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Transport of perchlorate in the Las Vegas Wash and Lake Mead

Manjula Roshan Boralessa
University of Nevada, Las Vegas

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TRANSPORT OF PERCHLORATE IN THE LAS VEGAS WASH AND LAKE MEAD

by

Manjula Roshan Boralessa

Bachelor of Science
Cornell University, Ithaca
1994

Masters of Engineering
Cornell University, Ithaca
1995

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Manjula Roshan Boralessa

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative

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ABSTRACT

Transport of Perchlorate in Las Vegas Wash and Lake Mead

by

Manjula Roshan Boralessa

Dr. Jacimaria R. Batista, Examination Committee Chair
Assistant Professor of Environmental Engineering
University of Nevada, Las Vegas

This thesis investigates the fate of perchlorate in the Las Vegas Wash and Lake Mead resulting from the long-term contamination by the manufacturing of rocket fuels in Henderson, Nevada. The changes in perchlorate concentrations for the Las Vegas Wash and Lake Mead were investigated for the last 10 years by analyzing frozen water samples. An attempt was made to model the transport of perchlorate along the Wash, and to observe the transport and mixing of perchlorate within the Lake. Statistical analyses were performed to observe seasonal variations in perchlorate levels within the epilimnion, metalimnion and hypolimnion layers of the Lake, and to correlate perchlorate levels with total dissolved solids concentrations. Investigation showed that multiple sources contribute to the perchlorate contamination in the Wash. Perchlorate levels had increased significantly from 1995. Lake stratification strongly influences perchlorate levels within each thermal layer; lake storage level is less significant.

TABLE OF CONTENTS

ABSTRACT iii

LIST OF FIGURES vi

LIST OF TABLES viii

ACKNOWLEDGEMENTS x

CHAPTER 1 STATEMENT OF THE PROBLEM 1
1.1 Introduction 1
1.2 Objectives 4

CHAPTER 2 BACKGROUND 5
2.1 Properties and Characteristics of Perchlorate 5
2.2 The Major Applications of Perchlorate 7
2.3 Occurrence of Perchlorate 9
2.4 Health and Toxicological Effects of Perchlorate 10
2.5 Regulatory Perchlorate Levels 11
2.6 Perchlorate Production in Henderson, Nevada 12
2.6.1 BMI Complex Site Location 13
2.6.2 History of the BMI Complex 14
2.6.3 PEPCON Facility Operations 14
2.6.4 The Production of Perchlorate at the KMCC Site 15
2.6.5 Perchlorate Manufacturing Process at the KMCC Facility 16
2.6.6 Production of Perchlorate at the PEPCON Plant 19
2.6.7 Perchlorate Waste Disposal at KMCC 19
2.6.8 The Major Components of the KMCC Perchlorate Disposal System 21
2.6.9 Perchlorate Migration Pathways from Operational Activities at KMCC 29
2.6.10 Perchlorate Waste Disposal at PEPCON 30
2.7 Key Geological and Hydrological Features of the BMI Complex 31
2.7.1 BMI Site Geology 31
2.7.2 BMI Site Hydrogeology 33
2.7.3 Key Geological Hydrological Features of the PEPCON Site 37
2.7.4 Perchlorate in Ground Water: KMCC Property 38
2.8 Perchlorate Loading on the Las Vegas Wash 40
2.8.1 History of Investigations on the LVW 40
2.8.2 Perchlorate Investigations in the LVW 43
2.9 Limitations on the Accuracy of the Background Information 44
2.10 Lake Mead Options 45

2.10.1 Limnology of Lake Mead 47
2.10.2 Lake Mead Water Quality and Monitoring 51

CHAPTER 3 MATERIALS AND METHODS 53
3.1 Source of Water Samples 53
3.2 Thawing Procedure 58
3.3 Quality Assurance (QA) and Quality Control (QC) 60

CHAPTER 4 HISTORICAL PERCHLORATE LEVELS IN LAKE MEAD AND LAS VEGAS WASH 61
4.1 Historical Perchlorate Concentrations along the Las Vegas Wash 62
4.1.1 Relationship between Wash Flow and Perchlorate Levels 73
4.1.2 Comparison of Perchlorate Data for the Wash Sampling Points 76
4.2 Perchlorate Level Trends in Lake Mead 78
4.2.1 Major Sampling Locations Analyzed 80
4.2.2 Perchlorate Level Distribution within Lake Mead 82
4.2.3 Influence of Stratification on Perchlorate Distribution 85
4.2.4 Perchlorate Levels at the Individual Sampling Points 92
4.3 Comparison of Total Dissolved Solids and Perchlorate Concentrations 107
4.4 TDS Concentrations along the Las Vegas Wash 108
4.5 TDS Concentrations in Lake Mead 110

CHAPTER 5 ESTIMATION OF THE TOTAL PERCHLORATE LOADING INTO THE WASH ISTORICAL PERCHLORATE 116
5.1 Estimation of the Total Perchlorate Loading from the Contaminated Area 116
5.2 Estimation of the Perchlorate Loading from the KMCC Seepage 120
5.3 Finite Difference Method 122
5.3.1 Single Source Model 123
5.3.2 Distributed Source Model 126
5.4 Discussion 129

CHAPTER 6 CONSLUSIONS AND RECOMMENDATIONS 131

Appendix A-Data on Perchlorate, Flow, Lake Storage and TDS Levels 138
Appendix B-Statistical Analyses of Perchlorate Data 166
Appendix C-Comparison of Perchlorate and TDS Levels 200
Appendix D-Finite Element Analyses Computer Code 230
Appendix E-Accuracy of the USGS Streamflow Data Records 236
Appendix F- Procedure for the Analyses of Low Concentration of Perchlorate in Water by Ion Chromatography 239

REFERENCES 244

VITA 249

LIST OF FIGURES

Figure 1.1	Lake Mead and Las Vegas Wash System	03
Figure 1.2	Surface Drainage System in the Project Area	03
Figure 2.1	The BMI Complex and KMCC Site	13
Figure 2.2	Raw Material Usage in the Production of Perchlorates	18
Figure 2.3	The Surface Drainage System of KMCC	22
Figure 2.4	BMI Site Geology	33
Figure 2.5	Approximate Perchlorate Levels in Groundwater	40
Figure 3.1	Water Sampling Locations of the Las Vegas Wash	55
Figure 3.2	Water Sampling Locations in Lake Mead.	57
Figure 3.3	Water Sampling Locations in the Las Vegas Bay, Lake Mead	57
Figure 4.1	Perchlorate Concentrations of LVW1 Sampling Point	64
Figure 4.2	Perchlorate Concentrations of LVW3K Sampling Point.	65
Figure 4.3	Perchlorate Concentrations of LVW5 Sampling Point	65
Figure 4.4	Perchlorate Levels along the Las Vegas Wash	67
Figure 4.5	Historical Perchlorate Concentrations in the Las Vegas Wash.	67
Figure 4.6	Historical Yearly Average Perchlorate Loadings along the Las Vegas Wash	68
Figure 4.7	Historical Yearly Average Perchlorate Loadings along the Las Vegas Wash	68
Figure 4.8	Average Perchlorate Loading Rates on Non-High Flow Dates	75
Figure 4.9	Average Perchlorate Levels within Different Thermal Layers	85
Figure 4.10	Average Perchlorate Concentration Profile within the Epilimnion.	86
Figure 4.11	Average Perchlorate Concentration Profile within the Metalimnion	87
Figure 4.12	Average Perchlorate Concentration Profile within the Hypolimnion	87
Figure 4.13.a	Perchlorate Concentrations at LM2CE.	92
Figure 4.13.b	Perchlorate Concentrations at LM2CH	93
Figure 4.13.c	Epilimnion and Hypolimnion Perchlorate Levels at LM2C.	93
Figure 4.14.a	Perchlorate Concentrations at LM2NE.	93
Figure 4.14.b	Perchlorate Concentrations at LM2NH	94
Figure 4.14.c	Epilimnion and Hypolimnion Perchlorate Levels at LM2N.	94
Figure 4.15.a	Perchlorate Concentrations at LM2SE	94
Figure 4.15.b	Perchlorate Concentrations at LM2SH	95
Figure 4.15.c	Epilimnion and Hypolimnion Perchlorate Levels at LM2S.	95
Figure 4.16.a	Perchlorate Concentrations at LM3CE.	96
Figure 4.16.b	Perchlorate Concentrations at LM3CM	97
Figure 4.16.c	Perchlorate Concentrations at LM3CH.	97
Figure 4.16.d	Epilimnion and Hypolimnion Perchlorate Levels at LM3C.	97
Figure 4.17.a	Perchlorate Concentrations at LM3NE.	98
Figure 4.17.b	Perchlorate Concentrations at LM3NH	98

Figure 4.17.c Epilimnion and Hypolimnion Perchlorate Levels at LM3N. 98
Figure 4.18.a Perchlorate Concentrations at LM3SE 99
Figure 4.18.b Perchlorate Concentrations at LM3SH 99
Figure 4.18.c Epilimnion and Hypolimnion Perchlorate Levels at LM3S. 99
Figure 4.19.a Perchlorate Concentrations at LM4E. 100
Figure 4.19.b Perchlorate Concentrations at LM4M 101
Figure 4.19.c Perchlorate Concentrations at LM4H 101
Figure 4.19.d Epilimnion Metalimnion and Hypolimnion Perchlorate Levels at LM4 101
Figure 4.20.a Perchlorate Concentrations at LM5E. 102
Figure 4.20.b Perchlorate Concentrations at LM5M 103
Figure 4.20.c Perchlorate Concentrations at LM5H 103
Figure 4.20.d Epilimnion, Metalimnion and Hypolimnion Perchlorate Levels at LM5 103
Figure 4.21.a Perchlorate Concentrations at LM8E. 104
Figure 4.21.b Perchlorate Concentrations at LM8M 105
Figure 4.21.c Perchlorate Concentrations at LM8H 105
Figure 4.21.d Epilimnion, Metalimnion and Hypolimnion Perchlorate Levels at LM8 105
Figure 4.22 Perchlorate Concentrations at LM9H 106
Figure 4.23 Perchlorate and TDS Concentrations of LVW5. 108
Figure 4.24 Perchlorate and TDS Concentrations of LVW3K 109
Figure 4.25 Average TDS Levels in Lake Mead 111
Figure 5.1 Water Sampling Locations of the Las Vegas Wash 118
Figure 5.2 Total Perchlorate Loading Model for the Las Vegas Wash. 119
Figure 5.3 Locations of the Key Sampling Points along the Las Vegas Wash 124
Figure 5.4 Perchlorate Load Distribution for the Single Source Model 125
Figure 5.5 Perchlorate Levels Predicted by the KMCC Main Plume. 126
Figure 5.6 Approximate Perchlorate Levels within the KMCC Site and the Las Vegas Wash 127
Figure 5.7 Perchlorate Concentration Distribution for the Distributed-Source Model 128

LIST OF TABLES

Table 2.1	Action Levels Adopted for Perchlorate by Several States	12
Table 2.2	Estimated Perchlorate Production within the KMCC Site	16
Table 2.3	The Major Waste Recipients for KMCC	19
Table 2.4	Summary of Perchlorate Disposal Information for KMCC	21
Table 2.5	Average Loading of Contaminants into the Beta Ditch Wastewater	23
Table 2.6	Major Characteristics of the Ammonium Perchlorate Ponds	26
Table 2.7	Major Features of the P-1, Old P-2 and S-1 Ponds	27
Table 2.8	Major Drainage Parameters of the BMI Site Alluvial Layers	35
Table 2.9	Pollutant Loading on the LVW from the BMI Tailing Ponds	41
Table 2.10	Major Water Quality Paramets of the BMI Seepage	42
Table 2.11	Major Physical Features of Lake Mead	46
Table 2.12	Lake Mead Water Budget	46
Table 2.13	Seasonal Intrusion Changes of the Wash Discharge in Lake Mead	49
Table 2.14	Key Limnological Parameters of Lake Mead	50
Table 2.15	Lake Mead Dispersion Coefficients	50
Table 3.1	Major Sampling Points along the Las Vegas Wash	54
Table 3.2	Major Sampling Points in the Las Vegas Bay Area, Lake Mead	55
Table 3.3	Major Sampling Points in Boulder Basin, Lake Mead	56
Table 4.1	Average Annual Perchlorate Data for Las Vegas Wash Samples.	66
Table 4.2	Wastewater Disposal Information for Henderson	72
Table 4.3	Comparision of Perchlorate Data on High-Flow and Typical Dates	73
Table 4.4	Average Perchlorate Loading Rates on Non-High Flow Dates	75
Table 4.5	Comparison of Perchlorate Levels for the Las Vegas Wash Samples	76
Table 4.6	Statistical Analyses of Perchlorate and Flow Data for the Wash	77
Table 4.7	Major Sampling Points in Lake Mead	81
Table 4.8	Ten-year Average Perchlorate Levels in Lake Mead	83
Table 4.9	Summary of Statistical Analyses for Perchlorate Concentrations among Hypolimnion, Metalimnion and Epilimnion Layers	84
Table 4.10	Summary of Statistical Analyses for Seasonal Variations in Perchlorate Levels in the Epilimnion	88
Table 4.11	Summary of Statistical Analyses for Seasonal Variation in Perchlorate Levels in the Hypolimnion	89
Table 4.12	Summary of Statistical Analyses for Comparison of Perchlorate Data Before and from 1995	90
Table 4.13	Summary of Statistical Analyses for Comparison of Perchlorate and Lake Storage Levels	91
Table 4.14	Summary of Average TDS Levels in the Las Vegas Wash	110
Table 4.15	Summary of Average TDS Levels in Lake Mead	111

Table 4.16 Summary of Statistical Analyses for TDS between Hypolimnion and Epilimnion Layers 112
Table 4.17 Perchlorate and TDS Regression Analyses 114
Table 5.1 Assumptions and Variable Definitions for Point Loading Model 118
Table 5.2 Average Wastewater Treatment Plant and Wash Discharges for 1997. 119
Table 5.3 Variables Definitions and the Major Assumption for the Alluvial Channel Seepage 121
Table 5.4 Summary of the Calculated and Measured Perchlorate Loadings 122
Table 5.5 The Main Model Input Parameters for the Wash Modeling 123
Table 5.6 Description of the Key Sampling Points along the Las Vegas Wash 124
Table 5.7 The Perchlorate Levels Predicted by the KMCC Main Plume 125
Table 5.8 Comparison of the Predicted Perchlorate Levels of the Distributed Source Model 128

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CHAPTER 1

STATEMENT OF THE PROBLEM

1.1 Introduction

The Lake Mead/Colorado River system is one of the highly utilized water systems in the USA. The combined system provides drinking water to over 22 million individuals in the Western United States, irrigation water for agriculture, and provides ample recreational opportunities (LaBounty and Horn, 1997). The recent discovery of perchlorate (ClO_4^-) in Lake Mead and downstream sections of the Colorado River System has generated considerable interest in the investigation of its occurrence, fate and transport. Perchlorate is of environmental concern because it is known to affect the thyroid gland by inhibiting the uptake of iodine into the gland. Studies are currently underway to further investigate the health effects of perchlorate on humans and the environment (EPA, 1999). Perchlorate is a highly water-soluble and non-volatile substance. These properties increase its mobility and its persistence in the natural environment. The current drinking water standards do not regulate perchlorate in water supplies. However, California has set an advisory standard of 18 ppb. The EPA has recently set a provisional level of 32 ppb for drinking water (EPA, 1999).

Groundwater contamination by perchlorate in Nevada is a direct result of the disposal of process effluents by perchlorate manufacturing industries located in

Henderson, Nevada. Manufacturing of perchlorate was started by the former Pacific Engineering & Production Company of Nevada (PEPCON) in 1958, and continued until it was destroyed by an explosion in May, 1988. Production at a second plant has been carried out from 1945 to the present. Kerr-McGee Chemical Corporation (KMCC) currently operates this plant. During this period, considerable amounts of process effluents have been discharged by both plants into unlined surface drainage channels that conveyed the effluents into a series of unlined evaporation ponds. As a result of continuous percolation of perchlorate contaminated water into the underlying aquifer, the groundwater in the vicinity of the industrial complex has been contaminated. Groundwater obtained from some of these monitoring wells has contained perchlorate levels as high as 18,000 ppm (Broadbent & Associates, 1998).

The contaminated groundwater seeps into the Las Vegas Wash (LVW) that runs approximately 3 miles north/northeast of the site. The LVW is the major drainage channel in the Las Vegas Valley. It originates from the Spring Mountains, and flows along the valley bottom into Lake Mead. The wash receives treated effluents from the three wastewater treatment plants, as well as storm water runoff, and return groundwater flow. The perchlorate-contaminated groundwater seeps into the Wash in the BMI area. The contaminated seepage contains about 100 ppm perchlorate. In the Wash, the perchlorate concentrations vary from 9 ppb to about 750 ppb depending on the location. Perchlorate concentrations of 10-20 ppb have been detected in the water intake area for Las Vegas, and in the Hoover Dam release area of Lake Mead (EPA, 1999). The pollutant is carried ultimately into the Colorado River System via the Hoover Dam release of Lake Mead (Figures 1.1 and 1.2).

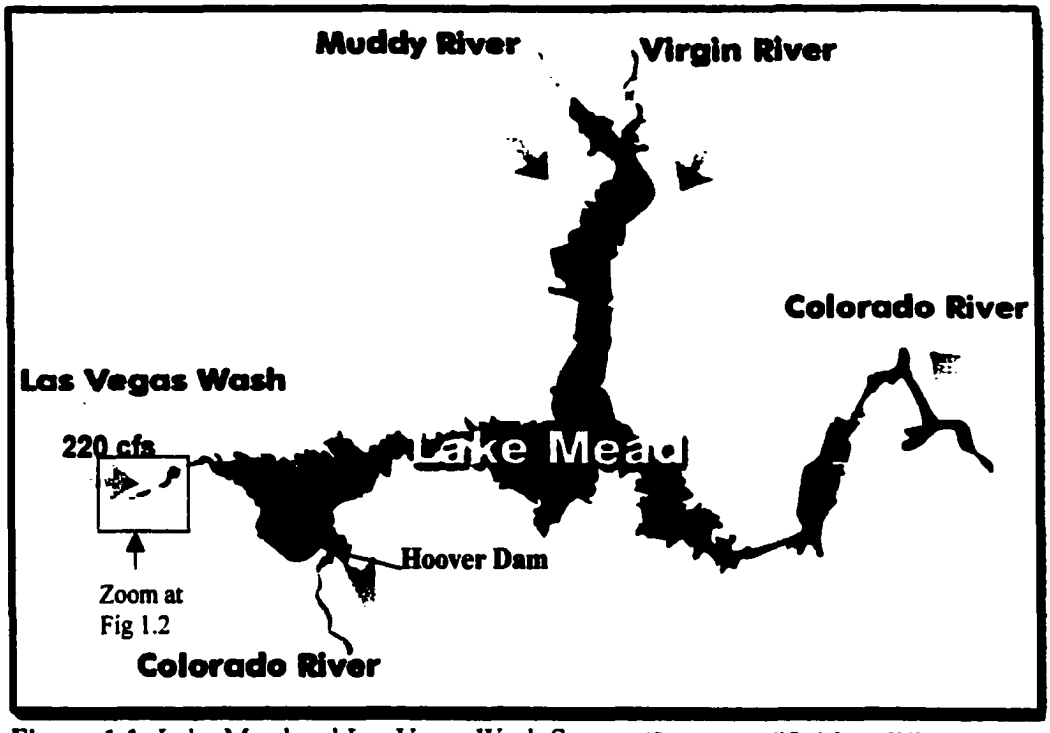


Figure 1.1: Lake Mead and Las Vegas Wash System (Source: Modified from SNWA, 2000)

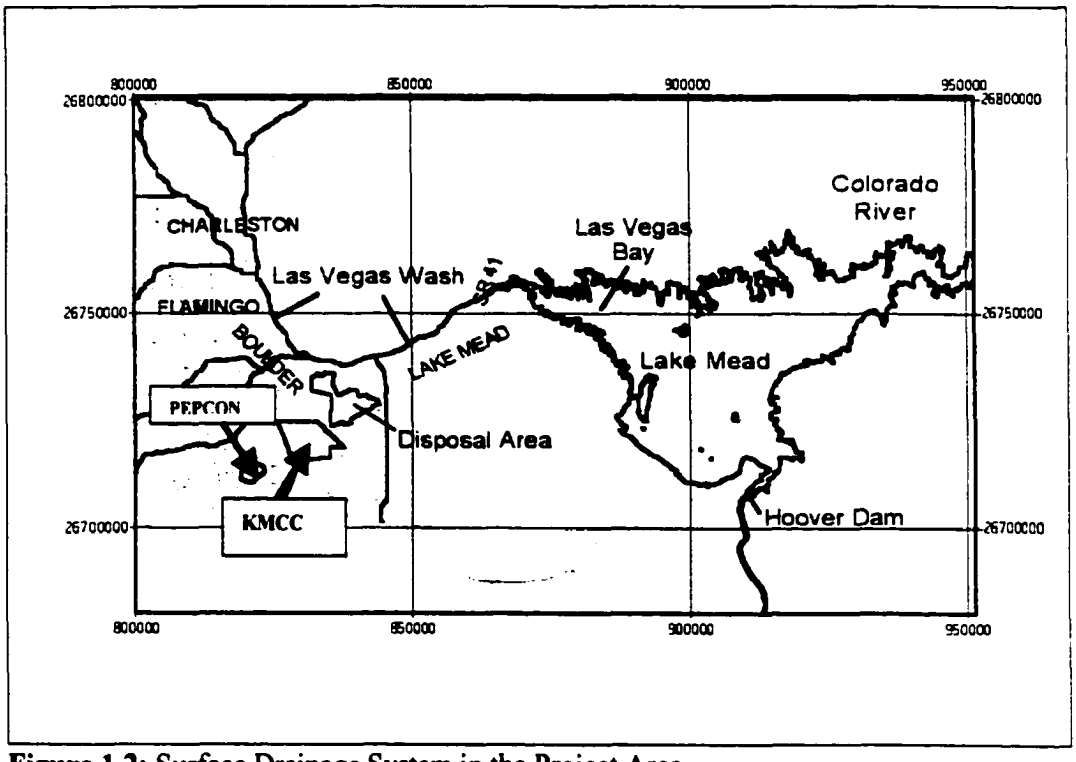


Figure 1.2: Surface Drainage System in the Project Area

1.2 Objectives

Groundwater quality investigations have been carried out within the contaminated site during the last four years, as an effort to investigate the fate of perchlorate underneath the BMI contaminated site. However, there is relatively little known about the fate and transport of perchlorate within the LVW and Lake Mead. Better understanding of the fate and transport of perchlorate in this area will certainly assist with implementing remedial measures.

This Thesis investigates the transport of perchlorate from the seepage in the BMI area through the Las Vegas Wash, and into Lake Mead. For this study, current and past perchlorate concentrations in the wash and the lake were investigated. The past perchlorate concentrations were obtained by analyzing frozen water samples from the Wash and the Lake. The specific objectives of this research are as follows:

1. To document past perchlorate concentrations of Lake Mead and Las Vegas Wash by analyzing frozen water samples.
2. Investigate the sources of perchlorate contamination in the Las Vegas Wash.
3. To model the transport of perchlorate from the contaminated site through the Las Vegas Wash using finite difference modeling.
4. Investigate temporal and spatial variations of perchlorate in the Wash and the Lake.

CHAPTER 2

BACKGROUND

2.1. Properties and Characteristics of Perchlorate

Perchlorate anion (ClO_4^-) is a non-volatile oxidizing anion, which originates from the dissociation of solid salts in water. In the solid state, it posses nearly a perfect tetrahedral geometry (Schilt, 1979). The most common sources of perchlorate are perchloric acid ($HClO_4$), ammonium perchlorate (NH_4ClO_4), and metal perchlorates such as Li, Na, K, Rb and Cs. In addition, perchlorate also exists as organic, inorganic and halogen compounds. Several hydrates of perchloric acid also exist. Except for potassium perchlorate, most other perchlorate salts are readily soluble in water.

Perchloric acid is extremely acidic and displays high oxidizing strengths towards active metals and also when both hot and concentrated. Ammonium perchlorate, which is the most widely used form of perchlorate in the world, is an extremely reactive, shock sensitive, and highly explosive. In its solid form, ammonium perchlorate has colorless rhombic, orthorhombic, and white crystal structures with a specific density of 1.95 (Prager, 1997). This has a high water solubility of 24.922 g/ 100 g of water at 25^0 C, and dissociates into its ionic constituents readily. Ammonium perchlorate is considered to be thermally stable below 110^0 C, decomposes at 130^0 C, and explodes at 380^0 C (Schilt, 1979). However, it is not considered to be persistent in the environment, and can

be reduced biologically to chlorides (Zhang, 2001). The rate of breakdown in the natural environment depends on many factors, and therefore, under many conditions perchlorate could persist in the natural environment for decades. The existence of perchlorate in the BMI Complex in Henderson, Nevada for several decades after the initial contamination, is a strong example for this behavior.

The most predominant characteristic of perchlorate is its explosive and flammable tendency. The most hazardous compounds in terms of explosive nature are those that are sensitive to heat or shock. Some of the most predominant compounds are silver perchlorates, fluorine perchlorates, and perchlorate esters of aliphatic alcohols (Schilt, 1979). Covalent perchlorates such as organic perchlorates and certain heavy metal perchlorates are also extremely explosive (Schilt, 1979). Some perchlorates, for example monohydrates, which are considerably stable under most conditions, tend to be extremely explosive when in contact with organic matter.

Several violent explosions had been caused during the production and usage of perchlorate in the past. One of the most violent reported explosions occurred in Los Angeles, California on February 20, 1947 that caused the death of 17 persons. The explosion occurred during the introduction of a plastic holder to a mixture of perchloric acid and acetic anhydride contained in a stainless steel tank fitted with a refrigeration system that had been shut off at the time of the explosion (Schilt, 1979). A second accident occurred in the former PEPCON plant in Nevada on May 4th, 1988 during the production of ammonium perchlorate. This accident took the lives of two individuals and injured about 350 (Committee on Science, Space and Technology, 1988). The shock

waves of this explosion were felt like a mini nuclear explosion, toppled cars and were even detected in California.

Due to its explosive nature, it is generally recommended not to store most perchlorate compounds for extended periods of times, and they should be prepared only when needed. Therefore, it has been a common practice to discard surplus batches and imperfect mixtures. Further, the perchlorate contained in missile and rocket inventory has to be replaced with fresh supplies due to its short shelf life.

2.2 The Major Applications of Perchlorate

Perchlorate was first synthesized by Von Stadion in 1816 using a vacuum distillation of a mixture of sulfuric acid and potassium chlorate with saturated aqueous solution of chlorine dioxide by electrolysis (Prager, 1997). Subsequently, several other processes were developed. However, the next important contribution was made by G.S. Serullas, who synthesized ammonium perchlorate, and several other metal perchlorates in 1830's. The first commercial production of perchlorate was initiated in Sweden in 1893, and was later spread to other European countries and USA. The production increased drastically during World Wars I and II. The application of ammonium perchlorate as a solid rocket fuel was discovered in the 1940's that gave a considerable boost to its production.

Ammonium perchlorate (AP) serves as an oxidizer in solid rocket fuel. During the manufacturing of rocket fuels, a raw fuel ingredient is mixed with an oxidizer (AP) to a specific recipe to form the propellant. Metallic particles such as magnesium are often used as the raw fuel ingredient (Committee on Science, Space and Technology, 1988).

The mixture is loaded into the rocket after further processing. Due to its strong reducing power AP can undergo a variety of reactions that lead to the release of many gaseous products, which provides a considerable thrust during reaction.

Today, perchlorate is widely known for its used in the aerospace and military industry as a major component in rocket fuel and explosives, and is primarily manufactured in the form of ammonium perchlorate (NH_4ClO_4). The largest users of AP in the United States are the National Aeronautics and Space Administration (NASA) and the U.S. Air Force. For example, a single space flight test requires over 1.7 million pounds of ammonium perchlorate (Committee on Science, Space and Technology, 1988).

The other major users are the Army, Navy, and industries. Some of the large-scale industrial uses are in nuclear reactors, electronic industry, components of air bag inflators, lubricating oils, tanning and fabric industries, electroplating, aluminum refining, rubber manufacturing, paints and enamels (EPA 1999 and Prager, 1997). Ammonium perchlorate is also used as an etching agent, animal fattening agent, engraving agent, in fireworks and in several industrial processes.

Potassium perchlorate has been widely used in the medical field to treat thyroid disorders. One such example is the application for the treatment of patients with Grave diseases that results from the over production of growth hormones by the thyroid gland. In such cases potassium perchlorate has been given as a competitive inhibition substance to iodine, which reduces thyroidal activity. Although this practice no longer exists, potassium perchlorate is still used diagnostically to monitor the function of the thyroid hormone.

2.3 Occurrence of Perchlorate

Initially perchlorate was considered only as an artificial substance. In 1958 Becking et al. reported the discovery of perchlorate in the sea. Their studies reported concentrations between 10 to 10,000 ppm. However, several other independent groups have later refuted this study. One such investigation was the study conducted by Greenhalgh and Riley in 1960 (cited in Schilt, 1979), who analyzed seawater samples from 30 locations spanned from the Northern and Southern hemispheres. There were no detectable levels of perchlorates in their samples. Another investigation was carried out by Johannesson in the seawater samples taken off the coast of New Zealand in 1960. There was no evidence for perchlorate in these samples as well. The main reason for the initial inaccurate findings is believed to be caused by the limitations in the analytical capabilities of the detection method adopted during this period (Schilt, 1979). Low levels of perchlorate have been detected in raw materials used for the manufacturing of fertilizers in Chile. However, a recent study conducted on 45 products that are used in agriculture, horticulture and retail markets demonstrated that the contribution of fertilizers as a perchlorate contaminant source to be insignificant (Susarla et al, 1999). During this study, perchlorate was only detected in sodium nitrate fertilizers derived from Chilean caliche; none of the others showed perchlorate levels beyond the detection limit.

Until 1997, the occurrence of perchlorate could not be adequately investigated due to the unavailability of sensitive detection methods. During this period the lowest detectable threshold level for perchlorate was 100 ppb. Most widespread occurrences went undetected since the concentrations were much below the minimum detection limit.

In 1997, the California Department of Health Services developed a new analytical method to detect perchlorate concentrations as low as 4 ppb. With the development of this technique, it was possible to identify many contaminated water bodies that had gone undetected before. Since then, perchlorate has been found in water supplies of California, Nevada, and Arizona that supply water to over 15 million people (EPA, 1999). Perchlorate also has been detected in several other states: AR, IA, IN, KS, MD, NM, NY, PA, TX, UT, and WV (EPA, 1999).

2.4 Health and Toxicological Effects of Perchlorate

The existing knowledge on the toxicological and health effects of perchlorate is very limited. The most predominant health risk is the explosive and flammable tendency. Exposure to perchlorate at high concentrations is considered to be irritant to skin and mucous membranes (Prager, 1997). However, the health and toxicological effects of long-term exposure of perchlorate at low concentrations are poorly understood. Existing data show its potential to affect thyroidal hormone production; however there are no strong supporting data to evaluate the dose-response for the effects on the thyroid, developing fetuses, and other target tissues (EPA, 2000). The only available human health studies are the clinical reports from the patients treated for Grave's disease. The patients who were administered potassium perchlorate to treat excessive thyroidal activity developed skin rashes, sore throat, gastrointestinal irritation and showed hematological effects (Mayer, 2000). Another reason of concern is the limited understanding of the effects of perchlorate on sensitive groups such as small children,

elderly, individuals with chronic health problems, and on fetuses. Further, there is limited information available on the ecological impacts of perchlorate.

An Interagency Perchlorate Steering Committee has been formed consisting representatives from the EPA, Department of Defense, Agency for Toxic Substances and Disease Registry, National Institute for Environmental Health Sciences, local government agencies, and affected Tribal communities (EPA, 2000). The main mandate of this committee is to promote and coordinate studies on the occurrence, health effects, treatment technologies, and ecological impacts of perchlorate in the USA. Currently, EPA is evaluating the toxicological and the human risk assessment studies, and the results are yet to be published (EPA, 2000).

2.5 Regulatory Perchlorate Levels

Currently, there is no federal National Primary Drinking Water Regulation level for perchlorate. However, perchlorate has been listed in the EPA's Safe Drinking Water Act's Contaminant Candidate List (EPA, 1999). EPA had established a provisional perchlorate reference dose (FRD) range of 4-18 ppb based on the information available in 1992 and on revised data of 1995 (EPA, 1999). To establish the dose the EPA considered a standard body weight (70 Kg) and a daily water consumption level of 2 L/day. EPA has also established a drinking water equivalent level (DWEL) of 31.5 ppb, based on the above criterion, assuming perchlorate is consumed only from drinking water. Besides the above EPA levels, several state agencies have recommended perchlorate levels. These levels are summarized in Table 2.1 below.

Table 2.1: Action Levels Adopted for Perchlorate by Several States

Agency/Year	Purpose	Perchlorate Level
California Department of Health Services (CDHS), (1997)	Provisional Action Level in public water supplies	18 ppb
Nevada Department of Environmental Protection, (March, 1999)	Recommended Temporary Action Level for cleanup	18 ppb
Arizona Department of Health Services, (March, 1999)	Provisional Health Based Guidance Level	32 ppb

(Source: Modified from EPA, 1999)

2.6 Perchlorate Production in Henderson, Nevada

Two perchlorate production facilities operated in the area. One of them is the site that is currently referred to as the Kerr-McGee Chemical Corporation (KMCC) facility. This facility is located within the Basic Management Industrial (BMI) Complex, and has been operated since 1945. Three perchlorate manufacturers operated this facility since 1945, including the present facility operator, KMCC. The other facility is the Pacific Engineering & Production Company of Nevada (PEPCON) plant. This facility is located outside the BMI complex, and had been manufacturing perchlorate from 1958 until it was destroyed by an explosion in May, 1988. Before the explosion, the PEPCON plant was manufacturing approximately 10,000-15,000 tons of ammonium perchlorate annually; the annual production for KMCC plant was 16,000-18,000 tons per year (Committee on Science, Space and Technology, 1988). The entire ammonium perchlorate demand for the USA and the "Free World" was supplied by these two facilities.

2.6.1 BMI Complex Site Location

The BMI complex is located in Henderson, Nevada approximately 13 miles southeast of Las Vegas (Figure 2.1). The BMI Complex houses many industries, including the KMCC facility. The City of Henderson is immediately to the east-southeast of the site. There are several residential communities located within one-two miles from the complex. The Las Vegas Wash runs approximately 3 miles from the site.

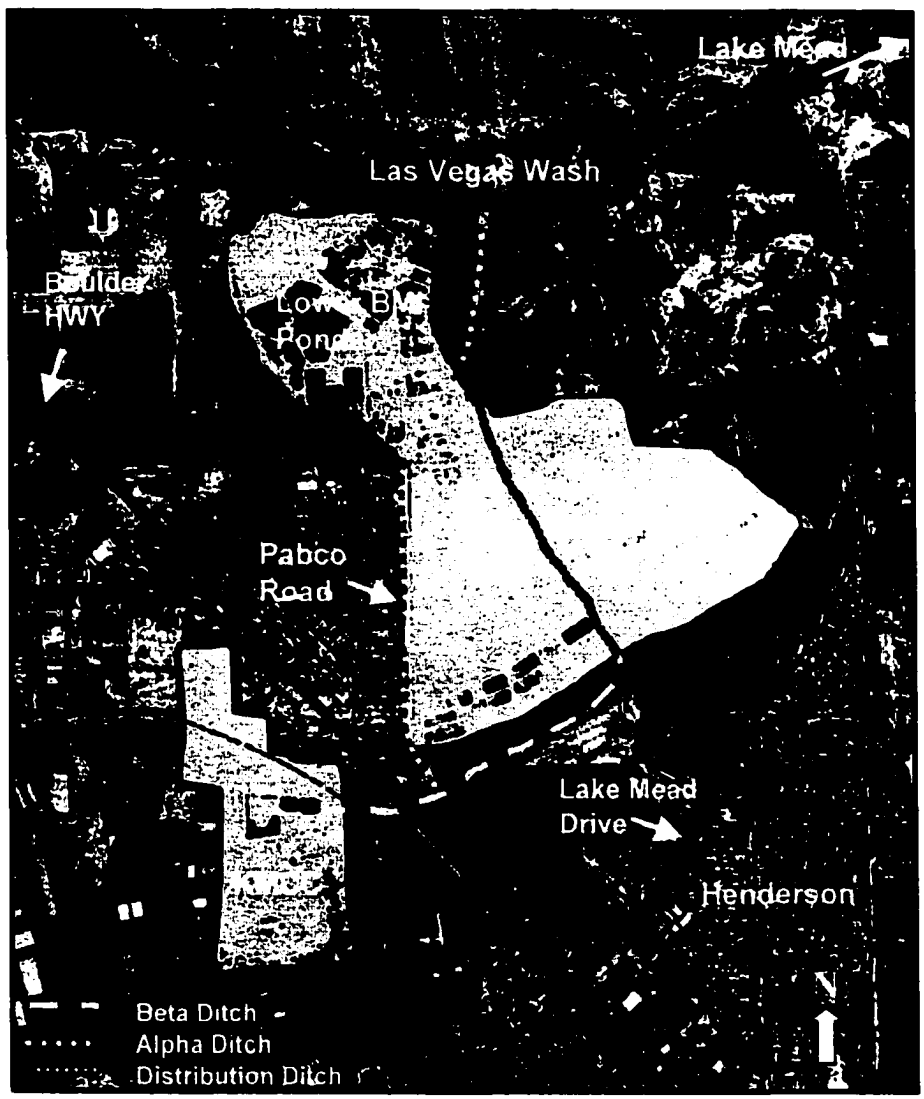


Figure 2.1: The BMI Complex and KMCC Site (Source: Modified from KMCC, 2000)

2.6.2 History of the BMI Complex

The BMI complex was originally developed by the United States Government as a magnesium production facility on July 5, 1941. The location of the site was chosen based on the availability of a large magnesium ore deposit within a reasonable distance, and the availability of water and power in the region. The production of magnesium continued for approximately two years until it was shut down on November 15, 1944 (Geraghty & Miller, 1993). However, the production of several other industrial chemicals continued under different management arrangements.

The next significant change came in 1945 when Western Electrochemical Company (WECCO), a privately owned company, acquired the operation of a section of the US Government site (present KMCC site). WECCO produced various chemicals ranging from sodium chlorate, potassium chlorate, potassium perchlorate, ammonium perchlorate and manganese dioxide (KMCC, 1980; Kleinfelder, 1993).

2.6.3 PEPCON Facility Operations

PEPCON began manufacturing of ammonium perchlorate in 1958. This plant was destroyed on May 4th, 1988 by an explosion. The site is located at the northeast intersection of Gibson Road and Lake Mead Drive in Henderson, Nevada. The distance to the Las Vegas Wash is approximately 4 miles. Figure 1.2 shows the location of the PEPCON facility

2.6.4 Production of Perchlorate at the KMCC Site

Production of perchlorate at the present KMCC site was initiated with the acquisition of section of the Government Site by WECCO. Initially the plant was operated solely for the Department of Navy; but in 1946 production of chlorates and perchlorates were also started for the commercial market (Kleinfelder, 1993). WECCO operated the plant from 1945 to 1955. In 1955 American Potash and Chemical Corporation (AP & CC) acquired the operation of the site through an agreement reached with WECCO. AP & CC operated the plant from 1955 until 1967. In 1967 Kerr-McGee Chemical Corporation (KMCC) began the operation of the facility. In addition to the chemicals produced by the predecessors, KMCC introduced six new chemicals into the final production process, including sodium perchlorate, magnesium perchlorate, and sodium chlorate (Kleinfelder, 1993). Although, sodium perchlorate has been produced since 1945, it has been primarily used as feed stock for the ammonium perchlorate and potassium perchlorate production (Kleinfelder, 1993). The activities of the perchlorate manufacturing industries are summarized in Table 2.2. According to these data, the total amount of perchlorate production within the KMCC facility could be estimated as 343,027 tons.

