	November	0.74	November	1.26	November	0.426
December	†	December	†	December	†	December	†	December	0.350

†: Denotes missing data

11. Average Vinyl Chloride Data:

1996		1997		1998		1999		2000	
Date	µg/l	Date	µg/l	Date	µg/l	Date	µg/l	Date	µg/l
January	†	January	†	January	†	January	†	January	†
February	†	February	†	February	†	February	†	February	†
March	†	March	†	March	2.50	March	3.00	March	1.00
April	†	April	†	April	†	April	†	April	†
May	†	May	†	May	†	May	†	May	†
June	†	June	†	June	2.50	June	3.00	June	3.00
July	†	July	†	July	†	July		July	†
August	†	August	†	August	†	August	3.00	August	†
September	†	September	†	September	†	September	1.50	September	0.50
October	†	October	1.90	October	†	October	†	October	†
November	†	November	1.90	November	0.50	November	†	November	†
December	†	December	1.90	December	†	December	†	December	2.00

2001		2002		2003		2004		2005	
Date	µg/l	Date	µg/l	Date	µg/l	Date	µg/l	Date	µg/l
January	†	January	0.50	January	†	January	†	January	2.00
February	†	February	0.60	February	†	February	†	February	2.00
March	†	March	†	March	20.00	March	1.90	March	2.00
April	†	April	†	April	†	April	†	April	2.00
May	5.00	May	0.50	May	†	May	†	May	2.00
June	†	June	†	June	2.00	June	†	June	2.00
July	†	July	†	July	†	July	†	July	2.00
August	†	August	0.60	August	†	August	3.30	August	2.00
September	2.00	September	†	September	5.00	September	3.30	September	2.00
October	†	October	†	October	†	October	2.00	October	2.00
November	†	November	0.50	November	3.00	November	2.00	November	2.00
December	†	December	†	December	†	December	†	December	2.00

†: Denotes missing data

12. Average Monthly Toluene Data:

1996		1997		1998		1999		2000	
Date	**µg/l**	**Date**	**µg/l**	**Date**	**µg/l**	**Date**	**µg/l**	**Date**	**µg/l**
January	†	January	68.70	January	†	January	†	January	†
February	†	February	68.70	February	†	February	†	February	†
March	†	March	68.70	March	120.0	March	100.0	March	9.40
April	†	April	112.0	April	†	April	†	April	†
May	†	May	112.0	May	†	May	†	May	†
June	†	June	112.0	June	36.70	June	32.0	June	51.00
July	†	July	40.30	July	†	July	†	July	†
August	†	August	40.30	August	†	August	30.0	August	†
September	†	September	40.30	September	40.30	September	18.8	September	0.50
October	†	October	36.80	October	†	October	†	October	†
November	†	November	36.80	November	†	November	†	November	†
December	†	December	36.80	December	3.20	December	†	December	0.50

2001		2002		2003		2004		2005	
Date	**µg/l**	**Date**	**µg/l**	**Date**	**µg/l**	**Date**	**µg/l**	**Date**	**µg/l**
January	†	January	28.4	January	†	January	†	January	5.0
February	†	February	7.5	February	†	February	†	February	128.0
March	55.0	March	†	March	150.0	March	49.5	March	5.0
April	†	April	†	April	†	April	†	April	21.25
May	†	May	37.9	May	†	May	†	May	221.25
June	†	June	†	June	45.7	June	†	June	143.0
July	†	July	†	July	†	July	†	July	94.2
August	†	August	13.0	August	†	August	6.4	August	6.0
September	23.8	September	†	September	5.0	September	240.0	September	5.0
October	†	October	†	October	†	October	29.0	October	6.0
November	†	November	34.6	November	81.0	November	298.0	November	108.0
December	†	December	†	December	†	December	†	December	91.0