Table 2.2 Estimated Perchlorate Production within the KMCC Site

Company	Potassium Perchlorate		Ammonium Perchlorate		Magnesium Perchlorate		Sodium Perchlorate	
	Amount (tons)	Perio d	Amount (tons)	Period	Amount (tons)	Period	Amount (tons)	Period
WECCO	10,402	1945-1955	7,142	1951-1955	none		none	Period
AP&CC	3,142	1956-1967	83,240	1956-1967	none		none	
KMCC	8,762	1967-1982	214,776	1967-1993*	744	1969-1976	14,819	1968-1993*
TOTALS	22,306		305,158		744		14,819	

The quantities shown above apply for the final products only; intermediate quantities are not included.
*The production was continuing at the time of publication of the source document in 1993.
(Source: Adapted from KMCC, 1980; KMCC, 1984; Kleinfelder, 1993)

2.6.5 Perchlorate Manufacturing Process at the KMCC Facility

Production of sodium chlorate was the first step in the manufacturing of perchlorates. Sodium chloride was dissolved in water, and then was converted to sodium chlorate using electrolytic cells. Initially, 1,300 Schumacher electrolytic cells were used for chlorate production; but in 1989 they were replaced by 24 Krebs cells (Kleinfelder, 1993). The main production process is illustrated in Figure 2.2. Pure sodium chlorate was separated from the brine solution by crystallization. The facility had a maximum production capacity of 32,000 tons of sodium chlorate per year initially. A small portion of the compound was removed as a finished product, and the balance was re-dissolved to make the feedstock to produce sodium perchlorate.

The production of sodium perchlorate was carried out by oxidizing sodium chlorate, using electrolytic cells. The main raw materials used in the process included water, hydrochloric acid, soda ash, cellulose filter aid, diatomaceous earth, and sodium dichromate. The batches that did not meet the desired specifications were redissolved and returned to the production process (KMCC, 1987). The reactions were carried out

by a batch process, and the process equipment included electrolytic cells and external holding tanks (Kleinfelder, 1993). The main waste stream included filter material and cell bottoms.

Sodium perchlorate was used as the feedstock for the production of potassium perchlorate. First, solid potassium chloride was dissolved in hot water. Then, the solution was filtered and added to a crystallization tank containing sodium perchlorate. The formation of potassium perchlorate occurs almost immediately. The mixture was cooled, and potassium perchlorate crystals were recovered by a primary centrifuge. The recovered crystals were washed and dissolved again. The solution was fed into a secondary centrifuge and then into a gas-fired rotary dryer for recovery. The crystals were then processed for shipment. The production process also had a recovery system to recycle the fines back into the crystallizer.

Production of ammonium perchlorate was carried out by reacting sodium perchlorate with ammonia and hydrochloric acid. Ammonium perchlorate crystals were recovered by a centrifuge. The recovered crystals were washed and dissolved again. The solution was fed into a concentrator and secondary centrifuge that had been placed in drying building. The product was subjected to several physical and chemical processing steps prior to shipping depending on the individual customer requirements.

Production of magnesium perchlorate was carried out with the reaction of magnesium carbonate with ammonium perchlorate, using steam condense as a liquid carrier (Kleinfelder, 1993).

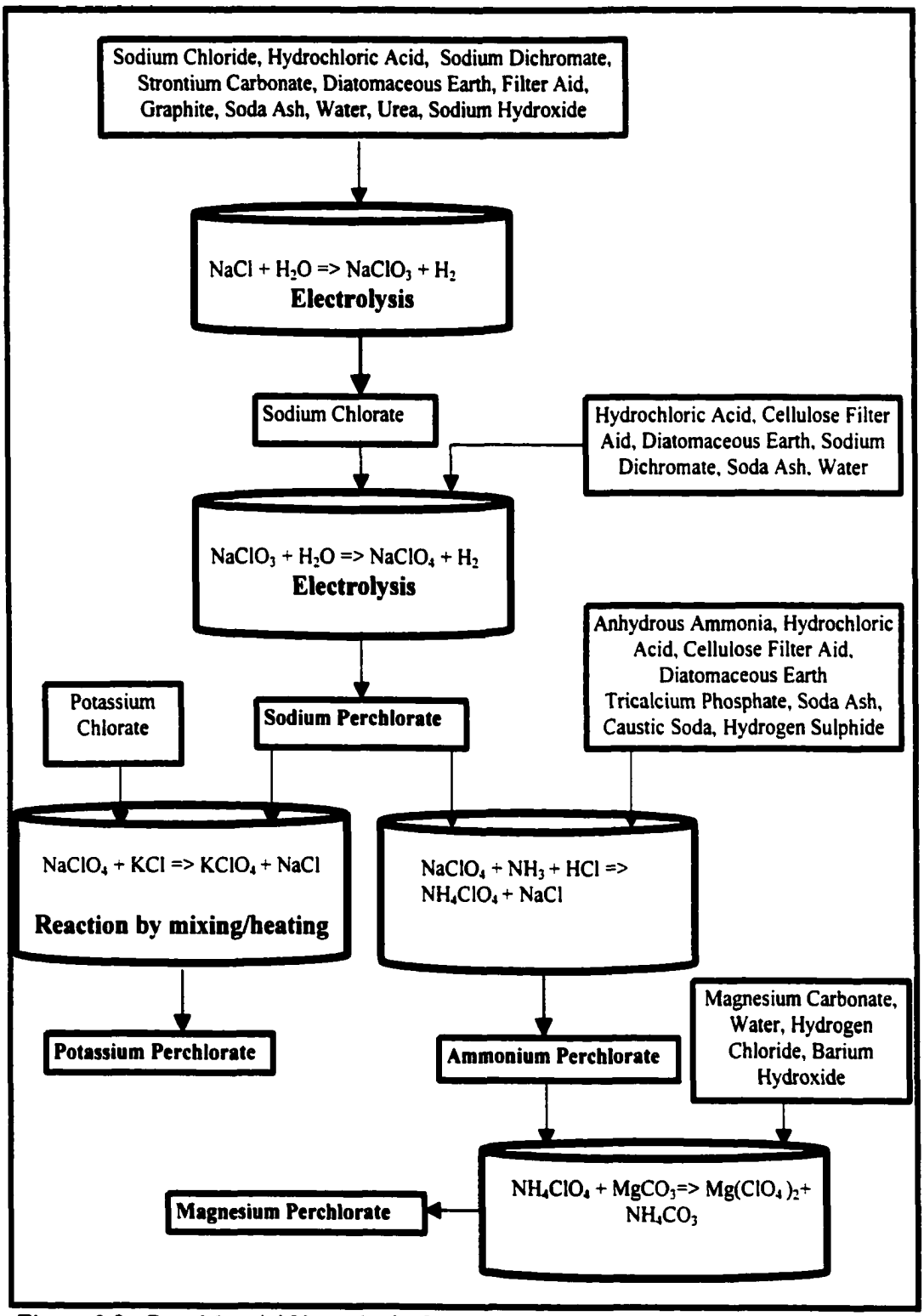


Figure 2.2: Raw Material Usage in the Production of Perchlorates (Modified from Kleinfelder, 1993; KMCC 1984, KMCC, 1979).

2.6.6 Production of Perchlorate at the PEPCON Plant

There is relatively limited information available on the manufacturing process of perchlorate, waste generation and disposal at this facility. This could be due to the fact that this plant was destroyed before the discovery of perchlorate in the Colorado River Samples in1997, and also the majority of the records kept by PEPCON could have been destroyed during the explosion. Before the explosion, the PEPCON plant was manufacturing approximately 10,000-15,000 tons of ammonium perchlorate annually (Committee on Science, Space and Technology, 1988). It is known that PEPCON utilized a different production technology to manufacture ammonium perchlorate.

2.6.7 Perchlorate Waste Disposal at KMCC

The perchlorate process effluents were discharged into a surface drainage system that carried the effluents into a series of evaporation ponds. Perchlorate solid wastes have also been disposed at the BMI and the Hazardous Waste (H.W.) landfills. The major recipients of perchlorate wastes are given in Table 2.3, and are shown in Figure 2.1.

Table 2.3: The Major Waste Recipients for KMCC

Waste Recipient	Period
BMI Ponds • Trade Effluent Ponds • Upper and Lower Ponds	1945 to1976
S-1, Old P-2 and P-1 Ponds	1976 to 1983
AP-1-5 Ponds	1974 onwards
BMI Landfill	1943 to 1980
KMCC Hazardous Waste Landfill	1980 to January 1983

(Modified from Kleinfelder, 1993).

In addition to the direct disposal of perchlorate wastes, groundwater contamination could have also occurred by the following means:

1. Infiltration from the surface Drainage System (Beta, Alpha, Western, and the Northwest Drainage Ditches, and the Western Trench System)
2. Temporary perchlorate material/waste storage pads.
3. Leaks in liquid perchlorate transport pipe system among plants.
4. Material handling within perchlorate manufacturing buildings.

The Beta Ditch (Figure 2.1) was the main surface channel that was used for the transport of perchlorate liquids from the perchlorate manufacturing in the KMCC site from 1941 to 1976 (Kleinfelder, 1993). Perchlorate liquid wastes were disposed into BMI unlined ponds, and several on-site leachbeds until 1976 via the Beta Ditch. During the mid 1970's these were gradually replaced by a combination of lined ponds, BMI Dump, Sanitary Landfill, and H.W. Landfill (Kleinfelder, 1993). Several operational and process modifications were carried out to reduce the generation of wastes, waste recovery and waste disposal. In 1976 the facility achieved " Zero Discharge " status. The " Zero Discharge" referred here implies that no process water or liquids was allowed to flow out from the site property or into the natural environment. There could have been other pathways for contaminants to migrate into the natural environment. For example, it is possible that perchlorate could have migrated into the natural environment via the solid wastes, as the unlined BMI Landfill has been used to dispose solid residue from the lined ponds. Perchlorate waste disposal information is summarized in Table 2.4 below:

Table 2.4: Summary of Perchlorate Disposal Information for KMCC

Waste Type/Process	Source	Period	Disposal
Sodium Perchlorate	filter cakes, cell bottoms	1951-1976 1976-1983	BMI Ponds S-1, P-1 and Old P-2 Ponds
Potassium Perchlorate	filter cakes,	1945-1976 1976-1983 1980-1983	BMI Ponds S-1 and P-1 Ponds KMCC Hazardous Waste Landfill
Magnesium Perchlorate	filter cakes and process area washing	1969-1976 Mid 70's to 1976	BMI Ponds S-1 and P-1 Ponds
Ammonium Perchlorate	filter cakes and process washing	1951-1974 1974 onwards	BMI Ponds AP-1,2,3 Ponds and recycling

(Modified from Kleinfelder, 1993).

2.6.8 The Major Components of the KMCC Perchlorate Disposal System

BMI Drainage Ditches:

As stated above, the Beta Ditch was the primary mode of transport of perchlorate liquids during the initial stages of the perchlorate production. The Beta Ditch was originally constructed by Basic during the early 1940's to convey process wastewater into the Upper and Lower BMI ponds. This drainage system was unlined, and had an average width of approximately 6-7 feet; the average depth was between 2-4.5 feet (Geraghty & Miller, 1993). As shown in Figure 2.3, the ditch originates from the Sixth Street storm sewer outfall within the KMCC property, and extends towards east beyond the KMCC property running underneath the Boulder Highway. WECCO, AP&CC and KMCC used this drainage system to convey salts, filter cakes and other liquid wastes to BMI ponds from 1945 to 1975. The average daily discharge of the Beta Ditch was approximately 600,000 gallons per day (KMCC, 1980). The average composition of this waste stream is shown in Table 2.5.

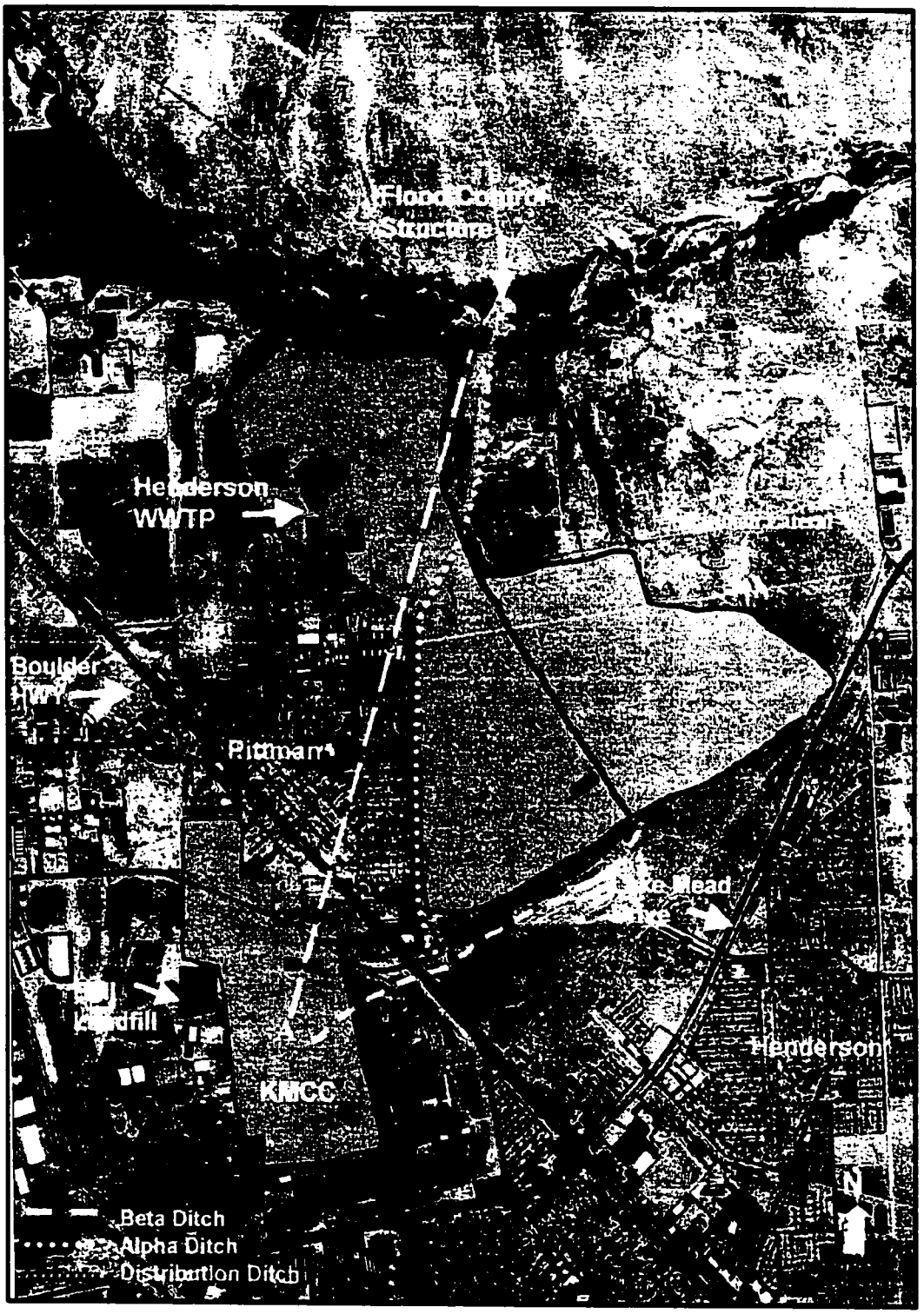


Figure 2.3 : The Surface Drainage System of KMCC (Source: KMCC, 2000; Geraghty & Miller, 1993). See Figure 2.4 for the geological profile of section A-A

Table 2.5: Average Loading of Contaminants into the Beta Ditch

Constituent	Mass Loading (lb/day)	Constituent	Mass Loading (lb/day)
Total Dissolved Solids	19,100	Magnesium	150
Total Solids	20,200	Zinc	130
Suspended Solids	1,080	Manganese	1,800
COD	110	Nickel	8
NH_3	35	Lead	4
Calcium	2000	Copper	4
Iron	1,100	Cobalt	1.5
Potassium	1,200	Chromium	0.3
Sodium	5,000	Phosphorus	.4

Note: This is the average composition before 1976.
(Source: KMCC, 1980; Kleinfelder, 1993).

BMI also utilized Alpha Ditch, Northwest Drainage Ditch, the Western Trench System, and the Western Drainage Ditch for conveyance of effluents, and for surface drainage management. The Alpha Ditch was primarily utilized to convey storm water and non-contact process water from the northwestern sections of the BMI complex to the Las Vegas Wash (Geraghty & Miller, 1993). The Western Drainage Ditch was originally a natural surface water channel, but was later converted by the U.S. Government to convey effluents from the Basic operations. There is limited information available on the actual use of this ditch. The documented information states that this ditch was utilized only by non-perchlorate manufacturing industries (Geraghty & Miller, 1993). However, the Northwest Drainage Ditch had been used by KMCC on occasional basis; but these discharges were small, infrequent and had been limited primarily to excess storm-water (Geraghty & Miller, 1993). There is no reported use of this ditch for the discharge of perchlorate process wastes. The Western Trench System was a series of trenches that had been constructed along the north-northeast direction. They were

connected to the Western Drainage Ditch. There is reported use of this system for the disposal of perchlorate wastes (Kleinfelder, 1993).

BMI Ponds:

The first four BMI ponds (Trade Effluent Disposal Ponds) were constructed for the discharge of effluents from the magnesium production by Basic under the contract with the U.S. Government. Each pond was approximately 79 acres in extent and had an average liquid level depth of 7.5 feet, which gave an overall capacity of 590 acre-feet (Geraghty & Miller, 1993). The ponds were constructed by forming 20 foot high earthen dikes. The Upper and Lower BMI ponds were constructed by Basic soon after the construction of the Trade Effluent Disposal Ponds by 1943, as the existing ponds were unable to meet the disposal capacity. The Upper Ponds are located east of the town of Pittman near the BMI Complex; and the Lower Ponds are located approximately 0.5 miles south of the Las Vegas Wash and approximately 0.5 mile north and down gradient of Pittman (Geraghty & Miller, 1993). The Lower Ponds consist of a combination of various small cells with a combined area of approximately 430 acres, which followed the natural grade of the existing site elevation. The Upper Ponds have a combined area of approximately 915 acres (Geraghty & Miller, 1993). All these ponds, constructed prior to 1976, were unlined and the primary modes of disposal were via evaporation and infiltration.

During the operation period, WECCO and AP & CC disposed an unknown quantity of perchlorate process wastewater in these ponds. Perchlorate quantities were not measurable since the majority of the waste was in the liquid form (Kleinfelder,

1993). The existing documentation does not provide the specific ponds that received these waste streams individually. KMCC also used the BMI ponds to dispose perchlorate process wastewater until they were replaced by onsite lined ponds.

The existing documentation shows that the majority of the wastewater was discharged into the Upper BMI ponds. The available documentation does not specify which ponds received the wastes, and also does not state the exact quantity of the solid perchlorate wastes. The total amount of perchlorate containing wastes discharged into the BMI ponds is estimated to be 293,756 tons (Jacobs, 1987). The exact quantity of pure perchlorate within these wastes is not known. However, based on information known about the perchlorate production process (Kleinfelder, 1993), a majority of the waste-stream was comprised of used filter material, and there was relatively little amount of perchlorate when compared to the other waste products (diatomaceous earth, etc.).

KMCC On-site Ponds:

Discharge of industrial process effluents into the BMI Upper and Lower ponds continued until late 1976. With the enactment of the Water Pollution Control Amendments Act of 1972 (also known as the Clean Water Act), BMI industries had to restrict the use of unlined BMI ponds as a disposal option. The companies were forced to take actions to limit the use of these ponds. This was achieved by constructing lined ponds within individual industrial properties and making modifications to the production processes.

In May 1974, KMCC introduced process modifications to accommodate recycling of the process wastewater from the perchlorate manufacturing process. Three

surface impoundments (SI) named AP-1, AP-2 and AP-3, were constructed in May 1995, to temporarily store and concentrate perchlorate process liquids (Kleinfelder, 1993). The term AP stands for Ammonium Perchlorate. The concentrated solutions were recycled back to the process. Two additional ponds were added to this system. The dried residue from these ponds had been disposed at the BMI Landfill, shipped off site as recyclable material and also had been disposed at the U.S. Ecology, Inc. site, Beatty, Nevada (Kleinfelder, 1993). All these SIs contained single and multiple impermeable basal liners. The major features of these ponds are summarized in Table 2.6 below.

Table 2.6: Major Characteristics of the Ammonium Perchlorate Ponds

SI	Lining System	Capacity	Major Use
AP-1	40 mm double HDPE liner system	14,000 ft^2 370,000 gal	Temporary storage of sodium perchlorate and ammonium perchlorate process solutions. Used alternatively with AP-2
AP-2	single PVC liner	14,000 ft^2 400,000 gal	Temporary storage of sodium perchlorate and ammonium perchlorate process solutions. Used alternatively with AP-1
AP-3	40/60 mm double HDPE liner system	2,000 ft^2 65,000 gal	Used as a pump basin for liquid wastes stored in AP-1 and Ap-2
AP-4	40/60 mm double HDPE liner system	20,000 ft^2 720,00 gal	Served as a surge basin for ammonium perchlorate process liquid wastes.
AP-5	40/60 mm double HDPE liner system	35,000 ft^2 1,817,000 gal	Flows from the ammonium perchlorate cooling towers.

(Modified from KMCC, 1990; Kleinfelder, 1993).

KMCC operated several lined SIs for the disposal/storage of industrial process wastes. S-1, Old-P-2 and P-1 ponds were utilized for the discharge of perchlorate process

wastes. Table 2.7 provides a summary of these ponds. In addition to the above ponds, KMCC also operated C1, MN-1, WC-1, WC-2, P-3 and the New P-2 ponds for the discharge of various other effluents. There was no recorded use of these ponds for the discharge or the storage of perchlorate process liquids.

Table 2.7: Major Features of the P-1, Old P-2 and S-1 Ponds.

SI	Operation	Wastes Received	Capacity	Remarks
S-1	1972-1983	potassium chlorate, potassium perchlorate, and sodium perchlorate, wastes.	47,000 ft^2 2,000,000 gal	• Constructed from a single 20 mil PVC. • After closure bottom liners and solids were deposited in the KMCC hazardous waste landfill • Possible liner failure in 1980.
P-1	1972-	potassium perchlorate, and sodium perchlorate	26,000 ft^2 700,000 gal	• Constructed from a single 20 mil PVC. • Relined in 1980 after the original liner failed in 1980. • After closer bottom liners and solids were deposited in a non-hazardous waste landfill. • Had evidence of leaking.
Old P-2	1972 onwards	Sodium perchlorate	Initially : 12,000 ft^2 350,000 gal After relined : 13,500 ft^2 675,000 gal	• Constructed from a single 20 mil PVC. • Relined between 1982-1984 after the original liner was failed in 1980. • After closer bottom liners and solids were deposited in a non-hazardous waste landfill • Leaked an unknown quantity of solution on more than one occasion.

(Source: Modified from EPA, 1980; KMCC, 1979; Kleinfelder, 1993)

BMI Landfill:

The BMI landfill was formed by converting the two western Trade Effluent Ponds into a solid waste disposal site. The BMI landfill is unlined, and had been used for the disposal of liquid, solid and semi-solid waste from 1943 to 1980. The landfill has

been capped with a moderately impermeable layer comprised of lime residue and two feet thick soil layer. The landfill has received wastes from the production process, housekeeping wastes, demolition wastes, and dried residue from the lined ponds. The perchlorate producers KMCC, AP&PC and WECCO utilized the BMI landfill for waste disposal. KMCC has disposed an unknown quantity of dried residue from the ammonium perchlorate, potassium perchlorate and sodium perchlorate operations (Geraghty & Miller, 1993). The waste disposal information for other perchlorate producers was not available.

BMI Solid Waste Disposal Site:

There is limited information available about BMI Solid Waste Disposal Site. This site was opened in late 1983 according to the records kept by some of the industries. The waste disposed at this site is reported to be uncontaminated demolition waste. This site is no longer in use for the disposal of wastes.

KMCC Hazardous Waste Landfill:

This landfill is located within the KMCC facility, and was constructed by converting one of the former Trade Effluent Ponds into a landfill. This landfill consists of one unlined subsurface cell with a maximum capacity of approximately 332,000 ft^3, and had been operated from February 1980 to January 1983 (Kleinfelder, 1993). The material placed within this landfill included potassium perchlorate process solids, and solid contents and liners from the S-1 ponds (KMCC, 1984; KMCC, 1986; Kleinfelder, 1993).

2.6.9 Perchlorate Migration Pathways from Operational Activities at KMCC

Temporary Waste/Material Storage Areas:

KMCC utilized several locations/units for the temporary storage and collection of perchlorate containing material. Ammonium Perchlorate Area (APA) was utilized from 1980 to 1989, for the accumulation of drummed, non-hazardous, solid and industrial waste from the AP (Kleinfelder, 1993). The migration could have occurred from the ammonium perchlorate deposited on the pad by leaky drums and AP contaminated solid waste, via surface runoff. KMCC also utilized the Sodium Perchlorate Platinum By-Product Filter Area for the filter press operations since 1968 (Kleinfelder, 1993). Filter cake material containing sodium perchlorate was processed at this location. Sodium perchlorate could have migrated through the cracks developed within the basal of the pad, surface runoff, and also by air. KMCC site operators also utilized several other storage units for various operational activities. However, their impact on perchlorate contamination is not significant, according to the available documentation.

Perchlorate Manufacturing Buildings and Transfer Lines:

The KMCC facility used a transfer line system to transport perchlorate among various production processes. AP production facility maintained three types of transfer lines: (1) permanent rigid lines (2) temporary flexible lines constructed with HDPE, and (3) permanent lines constructed of concrete/Transite (KMCC, 1992). Leaks had been developed in the AP transfer lines and the AP cooling lines; and on rare occasions some of these lines have broken and released AP solution to the ground (Kleinfelder, 1993). Several other pipelines have also broken, and have released perchlorate solutions to the environment.

The buildings that contain the perchlorate manufacturing equipment also released perchlorate waste through material handling, mixing and blending. Perchlorate migrated into the environment via dust and floor washing.

2.6.10 Perchlorate Waste Disposal at PEPCON

It is believed that PEPCON used a single unlined pond located by the Mary Crest Road for the discharge of effluents including perchlorate process wastes. This pond had been built by constructing a dam across a natural surface water channel. PEPCON used this pond for storm water management as well. It is possible that other surface water channels on the property were also used for the discharge of effluents. There is a large degree of uncertainty in the information with regard to the generation and disposal of effluents within PEPCON due to unavailability of recorded information on this facility.

In addition to the contamination resulted during operations, a considerable amount of perchlorate was transported downstream of the site by the large amount of water that was used to contain the fire during the 1988 explosion. It can be assumed that this surface water plume carried perchlorate following the natural gradient towards the Las Vegas Wash. However, precise information on this was not available. Subsequent to the explosion, a 2 foot thick soil layer has been removed from the downstream section of the former PEPCON facility. However, this effort was been carried out due to the presence of other hazardous chemicals within the topsoil layers.

2.7.0 Key Geological and Hydrogeological Features of the BMI Complex

2.7.1 BMI Site Geology

The Las Vegas is Valley surrounded by several mountain ranges: the Spring Mountains to the west, Sheep Range to the north, McCullough and River Mountains to the south and Frenchman and Sunrise Mountains to the east. The length of the valley is approximately 55 miles and the width varies between 10-25 miles. The valley floor is comprised of alluvial and playa deposits which had originated from the surrounding mountains. The central part of the valley contains fine sand, silt and clay material, and becomes coarser with gravels, cobbles, and boulders towards mountains (Geraghty & Miller, 1993). The deposits near the mountains are deep and often unconsolidated. The valley is underlain by Tertiary Muddy Creek Formation, comprised of a combination of clays, silty clays, gypsiferous sandy clays, clayey sands and conglomerates. The Muddy Creek Formation is believed to had been formed by a reservoir that existed above the Las Vegas Valley long time ago. Long-term sedimentation that occurred during the existence of this reservoir lead to the formation of this layer. After the reservoir disappeared, the exposed bottom layer was subsequently eroded by the infrequent flooding that took place, and a series of surface water channels were carved into the deposit. Later, sands and gravels deposited in these channels. There is limited information available on the exact depth and the locations of this formation.

The geology in the BMI complex area can be divided into two layers. The top layer is formed by the recent deposits originated from the McCullough Range, River Mountains and the other surrounding mountains. This layer is approximately 30-100 feet

thick and is comprised of highly permeable deposits: boulders, cobbles, gravels and coarse sands. The thickness of the deposits near the upper portion of the Lower Ponds is about 30 feet (Kaufmann, 1971). Underlying the top alluvial layer is the Muddy Creek Formation, which is comprised of much finer sands, silts and clays. The top alluvial layer has been deposited on the natural erosional channels formed on the Muddy Creek Formation during flood runoff. The thickness of the alluvial deposits is greater over erosional channels and thinnest over intervening interfluvial areas (Kleinfelder, 1993). A majority of these channel filled deposits lie linearly along the natural surface water flowing direction. The high permeability of the filled material combined with the orientation of these deposits play a vital role in the groundwater movement in the area. Figure 2.4 illustrates the geological profile along the main alluvial channel (Cross Section A-A in Figure 2.3). The profile shown in this figure is approximately 6 km long. Another important geologic characteristic is the existence of fault zones and semi-confining material, as this could provide hydraulic connections that allow for generally upward leakage between aquifer zones at some locations (Geraghty & Miller, 1993). The major geologic factors that govern the occurrence and the movement of groundwater are given below (Geraghty & Miller, 1993):

- existence of gravel/sand filled channels within the top alluvial layer;
- configuration and slope of the top of the Muddy Creek Formation; and
- lithology of the Muddy Creek Formation.

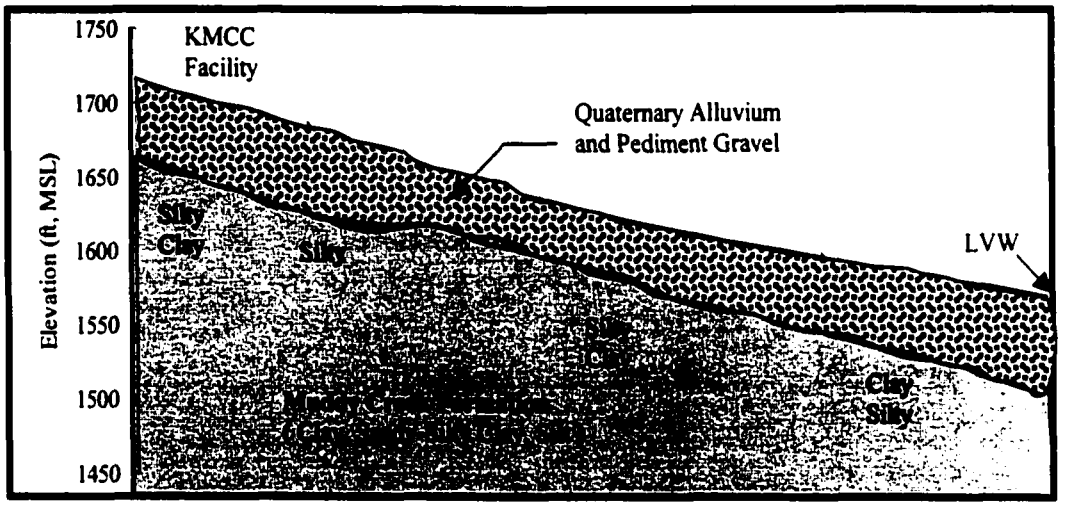


Figure 2.4: BMI Site Geology (Source: Modified from Geraghty & Miller, 1993)

2.7.2 BMI Site Hydrogeology

The aquifer system in the BMI area could be subdivided into two main components: the near-surface (or the upper unconfined aquifer) and the deep confined aquifer. The near-surface aquifer system exists within the valley filled deposit zone overlying the Muddy Creek Formation. This system is recharged mainly from the upward leakage from the artesian deep aquifer system, infiltration from surface irrigation, sewerage, and industrial processes.

The deep confined aquifer lies several hundreds of feet below the ground surface, and is separated from the upper aquifer by a layer of low permeability deposits consisting of fine grained silts, clays and even caliche at some locations (Kleinfelder, 1993). The deep aquifer system could be further divided into shallow, middle and deep zones. The groundwater wells drilled by Geraghty & Miller, Inc. (1980) penetrated these zones at depths of 200 to 400, 500, and 700 feet respectively. During these investigations, several

number of wells/borings encountered thin sand and gravel layers contained within the Muddy Creek Formation. Some of these isolated zones contained water under artesian conditions. A significant number of unsaturated zones were also encountered. This demonstrates the non-existence of hydraulic connections among the isolated gravel/sand layers within the upper part of the Muddy Creek Formation that impedes interaquifer movement of groundwater (Geraghty & Miller, 1993).

Due to the separation of the deep aquifer system by a highly impermeable layer, the potential contamination of this layer from any surface discharge of pollutants is unlikely. The existence of an upward water pressure gradient from this zone further prevents the movement of pollutants from the ground surface into this layer. Therefore, majority of the groundwater quality investigations conducted within the site excluded the deep aquifer zone as a contaminated region.

During site investigations conducted by Geraghty & Miller, Inc. (1980) revealed that the depth to the upper aquifer varied from 90 feet below the land surface at the southern boundary of the Stauffer site to 20 feet at the northern boundary of the BMI Complex. The same investigation also revealed that these water levels remained fairly constant. A hydrogeological study carried out by Kleinfelder in 1993 showed the depth of the upper aquifer to be 5 feet below ground surface near the northeast corner to approximately 35 feet below ground surface near the southern and the west-central sections of the site. During this investigation (June, 1983 to June, 1985), the maximum water level fluctuations in any one well varied from 1.54 to 3.08 feet, which was believed to be caused by the seasonal climatic changes. The test wells showed highest levels during fall and the lowest during the spring months.

The same study also revealed that in general, the larger saturation zones occur within the buried channel fill deposits, and smaller zones of saturation occur over the interfluvial areas that separate these channel fill deposits. The trasmissivity values were calculated based on pump tests performed on four wells. The lowest, and the highest observed transmissivity values were 16.4 m^2/day and 787 m^2/day respectively. The fine graned faces of the Muddy Creek formation had transmisivity less than 1.24 m^2/day. The summary of the calculated drainage parameters are illustrated in Table 2.8 below:

Table 2.8: Major Drainage Parameters of the BMI Site Alluvial Layers

Location	Flow Velocity (m/day)	Transmissivity (m^2/day)	Hydraulic Conductivity (m/day)
within channel fill deposits	4.9	90.0	61
Interfluvial area	0.15	0.9	2
Muddy Creek Formation	0.16	0.17-0.68	1.2 (horizontal)

(Modified from Kleinfelder, 1993 and Geraghty & Miller, Inc.,1980)

Laboratory studies performed by Geraghty & Miller, Inc. (1980) on undisturbed core samples taken from the Muddy Creek Formations showed vertical permeabilities ranging from 1.73×10^{-3} m/day to 4.8×10^{-5} m/day. These values were different by a factor of 100 from the value (1.6×10^{-1} m/day) calculated by Kleinfelder (1993). The main reason for the differences is that Kleinfelder calculated the values based on the performance of the test wells. Kleinfelder reported the significance of the thin sand and silt stingers embedded within the Muddy Creek Formation, which drastically increase the overall permeability of this layer; whereas in the laboratory test this effect was not

present.

The groundwater flow in the region is affected by the presence of the Muddy Creek Formation. The fine grained faces of the Muddy Creek Formation underlying the top alluvial deposit layer resists the downward movement of near surface water. The top face of the Muddy Creek Formation slopes north and northeast towards the Las Vegas Wash at approximately 100 ft/mile (or 1.9%) (Kaufmann, 1971). The combined effects of these two geological characteristics force the surface water entering the top alluvial layer to flow north and northeast towards Las Vegas Wash, instead of percolating down. The channel filled deposits within the top alluvial layer exhibit high permeabilities and account for majority of the lateral groundwater flow. The investigations carried out by Kaufmann (1971) revealed the gradual thinning of gravel and sand layers (top alluvial layer) towards the Las Vegas Wash, which results in the decreased storage capacity and the transmissivity of this layer. This formation increases groundwater flow velocity or induces surface discharge, which is consistent with what is observed in this region even today. Surface discharge of groundwater occurs even presently in this region.

The groundwater flow is primarily downwards within the Upper Tailing Ponds, which gradually becomes lateral in the intermediate zones, and later, develops an upward trend underneath the Lower Tailing Ponds near the Las Vegas Wash. This restricts the migration of pollutants from the Lower Tailing Ponds into the Las Vegas Wash.

Groundwater investigations carried out by KMCC (1998) observed an average gradient of 0.017 from KMCC facility to Las Vegas Wash. The lateral groundwater flow was calculated by KMCC for the Pittman Lateral using an equation proposed by Tolman (1937) and using parameters estimated (effective porosity 0.2, gradient 0.017, and

permeability 2 m/day) from the pumping tests. The estimated average groundwater flow within the alluvial layer for the Pittman Lateral was 67 m/year (0.6 ft/day or 220 ft/yr). The main alluvial channel has widths between 210 m to 305 m, a maximum depth of 18.3 m and has a groundwater underflow of 18,900 gal/day. The groundwater flow and the conductivity within the channel fill deposits are about 4.87 m/day (16 ft/day), and 61 m/day (1,496 gpd/ft^2) respectively (Kleinfelder, 1993).

2.7.3 Key Geological and Hydrogeological Features of the PEPCON Site

Unlike the KMCC Site, extensive hydrogeological and groundwater quality investigations have not been carried out for the PEPCON Site. The geological conditions of the PEPCON site are entirely different from that is found beneath the KMCC site and the BMI Complex; the fine grained faces of the Muddy Creek Formation observed underlying the BMI Complex site and KMCC are not observed within the PEPCON site. (Broadbent & Associates, 1998). Reports by Kleinfelder (1999) and Broadbent & Associates (1998) argue that the non-existence of the fine grained faces of the Muddy Creek Formation permits the downward movement of perchlorate. In contrast, within the KMCC property, the surface discharges entering the top alluvial layer are intercepted by the fine grained faces, and are forced to move laterally towards the Las Vegas Wash. The groundwater perchlorate investigations conducted by Kleinfelder (1999) also support this. During the investigations, the top water bearing zones had lower perchlorate concentrations. The perchlorate levels increased with depth. The highest perchlorate concentrations were detected from the samples from 161 to 181 feet.

The distribution of perchlorate in the region is appeared to be governed by the

absence of the fine grained faces of the Muddy Creek Formation and by the existence of a subsurface channel, that runs north-east (Broadbent & Associates, 1998). A similar but a larger channel exists east of the site that is believed to be influencing the perchlorate concentrations north of the KMCC site. Presence of a ridge between these two channels is considered to be the main governing factor in keeping the PEPCON and the KMCC plumes separated (Broadbent & Associates, 1998).

2.7.4 Perchlorate in Groundwater : KMCC Property

Groundwater investigations have been carried out in the region to monitor the groundwater quality. Hundreds of groundwater wells have been drilled into the subsurface layers underneath the BMI facility. KMCC (1998) reported that the perchlorate levels within the alluvial groundwater system are approximately 1500 ppm along the northern KMCC property, and 100 ppm immediately to the south of the LVW (Figure 2.5). The perchlorate plume is confined to a narrow plume within the main alluvial channel. The plume initially moves towards north close to the KMCC property, and then is diverted towards northeast due to the influence from a high conductivity plume that exists within the alluvial channel. The perchlorate plume is diluted and dispersed into a wider fan just south of the wash, by the percolating treated effluents from the Henderson Wastewater Treatment Plant (WWTP) rapid infiltration basins.