†: Denotes missing data

13. Average Monthly Copper Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	0.100	January	†	January	†	January	†	January	†
February	0.051	February	†	February	†	February	†	February	†
March	0.067	March	†	March	0.082	March	0.226	March	0.065
April	0.043	April	0.070	April	†	April	†	April	†
May	0.062	May	†	May	†	May	†	May	†
June	0.058	June	†	June	0.050	June	0.043	June	0.064
July	0.045	July	†	July	†	July	†	July	0.239
August	†	August	†	August	†	August	0.044	August	†
September	†	September	†	September	†	September	0.031	September	0.016
October	†	October	0.050	October	†	October	†	October	†
November	†	November	†	November	†	November	†	November	†
December	†	December	0.113	December	†	December	†	December	0.318

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	†	January	†	January	†	January	†	January	0.279
February	†	February	0.420	February	†	February	†	February	0.158
March	0.060	March	†	March	0.190	March	0.120	March	0.141
April	†	April	†	April	†	April	†	April	0.038
May	†	May	0.032	May	†	May	†	May	0.195
June	0.100	June	†	June	0.190	June	†	June	0.295
July	†	July	†	July	†	July	†	July	0.118
August	†	August	0.193	August	†	August	0.440	August	0.104
September	†	September	†	September	0.220	September	0.136	September	0.087
October	†	October	†	October	†	October	0.745	October	0.084
November	†	November	0.970	November	0.027	November	0.595	November	0.091
December	†	December	†	December	†	December	†	December	0.046

†: Denotes missing data

14. Average Monthly Lead Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	0.010	January	†	January	†	January	†	January	†
February	0.027	February	†	February	†	February	†	February	†
March	0.025	March	†	March	0.030	March	0.030	March	0.050
April	0.005	April	0.011	April	†	April	†	April	†
May	1.730	May	†	May	†	May	†	May	†
June	0.018	June	†	June	0.030	June	0.030	June	0.100
July	0.007	July	†	July	†	July	†	July	0.163
August	†	August	†	August	†	August	0.030	August	†
September	†	September	†	September	†	September	0.030	September	0.050
October	†	October	0.060	October	†	October	†	October	†
November	†	November	†	November	†	November	†	November	†
December	†	December	0.030	December	†	December	†	December	0.050

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	†	January	†	January	†	January	†	January	0.020
February	†	February	0.020	February	†	February	†	February	0.020
March	0.100	March	†	March	0.010	March	0.010	March	0.020
April	†	April	†	April	†	April	†	April	0.020
May	†	May	0.020	May	†	May	†	May	0.020
June	0.050	June	†	June	0.010	June	†	June	0.020
July	†	July	†	July	†	July	†	July	0.020
August	†	August	0.020	August	†	August	0.010	August	0.020
September	†	September	†	September	0.020	September	0.016	September	0.020
October	†	October	†	October	†	October	0.020	October	0.020
November	†	November	0.020	November	0.011	November	0.020	November	0.020
December	†	December	†	December	†	December	†	December	0.020

†: Denotes missing data

15. Average Monthly Iron Data:

1996		1997		1998		1999		2000	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	9.49	January	†	January	†	January	†	January	†
February	6.29	February	†	February	†	February	†	February	†
March	6.58	March	†	March	5.46	March	11.80	March	1.67
April	7.87	April	23.30	April	†	April	†	April	†
May	10.60	May	†	May	†	May	†	May	†
June	3.22	June	†	June	2.68	June	3.05	June	3.09
July	10.50	July	†	July	†	July	†	July	34.95
August	†	August	†	August	†	August	14.70	August	†
September	†	September	†	September	†	September	2.39	September	0.80
October	†	October	0.23	October	†	October	†	October	†
November	†	November	†	November	†	November	†	November	†
December	†	December	3.80	December	†	December	†	December	4.09

2001		2002		2003		2004		2005	
Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l	Date	mg/l
January	†	January	†	January	†	January	†	January	10.00
February	†	February	2.50	February	†	February	†	February	11.25
March	2.90	March	†	March	5.120	March	5.90	March	8.90
April	†	April	†	April	†	April	†	April	16.40
May	†	May	34.0	May	†	May	†	May	13.55
June	21.00	June	†	June	7.07	June	†	June	12.70
July	†	July	†	July	†	July	†	July	10.15
August	†	August	3.20	August	†	August	7.70	August	6.45
September	†	September	†	September	6.20	September	9.96	September	6.95
October	†	October	†	October	†	October	9.90	October	4.30
November	†	November	2.80	November	4.74	November	11.50	November	6.50
December	†	December	†	December	†	December	†	December	5.65

†: Denotes missing data

APPENDIX B

Monthly Precipitation and Temperature and Calculated Potential Evapotranspiration (PET)

13. Monthly Precipitation and Temperature Records
14. Calculated Potential Evapotranspiration

Notes:

- ➢ Data for precipitation and temperature were obtained from Environment Canada for Ottawa MacDonald-Carter International Airport Station
- ➢ Potential Evapotranspiration was calculated using Thornthwaite water balance method

1. Year: 1996

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	73.5	-11.7	---	---	73.50
February	68.2	-9.0	---	---	68.20
March	22.2	-3.2	---	---	22.2
April	100.2	4.1	0.74	18.09	82.11
May	58.6	12.2	3.86	58.09	0.51
June	67.6	19.0	7.55	93.32	-25.72
July	106.5	20.1	8.22	99.11	7.39
August	42.2	20.1	8.22	99.11	-56.91
September	117.0	16.3	5.98	79.20	37.80
October	95.2	7.9	2.00	36.49	58.71
November	63.8	-1.2	---	---	63.80
December	101.8	-2.5	---	---	101.80
Total	**916.8**		**36.56**	**483.41**	**433.39**

2. Year: 1997

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	91.8	-11.8	---	---	91.8
February	101	-8.3	---	---	101
March	85.3	-4.6	---	---	85.3
April	48	5.4	1.12	25.20	22.79
May	78.3	10.2	2.94	49.14	29.15
June	55.2	20.2	8.28	100.71	-45.51
July	67.5	20.8	8.65	103.85	-36.35
August	63.6	18.9	7.48	93.91	-30.31
September	86.1	14.1	4.80	69.04	17.05
October	46.2	7.2	1.73	34.09	12.10
November	79.4	-0.4	---	---	79.40
December	33.8	-6.4	---	---	33.80
Total	**836.2**		**35.03**	**475.97**	**360.22**

3. Year: 1998

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	135.3	-7.8	---	---	135.30
February	22.2	-3.9	---	---	22.20
March	120.5	-0.6	---	---	120.50
April	55.3	8.5	2.23	35.95	19.35
May	33.4	17.5	6.66	83.08	-49.68
June	119.0	19.1	7.61	91.95	27.05
July	85.1	20.8	8.66	101.51	-16.41
August	50.4	20.5	8.47	99.82	-49.42
September	72.6	15.7	5.65	73.25	-0.65
October	71.4	9.3	2.56	39.90	31.50
November	46.5	3.0	0.46	10.74	35.76
December	65.0	-2.9	---	---	65.00
Total	**876.7**		**42.30**	**536.20**	**340.50**

4. Year: 1999

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	103.1	-5.7	---	---	103.10
February	28.3	-6.0	---	---	28.30
March	105.5	-2.8	---	---	105.50
April	20.4	6.8	1.59	27.88	-7.48
May	36.4	16.3	5.98	77.55	-41.15
June	78.2	20.6	8.53	101.98	-23.78
July	133.0	22.4	9.68	112.48	20.52
August	46.6	19.4	7.79	95.07	-48.47
September	149.6	17.5	6.66	84.27	65.33
October	63.2	7.6	1.88	31.76	31.44
November	77.5	4.4	0.82	16.75	60.75
December	77.1	-4.3	---	---	77.10
Total	**918.9**		**42.95**	**547.74**	**371.16**

5. Year: 2000

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	55.4	-10.2	---	---	55.40
February	51.0	-7.1	---	---	51.00
March	73.1	1.8	0.21	8.03	65.07
April	108.6	5.0	1.00	23.49	85.11
May	126.8	13.2	4.35	65.09	61.71
June	131.0	16.9	6.32	84.37	46.63
July	70.1	19.5	7.85	98.05	-27.95
August	76.0	19.3	7.73	96.99	-20.99
September	80.5	13.9	4.70	68.72	11.78
October	28.2	8.6	2.27	41.51	-13.31
November	84.0	1.7	0.20	7.57	76.43
December	96.5	-10.5	---	---	96.50
Total	**981.2**		**34.63**	**485.78**	**487.39**