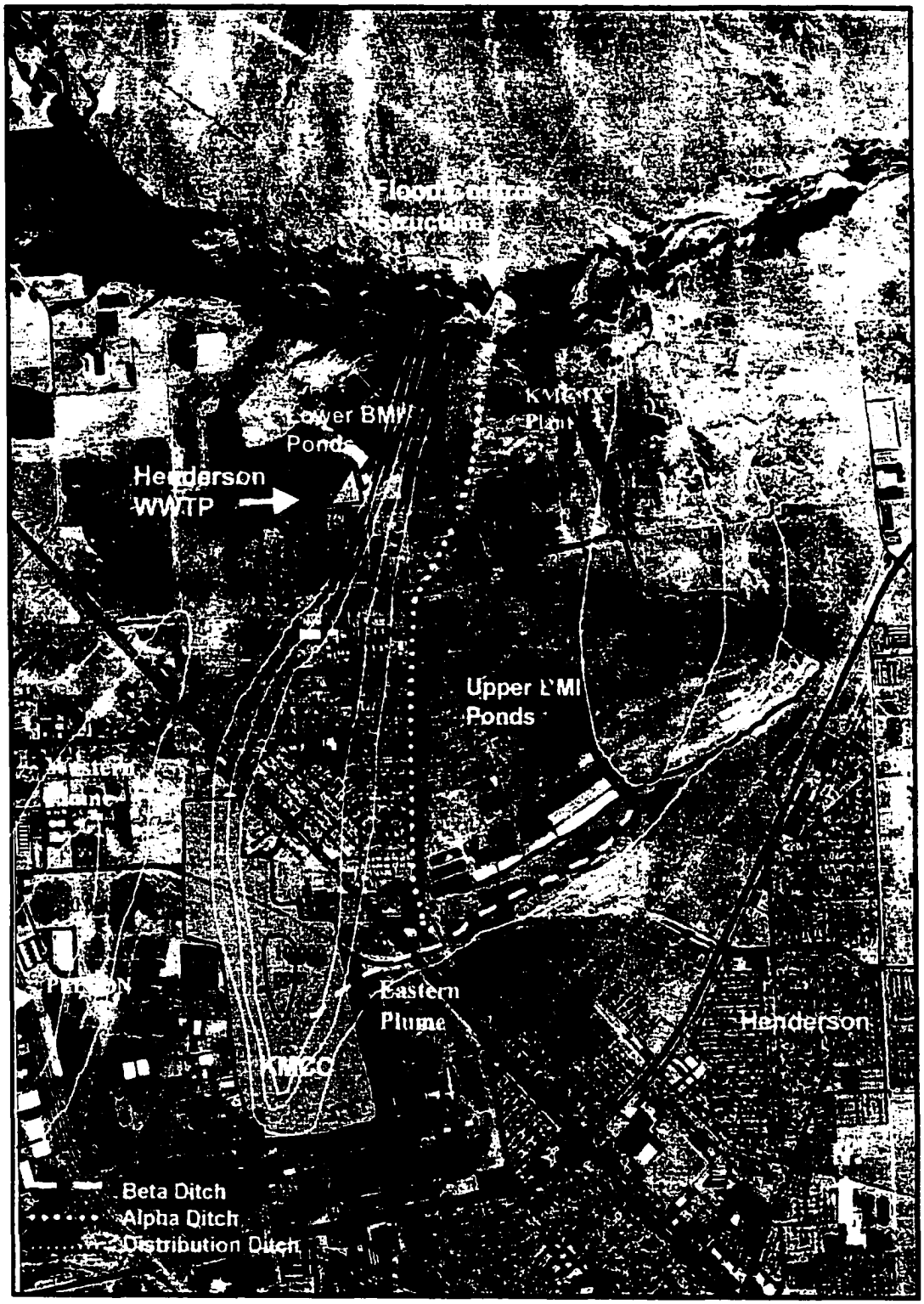


Figure 2.5: Approximate Perchlorate Levels in Groundwater (Source: Modified from KMCC, 2000; Geraghty & Miller, 1993, Broadbent & Associates, 1998)

2.8.0 Perchlorate Loading on the Las Vegas Wash

Studies conducted on the BMI and KMCC property have shown that the impact of the groundwater pollution resulting from the present KMCC facility to be more significant than the impact from the PEPCON site. Therefore, more emphasis was given to investigate the perchlorate production at the KMCC site and the BMI ponds.

2.8.1 History of Investigations on the LVW

There have been water quality investigations on the Las Vegas Wash since 1961. A report published by Leeds, Hill and Jewett, Inc. (1961) reported the rising of the groundwater in the Pittman area and water quality deterioration in the Wash, due to 5,000 ac-ft/yr of return flow from the Tailing Ponds. Water sampling in 1961 near Pabco Road had TDS concentration of 4,450 mg/l (Kaufmann, 1971). An investigation carried out by the Federal Pollution Control Administration (Now EPA) failed to prove any seepage of pollutants occurring into the Wash. However, after evaluating groundwater levels and flow at the sampling stations and effluent sources, this study concluded that 0.32 MGD of seepage with 8,140 mg/l of TDS occurs from the BMI Lower Ponds (Kauffmann, 1971). A study carried out by Tipton & Kalmbach (1968) stated that the majority of the dissolved solids in the Wash originate from the BMI Ponds. A report published by Boyle-CH2M (1969) showed the infiltration of approximately 3-7 MGD of groundwater containing nitrates and TDS from the BMI Ponds. A study carried out by the Bureau of Reclamation (Hoffman, et al., 1971) also showed the infiltration of TDS and nitrate containing groundwater close to Pabco Road.

The first comprehensive investigation was carried out by the Desert Research

Institute in 1971 (Kauffmann, 1971). This investigation looked into to the geological and hydrogeological features of the BMI region, and attempted to model the occurrence and movement of groundwater and surface water. Water quality analyses were also carried out. The average chemical loadings had been estimated by the direct measurement of direct chemical concentration and discharge, and also by the mass flux difference between the upstream and downstream stations along the Wash. The summary of the loading for the LVW above Pabco Road for July, 1971 is given in Table 2.9 below.

Table 2.9: Pollutant Loadings on the LVW from the BMI Tailing Ponds

Pollutant	Loading (lb/day)	Percent Increase in the LVW
TDS	297,822	166%
Na	47,728	87%
Cl^-	66,418	118%
SO_4^-	110,593	65%

(Source: Modified from Kauffmann, 1971)

The Kauffmann, Report (1971) also estimated the groundwater seepage rate as approximately 5 MGD. However, during this period the Upper and the Lower BMI Ponds had been used for the discharge of liquid effluents from the BMI operations. Therefore, a high seepage is expected to occur into the LVW.

The present situation is entirely different. Since, use of unlined ponds for the discharge of effluents is no longer practiced, it is expected to find a lower seepage from industrial activities into the LVW. However, the surface recharge of water from

residents and the Henderson Wastewater Treatment Plant has increased significantly due to the rapid growth in the region. KMCC and UNLV also have carried out investigations on the pollutant loading into the LVW. Table 2.10 below shows the major constituents in the seepage water from the BMI area.

Table 2.10: Major Water Quality Parameters of the BMI Seepage

Parameter	Concentration (ppb)	Parameter	Concentration (ppb)
Arsenic	140	Beta-BHC	0.37
Barium	0.0183 (J)	Delta-BHC	1.71
Boron	4,600	4,4'-DDT & metabolites	0.31
Chromium (total)	620	4,4'-DDE	0.0073 (J)
Chromium (VI)	Not Detected	4,4'-DDD	0.0114 (J)
Chromium (III)	620	Dalapon	0.79 (J)
Copper	8.1	Dicamba	0.099
Iron	100	Dieldrin	0.1
Magnesium	252,000	Dinoseb	0.39
Manganese	1800	Endrin	0.0042 (J)
Molybdenum	120	Heptachlor Epoxide	0.0044 (J)
Nickel	15.5	Lindane (gamma BHC)	0.110
Potassium	45,800	MCPA	42
Selenium	12	Pentachlorrophenbol	0.017 (J)
Sodium	1,520,000	Silvex (2,4,5-TP)	0.084 (J)
Strontium	11,200	2,4,5-T	0.257
Vanadium	51	Chloroform	2 (J)
pH	7.65	m-Dichlorobenzene (1,3)	0.5
Color	20 units	o- Dichlorobenzene (1,2)	0.6
Perchlorate	310,000	p- Dichlorobenzene (1,4)	0.7
Chlorate	100,000	1,1-Dichloroethane	2 (J)
TDS	7,300,000	Methyl Tert-butyl ether	5
TSS	14,000	di-2-Ethylhexyl phthalate	4 (J)
TOC	5,600	1,2,4-trichlorobenzene	2 (J)
Ammonia-N	150 (J)	Oil and Grease	3,800
BOD	1,420	Gross Alpha (pCi/l)	96.1
COD	140,000	Gross Beta (pCi/l)	204
Fluoride	1,600	Radium 226+228 (pCi/l)	595
Sulfate	1,950,000	Aldrin	0.0155
Total P	136	Chlordane Alpha	0.0025 (J)
Alpha-BHC	65		

(Source: Modified from the Draft NPDES Permit NV 0023060 Submitted to NDEP by KMCC)

2.8.2 Perchlorate Investigations in the LVW

Limited studies have been carried out to investigate the perchlorate concentrations along the LVW. In 1998 Broadbent & Associates Inc. and Geotechnical Environmental Services, Inc (GES) carried out limited analyses of on the perchlorate concentrations at several sampling points along the LVW (Broadbent & Associates, 1998). A second, but a more detailed investigation followed the above, by the same consultants. During this investigation, water samples were collected from the Wash between January 19th and January 21st , 1998. Two water samples were taken from each location; one from the surface and the other from the bottom. The perchlorate concentrations were about 10 μg/l within the upstream section of the Wash; but increased to over 400 μg/l after reaching the Pittman Bypass Outfall (Broadbent & Associates, 1998). Pittman Bypass Outfall is considered to be the location where the Eastern Plume (that is contaminated from the KMCC Facility) intersects the Wash.

Water samples were also analyzed from the culverts that carry the Wash under the Poleline Road. This road is located approximately 1 mile downstream from the Pittman Bypass Outfall. The observed perchlorate concentrations in the culverts increased from north to south. The northern, middle and the southern culverts had concentrations 390 μg/l, 560 μg/l and 610 μg/l respectively (Broadbent & Associates, 1998). The perchlorate concentrations remained fairly constant within the next 1 mile, and increased to about 770 μg/l after reaching the BMI Upper Evaporations Ponds area. The perchlorate concentration within the groundwater in this region was about 1500 μg/l to 2000 μg/l. Broadbent & Associates Report (1998) also estimated the groundwater intrusion into the Las Vegas Wash using Darcy's Law as 0.56 MGD. Based on the

average perchlorate concentrations observed in the groundwater wells close to the Las Vegas Wash (334 mg/l) the estimated loading was 706 kg/day (1556 lb/day).

Therefore, the perchlorate loading rate estimated based on the groundwater flow into the Wash from the Eastern Plume is more than sufficient to explain the elevation in the concentrations within this reach of the Wash. The difference in the predicted values and the actual loading could be due to the high uncertainties in the parameters used for the groundwater flow calculations. The average perchlorate concentration used by Broadbent & Associates report is rather high. Based on the information known at this stage (Zhang, 2001), the perchlorate concentration in the seepage varies from 80 to 150 mg/l.

2.9 Limitations on the Accuracy of the Background Information

The environmental legislation with respect to the discharge of effluents was only developed after 1972. The actual implementation of most of this legislation was not even carried out until late 1970's and early 1980's. Before late 1970's, it was an accepted practice to dispose waste on lands and other natural systems without adequate precautions. There was no special reason for industries to keep accurate and complete records on such discharges. During the literature review, information of the BMI Complex, KMCC site and the former PEPCON facility site was carried out by evaluating several reports published on this subject. The reports that provide the past operations of BMI industries and PEPCON were developed mainly based on the information provided by various source groups, evaluation of the documents provided by the industries,

interviews and visual observations. Therefore, during development it can be presumed that consultants would have made their own interpretation based on the information available to them. The accuracy of these reports depends on the accuracy and the completeness of the source documentation and the interpretations made from them. Therefore, the literature review presented in this study, especially the background information on the past perchlorate productions, site geohydrology, water quality and environmental assessment, should be viewed in this context.

2.10 Lake Mead Operations

The Lake's operations started when the construction of the dam was completed in 1935. Initially, the primary uses of Lake Mead were to generate electricity and to temporary store water for downstream use, especially for California. Despite the close proximity to Lake Mead, the Las Vegas valley did not utilize Lake water until 1942. Instead the valley depended on the groundwater resources. The first reported use of Lake Mead water for the Las Vegas Valley was carried out in 1942 for the BMI operations. In 1954, the water lines were extended to Las Vegas, and approximately 11,100 ac-ft was pumped from the lake during this year (Meier, 1969). This amount gradually increased annually, was doubled by year 1963 (Meier, 1969).

The utilization and management of Colorado River water is controlled by federal, state, interstate and international laws and agreements. In 1928, the Boulder Canyon Project allocated 300,000, 2.8 million and 4.4 million acre-feet of water to Nevada, Arizona and California respectively; which was later confirmed by the United States Supreme Court in 1964 (State of Nevada Colorado River Commission, 1990). The water

allocations to Nevada are based on the intake volumes and also by the return flows via the treated effluent discharges. The major inflows into the lake are Colorado, Virgin and Muddy Rivers, and the Las Vegas Wash. The main dimensions and features of Lake Mead are illustrated in Table 2.11. The water budget for Lake Mead is illustrated in Table 2.12.

Table 2.11: Major Physical Features of Lake Mead

Parameter	Value (US units)	Value (SI units)
Volume	3 x 10^7 ac-ft	36.7 x 10^9 m^3
Surface Area	160,000 ac	660 km^2
Highest Reservoir Level	1230 ft	374 m (mean sea level)
Max Width	9.3 mi	15 km
Max Length	66 mi	106 km
Shoreline Length	550 mi	885 km
Hydraulic Retention Time	3.9 years	3.9 years

(Modified from LaBounty and Horn, 1997; Lara and Sanders, 1970).

Table 2.12: Lake Mead Water Budget

Parameter	Amount	Percentage
Major Inflows		
• Colorado River	1.2 x 10^{10} m^3/yr (1.0 x 10^7 ac-ft/yr)	97%
• Virgin	1.8 x 10^8 m^3/yr (1.5 x 10^5 ac-ft/yr)	1.4%
• Muddy Rivers	1.2 x 10^5 m^3/yr (1.0 x 10^4 ac-ft/yr)	0.1%
• Las Vegas Wash	1.9 x 10^8 m^3/yr (1.5 x 10^5 ac-ft/yr)	1.5%
Major Outflows		
• Hoover Dam Release	1.0 x 10^{10} m^3/yr (8.9 x 10^6 ac-ft/yr)	86%
• Evaporation (estimated)	1 x 10^8 m^3/yr (8.9 x 10^5 ac-ft/yr)	10%
• Southern Nevada Water System	5.5 x 10^8 m^3/yr (4.4 x 10^5 ac-ft/yr)	4%

(Modified from LaBounty and Horn, 1997; Roefer et al., 1996; SNWA 2000).

Lake Mead has four main sub basins: Boulder, Virgin, Gregg, and Temple, that are separated by four canyons: Boulder, Black, Virgin, and Iceberg. Lake Mead is considered to be subtropical, mildly mesotrophic (Vollenweider 1970, Carlson 1977). However, individual basins exhibit unique ecological and water quality characteristics (LaBounty and Horn, 1997). Boulder Basin is the most polluted and nutrient rich basin mainly due to the discharge from the Las Vegas Wash carrying nutrients and pollutants originated from urban runoff and treated effluents from the wastewater treatment plants in the Las Vegas Valley. Therefore, the Boulder Basin exhibits the highest level of productivity.

2.10.1 Limnology of Lake Mead

According to Deacon (1976) the lake surface water temperatures vary from 10.5^0 C in January/ February to 27^0 C in July/August. Thermal stratification develops in May and June. A well defined thermocline is established between a depth of 10 -15 m in July when the surface water temperature reaches 26^0 C. As the surface water temperature drops in September, the lake begins to mix. Mixing continues until January/February when the lake's surface water temperature drops below 10.5^0 C. By this time the Lake is completely destratified. The hypolimnetic water temperature (90 m) remained constant at 10.5^0 C during the investigations (1972-1975), that resulted in a weak turnover.

The Las Vegas Wash is another important factor in influencing the limnology of Lake Mead. The movement and dispersion of the wash within the initial mixing zone (Las Vegas Bay) of the lake is governed by mainly two factors, in addition to the physical factors (lake bottom topology, wind, etc.). One factor is the difference between the

temperature of the two water bodies. The temperature of the wash is about 20°C, while the temperature of the inner Las Vegas Bay (initial mixing zone) is about 14°C (Roline and Sartoris, 1996). The higher temperature of the Wash water forces it to float once it enters the bay area of the lake. However, on the other hand, the wash water has a higher density than the lake water, due to the presence of high salinity. This generates a tendency for the wash to sink to the lake bottom. The effect of higher density governs the movement of the wash within the lake. LaBounty and Horn, (1997) used conductivity to investigate the movement of the wash within Lake Mead. The Wash has a conductivity of 2400 $\mu S.cm^2$, and the lake water has a conductivity of 1000 $\mu S.cm^2$. When the wash water enters the lake, there is a significant amount of mixing within the bay area, which is indicated by the higher total dissolved solids (or conductivity) in the area when compared to the rest of the lake. However, some of the inflowing wash water retains its identity, and an intrusion occurs as a distinct bottom water current following the path of the historic Las Vegas Wash (existed before the construction of Hoover Dam). The identity of this current gradually disappears, and an equilibrium occurs between the lake water and the inflowing wash water. The bottom current runs about 4-8 km into the Boulder Basin, but on some occasions, this intrusion extends up to the Hoover Dam. The intrusion depth, thickness, and the distance vary with season of the year, and degree of thermal stratification of the lake. Table 2.13 shows some of the observed intrusion depths and distances.

Table 2.13: Seasonal Intrusion Changes of the Wash Changes in Lake Mead

Month	Distance into the Boulder Basin (km)	Depth (m)
January	6-8	40-60
February	6-8	40-60
March	>8	15-40
April	>5	15-35
May	>5	10-15
June	>8	10-45
July	>8	15-45
August	8	15-45
September	8	20-45
October	8	20-45
November	8	40-50
December	8	40-55

(Source: LaBounty and Horn, 1997)

The density of the wash water remains fairly constant throughout the year. However, the wash temperature fluctuates between 20° C in winter to about 28° C in summer (Roline and Sartoris, 1996). In early spring, the intrusion flow depth is gradually elevated within the bay area, and reaches the shallowest depth in late spring when the temperature difference between the wash water and the lake water is at its maximum. The thermocline begins to develop in May and the warm lake surface water forces the intrusion to flow deeper. During the summer the intrusion sinks as the thermocline is further developed. In fall the thermocline breaks and the wash water begins to cool down. This forces the intrusion to flow deeper in the lake, within the former hypolimnetic region. The intrusion continues to flow within the hypolimnetic layer until early spring when the system goes into the next cycle. Tables 2.14 and 2.15

show the approximate temperature and dissolved oxygen (DO) profiles for the different thermal layers, and the dispersion coefficients, respectively.

Table 2.14: Key Limnological Parameters of Lake Mead

Thermal Layer	Depths (m)	Temperature (^{0}C)	Dissolved Oxygen (mg/l)
Epilimnion	5-7	April : 13.5 June : 22.5 Aug : 26 Oct. : 25 Nov : 18 Feb : 13	April : 9.6 June : 10.5 Aug : 9.2 Oct : 10 Nov : 7 Feb : 9.5
Metalimnion	7-15	April : 13-11 June : 22-12.5 Aug : 25-15 Oct : 24-14 Nov : 17-13 Feb : 13-12	April : 9.3-8 June : 10-7.5 Aug : 9 -4 Oct : 8.5 Nov : 7-6 Feb : 8.5-8
Hypolimnion	> 15	April : < 10 June : < 12 Aug : < 14 Oct : < 13 Nov : < 13 Feb : < 12	April : 7.8 June : < 7.6 Aug : 6.5 Oct. : 5.9 Nov : < 7 Feb : < 8

The reported temperature and DO profiles are for a sampling station located approximately halfway between Saddle Island and Black Island (Boulder Basin) in 1975.
(Source: Modified from Dan Szumski & Associates, 1991; Baker et al., 1977; LaBounty and Horn, 1997)

Table 2.15: Lake Mead Dispersion Coefficients

Depths	Dispersion Coefficients
Horizontal:	• Summer epilimnion: 2-10 m^2/s • Epilimnion winter: 10-50 m^2/s • Epilimnion spring 2-10 m^2/s
Vertical:	• During peak stratification: 0.0-0.5 cm^2/s • During peak non-stratification: 1.0-6.0 cm^2/s

(Source: Modified from Dan Szumski & Associates, 1991)

2.10.2 Lake Mead Water Quality and Monitoring

Monitoring of the Colorado River was started several decades ago. Water quality records for Colorado River and the Grand Canyon Reach have been founds as early as 1926 (Meier, 1969). Water quality records for Lake Mead were begun in 1935 with the completion of the Lake. Initially the records were restricted to a point below the Hoover Dam; however after 1941, continuous monitoring was begun for four stations: Imperial Dam, below Lake Havasu, below Hoover Dam, within the Grand Canyon and Lees Ferry (Meier, 1969).

The three wastewater treatment plants, Clark County Sanitation District (CCSD), City of Las Vegas, and City of Henderson have being collecting water samples from the Las Vegas Wash and Lake Mead as part of their NPDES permit to monitor the effect of the discharge of effluents from the wastewater treatment plants (WWTP) on water quality.

Lake Mead and the Colorado River System have been subjected to extensive investigations by various organizations. Therefore, in order to maximize resource utilization and data quality, a committee was formed comprising members from the Bureau of Reclamation, Southern Nevada Water Authority (SNWA), City of Las Vegas, Clark County Sanitation District and City of Henderson. This committee has been operational since 1997.

Monitoring of water quality of the wash and Lake Mead at 31 sampling locations has been carried out on a weekly, biweekly, monthly, quarterly and semi annual basis (Interagency Lake Mead and Las Vegas Wash Monitoring Program, 1999). Chemical, physical and biological parameters have been measured. In addition, the US Bureau of

Reclamation has been carrying out limnological investigations in the lake. A Hydrolab Surveyor IV ® is used to measure profiles of temperature, dissolved oxygen concentration and saturation, pH, conductivity, and turbidity at each sampling location (Lake Mead Interagency Sampling Manual, 1999). The SNWA monitors the perchlorate concentrations within the lake on monthly basis.

USGS, US Department of Interior, and UNLV have jointly carried out a sediment study within Lake Mead. Sidescan sonar imagery and high-resolution seismic-reflection profiles were collected in the Las Vegas Bay and Boulder Basin of Lake Mead to determine the surficial geology as well as the distribution and thickness of sediment that has been accumulated on the Lake bottom (Twichell et al, 1999). The results show that sediment accumulation on the Lake bed is restricted only along the historical flow path of the LVW and the Colorado River. The sediment thickness within the Las Vegas Bay area rarely exceeded 2m. However, the observed sediment thickness along the Colorado River bed area was above 10 m.

Lake Mead is also under the monitoring of the Nevada Department of Environmental Protection (NDEP) and also by the EPA. The EPA (1999) reported the presence of 4 to 16 ppb of perchlorate at the water intake point for Las Vegas, and approximately 5 to 9 ppb for California water intake points from the Colorado River.

CHAPTER 3

MATERIALS AND METHODS

3.1 Source of Water Samples

The Clark County Sanitation District (CCSD), the City of Las Vegas, and the Henderson wastewater treatment plants have been collecting water samples at about 30 sampling locations along the Wash and Lake Mead. This has been carried out as part of the NPDES agreement to monitor the effect of the discharge of effluents from the wastewater treatment plants (WWTP). An archive of the samples kept frozen at the CCSD was available for this study and contained samples dating back to 1991. Since perchlorate concentrations were not monitored prior to 1997, the availability of the frozen samples provided a unique opportunity to investigate the spatial and temporal variation of perchlorate in the Wash and Lake Mead. Although systematic studies on the effects of freezing and storage on perchlorate degradation are not available, it is expected that this preservation method would not significantly affect on the concentration of perchlorate. Biological reduction, a possible mechanism for perchlorate degradation, would be halted by freezing. Adsorption of perchlorate to the walls of storage containers is unlikely. Volatilization is also unlikely since perchlorates have very low vapor pressures.

The major sampling points in the Wash and the Lake from which the samples were taken are illustrated in Tables 3.1-3.3 and Figures 3.1-3.2 below. The sampling

points were analyzed from the Wash, namely LVW1, LVW3K and LVW5. The locations of the points, their distances from Lake Mead, as well as the number of frozen samples analyzed in each point are shown in Table 3.1 and Figure 3.1. The contaminated seepage stream discharges into the Las Vegas Wash very close to the Henderson WWTP effluent discharge.

The sampling points of the LVW include both upstream and downstream points from the contaminated BMI/PEPCON site area. This provides the opportunity to determine the perchlorate loading from the contaminated area. Perchlorate could potentially be used as a tracer because the LVW is the primary source of perchlorate into Lake Mead. Another reason is that biodegradation of perchlorate in the Wash is not very likely due to the presence of nitrate, the Wash's high TDS content, the lack of adequate source of carbon, and the high oxygen content of the Wash (Zhang, 2001).

Table 3.1: Major Sampling Points along the Las Vegas Wash

Station	Approximate Location	Total Samples Available	Number Analyzed	GPS Location
LVW1	Immediately downstream of the effluent discharge point of the CCSD WTP (approx. 14 km upstream from Lake Mead).	175	32	N 36 06 28.584 W 115 01 31.404
LVW3K	Near the 3 Kidds Mines area of the deeply eroded Lower Wash (approx. 5.5 km upstream from Lake Mead).	175	84	N 36 05 53.052 W 114 56 42.000
LVW5	Near the intersection of North Shore Road and the Wash (approx. 1.0 km upstream from Lake Mead).	175	37	N 36 07 20.748 W 114 54 13.284

(Source: Modified from Lake Mead Interagency Sampling Manual, 1999)

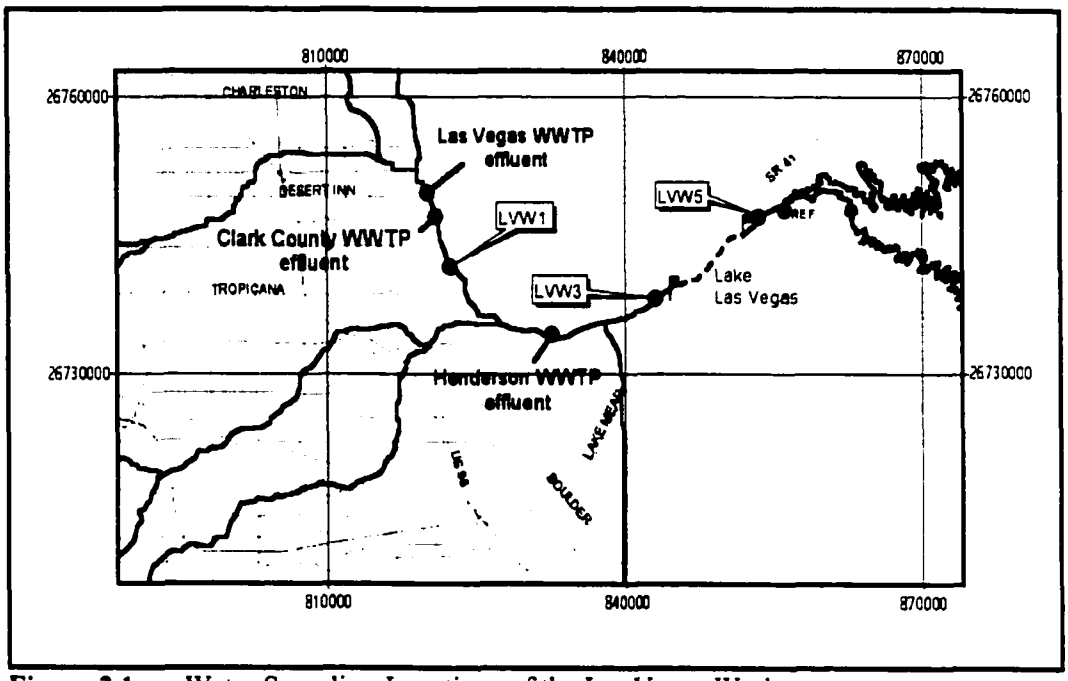


Figure 3.1: Water Sampling Locations of the Las Vegas Wash

Table 3.2: Major Sampling Points in the Las Vegas Bay, Lake Mead

Station	Sampling Location	Total Samples Available	Number Analyzed	Distance from the Reference Point
LM2CE*	Center of the Inner LVB.		95	2.45 km
LM2CH*	N 36 07 705 W 114 52 034		50	
LM2NE*	North side of the inner LVB.		32	2.45 km
LM2NH*	N 36 07 759 W 114 52 053		32	
LM2SE*	South side of the Inner LVB.		26	2.45 km
LM2SH*	N 36 07 723 W 114 52 080		28	
LM3CE*	Center of the Inner LVB.		47	2.67 km
LM3CM*	N 36 07 652 W 114 51 975		24	
LM3CH*			36	
LM3NE*	North side of the inner LVB.		31	2.67 km
LM3NH*	N 36 07 684 W 114 51 928		29	
LM3SE*	South side of the Inner LVB.	275	28	2.67 km
LM3SH*	N 36 07 639 W 114 52 012	275	31	

*Note: E/M/H stand for eplimnion, metalimnion and hypolimnion layers of the Lake, respectively. Sampling location changes with lake level changes.

(Source: Modified from Lake Mead Interagency Sampling Manual, 1999)

From Lake Mead, samples were analyzed from the Las Vegas Bay area, from Black Canyon, Crescent Island, and Hoover Dam. Several samples were analyzed from the Las Vegas Bay area, where the Vegas Wash enters the Lake. The locations of these stations (LM2/LM3) are shifted periodically to compensate for the changes in the lake water level. When the water levels are high, the sampling locations are shifted towards the discharge point of the Wash, and revert to the original locations when the levels reach initial stages. The distance shifted each year depends on the degree of change in the lake elevation. During 1991-1996 they were shifted 300 yards east of the campground, and from 1997 to 1999 they were shifted 100 yards west to the campground (Fellows, 1999). However, the interior lake sampling locations (Center Bay of Boulder Basin) do not change with reservoir level (Table 3.3 and Figure 3.2).

Table 3.3: Major Sampling Points in Boulder Basin, Lake Mead

Station	Sampling Location	Total Samples Available	Number Analyzed	Distance from the Reference Point
LM4E	Next to buoy RW "1", just outside of the	170	45	3.96 km
LM4M	Las Vegas Wash launch ramp and marina.	100	35	
LM4H	(N 36 07 168 W 114 51 359)	100	21	
LM5E	Next to buoy RW "A", south shore	150	32	5.2 km
LM5M	landmark is Crescent Island.	100	30	
LM5H	(N 36 07 085 W 114 50 535)	100	28	
LM8E	Between Sentinel Island and the shoreline	160	37	16.7 km
LM8M	of Castle Cove.	110	26	
LM8H	(N 36 03 967 W 114 44 224)	110	25	
LM9H	Center of the Black Canyon halfway between the mouth of the canyon and Hoover Dam, at a depth of 70m. (N 36 01 427 W 114 43 669)	50	10	21.7 km

Note: E,M and H stand for eplimnion , metalimnion and hypolimnion layers of the lake.
(Source: Modified from Lake Mead Interagency Sampling Manual, 1998)

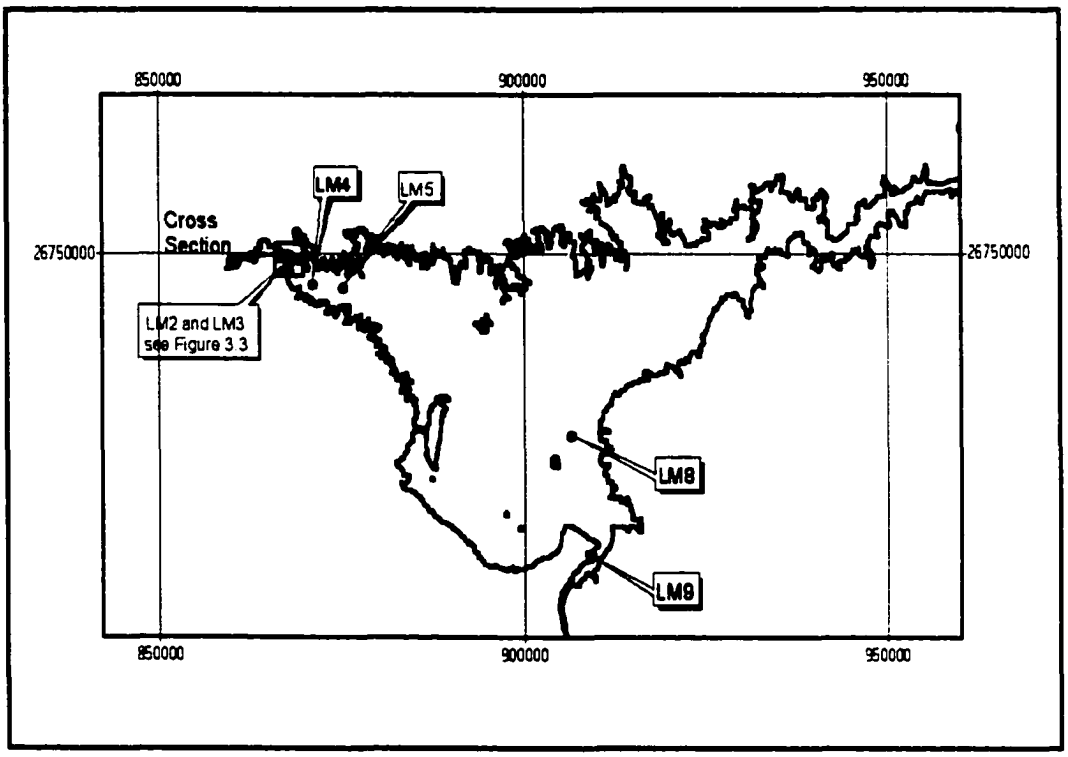


Figure 3.2: Water Sampling Locations in Lake Mead .

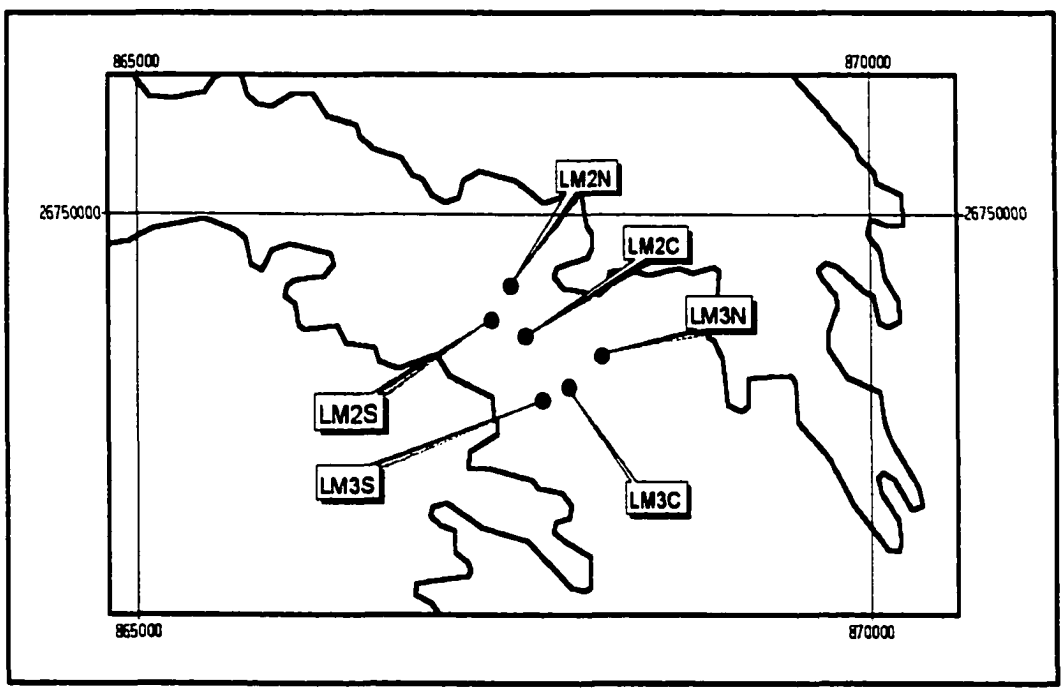


Figure 3.3: Water Sampling Locations in the Las Vegas Bay, Lake Mead .

A historical water quality database of Lake Mead has been maintained by the Limnology Research Center at UNLV since 1976 for the sampling locations LM 2, 5 and 8 (Lake Mead Interagency Sampling Manual, 1998). Several other sampling locations were added during the next few years. This included the addition of the sampling points LM3 and LM4 in 1979. The water samples collected since 1991 have been cataloged and are preserved by the CCSD laboratory. The total number of frozen samples stored from 1991 to 2000 is approximately 5500. A copy of the sample catalogue is given in Appendix C. The sample dates given in the catalogues are not necessary the actual sample collection dates; they correspond to the scheduled sample collection dates. During this research, the actual sampling dates were used instead of the date indicated in the catalogue. Recently, the Southern Nevada Water Authority (SNWA), through the Las Vegas Wash Coordination Committee created a database (www.lvwaterquality.org) where the water quality data generated by the CCSD, City of Las Vegas, City of Henderson and other local agencies are maintained and can be retrieved.

3.2 Thawing Procedure

The frozen water samples were transferred from the freezer to a cooling room, and were allowed to thaw for three days. The original samples were mixed by inverting several times, and aliquots were taken. At least 50% of the sample quantity was left with the original sample, and was placed back into the freezer immediately. Approximately 100 ml sample volume of 10% of the total samples taken from the CCSD was given to the Las Vegas Wash Coordination Committee. The samples were carried

in a chilled container to the UNLV Environmental Engineering Laboratory and were placed under refrigeration until analyses.

Samples were analyzed using the Dionex 120 ion chromatograph with the AS40 automated sampler at the UNLV Environmental Engineering Laboratory. The analytical procedure developed by the California Department of Health Services (CDHS) and the Dionex Company (California Department of Health Services, 1997; Dionex, 1998) was adopted in perchlorate analyses (Appendix F). However, a minor modification was made to the CDHS procedure to suit the Dionex 120 machine that was used in the experiments, whereas the CDHS procedure had been developed for the Dionex 500. The amended analytical procedure used a 49 mM NaOH eluent solution instead of the CDHS recommended 100 nM eluent. Dionex AS11-4mm and AG11-4mm with 100 μL injection loop were used as separation and guard columns.

Calibration was carried out for each experimental run. The calibration procedure included two deionized water samples, calibration standards of 5, 10, 30, 60, 80 and 100 μg/l of perchlorate solutions, followed by three deionized water samples. The calibration standard solutions were made on weekly basis from a 1000 μg/l stock solution. The stock solution was prepared each month, and both the stock and the calibration standard solutions were kept under refrigeration. Water samples that were expected to have high perchlorate concentration were diluted with deionized water to concentrations between 5 μg/l to 100 μg/l.

3.3 Quality Assurance (QA) and Quality Control (QC)

The calibration was carried out to achieve a minimum 0.997 least square value (R^2). If the R^2 was not met, a new set of calibration standards were prepared and the calibration procedure was repeated. During analyses, after every 20 samples, a QC sample was run to confirm the accuracy of the measurements. This sample was prepared by a different member of the research group other than the student who prepared the calibration standards. Subsequent to analyses, the remaining portions of all the samples have been kept in a freezer for any future use.

CHAPTER 4

HISTORICAL PERCHLORATE LEVELS IN LAKE MEAD AND LAS VEGAS WASH

Past perchlorate levels were obtained by analyzing frozen water samples from the Las Vegas Wash and Lake Mead. Investigation of perchlorate levels within the Wash and the Lake is important not only because perchlorate is a potentially harmful contaminant, but also because perchlorate behaves as a conservative tracer, and it could be used to track the fate of other contaminants. The Wash discharge into the Lake is expected to contain many other contaminants besides perchlorate, as it is polluted from the seepage from the BMI area (Table 2.10), urban runoff, and discharges from the WWTPs. Because Lake Mead is the primary drinking water supply to the Las Vegas Valley and it is for several recreational purposes, it is imperative to control the water quality of the Las Vegas Wash. The drinking water intake point at Lake Mead (Saddle Island) is located approximately 12 km from the Wash discharge point at a depth approximately 35- 45 m below the Lake surface. This distance was considered adequate at the time of construction of the water intake for Las Vegas. However, the increase in the flow of the Wash resulting from the rapid growth in the Valley extends the intrusion distance of the Wash discharge into the lake every year. Therefore, prediction of the movement and the mixing of the Wash discharge as it reaches the Lake is extremely important in understanding the fate of perchlorate and other contaminants in the Lake.

The perchlorate levels within Lake Mead are affected by lake hydrodynamics as well as by its fluctuations in the Wash. The perchlorate levels in the LVW were evaluated to investigate the major perchlorate loading zones along the Wash, seasonal loading patterns and factors that influence perchlorate levels within the Wash. The Wash perchlorate levels can be influenced by many factors including hydrogeological changes within the seepage area, changes in the perchlorate discharge practices by the manufactures, as well as by natural events such as rainfall/flooding, and changes in the Wash flow.

The perchlorate levels within the Lake were also investigated. Because perchlorate behaves as a tracer, its levels in the Lake can be used to investigate the movement and the mixing of the Wash discharge within the Las Vegas Bay. Annual and seasonal limnological changes, water quality and flowrate of both the Wash and the Colorado River, Lake storage levels, and several other factors govern the movement of the Wash within Lake Mead. The past perchlorate levels at several sampling locations were evaluated to study seasonal and long-term changes, and spatial variations of perchlorate levels in Lake Mead. Data on perchlorate levels, TDS, Wash flow, and Lake storage volume were used in the analysis presented here are given in Appendix A.

4.1 Historical Perchlorate Concentrations along the Las Vegas Wash

Frozen water samples from several locations in the LVW were analyzed. Although the Wash originates from the Spring Mountains, 28 miles north of Las Vegas (Bierly et al, 1980), it does not support a continuous flow until it reaches discharge point of the Las Vegas City WWTP. The effluent from the CCSD WWTP is also discharged

into the Wash approximately 800 m downstream from the City discharge. The first perchlorate sampling point of the Wash (LVW1) is located approximately 2 km downstream of the discharge point of the CCSD WWTP. The next perchlorate sampling point is LVW3K, and this is located near the Three Kids Mines area, approximately 11 km downstream of the City WWTP. The main perchlorate seepage from the BMI area and the discharge of the Henderson WWTP are added to the Wash between LVW1 and LVW3K, approximately 7 km downstream from the City WWTP discharge point. The sampling point LVW5 is located approximately 4.5 km downstream from LVW3K (16 km downstream from the City WWTP discharge).

The availability of frozen samples from both upstream and downstream of the contaminant seepage area for the last ten years provides the opportunity to investigate the total perchlorate loading from the contaminated area, and it also allows for the observation of temporal variations in perchlorate levels. However, there are several other factors that need to be investigated further in order to understand the transport of perchlorate in the Wash. For example, how do perchlorate levels change with respect to external factors? These could include natural factors such as floods, hydrogeological changes within the drainage area, or changes in the discharge practices adopted by the industries. Another important factor is the correlation between perchlorate levels and other water quality parameters such as total dissolved solids (TDS).

Analysis of the frozen water samples from sampling point LVW1 (Figure 4.1) shows that perchlorate concentrations upstream of the contaminated site are relatively low (average 8.8 ppb). Perchlorate concentration at this point remained relatively constant during the period analyzed. The presence of perchlorate at LVW1 is believed to

be caused by the unintentional long-term use of perchlorate-containing coagulation chemicals at the City of Las Vegas WWTP. The perchlorate levels in the LVW increased by a factor of 70-100 once it reaches the downstream portion of the contaminated site (Figure 4.4).

The perchlorate concentrations in the LVW3K sampling point, averaged about 570 ppb before 1995, and have increased and stabilized around 870 ppb after 1995 (Figure 4.2). Notice that the flow of the wash for the two periods did not change significantly (increase of about 15%, from 182 cfs to 211 cfs). One would expect lower perchlorate concentrations with higher flows, but that is not what was observed. Thus, there may have been other factors controlling perchlorate concentrations in the Wash. The flow data for the Wash for the period of concern was obtained from the US Geological Survey (USGS, 2001). The LVW5 sampling point located further downstream from LVW3K had an average perchlorate concentration of 530 ppb until 1995, and averaged about 800 ppb from 1995 (Figure 4.3).

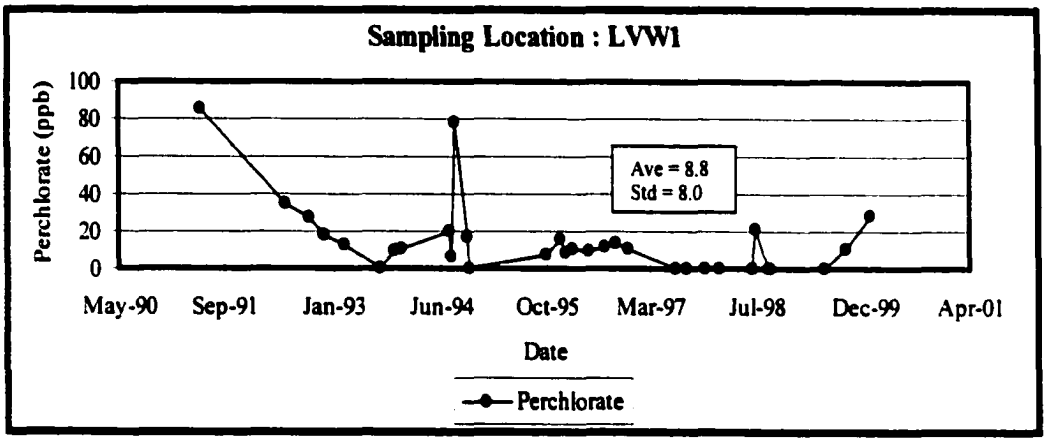


Figure 4.1: Perchlorate Concentrations of LVW1 Sampling Point

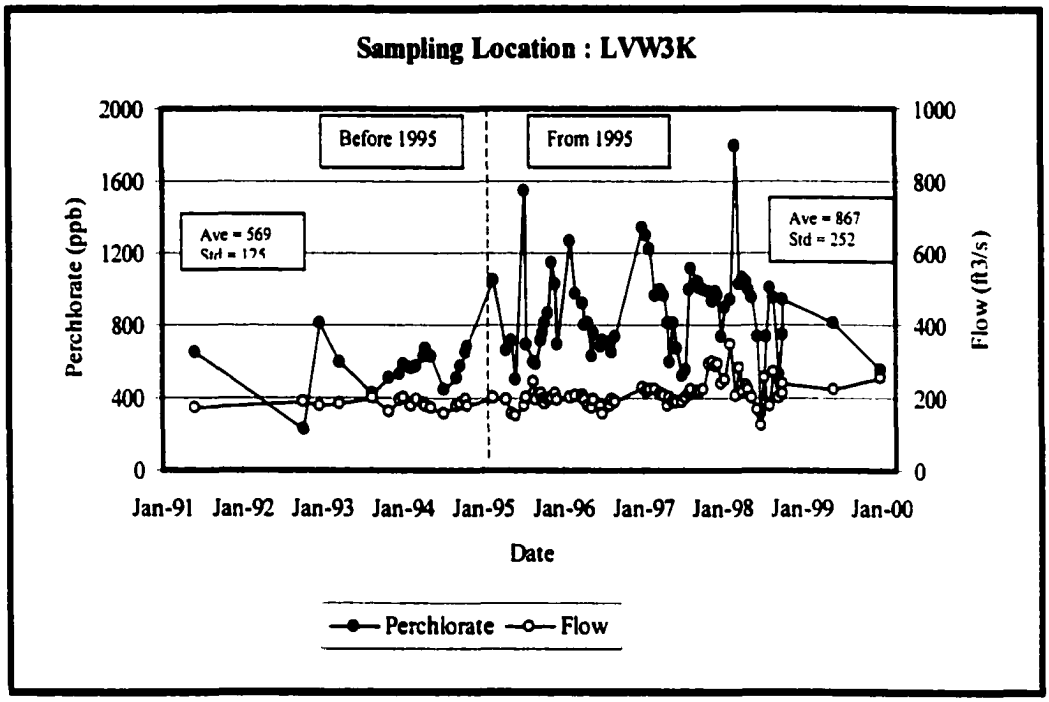


Figure 4.2: Perchlorate Concentrations of LVW3K Sampling Point

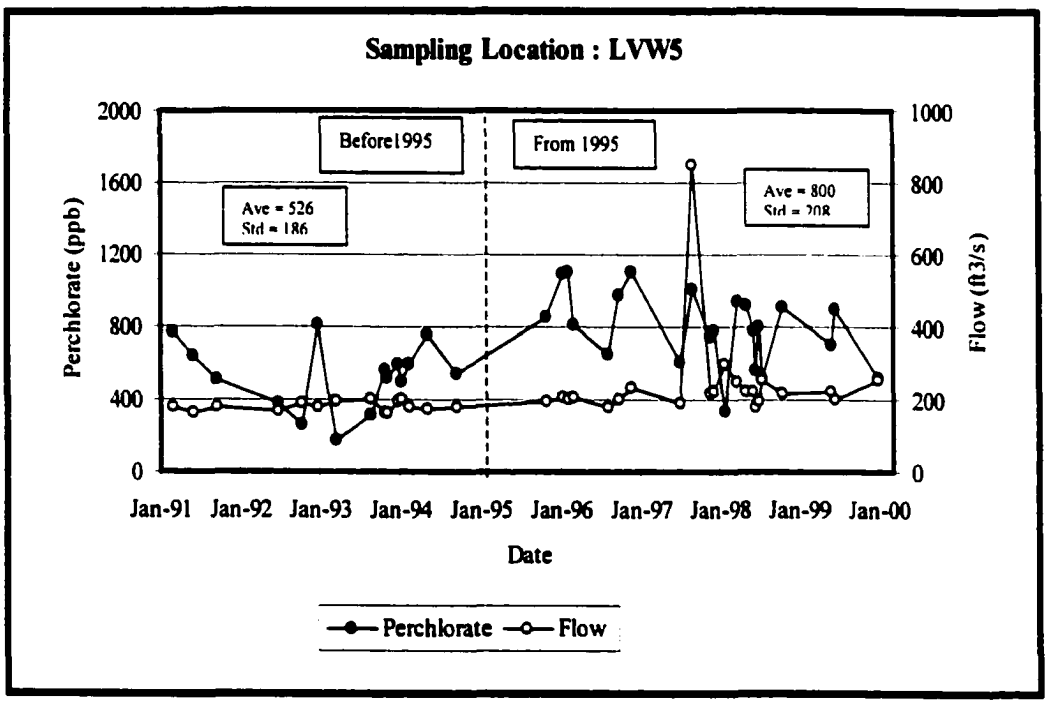


Figure 4.3 : Perchlorate Concentrations of LVW5 Sampling Point

The average perchlorate concentrations for each year in sampling points LVW3K and LVW5 are shown in Table 4.1. The perchlorate concentration and loading profiles for the LVW sampling locations are shown in Figures 4.4-4.7. The profiles were built by taking the average perchlorate concentrations that were available for each year (Table 4.1). The average annual loading rates (Figures 4.6 and 4.7) were estimated by using the perchlorate concentrations and the Wash flow data for the individual dates, and taking the average. The flow of the Wash at the LVW1 sampling location was estimated to be 90% of the flow of LVW5. This estimate was based on the discharges of the three wastewater treatment plants for 1998 (see Chapter 5 for detailed explanations).

Table 4.1: Average Annual Perchlorate Data for the Las Vegas Wash Samples

Year	Average Perchlorate (ppb)		Average Flow (cfs)	Average Perchlorate (kg/day)	
	LVW3K	LVW5	LVW5	LVW3K	LVW5
1991	637	648	170	273	270
1992	484	516	193	226	208
1993	431	514	185	232	189
1994	595	592	188	264	265
1995	854	823	196	390	405
1996	927	803	203	373	451
1997	760	939	226	522	404
1998	720	884	235	493	394
1999	804	806	234	442	414
2000	516	552	250	340	316

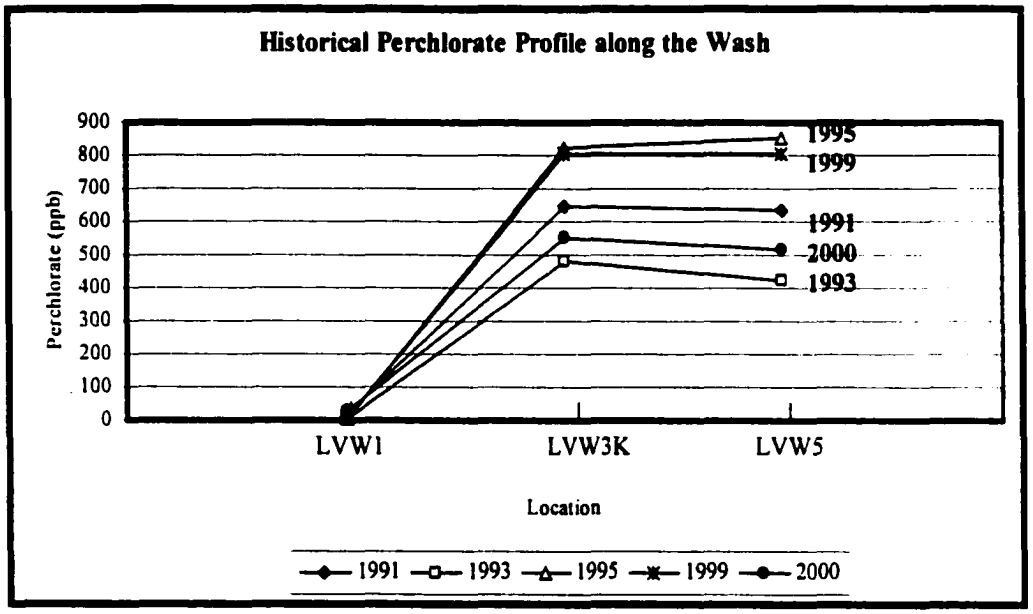


Figure 4.4: Perchlorate Levels along the Las Vegas Wash.

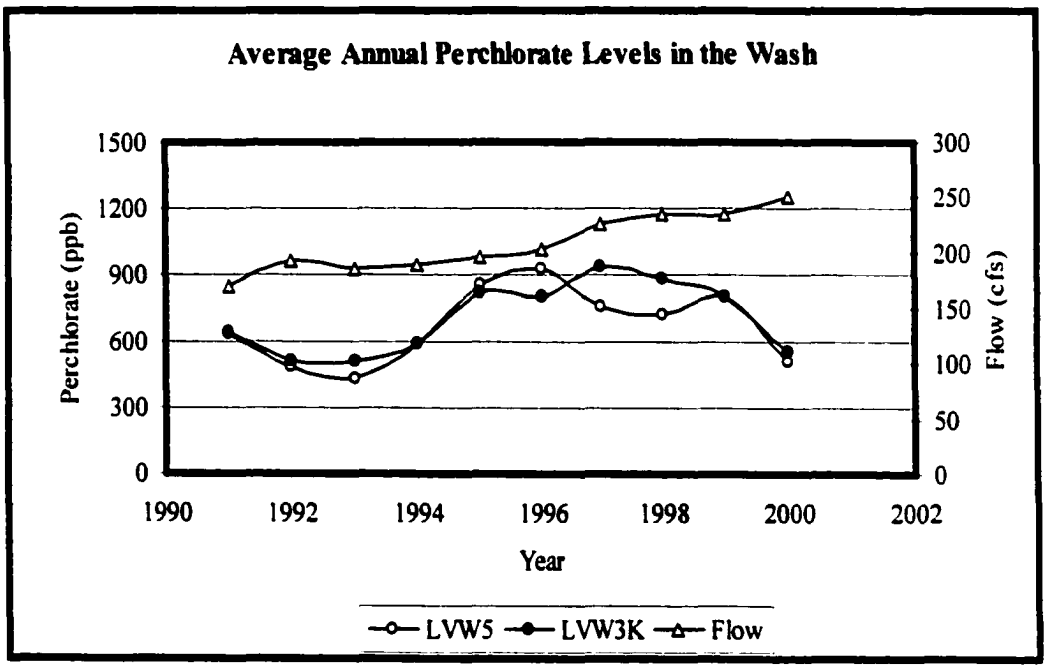


Figure 4.5 : Historical Profiles of Perchlorate along the Las Vegas Wash.

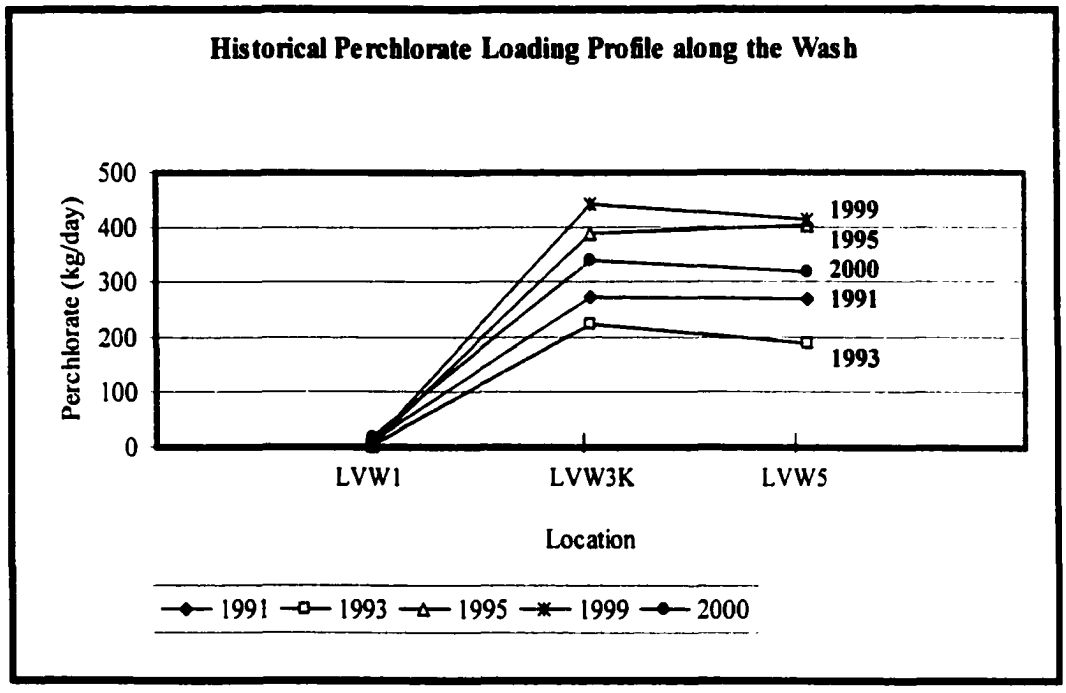


Figure 4.6: Historical Yearly Average Perchlorate Loadings along the Las Vegas Wash.

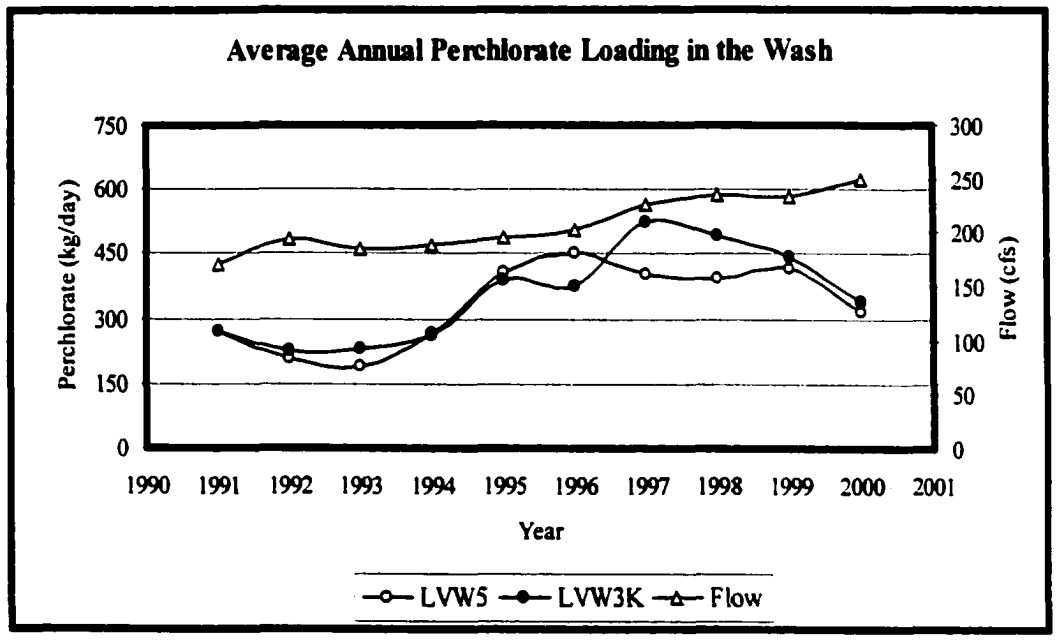


Figure 4.7: Historical Yearly Average Perchlorate Loadings along the Las Vegas Wash.

Evaluation of the average annual perchlorate data shows that perchlorate levels have decreased slightly from 1991 to 1993, and have started increasing thereafter, reaching a maximum during the period from 1995-1997 (Figure 4.5). It has since fallen from the 1997 peak. The average perchlorate loading data followed a similar pattern, also gradually increasing, reaching a maximum in 1997 (Figure 4.7).

Both perchlorate levels and loading rates started to increase after 1994 based on the annual averages. The Wash had the highest perchlorate levels for the period 1995-1997 (Figure 4.5). Statistical analyses (Appendix B) were carried out to determine the significance of perchlorate concentration increase from 1995. Results strongly support (99.9% confidence) that the perchlorate concentrations have increased from the year 1995. Statistical analyses of perchlorate concentrations (data before and from 1995) predicted confidence interval of (confidence interval for the difference between the mean-before and mean-after: -384,-213) for LVW3K at the 95% level. For LVW5 confidence interval of (-404,-141) were predicted at the 95% level. This increase is despite a 10% increase in the flow of the Wash. Therefore, 1995 was considered as a focal point of this investigation. However, the reasons for the sudden increase in the perchlorate concentration in 1995 are not fully understood at this stage. There may be several reasons for the variations in perchlorate concentrations in the Wash from 1995. Reasons include:

- Fire-flows resulting from the explosion of the PEPCON plant in 1988.
- Use of rapid infiltration basins (RIBs) by the City of Henderson WWTP.
- Increase in the Wash flow.

- Changes of waste disposal practices by the perchlorate manufacturing industries.
- Hydrogeological changes within the contaminated area.
- Erosion and changes in the flow path of the Wash.
- Major floods and climatic factors.

One probable cause for the higher perchlorate concentrations after 1995 is the large-scale perchlorate contamination resulted from the explosion of the PEPCON Plant in 1988. The large quantity of water that was used to extinguish the fire could have carried a substantial quantity of perchlorate, and could have potentially contaminated the downstream sections of the PEPCON Plant. The linear distance from PEPCON Plant to the LVW is approximately 5.5 km. The groundwater flow in the BMI area varies between 0.5 to 2.2 km/year (Geraghty & Miller, 1980). Based on these the hydrological characteristics of the site, perchlorate contamination from PEPCON site could reach the Wash within 2.5-11 years.

There is limited information available on the effects of the hydrological changes within the region on the perchlorate levels. However, the area has been subjected to rapid development during the last five years. Several residential communities have been developed within the contaminated region. This could have involved some degree of disturbance to the existing drainage system due to excavations, displacement of the top-soil, and infiltration of water from residents. It is also known that approximately 2 feet of the top soil layer of certain contaminated (by Pb from PEPCON operations) lands downstream of PEPCON Plant has been removed and deposited within adjacent lands prior to development.

Another influential factor in variations of perchlorate concentrations in the Wash is the wastewater discharge of the City of Henderson WWTP (CHWWTP). The CHWWTP uses rapid infiltration basins (RIB), built in Lower BMI Ponds area, to dispose of its treated effluent wastewater. The RIBs are located on top of the flow path of the KMCC main perchlorate plume, and could impact the lateral movement of perchlorate containing groundwater from the BMI site to the Wash. A hydrogeological study conducted by KMCC (2001) reported that the operation of the RIBs impacted the movement of the groundwater from the KMCC property to the Wash. The Henderson WWTP currently uses three main methods to dispose its treated effluents: use of RIBs, recycling for irrigation purposes, and the direct discharge into the Wash (Table 4.2). However, RIBs were put into the operation in 1980 and 1981. Based on the timing of the operation of the RIB and the increase of perchlorate levels after 1995, this could not be the cause. The City of Henderson solely relied on these RIBs until 1994 for the treatment and disposal of wastewater from their aerated lagoons until the plant started the operation of their new WWTP (referred to as the Reclamation Facility) in June 1994. This coincides with the increase in the perchlorate levels in the Wash. However it is difficult to establish any direct connection between the two events based on the available information.

Table 4.2: Wastewater Disposal Information for Henderson

Year	Influent (MGD)	Recycled (MGD)	RIBs (MGD)	Discharged to the Wash (MGD)
1988	5.25	N/A	N/A	N/A
1989	5.94	N/A	N/A	N/A
1990	6.73	N/A	N/A	N/A
1995	9.94	2.61	4.71	2.19
1996	11.07	3.10	4.31	3.00
1997	12.38	2.91	2.16	7.48
1998	14.87	6.21	2.78	6.15
1999	15.72	5.76	4.34	5.55
2000	17.07	6.75	4.62	5.60

(Source: Henderson WWTP Plant, 2001)

Another probable cause is the use of a center-pivot spray disposal by one of the BMI industries. It is believed that TIMET used this water wheel for the application of industrial wastewater approximately for a period of 1-2 years, sometime between 1989 to 1992. This was located partially over the Upper BMI ponds, and could have increased the flushing of perchlorate containing groundwater towards the Wash.

The development of head-cut erosion caused the flow depth of the Wash to drop significantly during the last decade. This increases the hydraulic gradient between the perchlorate contaminated site and the Wash, resulting in an increase in the lateral groundwater flow rate towards the Wash from the BMI area. This could not be further investigated due to the unavailability of the Wash elevations during this period. All these factors could influence the perchlorate levels within the Wash, but is difficult to relate to the pattern observed in the Wash with the information available at this stage.

4.1.1 Relationship between Wash Flow and Perchlorate Levels

As a result of the population growth in the Las Vegas Valley, the volume of wastewater and consequently the Wash flow rate increased from 1995 (Figure 4.5). In addition, there are also increases in the Wash flow during rain and flood events. To examine the effects of rain and flooding on Wash perchlorate levels, perchlorate concentrations at high flow days were compared to those of typical days (closest day within one month in the following year) for the LVW5 and LVW3K sampling points. It would be expected, if the flow and concentration of the KMCC seepage remained constant, that the perchlorate concentration would decrease with increasing Wash flow (Table 4.3). A high flow day was considered as a day that had a flow increase of 25% or higher.

Table 4.3: Comparison of Perchlorate Data on High-flow and Typical Days

High Flow Days			Typical Day			Sampling Point
Date	Perchlorate (ppb)	Flow (cfs)	Date	Perchlorate (ppb)	Flow (cfs)	
2-Sep-98	948	270	30-Sep-98	528.7	200	LVW3K
18-Feb-98	937	347	18-Mar-98	1798	207	LVW3K
1-Apr-98	1031	281	15-Apr-98	1063	218	LVW3K
27-Nov-96	1100.4	230	26-Nov-97	746.94	216	LVW5
3-Sep-97	1009.56	950	30-Sep-96	968.4	198	LVW5
4-Feb-98	331.56	299	7-Feb-96	1103.4	199	LVW5
1-Apr-98	945.54	246	9-May-94	757.8	172	LVW5
22-Jul-98	517.2	255	23-Jun-99	900.4	200	LVW5

Pair-wise statistical analyses of perchlorate concentrations could not establish that higher flows change perchlorate concentrations at the 95% confidence level. There was a limited number (11 data points) of perchlorate data for the high flow dates, therefore this sampling could have impacted the outcome of the analyses. The analyzed perchlorate sample data did not fall on actual flood events (defined by the Clark County Flood District) in Las Vegas. Therefore, the effect of flooding could not be studied.

This does not mean that the flow has insignificant effect on the perchlorate loading of the Wash. Although the actual perchlorate concentration may not change on high flow dates, but this could have significant effect on the overall loading of perchlorate into the Lake. Therefore, statistical analyses were carried out to compare the perchlorate loading rates for high-flow and typical-flow dates. The results showed that the high-flow perchlorate loading was significantly higher than that of the low-flow dates at the 90% confidence level (Appendix B).

The effects of increased WWTP discharge in the concentration of perchlorate in the Wash was investigated by comparing average Wash flow with average perchlorate loading. It would be expected that higher flows would dilute the perchlorate concentrations, but the total loading of perchlorate would remain constant. This assumes that no other factors affected perchlorate levels in the Wash. A significant factor to be considered is the erosion of the Wash banks and the potential transport of considerable amounts of perchlorate contained in contaminated soils along Wash. To exclude the effects of high flows (due to precipitation), the average annual perchlorate loading rates for non-rainy dates were compared with average annual flows (excluding high flow

days). This allows studying the effects of the gradual increase of the flow from the discharge of the wastewater treatment plants (Table 4.4).

Table 4.4: Average Perchlorate Loading Rates on Non-High Flow Dates

Year	Perchlorate Loading (kg/day)	Average Annual Wash Flow (cfs)
1991*	273	170
1992	226	193
1993	232	185
1994	264	188
1995	390	196
1996	379	203
1997	520	226
1998	430	235
1999	442	234
2000	340	250

*1991 average loading is based only on one data point

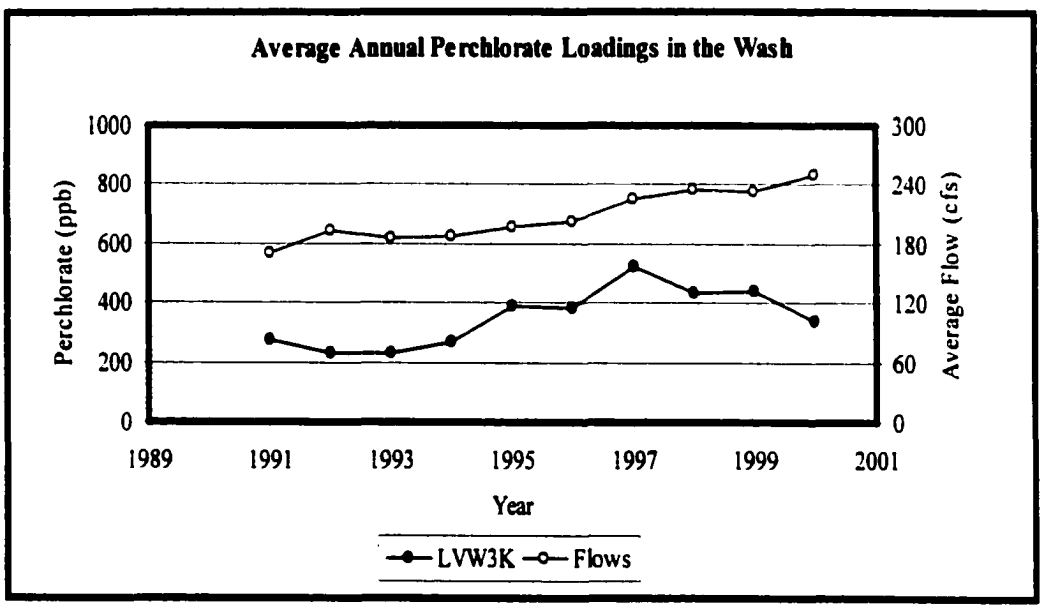


Figure 4.8: Average Perchlorate Loading Rates on Non-High Flow Dates

4.1.2 Comparison of Perchlorate Data for the Wash Sampling Points

The average perchlorate concentration at LVW5 is slightly lower than that of LVW3K (Figure 4.5). Statistical analyses were carried out to determine the significance of the difference in perchlorate concentrations between LVW3K and LVW5 sampling points. Since the two sampling points are located along the same stream, it was assumed that the perchlorate concentration data sets for the two sampling locations to be dependent. Therefore, pair-wise comparisons (Paired-T Tests) were performed for the concentrations with the same date, where possible. At points where data were not available for the same date, comparisons were carried out for the perchlorate levels from the same month. The test results showed that there is a significant difference between the perchlorate levels at the two sampling points at the 95% confidence level for the post 1995 period (Appendix B). The pair-wise comparison of perchlorate data for the LVW3K and LVW5 sampling points were also carried out separately for data before and from 1995 (Table 4.5).

Table 4.5: Comparison of Perchlorate Levels for the Las Vegas Wash Samples

Period	Sample Mean (ppb)	P-value	Remarks
Before 1995 LVW3K LVW5	 556.0 526.4	 P : 0.316	Could not establish that LVW5 level is significantly lower than that of LVW3K.
From 1995 LVW3K LVW5	 921.8 780.7	 P : 0.019	Perchlorate level at LVW5 is significantly lower than that of LVW3K.
Combined Data Set LVW3K LVW5	 765.1 671.8	 P : 0.023	Perchlorate level at LVW5 is significantly lower than that of LVW3K.

The lower perchlorate levels at LVW5 sampling location could be due to the seepage of relatively cleaner water within the reach area between the two sampling points. The residential developments surrounding the Lake Las Vegas resort area could contribute to this additional flow.

Linear regression analyses were performed to examine the correlation between the perchlorate concentration and the flow for the LVW3K and LVW5 sampling locations. This was performed with the objective of finding any relationship between the perchlorate levels and the Wash flow. Summary of the regression analyses is shown in Table 4.6. Based on the statistical results, the flow significantly affects the perchlorate concentration at LVW3K sampling point (Appendix B). However, for LVW5 and at the 95% confidence level a relationship could not be established between the Wash flow and perchlorate concentrations.

Table 4.6: Statistical Analyses of Perchlorate and Flow Data for the Wash

Location	Regression Equation	P values	Remarks
LVW3K*	Perch = 253 + 2.69 Flow	Flow: 0.024 Const: 0.06	Flow is significant at the 95% confidence level.
LVW5*	Perch = 575 + 0.72 Flow	Flow: 0.53 Const: 0.00	Cannot establish that the flow and the constant are significant at the 95% confidence level.
LVW3K**	Perch = 358 + 2.09 Flow	Flow: 0.15 Const: 0.271	Cannot establish that the flow and the constant are significant at the 95% confidence level.
LVW5**	Perch = 575 + 0.72 Flow	Flow: 0.97 Const: 0.006	Cannot establish that the flow and the constant are significant at the 95% confidence level.

* Using all the available data points; * Using the same day samples for LVW5 and LVW3K

There could be several reasons for the difference between the two sampling points for the different correlation between perchlorate concentration and flow at LVW3K and LVW5. The LVW3K sampling location had more than twice the number of data points than LVW5. The lower number of data points for LVW5 could have been the reason for the different results in the analyses. To investigate this hypothesis data from LVW3K was selected to match the same dates and numbers as those of LVW5 (Table 4.6). The statistical analyses for the same dates predicted less significance levels (based on P-values) for the flow in explaining the variability of perchlorate level at LVW3K and LVW5 sampling points. Use of less sampling data points could have caused this decrease. However, the flow of the Wash is still significant at the 85% confidence level for the LVW3K sampling point. The seepage streams probably have lower perchlorate concentrations and significant flow in order to contribute to the observed decrease in concentration.

4.2. Perchlorate Level Trends in Lake Mead

The transport of perchlorate within Lake Mead is more complex than the LVW. This can be influenced by variations in the flow and perchlorate levels of the Wash, as well as by limnological changes that occur within the Lake. In general, the movement of a discharge within a recipient water body is governed by the relative difference in the densities (net effect of temperature and TDS) of the discharge and the recipient water body, the ambient velocities, and bathymetry. The main factors that could potentially affect the transport of perchlorate within the Lake are given below.

1. Relative temperature difference between the Wash discharge and the Lake water.
2. Relative TDS levels of the Wash and the Lake.
3. Lake stratification (caused by seasonal climatic changes).
4. Lake storage level.
5. The flows of the Wash and the Colorado River.
6. Wind and Lake currents, and Lake bathymetry.

The Wash has a higher temperature (20° C to 28° C) and a higher TDS (1500-2000 μg/l) compared to Lake Mead (TDS: 700-800 μg/l, temperature 10° C -27° C) (Roline and Sartoris, 1996; Deacon, 1976). The higher temperature of the Wash imposes a positive buoyancy, on the other hand, the higher TDS imposes a negative buoyancy effect on the Wash discharge within the Lake. As described in Section 2.10.1, the high TDS in the Wash water dominates the movement of the Wash discharge within the Lake causing it to sink to the lower layer of the Lake. Thus, the Wash moves as a bottom density current within the Las Vegas Bay (LaBounty and Horn, 1997). Because perchlorate is highly soluble in water, it also contributes to the Wash's TDS. Therefore, the perchlorate concentration distribution along the Wash and the Lake should follow TDS levels. For example, if the Wash plume moves within the hypolimnion layer, higher perchlorate concentrations should be observed within the hypolimnion layer as compared to the epilimnion layer. Besides water quality parameters, seasonal climatic changes also govern the movement of the Wash within the Lake.

Lake stratification also may influence the movement of the Wash plume within the Lake. Stratification is the result of the changes in the density of the water column

caused by seasonal variations in temperature. However, changes in the density and the flow of the Colorado River could also influence the degree and timing of stratification in Lake Mead. Lake Mead develops stratification during the months of May through September. During the stratified period the vertical mixing of the lake is restricted, and the movement and mixing of the Wash is primarily contained within the epilimnion layer. Thus, higher perchlorate concentrations should be observed within the epilimnion layer during May-September (stratified) period when compared to the rest of the year (non-stratified conditions), because perchlorate loading from the Wash would be diluted by a smaller volume of water within the Lake. The hypolimnion layer should exhibit exactly the opposite behavior.

The flow and the water quality of the Colorado River also influence the movement of the Wash plume within the Lake. Increase of the Colorado flow decreases retention time of perchlorate within the Lake, and is expected to reduce perchlorate levels. The flow patterns of the Colorado could also alter bottom and surface currents within the Lake. Changes in density of the Colorado River water affect the density of the Lake, and as a result could alter the degree and level of stratification within the Lake.

4.2.1 Major Sampling Locations Analyzed

Perchlorate levels at the Las Vegas Bay area, from Black Canyon, Crescent Island, and Hoover Dam were analyzed. The closest set of Lake Mead sampling locations to the discharge point of the Wash are LM2C, LM2N and LM2S. The appoximate distance from the discharge point of the Wash (the Reference Point) to these sampling points are about 2.5 km. As shown in Figure 3.3, these sampling points are

located across the flow path of the Wash within the Bay Area of the Lake. The subscripts C, N and S stand for center, north and south respectively. The locations of the sampling points and the approximate depth at each sampling point are shown in Table 4.7. The depths were estimated from the USGS 50m contour lake bottom elevation GIS map considering lateral and axial distances. The next set of sampling points (LM3C, LM3S and LM3N) are located 2.7 km from the discharge point of the Wash. Higher perchlorate levels are expected to be found at these points due to the close proximity to the discharge point and the restriction of horizontal mixing due to the existence of narrow banks within the initial Bay Area.

Table 4.7: Major Sampling Points in Lake Mead

Station	Sampling Location	Distance from the Reference	Approximate Lake Depth
LM2C	Center of the Inner LVB. N 36 07 705 W 114 52 034	2.45 km	28 m
LM2N	North side of the inner LVB. N 36 07 759 W 114 52 053	2.45 km	28 m
LM2S	South side of the Inner LVB. N 36 07 723 W 114 52 08	2.45 km	22 m
LM3C	Center of the Inner LVB. N 36 07 652 W 114 51 975	2.67 km	30 m
LM3N	North side of the inner LVB. N 36 07 684 W 114 51 928	2.67 km	42 m
LM3S	South side of the Inner LVB. N 36 07 639 W 114 52 012	2.67 km	28 m
LM4	Just outside of the LVW launch ramp and marina. N 36 07 168 W 114 51 359	3.96 km	48 m
LM5	Next to buoy RW "A". N 36 07 085 W 114 50 535	5.2 km	50 m
LM8	Between Sentinel Island and the shoreline of Castle Cove. N 36 03 967 W 114 44 224	16.7 km	>150 m
LM9H	Center of the Black Canyon halfway between the mouth of the canyon and Hoover Dam, at a depth of 70m. N 36 01 427 W 114 43 669	21.7 km	>150 m

Note: Reference point GPS: N 36 07 39.97 W 114 52 32.38
(Source: Modified from Lake Mead Interagency Sampling Manual, 1998)

The next set of sample points, LM4 and LM5, are located approximately 4 km and 5 km from the discharge point of the Wash, respectively. Their further location from the Wash discharge and wider banks allow for adequate mixing of the Wash discharge by the time the plume reaches these sampling points. Therefore, relatively lower perchlorate levels are expected to be found at these points. The LM8 sampling point is located in the interior section of the Lake, approximately 16.7 km from the discharge point of the Wash. It is expected that the Wash discharge and the Colorado River have almost completely mixed by the time the currents reach this point. The LM9H sampling point represents the release of the Hoover Dam. This sampling point is located just upstream of the Dam at a depth of 70m. The distance to this sampling point is approximately 21.7 km from the discharge point of the Wash.

Perchlorate levels at the epilimnion, metalimnion and hypolimnion layers were analyzed in frozen samples for all the sampling locations. The epilimnion samples were obtained from a depth of 0-2.5 m (Lake Mead Interagency Sampling Manual, 1998). The depths of the metalimnion and hypolimnion samples were based on the level of stratification of the Lake (Table 2.13). Perchlorate concentrations at different locations, depths and different time period were compared, and statistical analyses were performed to further investigate temporal and spatial patterns.

4.2.2.Perchlorate Level Distribution within Lake Mead

Analyses of the frozen water samples from Lake Mead, within the Las Vegas Bay show that perchlorate is quickly diluted to concentrations around 100-200 ppb by Lake Mead Water (Table 4.8). Table 4.8 was built by including only perchlorate

concentrations for which the sampling dates were very close. The goal was to have an approximate estimate of the dilution effects on perchlorate levels. Perchlorate levels in the interior sections of the lake are around 10-15 ppb. Based on the average perchlorate concentration for the all samples analyzed, and statistical analyses (Table 4.9), the perchlorate levels in the hypolimnion layer are significantly higher (at the 95% confidence level) than those of the epilimnion layer, specifically for the sampling points within the Las Vegas Bay Area. The difference between the hypolimnion and the epilimnion perchlorate levels were highest among the sampling points closer to the discharge point of the Wash, and gradually decrease with distance towards the Lake interior. From points LM5 to LM8 a reversal is observed; the concentrations of perchlorate in the epilimnion layer are greater than those of the hypolimnion.