6. Year: 2001

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	44.9	-9.4	---	---	44.90
February	69.2	-8.7	---	---	69.20
March	50.7	-3.0	---	---	50.70
April	14.0	6.7	1.56	27.72	-13.72
May	81.1	14.9	5.22	68.95	12.15
June	98.0	19.7	7.97	94.80	3.20
July	38.6	19.8	8.03	95.34	-56.74
August	68.6	22.0	9.42	107.51	-38.91
September	78.4	15.9	5.76	74.25	4.15
October	98.0	9.4	2.60	40.78	57.22
November	81.6	4.3	0.80	16.72	64.88
December	69.8	-1.4	---	---	69.8
Total	**792.9**		**41.37**	**526.08**	**266.82**

7. Year: 2002

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	36.0	-4.9	---	---	36.00
February	49.7	-5.9	---	---	49.70
March	72.4	-3.0	---	---	72.40
April	85.3	6.4	1.45	28.55	56.75
May	91.5	10.9	3.25	51.02	40.48
June	224.8	17.3	6.55	84.41	140.39
July	47.8	21.7	9.23	108.06	-60.26
August	39.4	21.2	8.91	105.35	-65.95
September	71.6	17.8	6.84	87.07	-15.47
October	78.0	6.2	1.38	27.58	50.42
November	72.8	0.2	0.01	0.65	72.15
December	19.4	-5.5	---	---	19.4
Total	**888.7**		**37.62**	**492.69**	**396.01**

8. Year: 2003

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	22.1	-13.5	---	---	22.10
February	51.9	-12.1	---	---	51.90
March	73.0	-3.8	---	---	73.00
April	56.8	3.8	0.66	16.05	40.75
May	129.4	13.0	4.25	61.34	68.06
June	57.0	18.5	7.25	90.10	-33.10
July	93.6	20.8	8.66	102.38	-8.78
August	63.6	21.0	8.78	103.45	-39.85
September	65.2	16.8	6.26	81.12	-15.92
October	148.0	7.1	1.70	31.72	116.28
November	105.2	2.4	0.33	9.73	95.47
December	112.4	-5.3	---	---	112.4
Total	**978.2**		**37.89**	**495.90**	**482.30**

9. Year: 2004

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	29.0	-15.8	---	---	29.00
February	33.3	-7.9	---	---	33.30
March	67.2	0.0	0.00	0	67.20
April	70.6	5.5	1.16	25.14	45.46
May	72.2	12.8	4.15	62.06	10.14
June	76.4	17.1	6.43	84.61	-8.21
July	65.2	20.7	8.59	103.80	-38.60
August	111.0	18.6	7.31	92.57	18.43
September	142.8	16.1	5.87	79.32	63.48
October	60.4	8.7	2.31	41.06	19.34
November	87.8	1.9	0.23	8.06	79.74
December	91.2	-8.3	---	---	91.2
	907.1		36.06	496.62	410.48

10. Year: 2005

Month	Total Precip. (mm)	Mean Temp. (C)	Heat Index(i)	PET	Net Water Balance (mm)
January	52.1	-11.7	---	---	52.10
February	32.4	-7.0	---	---	32.40
March	32.8	-3.6	---	---	32.80
April	143.8	7.2	1.74	29.91	113.89
May	48.0	11.4	3.48	50.74	-2.74
June	125.4	21.2	8.91	103.56	21.84
July	106.2	22.1	9.49	108.63	-2.43
August	82.2	21.5	9.10	105.24	-23.04
September	104.0	17.1	6.43	80.88	23.12
October	100.4	9.5	2.64	41.14	59.26
November	n/a	n/a	---	---	---
December	n/a	n/a	---	---	---
	827.3		41.79	520.09	307.21