Table 4.8: Ten-year Average Perchlorate Levels in Lake Mead

Sample	Epilimnion (ppb)	Metalimnion (ppb)	Hypolimnion (ppb)
LM2C	91.0	N/A	237.3
LM2N	83.9	N/A	226.9
LM2S	70.0	N/A	222.0
LM3C	75.0	76.5	142.2
LM3N	72.3	N/A	132.9
LM3S	81.1	N/A	164.0
LM4	43.9	49.3	95.9
LM5	37.7	40.0	35.8
LM8	15.8	13.6	12.4
LM9	N/A	N/A	11.7

Note: Perchlorate concentrations were obtained from frozen samples stored by the CCSD. N/A: Samples were not available.

Table 4.9: Summary of Statistical Analyses for Perchlorate Concentrations among Hypolimnion, Metalimnion and Epilimnion Layers

Sampling Points	P values	Conclusion Based on 95% Confidence Level
LM2CE - LM2CH	P-Value = 0.003	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM2NE - LM2NH	P-Value = 0.0002	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM2SE - LM2SH	P-Value = 0.000	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM3CE – LM3CH	P-Value = 0.000	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM3CE-LM3CM	P-Value = 0.183	Could not establish that metalimnion ClO_4^- is higher than epilimnion.
LM3CH-LM3CM	P-Value = 0.005	Hypolimnion ClO_4^- is significantly higher than the metalimnion.
LM3NE – LM3NH	P-Value = 0.0018	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM3SE – LM3SH	P-Value = 0.0012	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM4E – LM4H	P-Value = 0.008	Hypolimnion ClO_4^- is significantly higher than the epilimnion.
LM4E-LM4M	P-Value = 0.094	Could not establish that metalimnion ClO_4^- is higher than epilimnion.
LM4H-LM4M	P-Value = 0.021	Hypolimnion ClO_4^- is significantly higher than the metalimnion.
LM5E – LM5H	P-Value = 0.169	Could not establish that hypolimnion ClO_4^- is higher than epilimnion.
LM5E-LM5M	P-Value = 0.673	Could not establish that metalimnion ClO_4^- is higher than epilimnion.
LM5M-LM5H	P-Value = 0.475	Could not establish that metalimnion ClO_4^- is different from hypolimnion.
LM8E – LM8H	P-Value = 0.026	Hypolimnion ClO_4^- is significantly lower than the epilimnion..
LM8E-LM8M	P-Value = 0.075	Could not establish that metalimnion ClO_4^- is higher than epilimnion.
LM8H-LM8M	P-Value = 0.108	Could not establish that metalimnion ClO_4^- is higher than hypolimnion.

However, statistical significance could be established only for points LM8. At the LM8 sampling location, the epilimnion perchlorate levels were significantly higher than the hypolimnion layer. This indicates that the perchlorate plume moves within the hypolimnion layer (LM2C-LM4) initially, and moves up within the intermediate zone (LM5), and mixes into the Lake surface water in Boulder Basin.

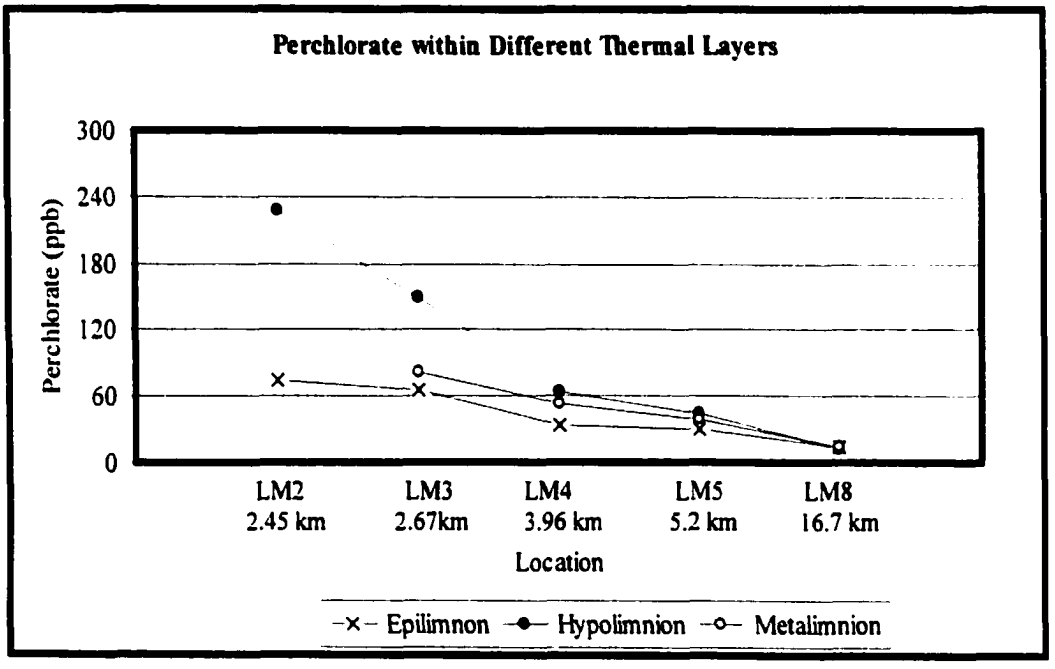


Figure 4.9: Average Perchlorate Levels within Different Thermal Layers

4.2.3 Influence of Stratification on Perchlorate Distribution

The average perchlorate levels (observed during the last 10 years) of the stratified and non-stratified periods of the Lake Mead sampling points are shown in Figures 4.10 to 4.11. The epilimnion and metalimnion perchlorate levels during the stratified period were higher than those of the non-stratified period. The hypolimnion

perchlorate levels showed the exactly the opposite behavior. Therefore, perchlorate data agree with the information known about the movement of the Wash.

Also notice that the degree of difference between the stratified and non-stratified periods is highest within the initial sampling points, and gradually decreases as the Wash plume progresses into the Lake. Based on the averages, there was insignificant difference between the two periods at the LM8 sampling location for all the thermal layers. The impact of the stratification should be greatest within the initial sections of the mixing zone. As the Wash progresses into the Lake, it has higher chances of getting mixed into the underlying hypolimnion layer.

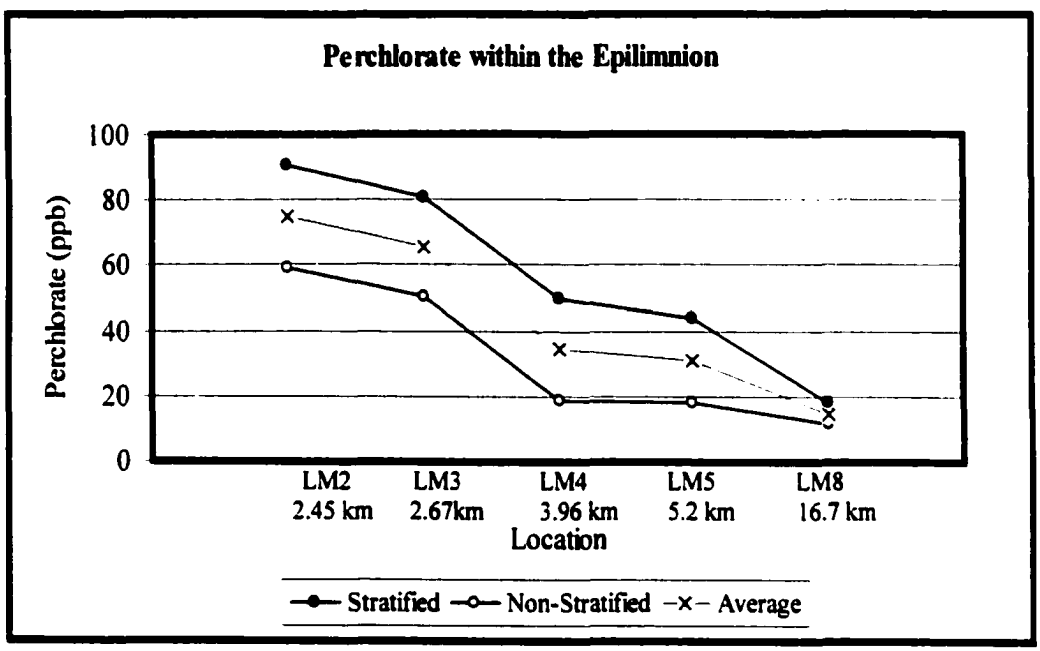


Figure 4.10: Average Perchlorate Concentration Profile within the Epilimnion

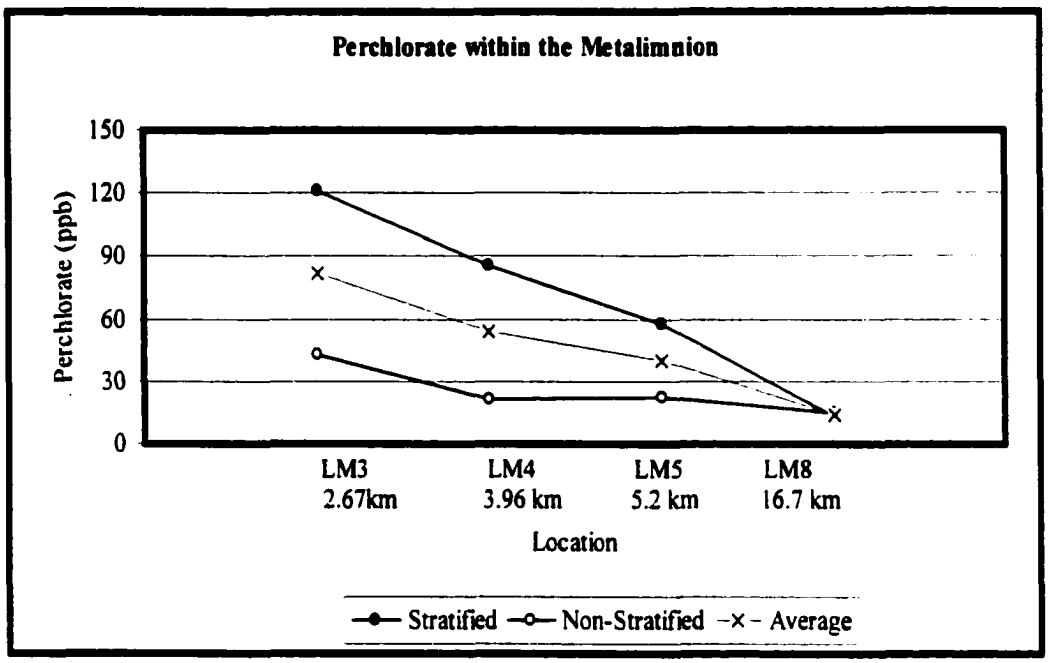


Figure 4.11: Average Perchlorate Concentration Profile within the Metalimnion

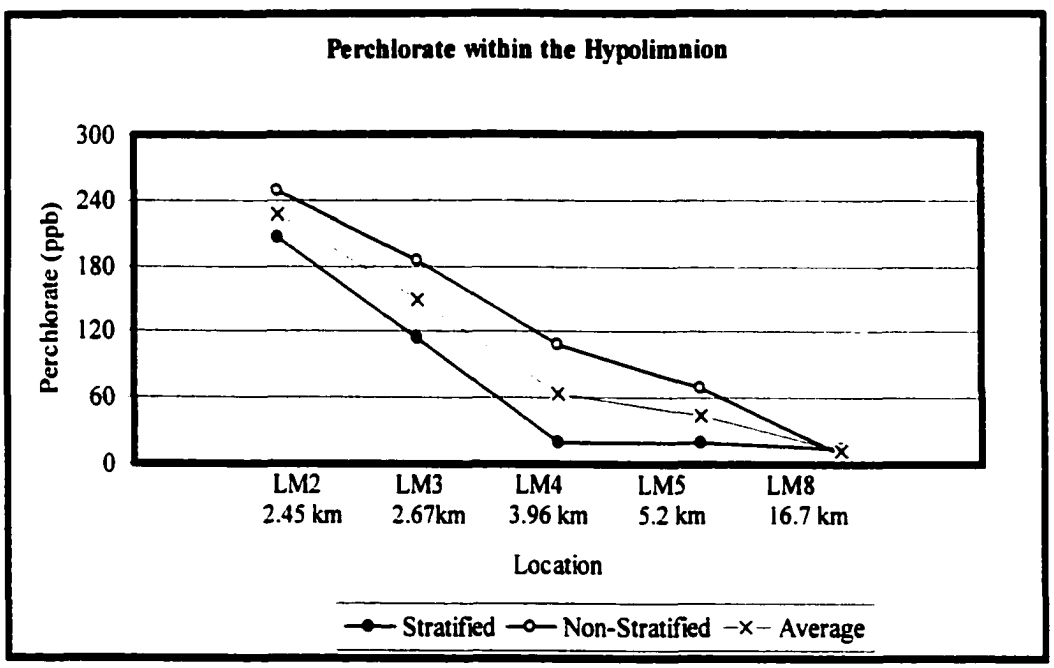


Figure 4. 12: Average Perchlorate Concentration Profile within the Hypolimnion

Statistical analyses were carried out to observe the differences between the perchlorate concentrations for stratified and non-stratified conditions, for both epilimnion and hypolimnion layers. This was performed to study the effects of stratification on the movement of the Wash within the Lake. For analyses, the lake was divided into three sections after considering their locations:

(1) initial mixing zone (LM2C, LM2S, LM2N, LM3C, LM3S, and LM3N),

(2) middle zone (LM4 and LM5), and

(3) interior zone (LM8 and LM9).

May 01 to October 01 was considered as stratified, and November 01 to April 01 was considered as non-stratified. The results are summarized in Tables 4.10 and 4.11. The null hypothesis was considered as the case where the perchlorate levels were the same for the two periods. This was tested against alternative hypotheses, that are stated in Tables 4.10 and 4.11. The detailed results of the statistical analyses are given in Appendix B.

Table 4.10: Summary of Statistical Analyses for Seasonal Variation in Perchlorate Levels in the Epilimnion

Zone	Alternative Hypothesis	P values	Conclusions (95% Confidence Level)
Initial mixing zone	H_a= non-stratified ClO_4^- < stratified ClO_4^-	P : 0.000	The non-stratified perchlorate concentrations are significantly less than the stratified conditions.
Middle zone	H_a= non-stratified ClO_4^- < stratified ClO_4^-	P : 0.000	The non-stratified perchlorate concentrations are significantly less than the stratified conditions.
Interior zone	H_a= non-stratified ClO_4^- < stratified ClO_4^-	P : 0.041	The non-stratified perchlorate concentrations are significantly less than the stratified conditions.

Table 4.11: Summary of Statistical Analyses for Seasonal Variation in Perchlorate Levels in the Hypolimnion

Zone	Alternative Hypothesis	P values	Conclusions (95% Confidence Level)
Initial mixing zone	H_a= non-stratified ClO_4^- > stratified ClO_4^-	P : 0.042	The non-stratified perchlorate concentrations are significantly higher than the stratified conditions.
Middle zone	H_a= non-stratified ClO_4^- > stratified ClO_4^-	P : 0.000	The non-stratified perchlorate concentrations are significantly higher than the stratified conditions.
Interior zone	H_a= non-stratified ClO_4^- > stratified ClO_4^-	P : 0.10	Could not establish that non-stratified perchlorate concentrations are lower than the stratified conditions.

Statistical analyses showed that the epilimnion perchlorate concentrations were indeed significantly lower during the non-stratified period than the stratified period. The hypolimnion perchlorate concentrations were significantly higher during the non-stratified period than the stratified period for the initial and middle lake zones. Therefore, the perchlorate data support the existing hypothesis on the movement and the mixing of the Wash plume within the Lake. Another observation was that the statistical significance was stronger (based on the P values) within the Lake's initial and middle zones. The seasonal perchlorate variation became less significant at the interior sampling points (LM8 and LM9). Notice that the alternative hypothesis (non-stratified ClO_4^- > stratified ClO_4^-) for Lake interior hypolimnion samples (Table 4.11) could not be rejected at the 95%, but could be rejected at the 90% (P value is 0.10). This should be the case, since the influence of the Wash is stronger within the Las Vegas Bay area (initial mixing zone), and gradually becomes weaker within the interior sections of the Lake.

Evaluation of the perchlorate data also shows that perchlorate levels had increased after 1995 for all the sampling locations. Statistical analyses were carried out to determine the significance of the increase after 1995. Results strongly support that the perchlorate concentrations have increased since year 1995 (Table 4.12). The effect of Lake storage level on the perchlorate concentrations was also investigated. During the past, Lake Mead elevations had changed. Regression analyses were performed to investigate this effect (Table 4.13).

Table 4.12: Summary of Statistical Analyses for Comparison of Perchlorate Data Before and from 1995

Sampling Point	Before 1995	From 1995	95% Confidence Intervals for the Difference and P values
LM2CE	Mean = 42.9, Std = 27.6	Mean = 109.5, Std = 96.2	CI = (-91.8, -41), P = 0.0003
LM2CH	Mean = 138 , Std = 136	Mean = 245, Std = 119	CI = (-183, -32), P = 0.000
LM2NE	Mean = 40.2, Std = 43.3	Mean = 106.4, Std = 81.2	CI =(-125.4, -7.9), P = 0.0015
LM2NH	Mean = 81.6, Std = 55.1	Mean = 292, Std = 210	CI = (-304, -118), P = .0000
LM2SE	Mean = 37.4, Std = 26.9	Mean = 76.4, Std = 35.8	CI = (-59.22, -18.76), P = 0.001
LM2SH	Mean = 93.4, Std = 76.7	Mean = 266, Std = 100	CI =(-289.5,-57.3), P = 0.006
LM3CE	Mean = 24.8, Std = 16.4	Mean = 105.4, Std = 57.7	CI = (-117.7, -43.5), P = 0.0000
LM3CH	Mean = 70.2, Std = 46.6	Mean = 179, Std = 117	CI = (-164, -54), P = 0.0001
LM3CM	Mean = 43.6, Std = 45.4	Mean = 93.7, Std = 75.5	CI = (-101, 1), P = 0.028
LM3CE	Mean = 24.8, Std = 16.4	Mean = 96.2, Std = 62.9	CI = (-94.5, -48), P = 0.0001
LM3NH	Mean = 65.5, Std = 42.6	Mean = 183, Std = 109	CI = (-179, -56), P = 0.0004
LM3SE	Mean = 57.7, Std = 40.7	Mean = 80.8, Std = 66.6	CI = (-65, 19), P = 0.13
LM3SH	Mean = 61.8, Std = 39.0	Mean = 178, Std = 117	CI = (-174, -59), P = 0.0001
LM4E	Mean = 26.5, Std = 19.1	Mean = 46.7, Std = 28.7	CI = (-34.7, -5.6), P = 0.0039
LM4M	Mean = 24.4, Std = 21.1	Mean = 70.9, Std = 80.8	CI = (-84.5, -9), P = 0.0091
LM4H	Mean = 74.0, Std = 96.6	Mean = 164, Std = 148	CI = (-210, 30), P = 0.062
LM5E	Mean = 19.0, Std = 9.67	Mean = 44.0, Std = 20.6	CI = (-36.0, -14.0), P = 0.000
LM5M	Mean = 6.4, Std = 4.75	Mean = 45.1, Std = 34.2	CI = (-54.6, -22.8), P = 0.000
LM5H	Mean = 15.0, Std = 16.7	Mean = 39.1, Std = 41.5	CI = (-46.8, -1.5), P = 0.019
LM8E	Mean = 6.4, Std = 4.75	Mean = 17.65, Std = 9.23	CI = (-16.2,-6.3), P = 0.0001
LM8M	Mean = 11.9, Std = 9.13	Mean = 13.75, Std = 7.23	CI = (-10.6, 6.9), P = 0.32
LM8H	Mean = 3.99, Std = 3.32	Mean = 14.16, Std = 8.16	CI = (-14.8, -5.5), P = 0.0001
LM9H	Mean = 5.88, Std = 0.37	Mean = 12.34, Std = 6.6	CI = (-11.58,-1.3), P = 0.0098

Table 4.13: Summary of Statistical Analyses for Comparison of Perchlorate and Lake Storage Levels

Sampling Point	P-values for Storage	Conclusions (95% Confidence Level)
LM2CE	0.391	Storage does not explain significant portion of variance
LM2CH	0.103	Storage does not explain significant portion of variance
LM2NE	0.734	Storage does not explain significant portion of variance
LM2NH	0.185	Storage does not explain significant portion of variance
LM2SE	0.817	Storage does not explain significant portion of variance
LM2SH	0.239	Storage does not explain significant portion of variance
LM3CE	0.435	Storage does not explain significant portion of variance
LM3CH	0.252	Storage does not explain significant portion of variance
LM3CM	0.738	Storage does not explain significant portion of variance
LM3NE	0.772	Storage does not explain significant portion of variance
LM3NH	0.025	Storage explains significant portion of variance
LM3SE	0.875	Storage does not explain significant portion of variance
LM3SH	0.341	Storage does not explain significant portion of variance
LM4E	0.142	Storage does not explain significant portion of variance
LM4M	0.508	Storage does not explain significant portion of variance
LM4H	0.545	Storage does not explain significant portion of variance
LM5E	0.042	Storage explains significant portion of variance
LM5M	0.028	Storage explains significant portion of variance
LM5H	0.010	Storage explains significant portion of variance
LM8E	0.272	Storage does not explain significant portion of variance
LM8M	0.129	Storage explains significant portion of variance
LM8H	0.001	Storage explains significant portion of variance
LM9H	0.657	Storage does not explain significant portion of variance

Based on the statistical analyses storage level did not have a significant effect on perchlorate levels for the initial sampling points. However, storage becomes more significant at interior sampling points. This could be due to the fact that perchlorate levels within the initial sampling points are more dependent on the movement of the Wash plume, that is not significantly affected by the Lake storage. However, within the interior sections the plume has already been mixed into the Lake. Therefore, the movement of the Wash plume is not significant, but the storage is important as it affects the degree of dilution of the Wash discharge.

4.2.4 Perchlorate Levels at Individual Sampling Points.

The closest set of Lake Mead sampling locations to the discharge point of the Wash is LM2C, LM2N and LM2S. Figures 4.13.a to 4.15.c show the perchlorate data for the LM2 sampling points and the Lake storage levels for the same time period.

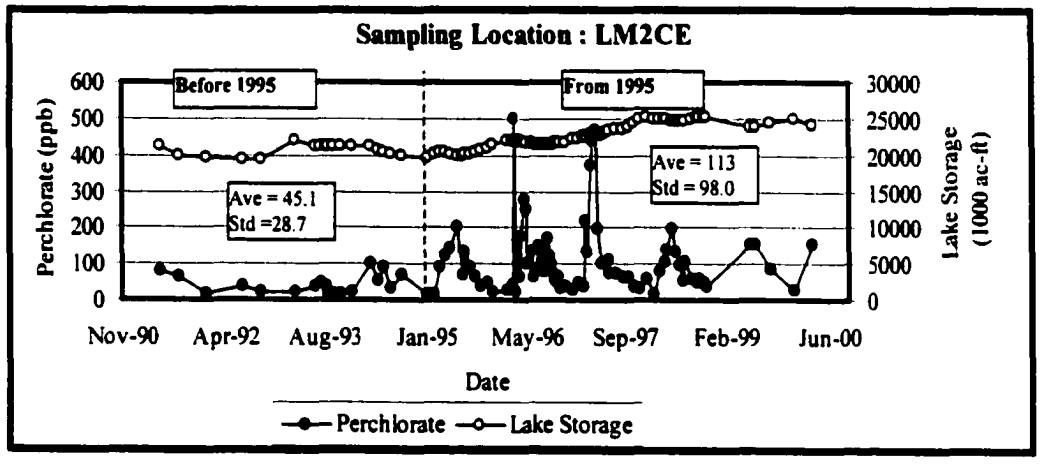


Figure 4.13.a: Perchlorate Concentrations at LM2CE

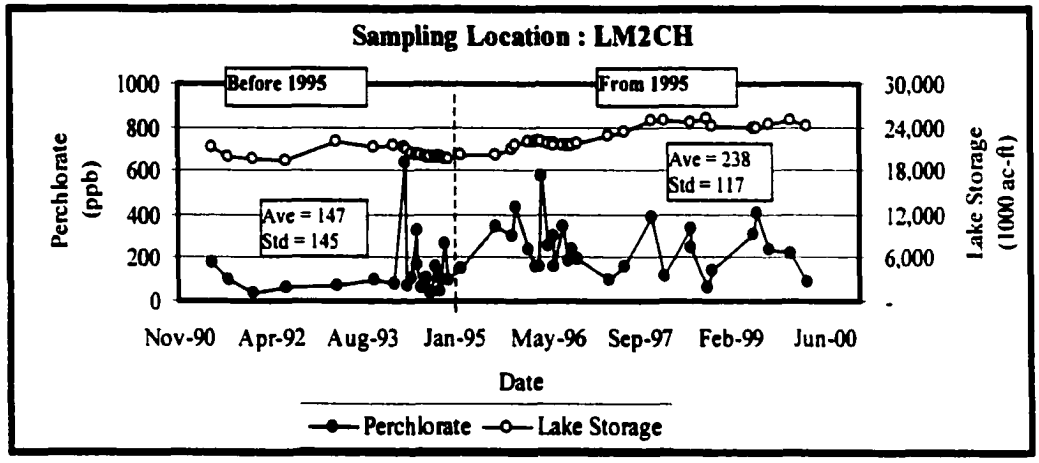


Figure 4.13.b: Perchlorate Concentrations at LM2CH

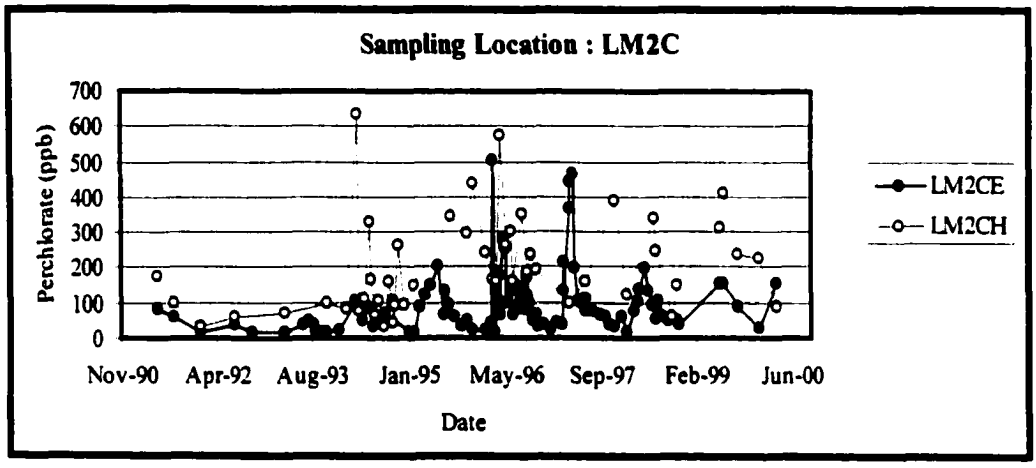


Figure 4.13.c: Epilimnion and Hypolimnion Perchlorate Levels at LM2C

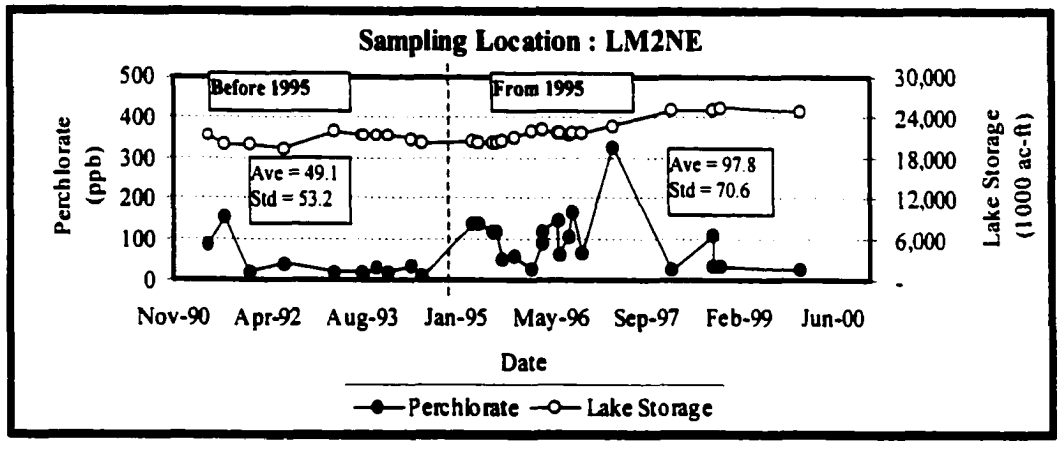


Figure 4.14.a: Perchlorate Concentrations at LM2NE

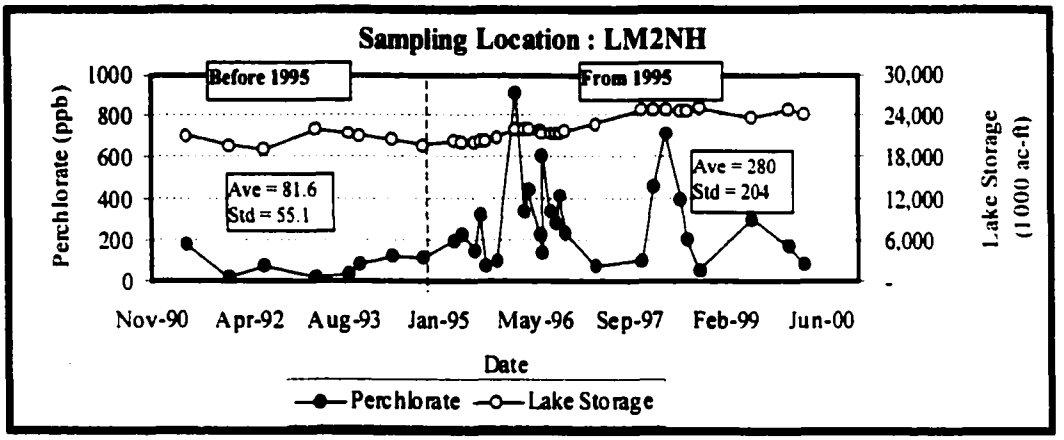


Figure 4.14.b: Perchlorate Concentrations at LM2NH

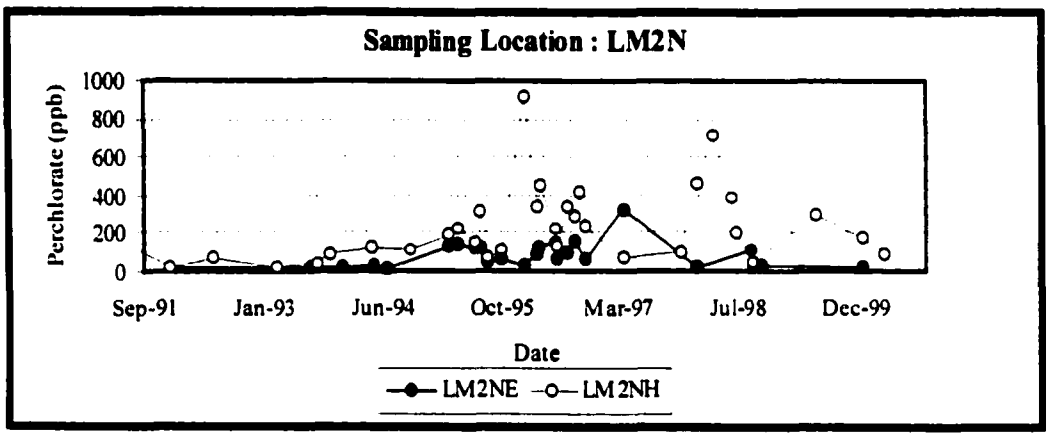


Figure 4.14.c: Epilimnion and Hypolimnion Perchlorate Levels at LM2N

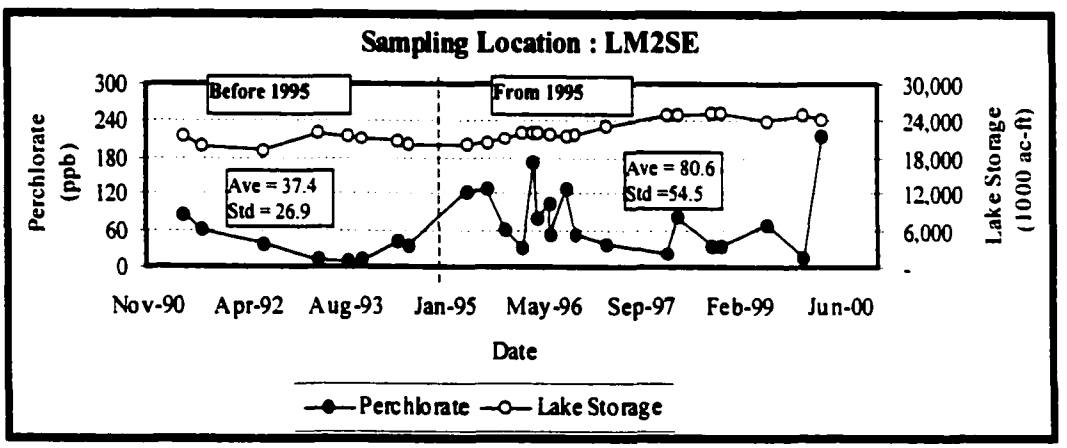


Figure 4.15.a: Perchlorate Concentrations at LM2SE

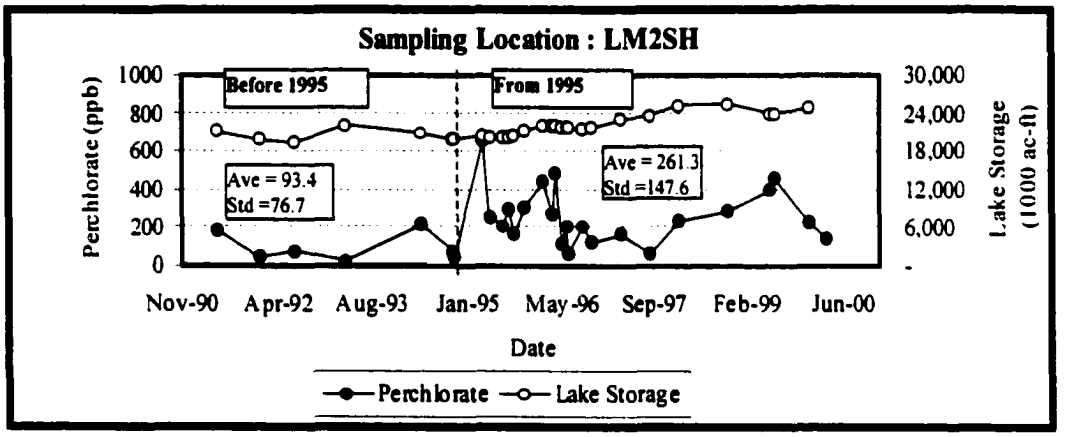


Figure 4.15.b: Perchlorate Concentrations at LM2SH

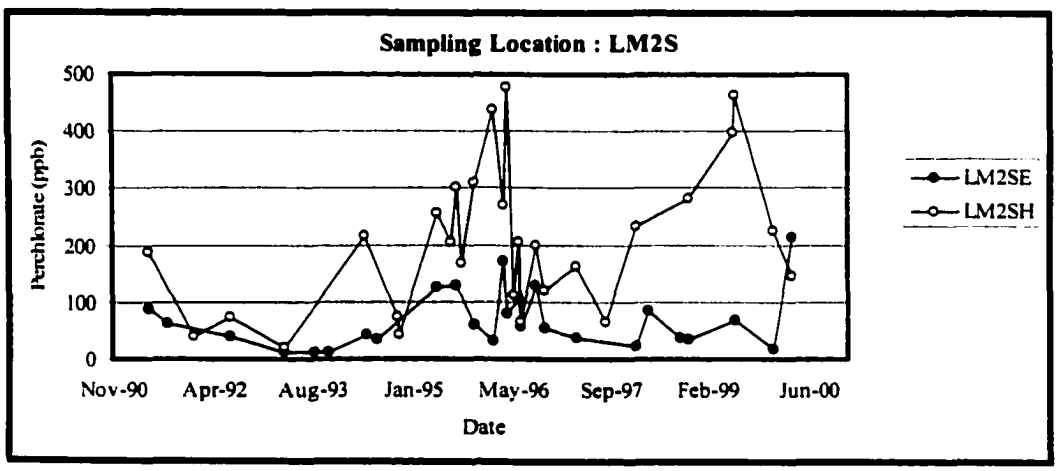


Figure 4.15.c: Comparison of Epilimnion and Hypolimnion Perchlorate Levels at LM2S

The historic data for the LM2 sampling locations show that the perchlorate concentrations are quickly diluted from 750 ppb in the Wash to approximately 250 ppb by the time the discharge of the Wash reaches these sampling points (Table 4.8). An estimate of the dilution effects on perchlorate concentrations within the Las Vegas Bay is given in Chapter 5. The average perchlorate concentration within the epilimnion layer varied from 70.0-91.0 ppb depending on the location . LM2C sampling point had the highest average perchlorate concentration of 91.0 ppb, while the LM2S had the lowest

perchlorate level of 70.0 for the epilimnion layer of the Lake (Table 4.8). The hypolimnion perchlorate concentrations varied between 237.3 ppb to 222.0 ppb, observed at LM2C and LM2S sampling points respectively.

The high perchlorate concentrations of the hypolimnion layer samples indicate that the Wash moves predominantly through the hypolimnion layer within the initial mixing zone. Also notice that the perchlorate levels for these sampling points had increased since 1995 (Figures 4.13.a to 4.15.c).

The next set of sampling locations are LM3C, LM3N and LM3S. These are located approximately 200 m from the LM2 sampling points. The historic perchlorate levels within the LM3 sampling locations are shown in Figures 4.16.a to 4.18.c.

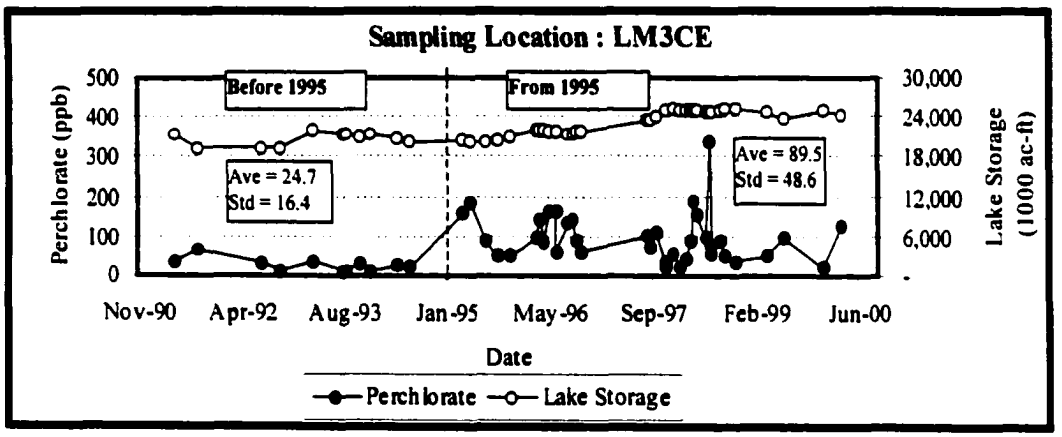


Figure 4.16.a: Perchlorate Concentrations at LM3CE

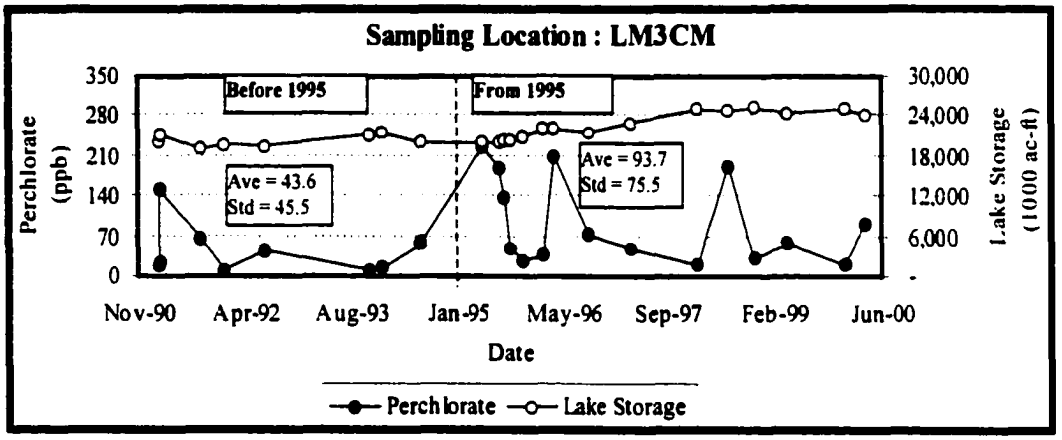


Figure 4.16.b: Perchlorate Concentrations at LM3CM

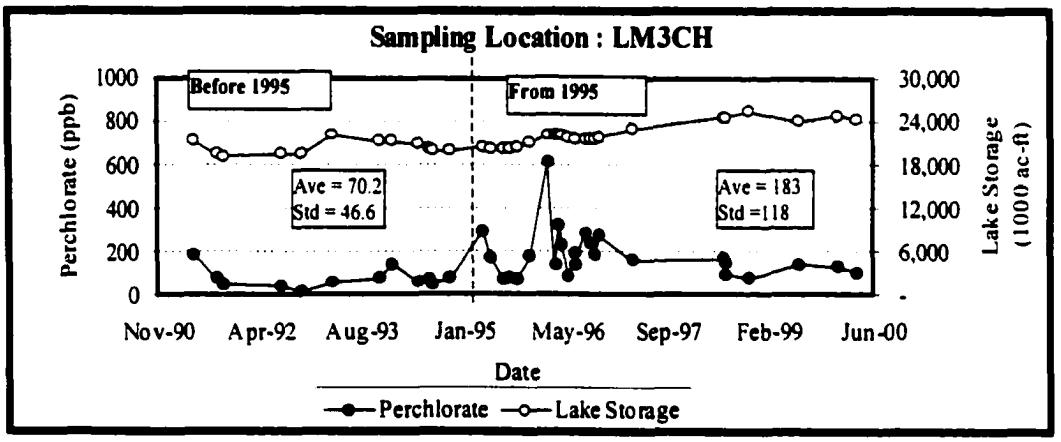


Figure 4.16.c: Perchlorate Concentrations at LM3CH

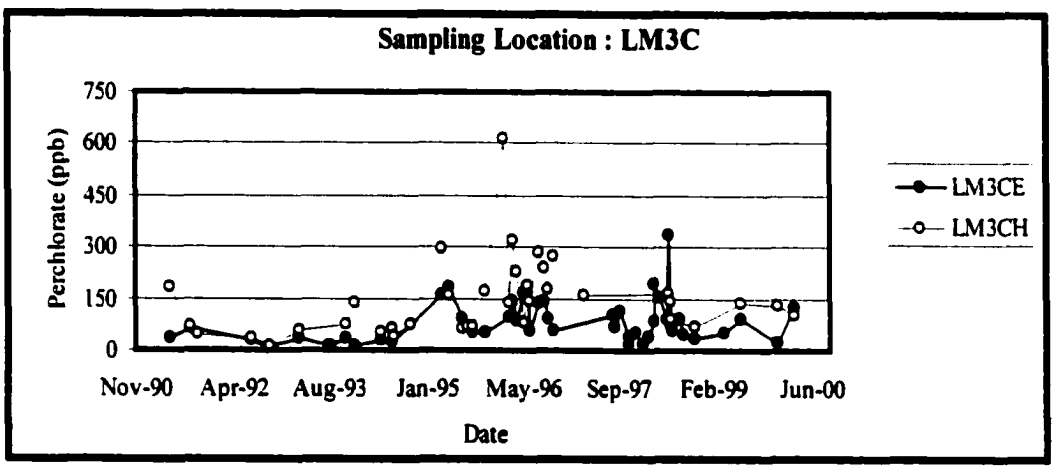


Figure 4.16.d: Epilimnion and Hypolimnion Perchlorate Levels at LM3C

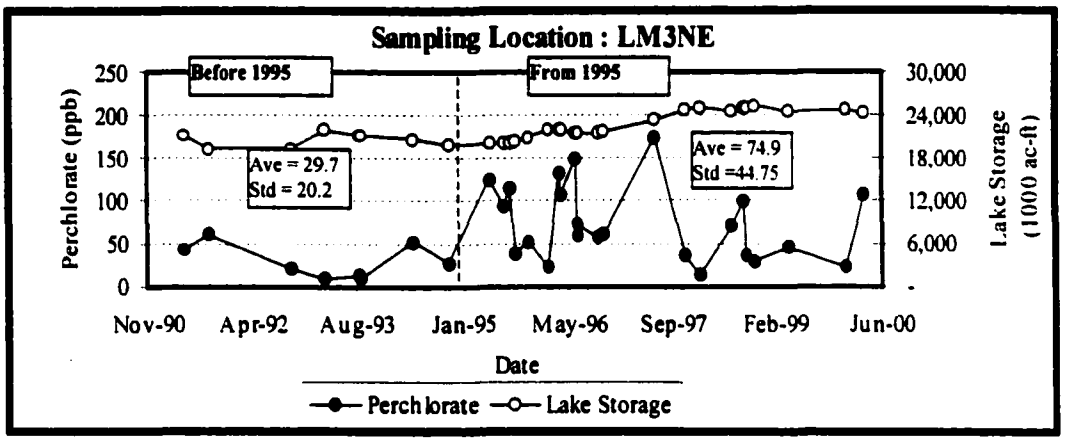


Figure 4.17.a : Perchlorate Concentrations at LM3NE

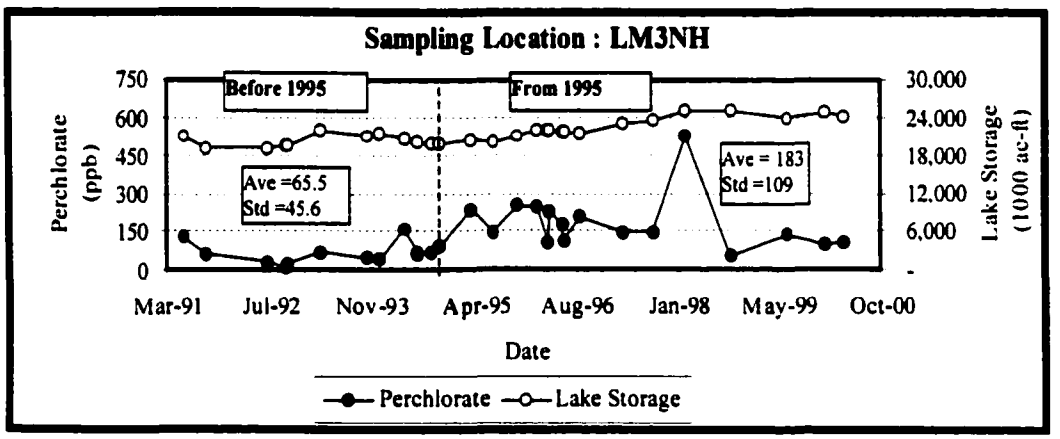


Figure 4.17.b : Perchlorate Concentrations at LM3NH

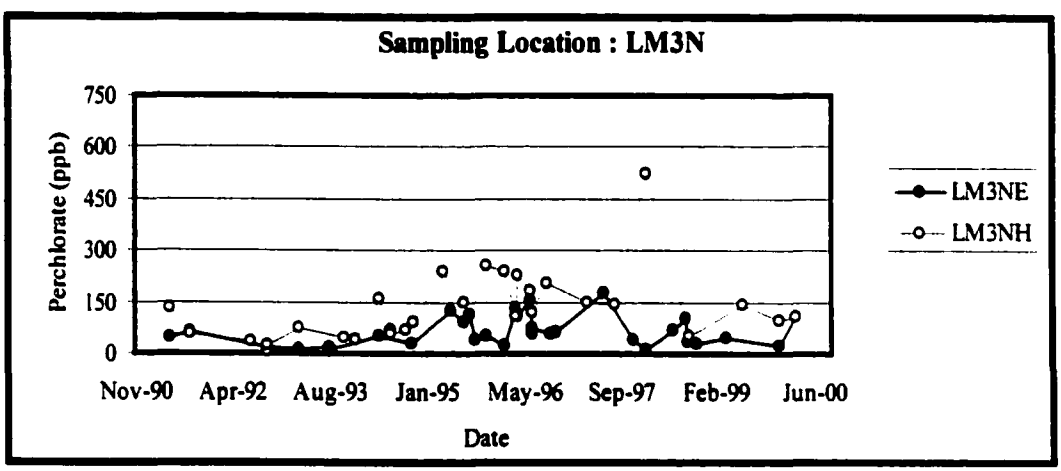


Figure 4.17.c : Epilimnion and Hypolimnion Perchlorate Levels at LM3N

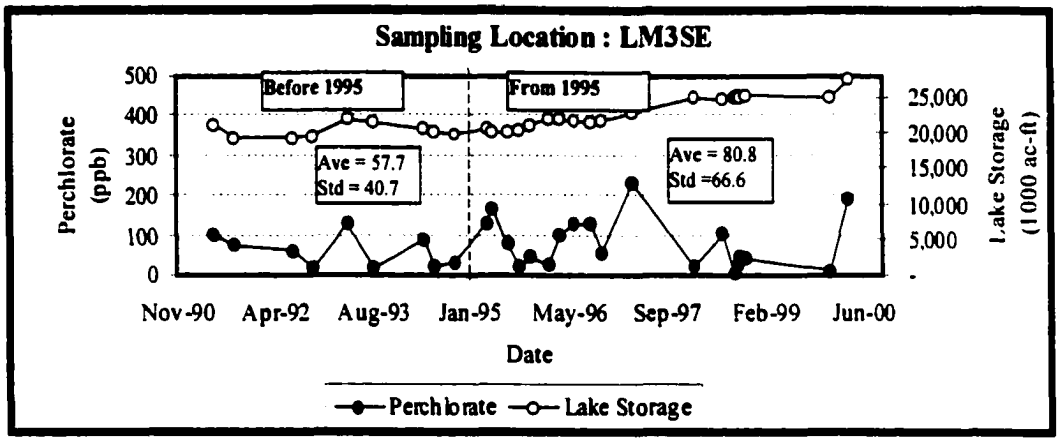


Figure 4.18.a : Perchlorate Concentrations at LM3SE

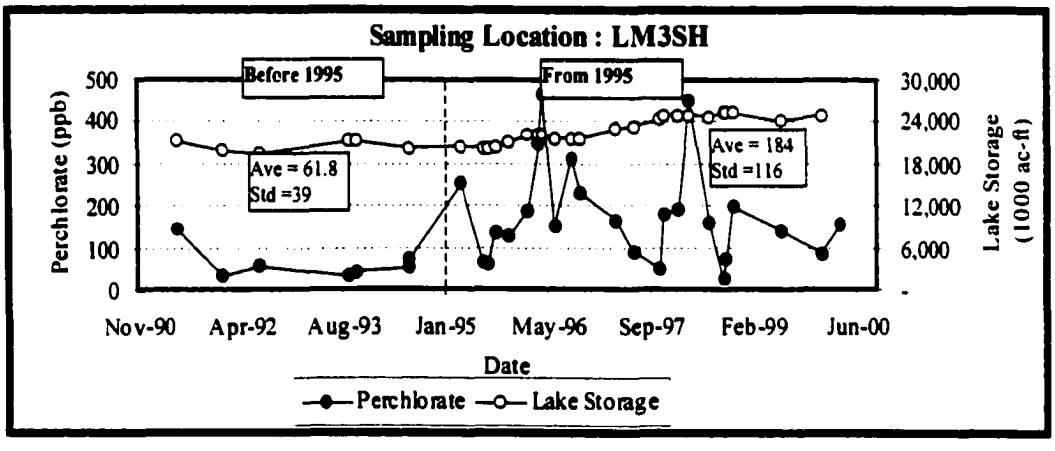


Figure 4.18.b : Perchlorate Concentrations at LM3SH

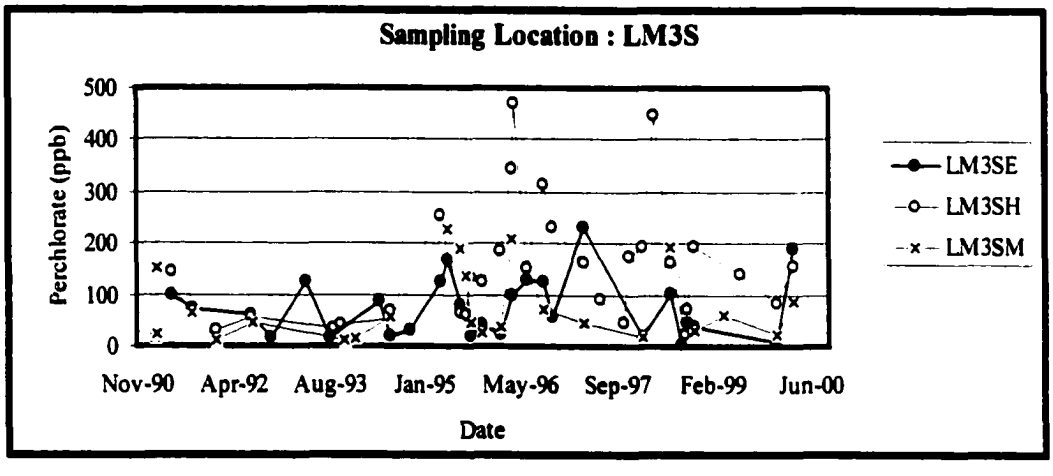


Figure 4.18.c : Epilimnion and Hypolimnion Perchlorate Levels at LM3H

The historic data for the LM3 sampling locations show that the perchlorate levels decrease below 165 ppb by the time the discharge of the Wash reaches these sampling points. The average perchlorate concentration within the epilimnion layer varied from 72.3 (LM3N) to 81.1 ppb (LM3S). The hypolimnion perchlorate concentrations varied between 142.2 ppb and 164.0 ppb, observed at LM3N and LM3S sampling points, respectively.

The hypolimnion layer samples had significantly higher perchlorate average levels than the epilimnion. Statitistical analyses also showed a high significance for the hypolimnion layer (Table 4.9). This indicates that the Wash plume continues to move within the hypolimnion layer in the LM3 sampling locations.

The next sampling point in the Lake is LM4 (Figures 4.19.a to 4.19.d). This is located approximately 1.3 km from the LM3 sampling points.

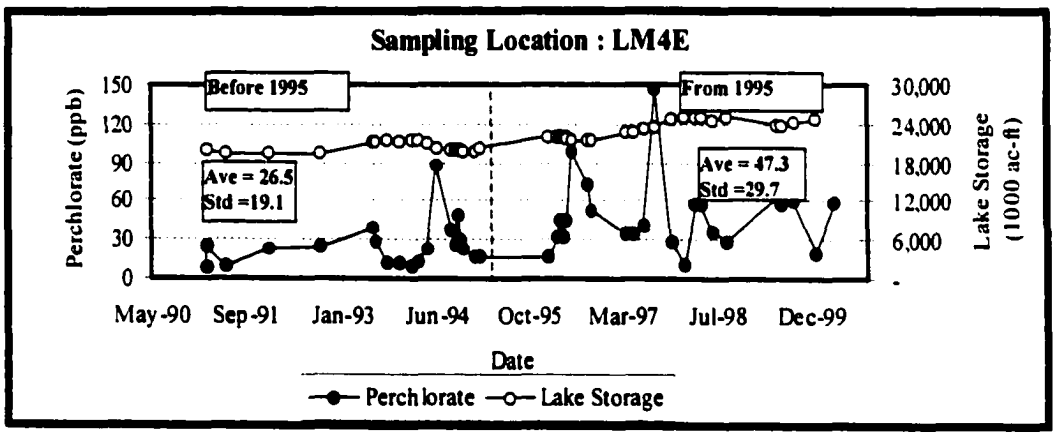


Figure 4.19.a : Perchlorate Concentrations at LM4E

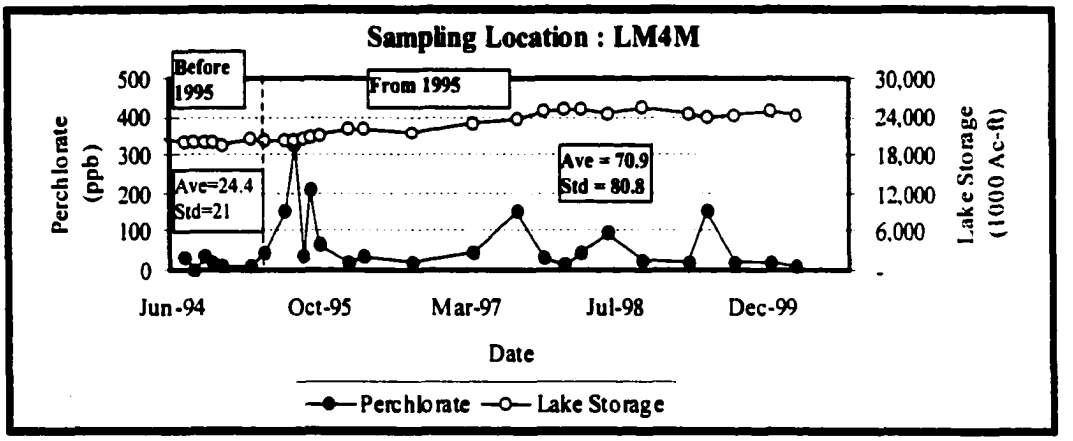


Figure 4.19.b: Perchlorate Concentrations at LM4M

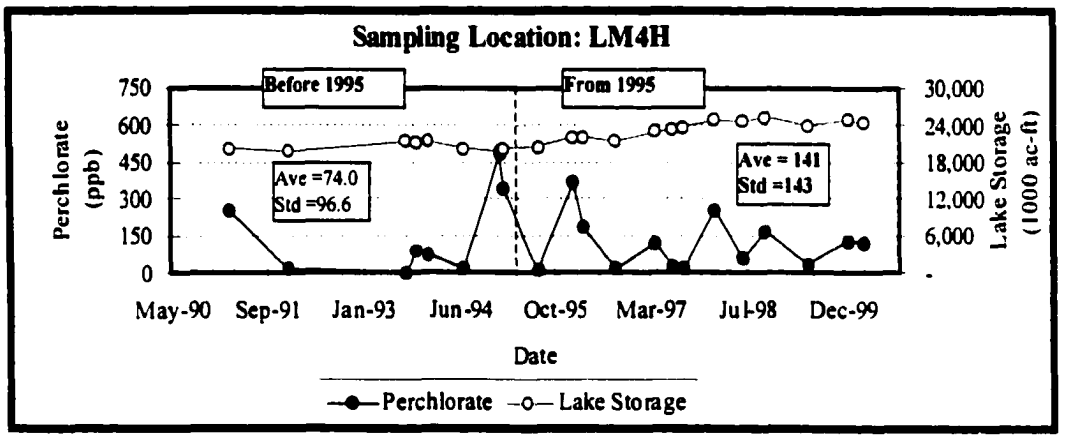


Figure 4.19.c: Perchlorate Concentrations at LM4H

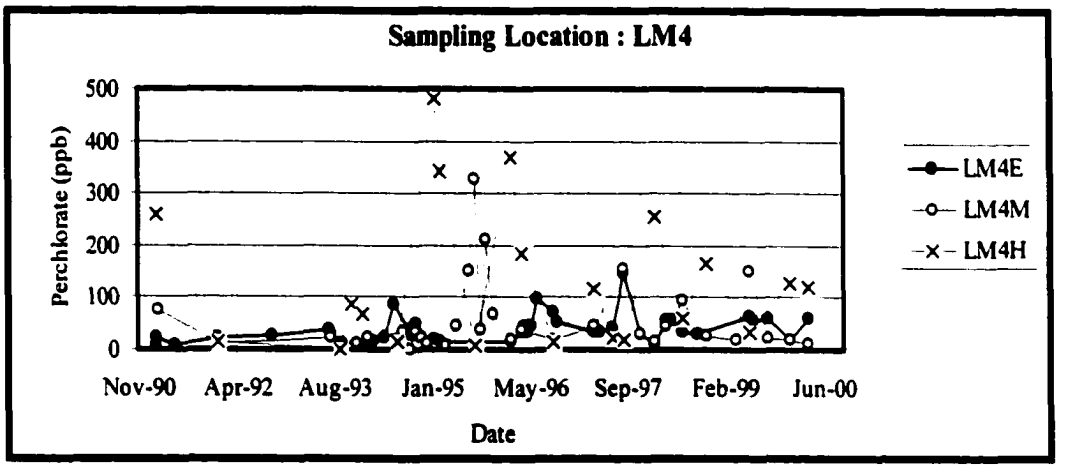


Figure 4.19.d: Epilimnion. Metalimnion and Hypolimnion Perchlorate Levels at LM4

The historic data for the LM4 sampling locations show that the perchlorate levels decrease below 100 ppb by the time the discharge of the Wash reaches this sampling point. The average perchlorate concentrations within the epilimnion, metalimnion and the hypolimnion layers were 43.9 ppb, 49.3 ppb and 95.9 ppb, respectively. Statistical analyses were performed. Pair-wise perchlorate levels showed that the perchlorate levels within the hypolimnion are higher than those of the epilimnion. Statistically no significant difference could be established between the epilimnion-metalimnion layers and the metalimnion-hypolimnion layers at the 95% confidence level. These results indicate that the perchlorate plume continues to move within the hypolimnion layer in the LM4 sampling locations.

The next sampling point in the Lake is LM5 (Figures 4.20.a to 4.20.d). This is located approxiamtely 1.2 km from the LM4 sampling point.

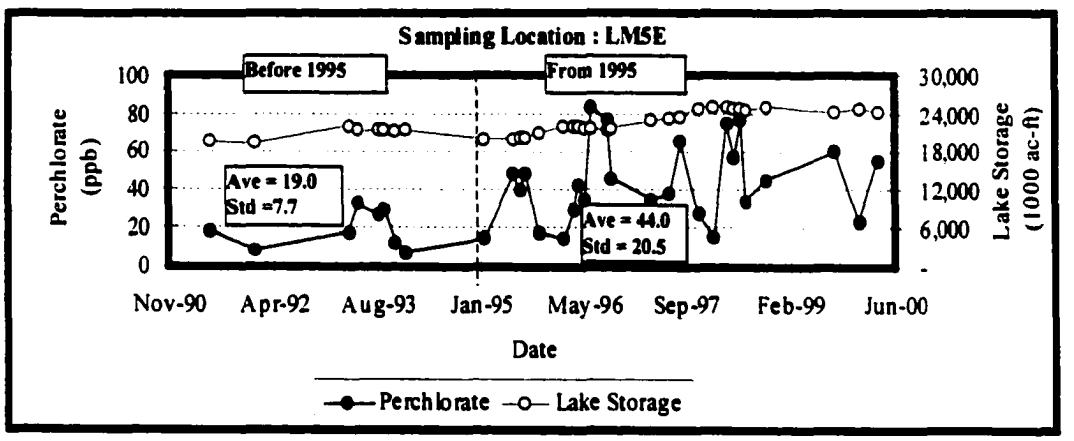


Figure 4.20.a : Perchlorate Concentrations at LM5E

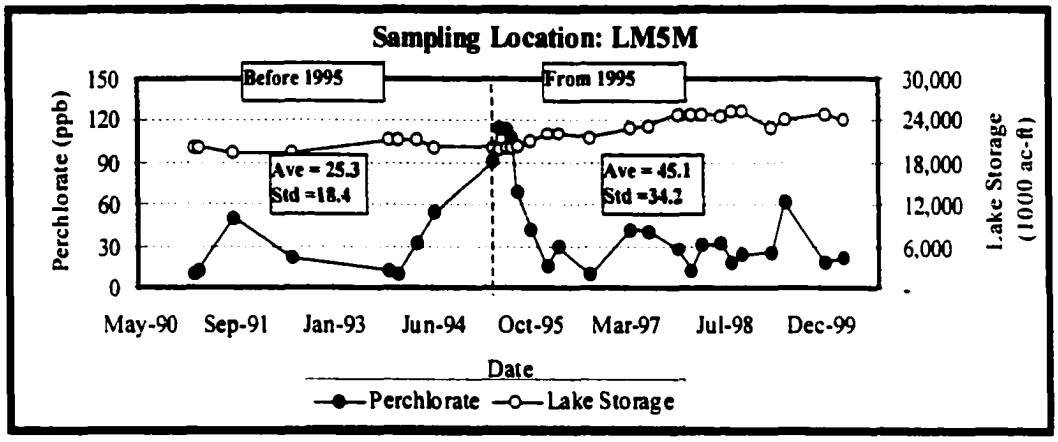


Figure 4.20.b: Perchlorate Concentrations at LM5M

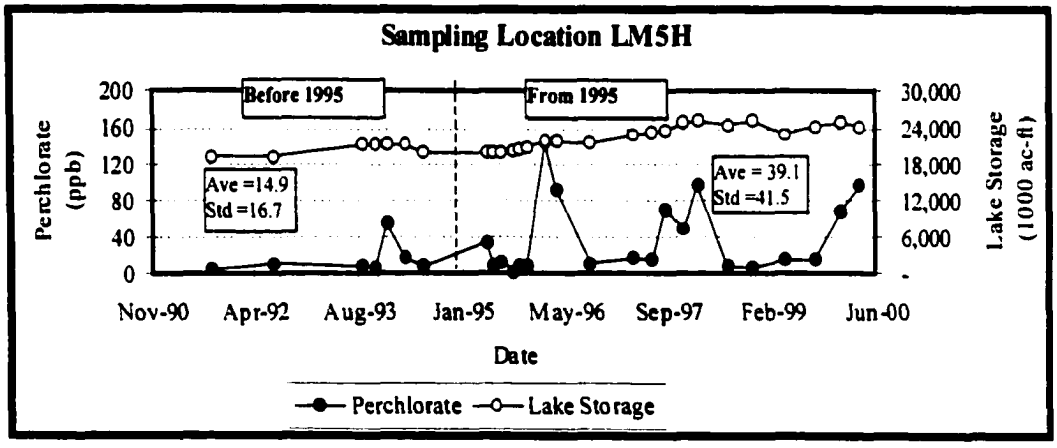


Figure 4.20.c: Perchlorate Concentrations at LM5H

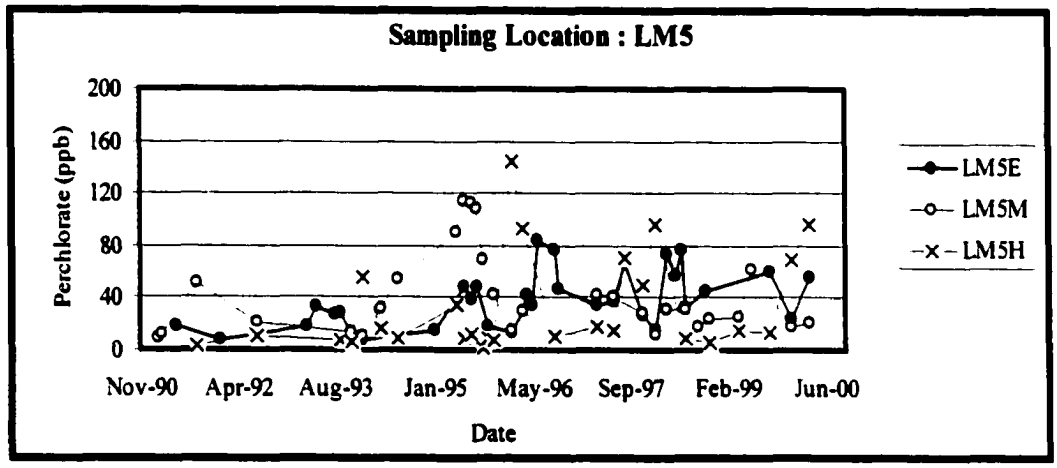


Figure 20.d: Epilimnion and Hypolimnion Perchlorate Levels at LM5

The historic data for the LM5 sampling locations show that the perchlorate levels generally decrease below 40 ppb by the time the discharge of the Wash reaches this sampling point. The average perchlorate concentration within the epilimnion, metalimnion and the hypolimnion layers were 37.7 ppb, 40.0 ppb and 35.8 ppb, respectively. The average perchlorate concentration within the epilimnion layer is slightly higher than that of the hypolimnion. The metalimnion layer had the highest perchlorate level. Statistical significance could not be established between the epilimnion and hypolimnion layers.

The next sampling point in the Lake is LM8 (Figures 4.21.a to 4.21.d). This is located approxiamtely 11 km from the LM5 sampling point.

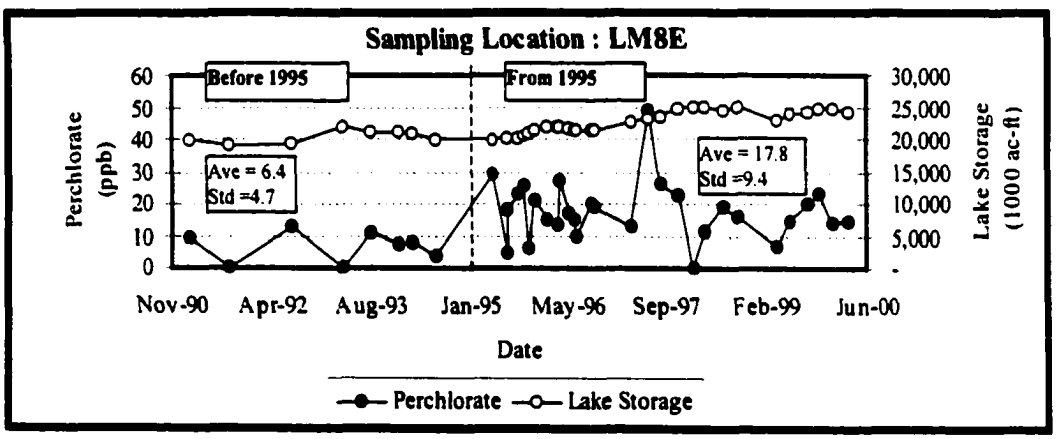


Figure 4.21.a: Perchlorate Concentrations at LM8E

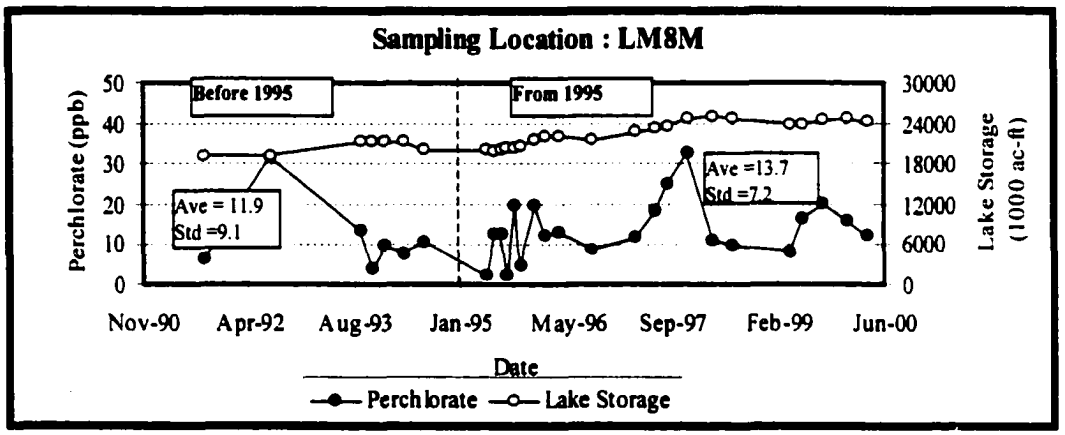


Figure 4.21.b: Perchlorate Concentrations at LM8M

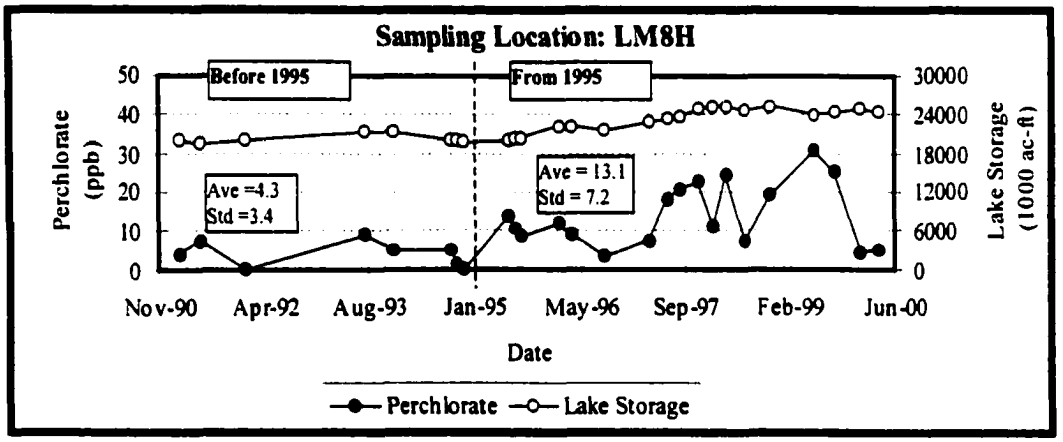


Figure 4.21.c: Perchlorate Concentrations at LM8H

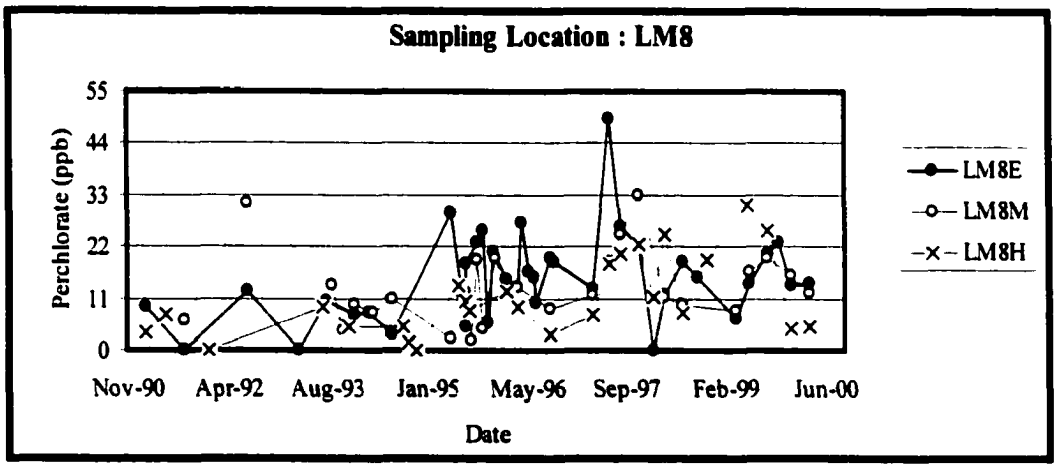


Figure 4.21.d: Epilimnion and Hypolimnion Perchlorate Levels at LM8

The average perchlorate concentration within the epilimnion, metalimnion and the hypolimnion layers were 15.2 ppb, 13.6 ppb and 12.4 ppb respectively. The lower perchlorate levels indicate that the discharge from the Wash has been mixed well with the incoming water from the Colorado River. The perchlorate levels also decrease with depth. Statistical analyses were performed, and the results indicate that the perchlorate levels within the epilimnion layer are significantly higher than those of the hypolimnion. This indicates that the perchlorate plume has mixed up into the epilimnion layer in this region.

The average perchlorate level within the hypolimnion layer in the LM9 sampling location (Hoover Dam release area) was 11.7 ppb (Figure 4.22). This is almost the same perchlorate level as the LM8 (12.4 ppb).

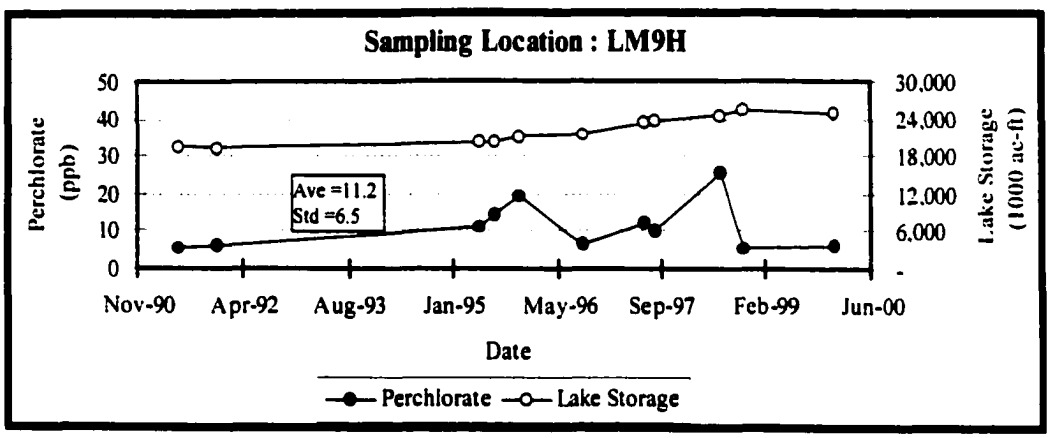


Figure 4.22: Perchlorate Concentrations at LM9H

4.3 Comparison of Total Dissolved Solids and Perchlorate Concentrations

Total Dissolved Solids (TDS) can be used to trace the movement of the Wash within Lake Mead. LaBounty and Horn, (1997) used conductivity to investigate the movement of the Wash within Lake Mead. This was possible because the Wash's conductivity (2400 $\mu S.cm^2$) is more than twice that of the Lake's (1000 $\mu S.cm^2$) (LaBounty and Horn, 1997). Although, conductivity could be used successfully to track the Wash's movement within Lake Mead, it is believed that its sensitivity would decreased in the interior sections of the Lake because of the influence of the TDS loading from the Colorado, Muddy, and Virgin rivers.

Because perchlorate is highly water soluble and quickly becomes part of the TDS loading, the availability of both perchlorate and TDS values for the all sampling locations provides the opportunity to ensure the accuracy of the measured perchlorate levels, especially since the measurement of TDS has been carried out by the wastewater dischargers (Clark County Sanitation District (CCSD) Laboratory). The TDS measurements were carried out by CCSD for the identical samples that were later used for the analyses of perchlorate during this research. This is considered as beneficial since this would reduce the errors that can be caused during sample collection and handling.

Perchlorate data were used to analyze the Wash's movement within the Lake, annual seasonal variations and long-term fluctuations of perchlorate levels. Because perchlorate is highly soluble and considered to behave as a tracer, if the analyses of TDS concentrations show the same results as the perchlorate level evaluations, that

would stregthen the findings regarding the the movement of the Wash within Lake Mead.

The perchlorate and TDS concentrations were plotted and statistically analyzed to compare the TDS and perchlorate levels at different depths and time periods. Regression analyses were performed to correlate TDS and perchlorate data. These were carried out to find out (a) how TDS and perchlorate levels change spatially and temporally with respect to each other, (b) if perchlorate and TDS levels follow the same seasonal and long-term trends.

4.4 TDS Concentrations along the Las Vegas Wash

The TDS and the Perchlorate levels for the Las Vegas Wash sampling points are given in Figures 4.23 and 4.24.

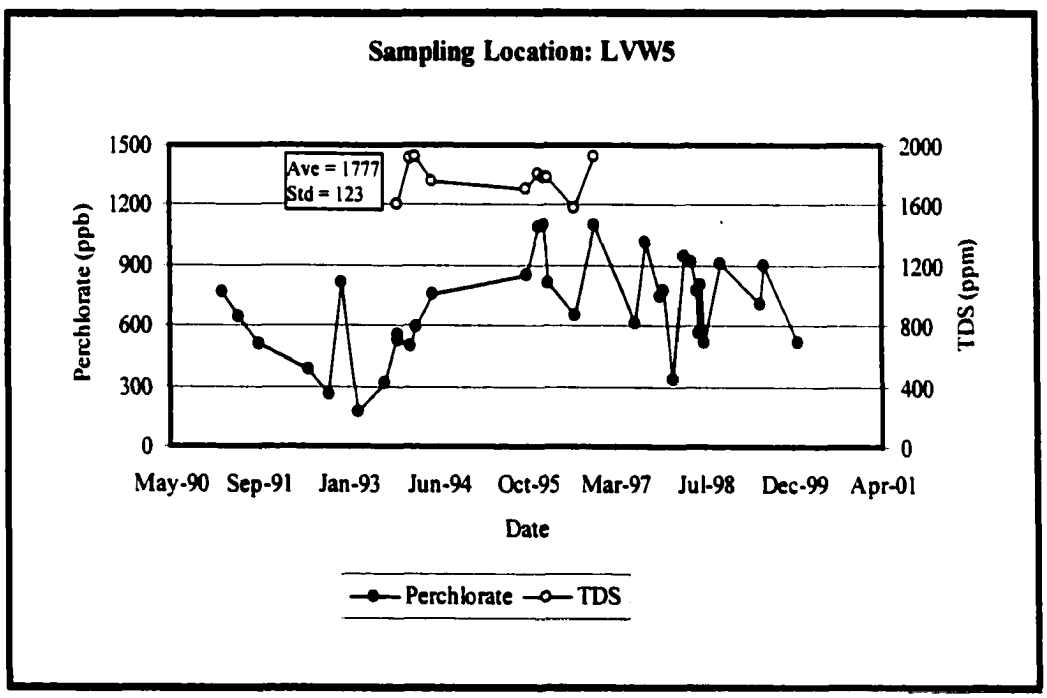


Figure 4.23 : Perchlorate and TDS Concentrations of LVW5

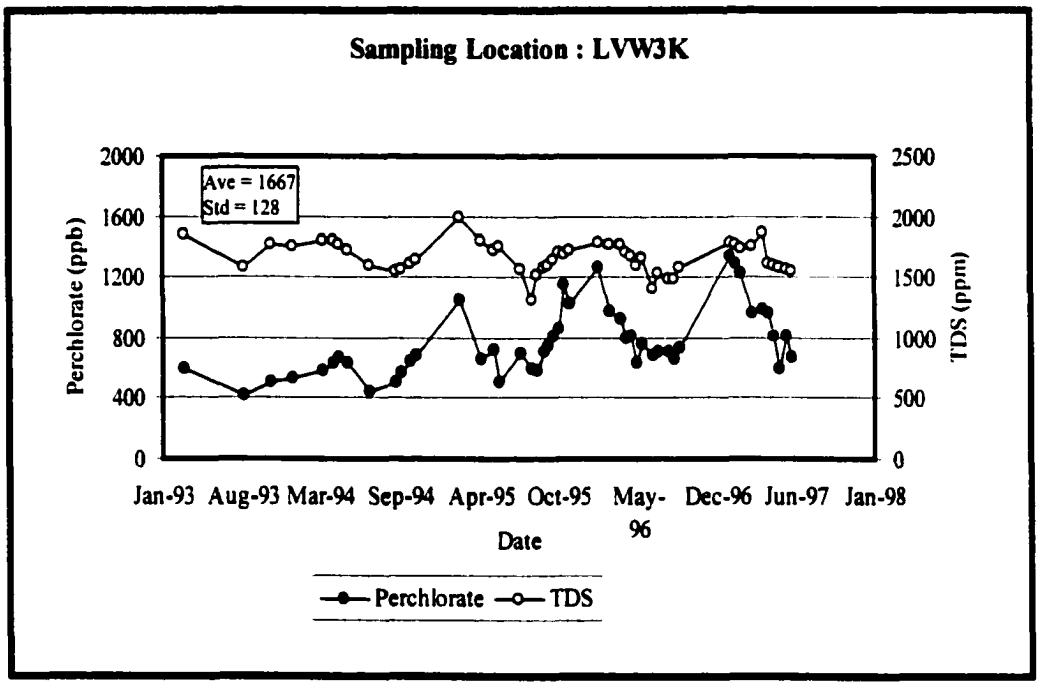


Figure 4.24 : Perchlorate and TDS Concentrations of LVW3K

The average TDS levels at LVW3K and LVW5 sampling locations were 1667 ppb and 1777 ppm. The average TDS levels in the Wash decreased from LVW3K to LVW5 (Table 4.5). This was the exactly the opposite behaviour of what was observed for perchlorate, where the level at LVW3K was significantly higher than that of LVW5. A probable cause is the infiltration of high TDS and low perchlorate containing groundwater between LVW3K and LVW5. Another reason for the discrepancy could be the availability of less than 10 TDS values for LVW5 from mid 1994 to mid 1997. The LVW3K sampling point had over 45 data values representing the period from 1993 to 1997. Fewer data points and seasonal TDS variations could have impacted the outcome of the results.

Table 4.14: Summary of Average TDS Levels in Las Vegas Wash

Sample Location	Mean TDS Concentration (ppm)	Standard Deviation
LVW3K	1667	128
LVW5	1777	123

4.5 TDS Concentrations in Lake Mead

The TDS levels within the Lake were also evaluated. The analyses for TDS levels showed similar patterns as the perchlorate within the Lake TDS. The TDS and perchlorate levels have been plotted to observe any patterns, and are shown in Appendix C. The TDS levels within the hypolimnion layer are higher than those of the epilimnion layer for all the sampling locations, except for LM8 (Table 4.15). The difference between the hypolimnion and the epilimnion perchlorate levels were highest among the sampling points closer to the discharge point of the Wash, and gradually decrease with distance towards the Lake interior. This pattern reverses after the sampling location LM5 (Figure 4.25). Notice that the average TDS concentration within the epilimnion layer is higher than the hypolimnion at the sampling location LM8. This closely resembles perchlorate trends within the Lake. Statistical analyses were performed to further investigate the difference between the TDS levels of the two thermal layers. The results showed that TDS levels within the hypolimnion layer were signigicantly higher than the TDS levels within the epilimnion layer for the LM2, LM3 and LM4 sampling locations at the 95% confidence level (Table 4.16). The results for LM5 sampling were inconclusive, and at the LM8 sampling location, the epilimnion TDS levels were significantly higher than those of the hypolimnion layer. Thus, the behavior of TDS within the Lake is exactly the same that was observed for perchlorate.

Table 4.15: Summary of Average TDS Levels in Lake Mead

Sample	Epilimnion (ppm)	Metalimnion (ppm)	Hypolimnion (ppm)
LM2C	783 (147)	N/A	947 (148)
LM2N	797 (127)	N/A	1028 (254)
LM2S	790 (131)	N/A	968 (160)
LM3C	747 (105)	788 (193)	908 (143)
LM3N	729 (107)	N/A	892 (171)
LM3S	770 (120)	N/A	898 (151)
LM4	706 (63)	730 (136)	785 (185)
LM5	681 (71)	693 (148)	702 (69)
LM8	638 (60)	626 (60)	620 (72)
LM9	N/A	N/A	618 (55)

N/A: Samples were not available; sample standard deviations are given within parentheses.

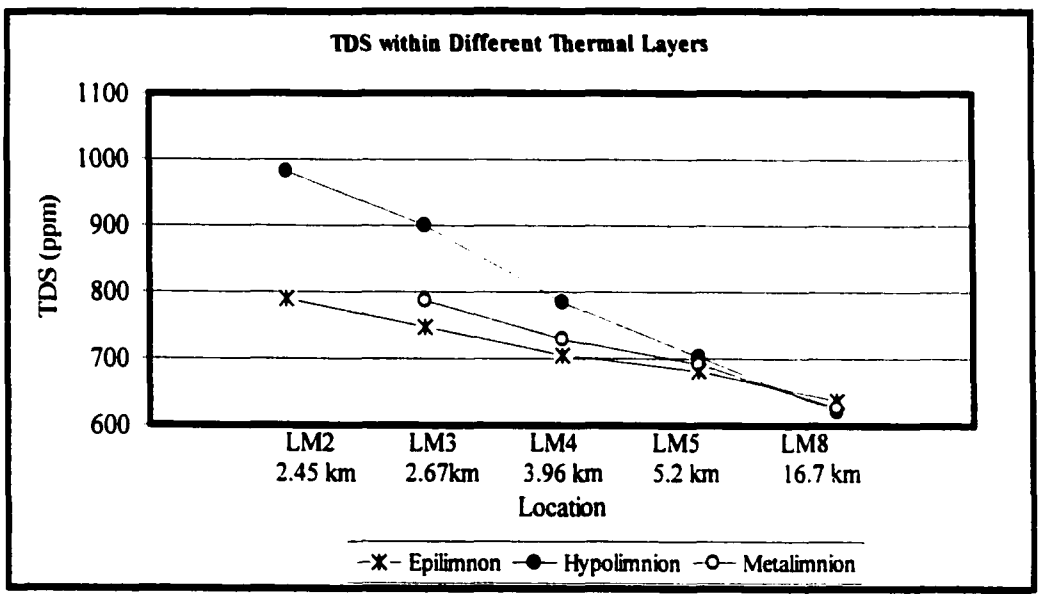


Figure 4.25: Average TDS Levels in Lake Mead

The TDS data also support the initial conclusion made on the mixing of of the Wash plume based on perchlorate data. Therefore, both TDS and perchlorate levels substantially support the hypothesis that, in the initial mixing zone (LM2C to LM3N) the Wash plume moves within the hypolimnion; in the middle zone (LM4 to LM5) the mixing of the plume progressively shifts towards the epilimnion position; in the interior zones (LM8 to LM9) the plume remains within the epelimnion. Statistical analyses were performed for individual sampling points to correlate TDS and perchlorate levels. Linear regression analyses results show (Table 4.17) that TDS levels are significant in explaining the perchlorate levels with the Lake. This was based on low P-values (less than 0.05), and relatively high R^2 (> 45%) values. Detail statistical analyses are given in Appendix B.

Table 4.16: Summary of Statistical Analyses for TDS Concentrations between Hypolimnion and Epilimnion Layers

Sampling Points	95% Confidence Intervals for the Difference and P values	Conclusion Based on 95% Confidence Level
LM2CE - LM2CH	CI : (-235.9, -103.2)* P-Value = 0.000	Hypolimnion TDS is significantly higher than the epilimnion.
LM2NE - LM2NH	CI : (-262.7, -87.9)* P-Value = 0.000	Hypolimnion TDS is significantly higher than the epilimnion.
LM2SE - LM2SH	CI : (-284.8, -73.1)* P-Value = 0.001	Hypolimnion TDS is significantly higher than the epilimnion.
LM3CE – LM3CH	CI : (-83.2, -24.7)* P-Value = 0.000	Hypolimnion TDS is significantly higher than the epilimnion.
LM3NE – LM3NH	CI : (-256.3, -78.3)* P-Value = 0.001	Hypolimnion TDS is significantly higher than the epilimnion.
LM3SE – LM3SH	CI : (-166.8, -43.7)* P-Value = 0.001	Hypolimnion TDS is significantly higher than the epilimnion.
LM4E – LM4H	CI : (-209.7, 9.4)* P-Value = 0.035	Hypolimnion TDS is significantly higher than the epilimnion.
LM5E – LM5H	CI : (-63.3, 29.1)* P-Value = 0.224	Statistically could not establish that the TDS levels in the hypolimnion are higher.
LM8E – LM8H	CI : (2.37, 31.11)* P-Value = 0.012	Hypolimnion TDS is significantly lower than the epilimnion.

* Notice: The confidence intervals are for the $\mu_{epilimnion} - \mu_{hypolimnion}$

Table 4.17: Perchlorate and TDS Regression Analyses

Location	Regression Equation	P values	R^2	Remarks (95% Confidence Level)
LVW3K	perch = - 268 + 0.380 tds	TDS: 0.011 Const: 0.270	13.0%	TDS explains significant portion of variance.
LM2CE	Perch = - 332 + 0.573 tds	TDS: 0.00 Const: 0.00	80.1%	TDS explains significant portion of variance.
LM2CH	Perch = - 322 + 0.559 tds	TDS: 0.00 Const: 0.00	75.8%	TDS explains significant portion of variance.
LM2NE	perch = - 133 + 0.277 tds	TDS: 0.00 Const: 0.012	57.8%	TDS explains significant portion of variance.
LM2NH	perch = - 297 + 0.538 tds	TDS: 0.00 Const: 0.00	71.3%	TDS explains significant portion of variance.
LM2SE	perch = - 189 + 0.346 tds	TDS: 0.00 Const: 0.00	86.9%	TDS explains significant portion of variance.
LM2SH	perch = - 262 + 0.506 tds	TDS: 0.052 Const: 0.001	41.9%	TDS explains significant portion of variance.
LM3CE	perch = - 207 + 0.390 tds	TDS: 0.00 Const: 0.00	75.0%	TDS explains significant portion of variance.
LM3CM	perchl = - 185 + 0.353 tds	TDS: 0.00 Const: 0.00		TDS explains significant portion of variance.
LM3CH	perch = - 195 + 0.396 tds	TDS: 0.00 Const: 0.015	51.3%	TDS explains significant portion of variance.
LM4E	perch = - 3.6 + 0.0637 tds	TDS: 0.310 Const: 0.935	4.0%	TDS does not explain significant portion of variance.
LM4H	perch = - 507 + 0.796 tds	TDS: 0.00 Const: 0.00	78.0%	TDS explains significant portion of variance.
LM5E	perch = - 5.6 + 0.0728 tds	TDS: 0.224 Const: 0.890	6.4%	TDS does not explain significant portion of variance.
LM5H	perch = - 161 + 0.284 tds	TDS: 0.035 Const: 0.084	22.4%	TDS explains significant portion of variance based on p-value.
LM8E	perch = - 3.7 + 0.0319 tds	TDS: 0.181 Const: 0.803	7.3%	TDS does not explain significant portion of variance.
LM8M	perch = 15.3 - 0.0015 tds	TDS: 0.957 Const: 0.388	0.0%	TDS does not explain significant portion of variance.
LM8H	perch = 31.1 - 0.0295 tds	TDS: 0.400 Const: 0.17	4.5%	TDS does not explain significant portion of variance.
LM9H	perch = - 11.7 + 0.0389 tds	TDS: 0.401 Const:0.678	10.3%	TDS does not explain significant portion of variance.

Residual analyses were also performed to verify regression model assumptions. The results of almost all the LM2 sampling points analyses showed residual patterns, indicating that perchlorate levels cannot be exclusively represented by a linear relationship of the TDS levels (Appendix C). This shows that the factors influence TDS levels in the Lake does not affect perchlorate levels in the same extent. This is consistent with the information already known about the LVW system. One possible explanation for this observation is the fact that perchlorate levels in the Wash has only one source; but TDS has many sources including the perchlorate source. Perchlorate loading into the Wash and the Lake is mainly due to the contaminated surface and groundwater seepage from the industrial site; however, TDS has two main sources: the contaminated surface/ground water from the industrial area, as well as the three wastewater treatment plants. The use of chemicals by the wastewater treatment process and the use of water softners in the Las Vegas Valley contribute a significant amount of TDS into the treated effluent.

Recall that perchlorate data showed a significant increase from 1995. The same analyses were performed for TDS levels at selected sampling points. Statistical analyses were carried out to determine whether there is a significance increase in the TDS levels from 1995. The analyses of the TDS data for the LVW3K sampling point did not show any significant increase since 1995 (95% confidence interval: {-50.2,125.1}, P-value = 0.815). The analyses for the LM2 epilimnion and hypolimnion layers could not establish any significant increase since 1995 for the TDS levels. Analyses for other Lake Mead sampling points could not be performed due to the unavailability of adequate TDS data points prior to 1995. The lack of correlation could be expected specially since

the TDS loading from the BMI contaminated area is less than 1% of the total TDS in the Wash. The majority of the TDS loading is from the wastewater treatment plants. Any significant increase of TDS loading from the BMI site would not cause the total TDS levels in the Wash to go up.

CHAPTER 5

ESTIMATION OF THE TOTAL PERCHLORATE LOADING INTO THE LAS VEGAS WASH

5.1 Estimation of the Total Perchlorate Loading into the Wash from the Contaminated Area

The perchlorate loading into the LVW was estimated by calculating the difference between the perchlorate mass fluxes at LVW1 and LVW3K sampling locations (Figure 5.1). This calculation is possible because sampling locations LVW1 and LVW3K are located upstream and downstream of the contaminated area, respectively. The calculations were performed for the 1998 average Wash flow and perchlorate data. Figure 5.2 illustrates a simplified mass loading model for the perchlorate seepage area. Table 5.1 summarizes the major parameters used, and the model assumptions.

The flow of the downstream end of the recharge area (LVW3K; 150 MGD) is available and it is measured by a USGS flow station (USGS, 2001). The USGS (2001) reported daily flow averages were within 15% of the actual daily discharges for 1997 (Appendix E). The accuracy of streamflow records depends primarily on the stability of the stage-discharge relation, accuracy of measurements of stage, measurements of discharge, and interpretation of records (USGS, 2001).

The actual flow data for the Q_1 and Q_2 were not available, but they can be estimated. The flows for, Q_1 and Q_2 include the discharges of the wastewater treatment

plants as well as the dry weather flows (it includes dry weather drainage from storm-water channels and groundwater infiltration). The dry weather flows were estimated by taking the difference between the USGS reported flow at LVW3K and the sum of the discharges of the three wastewater treatment plants (125.2 MGD; Table 5.2). The amount of treated effluent recycled (for golf course irrigation) by the City of Henderson WWTP (6.21 MGD) was excluded from the calculations as this water is not discharged into the Wash. The difference between the Wash flow at LVW3K and the combined WWTP flows is 24.8 MGD; that corresponds to a 16.5% difference. Therefore, the dry weather flows were estimated as 16.5% of the WWTP discharges (Equation 5.1 and 5.2).

The City of Henderson WWTP uses three main methods to dispose of their treated effluent: discharge into the Wash directly, rapid infiltration basins (RIBs), and recycling. The direct Wash discharge does not contain a significant amount of perchlorate, referred as Q_{HenD}. A significant part of the water that is discharge via the RIBs (Q_{HenRIB}) will eventually seep into the Wash combined with the perchlorate contaminated groundwater. The combined groundwater flow into the Wash including the KMCC main plume referred to as Q_p.

Table 5.1: Assumptions and Variable Definitions for the Point Loading Model

Parameter	Variable Definitions
Q_T	Average flow of the Las Vegas Wash at LVW3K (based on 1998 flow data from January-August; source of flow: USGS, 2001).
Q_1	Total flow of the Wash at LVW1 sampling point. This is assumed to be equal to the total discharges (1998) of the CCSD flow (Q_{CCSD}) and the City of Las Vegas flow (Q_{CLV}) plus additional 16.5% to accommodate non-point discharge.
Q_2 ($= Q_P + Q_{HenD}$)	This is the total flow added to the Wash from the perchlorate seepage area. This is assumed to be the sum of the direct discharge of the Henderson WWTP effluent (Q_{HenD}) with 0 ppb perchlorate, and the groundwater seepage into the Wash (including the KMCC main seepage) from the contaminated area with C_p ppb. Q_{HenD} does not include the effluent recycled (Q_{HenR}) by the City of Henderson WWTP (Equation 5.2).
W	Perchlorate loading into the system within the reach area (kg/day) = $Q_p * C_P$ This includes the loading from the KMCC seepage (W_{KMCC}) 300 gpm with 100 ppm perchlorate, and other loadings (W_{Others}).

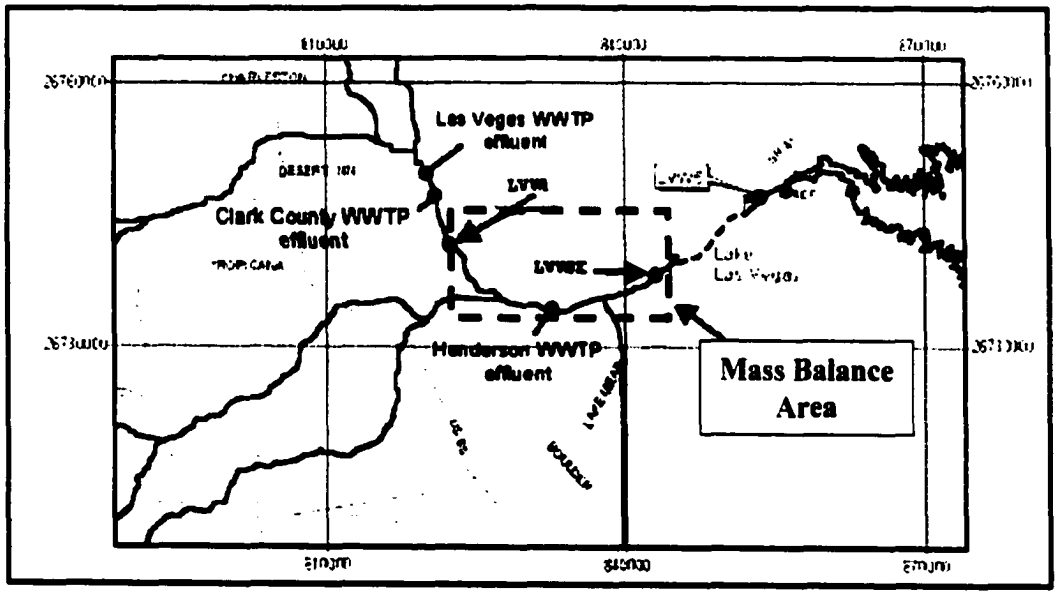


Figure 5.1: Water Sampling Locations of the Las Vegas Wash

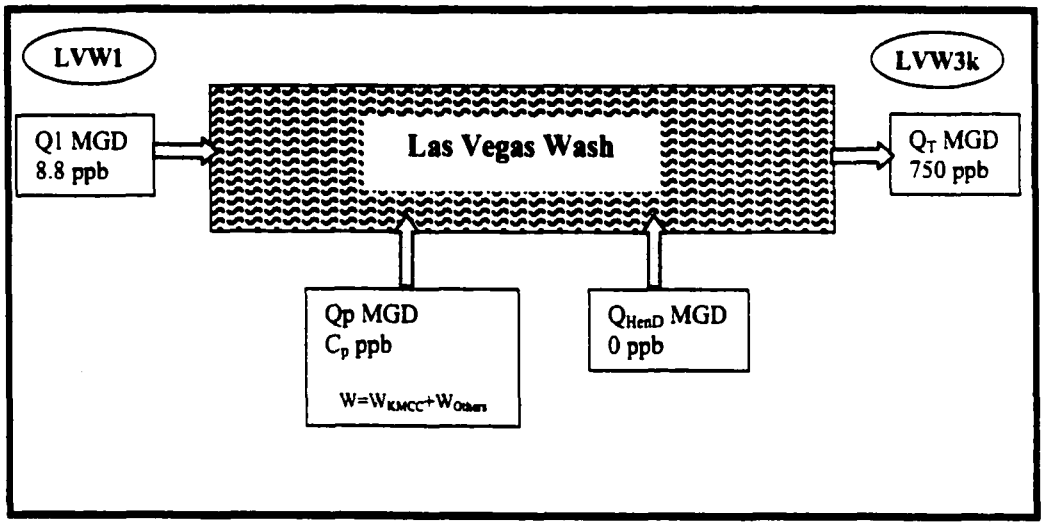


Figure 5.2: Total Perchlorate Loading Model for the Las Vegas Wash

Table 5.2: Average Wastewater Treatment Plant and Wash Discharges for 1997.

Flow	Flow (MGD)	Source
Q_T	150	USGS, 2001
Q_{CCSD}	67.4	CCSD WWTP, 2000
Q_{CLV}	48.9	City of Las Vegas WWTP, 2000
Q_{HenD}	6.15	City of Henderson WWTP, 2001
Q_{HenRIB}	2.78	City of Henderson WWTP, 2001
Q_{HenR}	6.21	City of Henderson WWTP, 2001

$Q_1 = (Q_{CCSD} + Q_{CLV})*1.165$ Equation 5.1

$Q_2 = (Q_{HenD} + Q_{HenRIB})*1.165$ Equation 5.2

$Q_2 = Q_{HenD} + Q_P$ (by definition) Equation 5.3

$Q_1 = (67.4 + 48.9)*1.165$ MGD

$Q_1 = 133.7$ MGD (512,919 m^3/day)

$Q_2 = (6.15+2.78)*1.165$ MGD

Q_2= 10.4 MGD (39,333 m^3/day)

Q_p = 10.4 MGD – 6.15 MGD (Equation 5.3)

Q_p = 4.25 MGD

Mass balance for perchlorate:

Perchlorate in the influent + Perchlorate point loading = Perchlorate in the effluent

Q_1 * 8.8ppb + W = Q_T *750ppb

W = Q_T *750ppb-Q1*8.8ppb

W= 567,852 (m^3/day)*0.750*10^{-3}(kg/ m^3)- 512,909 (m^3/day)*0.0088*10^{-3}(kg/ m^3)

W= 425.9-4.51 kg/day

W = 421.4 kg/day

Estimated perchlorate loading is 421 kg/day

5.2 Estimation of the perchlorate loading from the KMCC Seepage

Perchlorate loading from the main alluvial channel (KMCC Plume) can be determined by estimating the groundwater flow using Darcy's Law. The major parameters used, and the model assumptions are summarized in Table 5.3 below.

Table 5.3: Variable Definitions and the Major Assumption for the Alluvial Channel Seepage

Parameter	Variable Definitions
D	Average width of the alluvial channel. This was assumed to be equal to 250m (Source: KMCC (1998), reported that the with of the alluvial channel as 210-305 m)
H	Average height of the alluvial channel. Assumed to be 6.3 m (Source: Broadbent & Associates, 1998).
I	Hydraulic gradient. Assumed to be 0.017 (KMCC, 1988)
K	Hydraulic conductivity of the alluvial channel. Assumed to be 61 m/day (Kleinfelder, 1993)
C	Perchlorate Concentration in the seepage. Assumed to be 100 ppm (Source: KMCC, 2000)

Darcy's Law: $Q = KIA$

Q = Groundwater flow rate

A = cross section flow area = D*H= 6.3 m x 250 m = 1575 m^2

Q = 61 (m/day)* 0.017 * 1575 (m^2)

Q = 1633 m^3/day (=300 gpm= 0.43 MGD)

Loading Rate = Groundwater flow rate x Perchlorate Concentration in Groundwater

Loading Rate = 1633 m^3/day x 100 (mg/l)

Loading Rate = 163.3 kg/day

The estimated loading rate from the KMCC plume is 163 kg/day. KMCC (2000) and Zhang (2001), reported the flow and the perchlorate concentration of the seepage as 300-400 gpm, and 100 ppm respectively. The loading rate based on these reported values is about 190 kg/day. Therefore, the above estimated loading rate and the flow rates ciosely represent the KMCC estimates. Table 5.4 summarized the calculated and actual perchlorate loading rates.

Table 5.4: Summary of the Calculated and Measured Perchlorate Loadings

Loading Description	Value
Measured loading rate of the KMCC Plume (300 gpm at 100 ppm)	190 kg/day
Calculated loading rate of the KMCC Plume using Darcy's Law	163.3 kg/day
Calculated loading rate based on analyzed perchlorate data at LVW3K and LVW1 and using USGS Wash flows	421 kg/day

5.3 Finite Difference Method

Finite difference methods can be used to solve water-quality modeling for unsteady conditions. A computer algorithm (James and Howard, 2000) was used to calculate the perchlorate loading profile from the contaminated area. The original model source code had been written to model BOD in a surface water channel. Modifications were made to the original program to suit the modeling of a conservative substance like perchlorate. The model is applicable to unsteady conditions with constant loading rates over time. Loading could be unevenly distributed over the reach area. The software code is written in QBASIC and is given in Appendix D. Model assumptions and limitations are given below:

- Perchlorate is a conservative substance with a negligible decay rate, and does not decay by volatilization, biodegradation, settling, or any other removal mechanism.
- The reach of the LVW has constant flow and hydrological conditions.

5.3.1 Single Source Model

Modeling was carried out considering only the KMCC plume (Figure 5.4). The main input parameters are given in Table 5.5. The description of the key sampling points and the channel dimensions are given in Table 5.6 and Figure 5.3.

Table 5.5: The Main Model Input Parameters for the Wash Modeling

Parameter	Value	Assumptions and Sources of Data
Depth	0.3 m	Assumed to equal to the cross sectional area divided by the width. Based on the data gathered by Batista and Zhang (2000).
Width	15 m	Based on the data gathered by Batista and Zhang (2000).
Reach length	6,000 m	This is the approximate distance from the KMCC plume interception point to Lake Las Vegas
Dispersion	1,000,000 m^2/day	Estimated based on the information provided by James (2000).
Stream velocity	155,000 m/day (1.8 m/s)	Based on the data gathered by Batista and Zhang (2000).
Total time	1 day	This time was assumed to be adequate for the Wash to develop steady state conditions. Estimated after several simulations.
Size of grid	1000 m	Assumed to be adequate for the precision of the analyses.
Loading points	01	Based on the data gathered by Batista and Zhang (2000).
Total loading	190 kg/day	Based on the reported flow and concentration values by KMCC (2000).

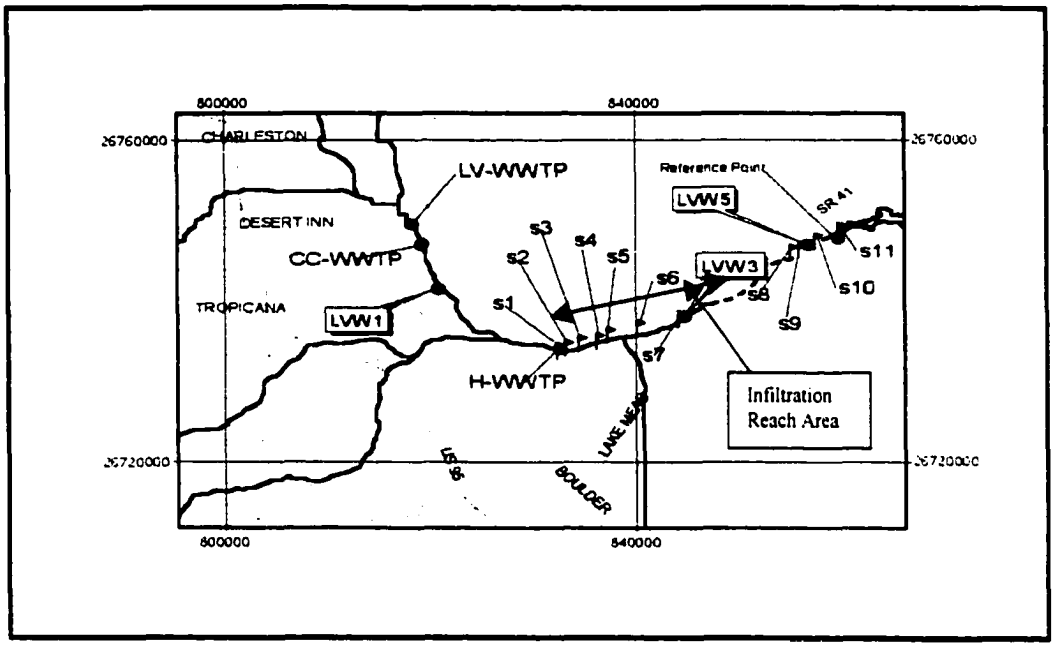


Figure 5.3: Locations of the Key Sampling Points along the Las Vegas Wash

Table 5.6: Description of the Key Sampling Points along the Las Vegas Wash

Point of Interest	Distance from the City WWTP Discharge (km)	Approximate Channel Depth (m)	Approximate Channel Width (m)
City WWTP	0	N/A	N/A
CCSD WWTP	0.87	N/A	N/A
LVW1	2.63	N/A	N/A
KMCC Perchlorate Seepage (S1)	7.486	0.33	20
S2	7.749	0.32	22
S3	8.182	0.46	12.5
S4	8.722	0.37	13.7
S5	9.132	0.37	15.2
S6	10.029	0.39	12.5
S7	11.304	0.47	12.8
LVW3K	11.410	N/A	N/A
S8	15.405	0.36	14.0
S9	15.729	0.32	21.0
S10	15.94	0.27	20.1
LVW5	16.29		
Reference Point	17252		

*KMCC perchlorate seepage enters the Wash almost at the same location as the City of Henderson's WWTP discharge. The distances represent the linear distances based on GIS data. (Source : Modified from Batista and Zhang, 2000)

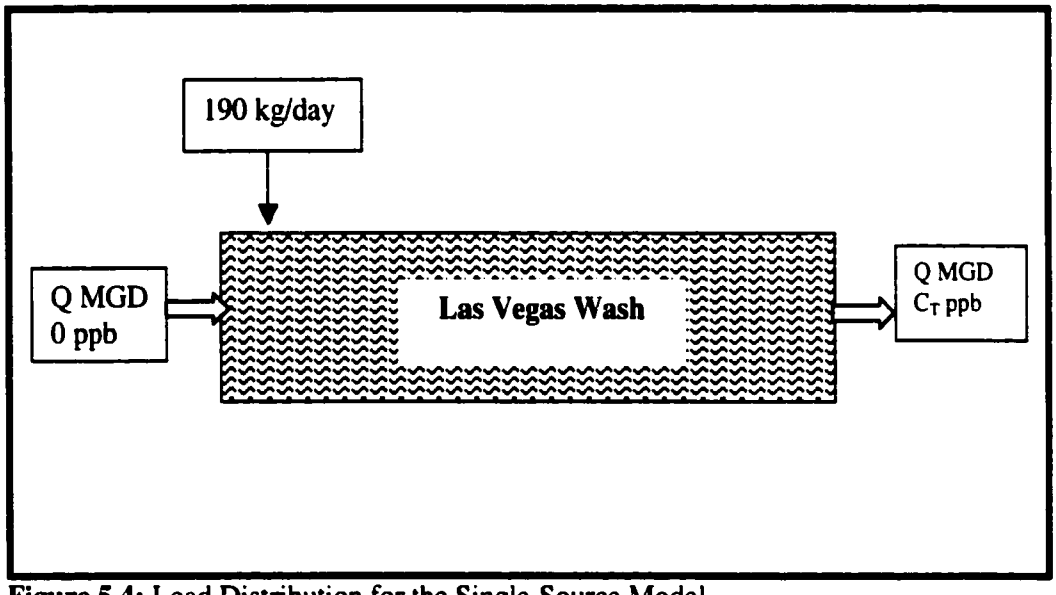


Figure 5.4: Load Distribution for the Single-Source Model.

Analyses results predicted Wash perchlorate levels up to 293 ppb. The results are illustrated in Table 5.7 and Figure 5.5.

Table 5.7: The Perchlorate Levels Predicted by the KMCC Main Plume

Distance (m)	Perchlorate Concentration (ppb)
100	293.2
200	273.1
300	274.4
400	274.3
500	274.4
600	274.3
700	274.3
800	274.3
900	274.3

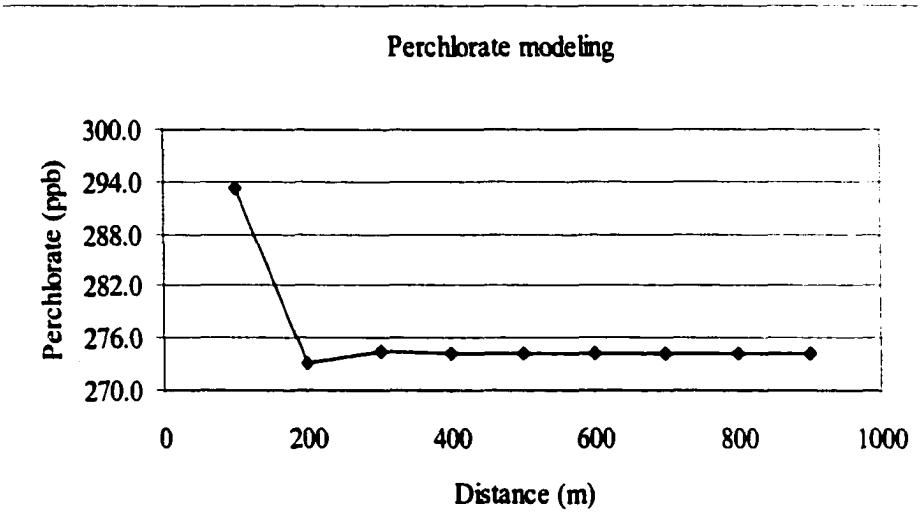


Figure 5.5: Perchlorate Levels Predicted by the KMCC Main Plume

This shows that the main KMCC plume could only account for about 36% of the total loading into the Wash. This supports the existence of other sources downstream from the KMCC main plume.

5.3.2 Distributed Source Model

Since the single source model was unable to represent the observed perchlorate levels, modeling was carried out for the perchlorate distribution shown in Figure 5.6. The perchlorate level profile shown in Figure 5.6 has been estimated based on the measured perchlorate concentrations along the Wash. The input parameters were the same as those used in the single discharge model, except for the number of discharge points that were modified to six. Figure 5.7 illustrates the model.

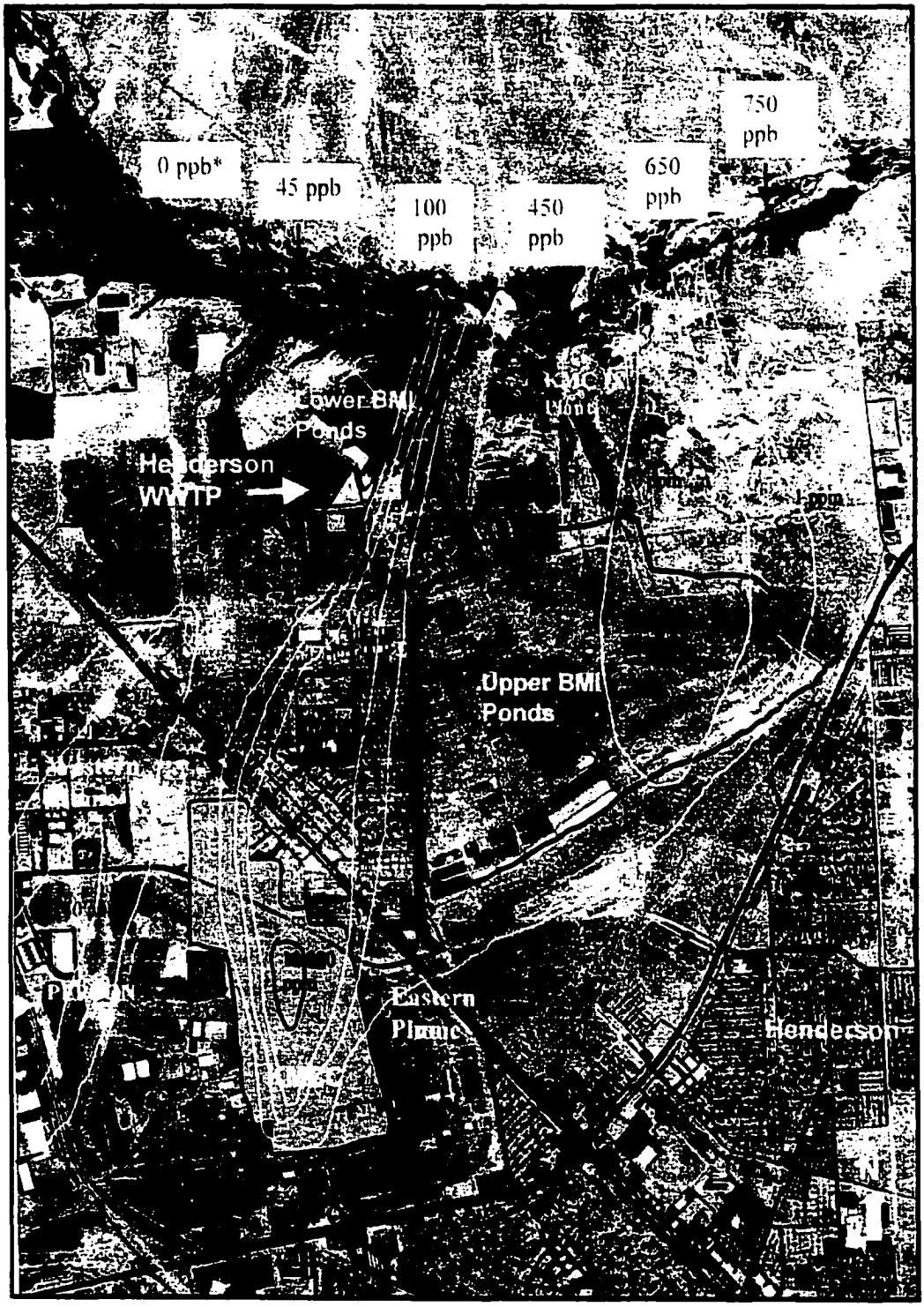


Figure 5.6: Approximate Perchlorate Levels within the KMCC Site and the Las Vegas Wash (Source: Modified from KMCC, 2000; Geraghty & Miller, 1993; Broadbent & Associates, 1998; Zhang, 2001) * Assumed to be zero for simplification.

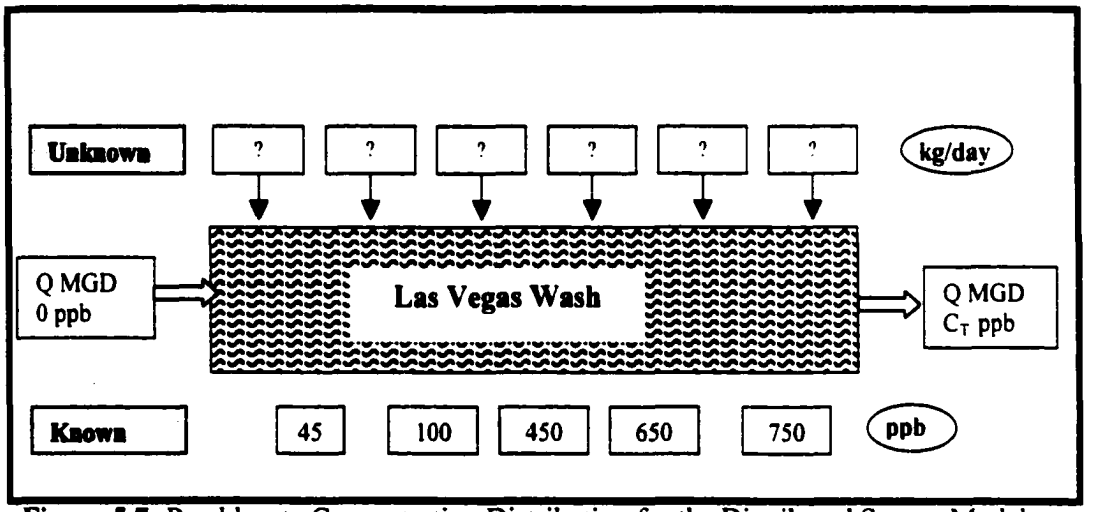


Figure 5.7: Perchlorate Concentration Distribution for the Distributed Source Model.

A perchlorate loading distribution was assumed by evaluating the perchlorate concentration distribution (Figure 5.7). The model was run several times with adjustments to assumed perchlorate loads until calculated perchlorate concentrations matched the observed levels (Table 5.8).

Table 5.8: Comparison of the Predicted Perchlorate Levels of the Distributed Source Model

Location (m)	Actual Concentration (ppb)	Predicted Concentration (ppb)
1000	45	45
2000	100	99
3000	450	459
4000	650	610
5000	750	735

5.4 Discussion

The finite difference method was able to predict the variation of the perchlorate concentration within a close margin. The deviations in the predicted values could be due to following model violations:

- inflow of water into the LVW within the infiltration reach area,
- the loading distribution used for the model is not accurate,
- inaccuracies of the stream dimensions and flows, and
- changes in the hydrological conditions along the LVW.

The accuracy of the model could be improved by better representing the actual conditions of the Wash. The available Wash perchlorate data were not adequate to perform detailed modelling, that could be used to determine the loading profile within the contaminated area. Based on the historical data, the Wash perchlorate levels showed high variation. Therefore, it is necessary to collect adequate number of samples (can be established based on the sample variance of the historic data) from the same sampling point. It is necessary to consider the time of sample collection, since the Wash flow can fluctuate due to the changes in the discharges of the wastewater treatment plants.

Perchlorate loading from the KMCC plume is governed by the hydrogeology in the area. The lateral groundwater movement within the main KMCC plume can be affected by the use of RIBs by the City of Henderson WWTP, especially since they are located on top of the flow path of the KMCC main perchlorate plume. A hydrogeological study conducted by KMCC (2001) reported that the operation of the

RIBs impacted the movement of the groundwater from the KMCC property to the Wash. The RIBs may affect perchlorate concentrations in the seepage at least in two ways: (a) the wastewater that infiltrates the soil layers contaminated with perchlorate may wash out perchlorate thereby increasing the perchlorate concentration; (b) the wastewater that infiltrates may form a barrier to the movement of the contaminated KMCC groundwater upgradient from the RIBs. This has also been hypothesized by KMCC hydrologists in their January 18th 2001 Report to the NDEP (KMCC, 2001). The City of Henderson solely relied on these RIBs until 1994 for the treatment and disposal of wastewater until the plant started the operation of their new WWTP (referred to as the Reclamation Facility) in June 1994.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions could be drawn from the investigations:

1. Perchlorate contamination in the Las Vegas Wash and Lake Mead has been documented back to 1991 by analyzing frozen water samples.

2. The Las Vegas Wash contains very low perchlorate levels (average: 8.8 ppb) upstream of the contaminated site. This is the result of unintentional use of perchlorate-containing chemicals by the City of Las Vegas WWTP.

3. The average perchlorate levels in the Wash decreased from 1991 to 1993, and have started increasing thereafter, reaching a maximum during the period from 1995-1997. The levels started decreasing after 1998. There were insufficient data to establish whether the perchlorate concentrations will reach the levels that were observed before 1995. Based on the available data, perchlorate levels after 1994 were significantly higher than the pre-1994 data. The exact cause of the sudden increase could not be established.

4. The average perchlorate loading rate into the Wash also displayed a pattern similar to the concentration profile, reaching a maximum in 1997. The average perchlorate loading rates varied between 300 to 450 kg/day from 1991 to 2000.

5. The perchlorate levels at the LVW3K sampling point are significantly higher than those of the LVW5 sampling point. Intrusion of relatively low-perchlorate water between the two sampling points is believed to decrease perchlorate levels from LVW3K to LVW5.

6. Based on the statistical results, the Wash flow significantly affects the perchlorate concentration at LVW3K sampling point, however for LVW5 a relationship could not be established between the Wash flow and perchlorate concentrations at the 95% confidence level. However, flow had a significant effect on the loading rates. The high-flow perchlorate loadings were significantly higher than those of the low-flow dates at the 90% confidence level

7. The main KMCC plume accounts for about 40% (190 kg/day) of the total loading (approximately 421 kg/day) into the Wash. This supports the existence of other sources downstream from the KMCC main plume. Evaluation of the perchlorate concentration profile also shows the existence of other sources between Lake Las Vegas and Pabco Road.

8. The high perchlorate levels of the Wash are quickly diluted to small concentrations after entering the Las Vegas Bay.

9. Interior Lake sampling points had perchlorate concentrations below 20 ppb, although sporadic higher concentrations have been detected in some samples.

10. The perchlorate levels within the hypolimnion and metalimnion were significantly higher than those of the epilimnion layers for the LM2 to LM4 sampling locations. Statistical significance could not be established for epilimnion and hypolimnion layers at LM5 sampling location. At LM8, the perchlorate levels within the epilimnion layer were higher than those of the hypolimnion. This shows that the flow of the Las Vegas Wash is primarily within the metalimnion and the hypolimnion layers within the Las Vegas Bay area, and mixes up into the Lake after LM4.

11. The difference between the hypolimnion and the epilimnion perchlorate levels were highest among the sampling points closer to the discharge point of the Wash, and gradually decrease with distance towards the Lake interior. This shows that the Wash plume maintains its identity until it reaches the interior sections of the Lake.

12. Lake stratification significantly affects perchlorate levels at all thermal layers. The epilimnion and metalimnion perchlorate levels during the stratified period were higher than those of the non-stratified period. The hypolimnion perchlorate concentrations were significantly higher during the non-stratified period than the

stratified period. The variations of perchlorate levels between stratified and non-stratified periods further strengthen the conclusions that had been reached on the movement of the Wash.

13. The increase of the perchlorate levels within the hypolimnion layer during the non-stratified period (that occurs during winter) could potentially impact the perchlorate levels in the drinking water supply of the Las Vegas Valley. The Las Vegas water intake pumps water from the hypolimnion, and therefore, higher perchlorate levels are expected to be present in the drinking water during winter.

14. The effects of stratification were strongest (based on the P values and the 95% Confidence Interval) within the Lake's initial and middle zones in the Las Vegas Bay, when compared to the Boulder Basin. This is expected as the Wash has mostly been mixed into the Lake by the time it reaches Boulder Basin.

15. Evaluation of the perchlorate data also shows that Lake perchlorate levels had increased after 1995 for almost all the sampling locations.

16. Based on the statistical analyses, Lake storage level did not have a significant effect on perchlorate levels for the Las Vegas Bay area sampling points. This could be due to the fact that perchlorate levels within the initial sampling points are more dependent on the movement of the Wash, rather than dilution. However, storage

becomes more important in Boulder Basin, since the discharge has already been mixed into the Lake water.

17. The analyses of TDS levels showed similar patterns as the perchlorate within the Lake. TDS levels within the hypolimnion were significantly higher than those of the epilimnion layer, for the LM2, LM3 and LM4 sampling locations. The results for LM5 sampling were inconclusive. At the LM8 sampling location, the epilimnion TDS levels were significantly higher than the hypolimnion layer. Therefore, TDS levels within the Lake support the conclusions that had been reached based on perchlorate levels.

Recommendations for Further Reseach

1. A detailed study of the effect of stormwater flows on perchlorate levels could not be performed due to the unavailability of perchlorate data on high flow dates. The presence of high perchlorate levels within the sediments along the Wash can also act as a potential source (Zhang, 2001). Stormwater flows can cause the perchlorate in the sediments to be released back into the Wash. Further research is needed to correlate stormwater flows and perchlorate levels in the Wash.

2. The exact cause/s that resulted in the increase of perchlorate levels since 1995 could not be established due to the unavailability of groundwater data. Although the perchlorate levels started decreasing after 1997, it was not possible to observe

whether the levels will decrease to the values that existed before 1995. Analyses of Wash and Lake perchlorate data for the years from 1999 onwards should be carried out.

3. The available perchlorate data along the Las Vegas Wash was not adequate to perform modeling to determine the loading profile within the contaminated area. Based on the historical data, the Wash perchlorate levels showed high variation. Therefore, it is necessary to collect adequate number of samples (can be established based on the sample variance of the historic data) from the same sampling point. It is necessary to consider the time of sample collection, since the Wash flow can fluctuate due to the changes in the discharges of the wastewater treatment plants.

4. Further hydrogeological studies should be performed to understand the groundwater flow and the distribution of perchlorate within the contaminated site. This will enable better modelling along the Wash.

5. The use of Rapid Infiltrations Basins significantly affects (KMCC, 2001) the groundwater flow underneath the KMCC contaminated site. The effects of the RIBs on perchlorate transport to the Wash should be further studied.

6. The initial mixing of the Wash discharge within Lake Mead should be further investigated. The discharge geometry of the Wash is unique and difficult to be modelled. It is not possible to identify an exact point of discharge since the Wash

gradually widens to form the Bay area of the Lake. Majority of the existing lake hydrodynamics models assume infinitely long lake shore lines. This is not the case with Lake Mead. The initial model trials made using CORMIX (Cornell Mixing Zone Expert System;) software, showed that the distance between the shorelines of the discharge point significantly affects the predicted perchlorate levels (Jirka et al, 2000. Further, unlike most models that assume positive buoyancy (where discharge is lighter than the receiving water), the Wash discharge has a negative buoyancy, that makes is even harder to model using the existing software. Lake modeling is vital in determining the response of the Lake perchlorate levels to any changes in the loading.

APPENDIX A

DATA ON PERCHLORATE , FLOW, LAKE STORAGE AND TDS LEVELS

Table A.1: Sampling Location LVW1

Date	Perchlorate (ppb)	Flow (cfs)	TDS (ppm)
28-May-91	23.4	160.0	N/A
22-Jun-92	6.9	154.4	N/A
13-Oct-92	3.4	174.8	N/A
23-Dec-92	17.5	164.6	N/A
22-Mar-93	12.4	173.0	N/A
7-Sep-93	0.0	152.5	1255
15-Nov-93	9.6	159.0	1398
14-Dec-93	11.0	167.4	1230
24-Jul-94	20.3	180.4	1191
8-Aug-94	6.2	160.0	1300
19-Oct-94	16.6	182.3	1328
2-Nov-94	0.0	165.5	1414
1-Nov-95	7.5	180.4	1402
10-Jan-96	16.3	184.1	1382
7-Feb-96	7.9	187.9	1342
6-Mar-96	10.2	193.4	1300
29-May-96	9.7	178.6	1256
6-Aug-96	11.7	166.5	1230
30-Sep-96	14.1	184.1	1350
27-Nov-96	10.1	213.9	N/A
9-Jul-97	0.0	177.6	N/A
3-Sep-97	0.0	818.4	N/A
26-Nov-97	0.0	200.9	N/A
8-Jul-98	0.0	114.4	N/A
22-Jul-98	21.3	237.2	N/A
8-Jun-99	0.0	208.3	N/A
16-Sep-99	10.1	255.8	N/A
5-Jan-00	28.1	234.4	N/A

Table A.2: Sampling Location LVW3K

Date	Perchlorate (ppb)	Flow (cfs)	Perchlorate Loading (kg/day)	TDS (ppm)
28-May-91	648.18	172	273	N/A
13-Oct-92	223.2	188	103	N/A
23-Dec-92	808.86	177	350	N/A
28-Mar-93	599.2	186	273	1849
23-Aug-93	421.5	199	205	1587
3-Nov-93	509.5	161	201	1777
27-Dec-93	525.4	194	249	1754
14-Mar-94	577.9	193	273	1809
11-Apr-94	627.8	183	281	1810
25-Apr-94	665.8	181	295	1779
19-May-94	631.8	172	266	1718
11-Jul-94	445	159	173	1596
12-Sep-94	507.4	176	219	1555
26-Sep-94	575	183	257	1571
19-Oct-94	647.6	196	311	1620
2-Nov-94	685.3	178	298	1650
22-Feb-95	1052.1	198	510	1998
19-Apr-95	664.1	192	312	1800
17-May-95	716.7	155	272	1722
31-May-95	500.6	149	183	1752
26-Jul-95	692.9	201	341	1572
23-Aug-95	594.4	243	353	1318
6-Sep-95	583.7	194	277	1522
25-Sep-95	713.1	213	372	1577
4-Oct-95	752.3	193	355	1606
18-Oct-95	810.8	186	369	1644
1-Nov-95	859.7	194	408	1702
15-Nov-95	1147.7	199	559	1694
29-Nov-95	1025.6	209	524	1728
7-Feb-96	1268.4	202	627	1782
6-Mar-96	975.7	208	497	1770
3-Apr-96	919.9	204	459	1772
17-Apr-96	798.3	196	383	1710
1-May-96	815.8	180	359	1678
15-May-96	627.7	175	269	1598
29-May-96	753.4	192	354	1662
26-Jun-96	679.9	181	301	1412
10-Jul-96	710	155	269	1536
6-Aug-96	704.3	179	308	1484
21-Aug-96	652.6	195	311	1480
4-Sep-96	735.8	191	344	1588
8-Jan-97	1343	225	739	1792
22-Jan-97	1295	218	691	1766

Table A.2: Continued

Date	Perchlorate (ppb)	Flow (cfs)	Perchlorate Loading (kg/day)	TDS (ppm)
5-Feb-97	1222	223	667	1736
5-Mar-97	966	224	529	1760
2-Apr-97	991	210	509	1868
16-Apr-97	966	205	485	1620
30-Apr-97	806	180	355	1600
14-May-97	596	201	293	1582
28-May-97	806	189	373	1572
11-Jun-97	665.3	190	309	1556
9-Jul-97	519.5	191	243	N/A
23-Jul-97	555	200	272	N/A
6-Aug-97	994	209	508	N/A
20-Aug-97	1110	224	608	N/A
17-Sep-97	1041	216	550	N/A
1-Oct-97	1001	215	527	N/A
15-Oct-97	993	222	539	N/A
12-Nov-97	984	292	703	N/A
29-Nov-97	930	295	671	N/A
10-Dec-97	979	287	687	N/A
23-Dec-97	966	293	693	N/A
7-Jan-98	739	239	432	N/A
21-Jan-98	898	250	549	N/A
4-Feb-98	271	515	341	N/A
18-Feb-98	937	347	796	N/A
18-Mar-98	1798	207	911	N/A
1-Apr-98	1031	281	709	N/A
15-Apr-98	1063	218	567	N/A
29-Apr-98	1038	234	594	N/A
13-May-98	995	219	533	N/A
27-May-98	951	200	465	N/A
24-Jun-98	740	167	302	N/A
8-Jul-98	311	123	94	N/A
22-Jul-98	512	255	319	N/A
5-Aug-98	738	185	334	N/A
19-Aug-98	1001	180	441	N/A
2-Sep-98	948	270	626	N/A
30-Sep-98	528.7	200	259	N/A
14-Oct-98	745.2	211	385	N/A
16-Oct-98	945	240	555	N/A
8-Jun-99	806.2	224	442	N/A
5-Jan-00	552.2	252	340	N/A

Table A.3: Sampling Location LVW5

Date	Perchlorate (ppb)	Flow (cfs)	Perchlorate Loading (kg/day)	TDS (ppm)
25-Feb-91	763.14	181	338	N/A
28-May-91	642.42	161	253	N/A
16-Sep-91	505.26	177	219	N/A
22-Jun-92	377.94	166	154	N/A
13-Oct-92	258.12	188	119	N/A
23-Dec-92	814.62	177	353	N/A
22-Mar-93	170.58	197	82	N/A
23-Aug-93	311.8	199	152	N/A
1-Nov-93	558.8	163	223	N/A
3-Nov-93	521.2	161	205	1602
10-Jan-94	498.2	202	246	1915
14-Feb-94	590.6	178	257	1920
9-May-94	757.8	172	319	1760
1-Nov-95	854.16	194	405	1706
10-Jan-96	1093.6	204	546	1804
7-Feb-96	1103.4	199	537	1780
6-Mar-96	816.2	208	415	1780
6-Aug-96	652.4	179	286	1582
27-Nov-96	1100.4	230	619	1924
9-Jul-97	608.7	191	284	N/A
3-Sep-97	1009.56	850	2100	N/A
26-Nov-97	746.94	216	395	N/A
10-Dec-97	772.98	219	414	N/A
4-Feb-98	331.56	299	243	N/A
1-Apr-98	945.54	246	569	N/A
13-May-98	920.6	219	493	N/A
15-Jun-98	776.88	222	422	N/A
24-Jun-98	560.4	176	241	N/A
8-Jul-98	798.6	194	379	N/A
22-Jul-98	517.2	255	323	N/A
28-Oct-98	907.8	216	480	N/A
8-Jun-99	707	224	388	N/A
23-Jun-99	900.4	200	441	N/A
5-Jan-00	516	252	318	N/A

Table A.4: Sampling Location LM2CE

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	81.3	N/A
26-Aug-91	19900	61.1	N/A
6-Jan-92	19770	16.0	N/A
7-Jul-92	19270	37.7	N/A
5-Oct-92	19450	18.6	N/A
29-Mar-93	21985	18.9	774
1-Jul-93	21175	37.0	791
1-Aug-93	21350	50.0	908
23-Aug-93	21290	36.0	791
30-Aug-93	21290	18.4	783
1-Oct-93	21370	15.3	726
1-Apr-94	21280	102.0	826
1-May-94	20789	51.6	901
1-Jun-94	20340	87.9	947
1-Apr-95	20445	120.0	927
1-May-95	20081	145.0	921
1-Jun-95	19906	200.0	913
1-Jul-95	20024	67.5	898
10-Jul-95	20092	133.5	863
1-Aug-95	20239	90.5	768
1-Sep-95	20371	61.9	783
1-Oct-95	20732	34.9	822
1-Nov-95	20964	47.7	722
5-Feb-96	22012	24.1	657
4-Mar-96	22043	41.0	706
11-Mar-96	21994	501.3	1320
25-Mar-96	21862	18.8	663
1-Apr-96	22069	163.3	849
15-Apr-96	22039	66.2	772
22-Apr-96	21981	175.7	958
6-May-96	21856	277.3	1050
13-May-96	21794	252.0	996
20-May-96	21753	98.9	781
17-Jun-96	21666	133.6	885
24-Jun-96	21613	64.0	717
1-Jul-96	21544	78.8	796
15-Jul-96	21585	147.1	861
29-Jul-96	21552	*141.8*	816
5-Aug-96	21513	81.3	738
12-Aug-96	21470	103.7	751
19-Aug-96	21474	83.0	734
26-Aug-96	21491	81.1	757
3-Sep-96	21508	170.3	756
9-Sep-96	21508	119.8	804

Table A.4 Continued.

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
16-Sep-96	21556	98.9	756
30-Sep-96	21613	71.9	699
7-Oct-96	21665	51.1	708
14-Oct-96	21711	48.5	678
28-Oct-96	21713	63.0	695
5-Nov-96	21743	33.1	664
3-Dec-96	21874	39.2	632
7-Jan-97	22189	24.1	640
4-Feb-97	22287	46.3	645
4-Mar-97	22471	38.6	688
10-Mar-97	22566	215.5	1171
17-Mar-97	22633	132.6	747
8-Apr-97	22854	369.1	1065
14-Apr-97	22884	441.9	1164
28-Apr-97	22921	466.6	1261
12-May-97	22936	195.9	875
27-May-97	22926	102.7	749
16-Jun-97	23052	98.6	765
1-Jul-97	23264	111.3	820
8-Jul-97	23349	74.4	685
11-Aug-97	23511	74.6	716
15-Sep-97	23570	65.2	671
13-Oct-97	23995	62.0	742
4-Nov-97	24401	38.2	652
2-Dec-97	24842	31.9	638
6-Jan-98	25110	58.1	609
10-Feb-98	25006	14.8	595
16-Mar-98	25001	78.0	683
7-Apr-98	25021	106.1	771
13-Apr-98	24950	137.3	790
11-May-98	24804	195.4	855
15-Jun-98	24665	93.9	738
7-Jul-98	24630	54.9	694
13-Jul-98	24652	104.5	676
17-Aug-98	24908	58.9	685
14-Sep-98	25288	47.5	653
28-Sep-98	25112	57.3	713
26-Oct-98	25222	47.4	640
3-Nov-98	25268	37.4	578
8-Jun-99	23996	151.4	743
28-Jun-99	23997	151.4	662
7-Sep-99	24333	85.1	617
5-Jan-00	*24866*	29.1	495
4-Apr-00	24212	152.4	841

Table A.5: Sampling Location LM2CH

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	176.4	N/A
26-Aug-91	19900	100.0	N/A
6-Jan-92	19770	33.1	N/A
7-Jul-92	19270	57.5	831
29-Mar-93	21984	73.1	950
25-Oct-93	21254	97.5	934
7-Feb-94	21510	81.2	794
7-Apr-94	21164	637.0	1151
14-Jun-94	20248	329.8	1026
20-Jun-94	20204	166.2	1058
1-Aug-94	20005	105.8	829
29-Aug-94	19946	33.6	946
19-Sep-94	19902	157.2	915
10-Oct-94	19917	106.5	901
17-Oct-94	19886	41.6	853
24-Oct-94	19872	95.3	853
7-Nov-94	19777	265.2	942
5-Dec-94	19584	94.4	848
6-Nov-95	21028	297.9	1067
5-Feb-96	22012	240.0	937
11-Mar-96	21994	161.6	918
1-Apr-96	22069	156.2	874
15-Apr-96	22039	575.8	1160
20-May-96	21753	260.5	1104
17-Jun-96	21666	301.6	1125
24-Jun-96	21613	156.7	904
12-Aug-96	21470	349.3	1172
9-Sep-96	21508	185.5	900
30-Sep-96	21613	236.8	954
28-Oct-96	21713	194.0	867
8-Apr-97	22854	98.7	747
8-Jul-97	23349	159.3	743
2-Dec-97	24834	387.1	1145
10-Feb-98	25006	119.0	791
29-Jun-98	24674	337.8	1353
7-Jul-98	24630	244.7	1058
28-Sep-98	25112	62.2	660
26-Oct-98	24222	145.8	810
8-Jun-99	23996	312.3	1071
28-Jun-99	23858	410.8	1146
7-Sep-99	24333	235.8	914
5-Jan-00	24996	224.4	908
4-Apr-00	24212	85.6	717

Table A.6: Sampling Location LM2NE

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	88.5	N/A
26-Aug-91	19900	154.2	N/A
6-Jan-92	19770	19.5	729
23-Aug-93	21290	17.5	822
3-Jan-94	21348	20.8	734
10-May-94	20641	31.7	817
5-Jul-94	20059	11.7	776
27-Mar-95	20503	137.3	957
1-May-95	20081	138.8	957
10-Jul-95	20092	122.4	913
7-Aug-95	20267	121.5	912
5-Sep-95	20407	47.9	799
6-Nov-95	21028	57.4	771
5-Feb-96	22012	25.6	698
1-Apr-96	22069	89.0	810
6-Apr-96	22181	118.8	1051
17-Jun-96	21666	148.1	893
24-Jun-96	21614	63.6	749
12-Aug-96	21471	104.7	798
9-Sep-96	21508	166.4	814
28-Oct-96	21713	65.0	720
8-Apr-97	22854	325.2	1049
10-Feb-98	25006	23.8	616
21-Sep-98	25178	110.5	669
28-Sep-98	25112	34.3	649
3-Nov-98	25268	35.3	656
5-Jan-00	24861	21.9	568
4-Apr-00	24212	N/A	N/A

Table A.7: Sampling Location LM2NH

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	180.5	N/A
6-Jan-92	19770	23.2	N/A
7-Jul-92	19270	72.9	N/A
29-Mar-93	21984	17.4	N/A
13-Sep-93	21390	40.9	N/A
8-Nov-93	21214	89.1	N/A
2-May-94	20789	119.1	994
17-Oct-94	19886	109.5	964
27-Mar-95	20503	195.1	958
1-May-95	20081	225.7	1125
10-Jul-95	20092	154.8	1118
7-Aug-95	20267	317.8	1187
5-Sep-95	20407	75.3	1016
6-Nov-95	21028	108.2	789
5-Feb-96	22012	917.5	1467
1-Apr-96	22069	340.0	1067
15-Apr-96	22039	445.8	1250
17-Jun-96	21666	228.3	1016
24-Jun-96	21614	137.2	880
12-Aug-96	21471	339.8	1146
9-Sep-96	21508	287.3	1046
30-Sep-96	21613	414.0	1205
28-Oct-96	21713	239.5	876
8-Apr-97	22854	74.6	733
2-Dec-97	24834	99.3	730
10-Feb-98	25006	461.9	1299
7-Apr-98	25021	718.9	1648
29-Jun-98	24674	392.8	1450
21-Jul-98	24642	204.6	641
28-Sep-98	25112	52.2	726
28-Jun-99	23865	300.6	839
5-Jan-00	24861	171.5	917
4-Apr-00	24212	87.4	669

Table A.8: Sampling Location LM2SE

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	87.4	N/A
26-Aug-91	19900	61.1	N/A
7-Jul-92	19270	39.6	N/A
29-Mar-93	21985	12.6	792
30-Aug-93	21290	10.5	806
8-Nov-93	21214	12.2	755
10-May-94	20641	41.3	818
5-Jul-94	20059	34.6	776
1-May-95	20081	125.8	940
7-Aug-95	20267	127.7	908
6-Nov-95	21028	59.5	738
5-Feb-96	22012	31.7	725
1-Apr-96	22069	171.1	994
15-Apr-96	22039	78.9	779
17-Jun-96	21666	104.6	878
24-Jun-96	21614	55.5	745
9-Sep-96	21508	128.4	830
28-Oct-96	21713	53.6	717
8-Apr-97	22854	36.7	1151
10-Feb-98	25006	21.7	603
7-Apr-98	25021	84.5	786
21-Sep-98	25178	36.5	652
3-Nov-98	25268	35.2	674
28-Jun-99	23858	68.8	639
5-Jan-00	24861	17.5	583
4-Apr-00	24212	212.7	893

Table A.9: Sampling Location LM2SH

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	188.3	N/A
6-Jan-92	19770	41.2	N/A
7-Jul-92	19270	74.3	N/A
29-Mar-93	21984	19.1	N/A
2-May-94	20789	214.7	N/A
17-Oct-94	19886	73.1	908
24-Oct-94	19872	43.0	803
27-Mar-95	20503	652.8	1007
1-May-95	20081	257.0	1176
10-Jul-95	20092	205.9	1178
7-Aug-95	20267	300.5	1123
5-Sep-95	20407	166.9	851
6-Nov-95	21028	309.8	1035
5-Feb-96	22012	437.1	1015
1-Apr-96	22069	268.9	1067
15-Apr-96	22039	478.2	1245
20-May-96	21753	112.2	1018
17-Jun-96	21666	203.3	1117
24-Jun-96	21614	66.3	772
9-Sep-96	21508	200.1	798
28-Oct-96	21713	120.5	798
8-Apr-97	22854	161.5	878
2-Sep-97	23555	65.3	871
10-Feb-98	25006	233.6	923
3-Nov-98	25268	281.0	803
14-Jun-99	23938	396.9	944
28-Jun-99	23858	462.5	1299
5-Jan-00	24861	223.4	843
4-Apr-00	24212	144.9	749

Table A.10: Sampling Location LM3CE

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
20-May-91	21254	33.4	N/A
9-Sep-91	19230	62.2	N/A
13-Jul-92	19270	29.8	N/A
13-Oct-92	19450	7.7	N/A
22-Mar-93	21984	33.9	N/A
23-Aug-93	21290	8.6	N/A
30-Aug-93	21290	9.4	N/A
8-Nov-93	21214	31.8	N/A
3-Jan-94	21348	8.9	N/A
9-May-94	20673	25.9	N/A
5-Jul-94	20059	20.7	N/A
27-Mar-95	20503	157.2	921
1-May-95	20081	182.5	1003
10-Jul-95	20092	88.3	855
5-Sep-95	20407	51.6	778
6-Nov-95	21028	50.4	752
11-Mar-96	21994	95.6	872
1-Apr-96	22069	142.0	863
15-Apr-96	22039	84.3	736
20-May-96	21753	162.0	830
17-Jun-96	21666	163.9	904
24-Jun-96	21614	58.0	738
12-Aug-96	21471	135.0	829
9-Sep-96	21508	143.4	819
30-Sep-96	21613	89.4	747
28-Oct-96	21713	57.4	709
2-Sep-97	23555	100.7	712
15-Sep-97	23570	68.6	694
13-Oct-97	23995	110.9	756
2-Dec-97	24834	18.8	654
6-Jan-98	25110	53.5	618
10-Feb-98	25006	19.1	612
9-Mar-98	25007	39.0	666
7-Apr-98	25021	87.1	753
13-Apr-98	24951	190.6	801
5-May-98	24808	153.4	914
15-Jun-98	24665	93.7	754
7-Jul-98	24630	74.9	749
13-Jul-98	24652	56.6	672
24-Aug-98	24963	88.3	749
14-Sep-98	25298	47.4	689
3-Nov-98	25268	34.0	698
6-Apr-99	24536	48.3	638
28-Jun-99	23868	92.0	652
5-Jan-00	24861	21.1	540
4-Apr-00	24212	125.4	567

Table A.11: Sampling Location LM3CH

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
9-Sep-91	19230	69.26	N/A
13-Oct-91	18995	43.74	N/A
13-Jul-92	19270	34.84	N/A
19-Oct-92	19450	11.89	N/A
22-Mar-93	21984	56.65	N/A
8-Nov-93	21214	75.61	N/A
3-Jan-94	21348	135.28	N/A
10-May-94	20641	53.65	N/A
5-Jul-94	20059	64.76	N/A
18-Jul-94	20028	41.12	N/A
10-Oct-94	19917	72.07	830
27-Mar-95	20503	292.76	1376
1-May-95	20081	160.78	980
10-Jul-95	20092	63.14	857
7-Aug-95	20267	68.86	860
5-Sep-95	20407	66.2	850
6-Nov-95	21028	171.26	880
5-Feb-96	22012	613.6	1114
11-Mar-96	21994	133.8	823
1-Apr-96	22069	316.08	1075
15-Apr-96	22039	228.83	986
20-May-96	21753	77.35	791
17-Jun-96	21666	189.8	898
24-Jun-96	21614	140.68	875
12-Aug-96	21471	281.92	1046
9-Sep-96	21508	236.95	993
30-Sep-96	21613	178.6	884
28-Oct-96	21713	270.4	827
8-Apr-97	22854	158.59	855
29-Jun-98	24674	162.98	923
7-Jul-98	24630	144.71	952
3-Nov-98	25268	69.73	731
28-Jun-99	23868	136.87	811
5-Jan-00	24861	127.94	821
4-Apr-00	24212	101.3	650

Table A.12: Sampling Location LM3NE

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
20-May-91	21254	43	N/A
9-Sep-91	19230	60.74	N/A
13-Oct-92	19450	19.803	N/A
22-Mar-93	21984	9.64	N/A
23-Aug-93	21290	14.39	N/A
30-Aug-93	21290	8.86	N/A
10-May-94	20641	52.92	N/A
17-Oct-94	19886	28.32	805
1-May-95	20081	125.08	925
10-Jul-95	20092	92.32	874
7-Aug-95	20267	115.22	863
5-Sep-95	20407	38.98	792
6-Nov-95	21028	53.22	741
5-Feb-96	22012	22.65	677
1-Apr-96	22069	131.48	821
15-Apr-96	22039	106.27	781
17-Jun-96	21666	150.74	876
26-Jun-96	21586	58.32	731
28-Jun-96	21586	72.22	770
30-Sep-96	21613	57.47	738
28-Oct-96	21713	60.4	703
8-Jul-97	23349	176.02	695
2-Dec-97	24834	37.04	643
10-Feb-98	25006	13.46	595
7-Jul-98	24630	70.92	721
8-Sep-98	25169	100.76	698
21-Sep-98	25178	36.42	674
3-Nov-98	25268	28.86	693
6-Apr-99	24536	44.52	627
5-Jan-00	24861	22.84	443
4-Apr-00	24212	107.2	612

Table A.13: Sampling Location LM3NH

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
20-May-91	21254	132.84	N/A
9-Sep-91	19230	57.44	N/A
13-Jul-92	19270	31.54	N/A
9-Oct-92	19450	7.56	N/A
13-Oct-92	19450	20.06	N/A
22-Mar-93	21984	72.3	N/A
8-Nov-93	21214	45.16	N/A
3-Jan-94	21348	37.92	N/A
2-May-94	20789	157.59	N/A
5-Jul-94	20068	66.94	N/A
5-Jul-94	20059	58.47	N/A
13-Sep-94	19880	70.34	945
24-Oct-94	19872	93.68	875
27-Mar-95	20503	239.06	1074
10-Jul-95	20092	146.32	896
6-Nov-95	21028	253.32	997
5-Feb-96	22012	241.1	885
1-Apr-96	22069	107.34	771
15-Apr-96	22039	226.3	1008
17-Jun-96	21666	179.48	932
24-Jun-96	21614	118.18	870
9-Sep-96	21508	204.44	948
8-Apr-97	22854	147.64	836
2-Sep-97	23555	142.68	841
10-Feb-98	25006	524.44	1354
28-Sep-98	25112	50.16	773
28-Jun-99	23868	140.26	827
5-Jan-00	24861	99.24	515
4-Apr-00	24212	106.52	700

Table A.14: Sampling Location LM3SE

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
28-May-91	21254	97.42	N/A
9-Sep-91	19230	72.08	N/A
7-Jul-92	19270	59.14	N/A
19-Oct-92	19450	14.13	N/A
15-Apr-93	21915	125.77	N/A
23-Aug-93	21290	15.04	N/A
10-May-94	20641	86.67	N/A
5-Jul-94	20059	19.458	N/A
17-Oct-94	19886	29.73	802
27-Mar-95	20503	126.76	921
1-May-95	20081	167	1010
10-Jul-95	20092	80.52	823
5-Sep-95	20407	20.82	786
6-Nov-95	21028	43.42	747
5-Feb-96	22012	23.32	684
1-Apr-96	22069	98.02	800
17-Jun-96	21666	128.82	872
9-Sep-96	21508	126.42	842
28-Oct-96	21713	56.18	709
8-Apr-97	22854	232.22	971
10-Feb-98	25006	20.46	629
7-Jul-98	24630	103.72	733
31-Aug-98	25052	4.97	715
21-Sep-98	25178	22.26	691
28-Sep-98	25112	45.23	630
3-Nov-98	25268	37.3	578
5-Jan-00	24861	7.91	603
4-Apr-00	24212	190.14	857

Table A.15: Sampling Location LM3SH

Date	Perchlorate (ppb)	Lake Storage (1000 ac-ft)	TDS (ppm)
28-May-91	144.9	21254	N/A
6-Jan-92	31.46	19770	N/A
7-Jul-92	56.78	19270	N/A
13-Sep-93	33.73	21390	N/A
19-Oct-93	43.07	21331	N/A
4-Jul-94	53.0	20068	N/A
5-Jul-94	69.87	20059	N/A
27-Mar-95	251.98	20503	1005
10-Jul-95	64.83	20092	871
7-Aug-95	62.1	20267	835
5-Sep-95	134.3	20407	912
6-Nov-95	125.4	21028	850
5-Feb-96	185.1	22012	821
1-Apr-96	346.0	22069	1032
15-Apr-96	468.79	22039	1177
17-Jun-96	151.08	21666	943
9-Sep-96	314.8	21508	1054
28-Oct-96	229.9	21713	906
8-Apr-97	162.31	22854	881
8-Jul-97	90.28	23349	749
2-Dec-97	175.84	24834	824
10-Feb-98	193.18	25006	904
7-Apr-98	448.36	25021	1298
7-Jul-98	161.16	24630	962
21-Sep-98	23.54	25178	631
28-Sep-98	71.88	25112	782
3-Nov-98	194.93	25268	937
28-Jun-99	141.34	23997	782
5-Jan-00	83.3	24861	650
4-Apr-00	155.26	24212	843

Table A.16: Sampling Location LM4E

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
25-Feb-91	20141	6.93	N/A
26-Feb-91	20141	23.76	N/A
3-Jun-91	19444	8.44	N/A
6-Jan-92	19270	22.13	N/A
5-Oct-92	19450	24.98	N/A
19-Jul-93	21105	38.8	N/A
2-Aug-93	21290	28.92	N/A
29-Sep-93	21372	12.32	N/A
6-Dec-93	21286	12.07	N/A
7-Feb-94	21510	9.26	N/A
7-Mar-94	21590	14.17	N/A
2-May-94	20789	22.36	N/A
20-Jun-94	20204	88.31	N/A
29-Aug-94	19946	37.84	758
19-Sep-94	19903	25.11	831
10-Oct-94	19917	48.22	798
17-Oct-94	19893	30.35	805
7-Nov-94	19777	23.23	745
9-Jan-95	19802	17.06	729
6-Feb-95	20239	16.01	680
5-Feb-96	22012	16.8	697
1-Apr-96	22069	32.56	725
15-Apr-96	22039	45.71	699
20-May-96	21753	44.87	719
17-Jun-96	21666	98.84	821
9-Sep-96	21508	72.98	755
30-Sep-96	21613	52.6	708
8-Apr-97	22854	35.44	664
8-May-97	22854	35.44	756
8-Jul-97	23349	40.45	693
2-Sep-97	23555	146.3	761
2-Dec-97	24834	28.96	592
10-Feb-98	25006	10.68	606
7-Apr-98	25021	56.82	687
7-May-98	25021	56.82	666
7-Jul-98	24630	35.68	677
21-Sep-98	25178	29.38	658
8-Jun-99	23997	63.86	651
28-Jun-99	23858	58.1	654
7-Sep-99	24333	61.08	633
5-Jan-00	24861	19.7	626
4-Apr-00	24212	59.29	671

Table A.17: Sampling Location LM4M

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
6-Mar-91	21254	76.7	N/A
6-Jan-92	19270	11.59	N/A
2-Aug-93	21290	21.15	N/A
6-Dec-93	21286	10.59	N/A
7-Feb-94	21510	21.97	N/A
1-Aug-94	20005	32.51	770
7-Sep-94	19883	0	731
10-Oct-94	19917	33.78	816
7-Nov-94	19777	22.76	745
5-Dec-94	19584	12.68	702
8-Mar-95	20519	8.22	863
1-May-95	20081	46.58	768
10-Jul-95	20092	152.18	928
7-Aug-95	20267	327.44	1114
5-Sep-95	20407	37.38	777
2-Oct-95	20743	209.18	962
6-Nov-95	21028	66.56	731
5-Feb-96	22012	19.84	672
1-Apr-96	22069	36.23	702
9-Sep-96	21508	18.42	658
8-Apr-97	22854	46.18	665
2-Sep-97	23555	155.22	831
2-Dec-97	24834	31.52	629
10-Feb-98	25006	14.69	596
7-Apr-98	25021	46.08	608
7-Jul-98	24630	95	767
3-Nov-98	25268	27.98	644
6-Apr-99	24536	18.12	630
8-Jun-99	23997	150.64	695
7-Sep-99	24333	22.7	714
5-Jan-00	24861	20.58	410
4-Apr-00	24212	9.56	583

Table A.18: Sampling Location LM4H

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
25-Feb-91	20141	258.79	N/A
6-Jan-92	19770	15.78	N/A
13-Sep-93	21390	0	N/A
8-Nov-93	21214	85.12	N/A
3-Jan-94	21348	69.39	N/A
5-Jul-94	20059	14.96	N/A
9-Jan-95	19802	481.44	1136
7-Aug-95	20267	7.72	758
5-Feb-96	22012	367.02	970
1-Apr-96	22069	183.9	882
9-Sep-96	21508	13.4	676
8-Apr-97	22854	117.34	796
8-Jul-97	23349	21.4	627
2-Sep-97	23555	17.06	670
10-Feb-98	25006	257.08	984
7-Jul-98	24630	58.9	720
3-Nov-98	25268	166.06	928
8-Jun-99	23997	35.4	387
5-Jan-00	24861	126.28	717
4-Apr-00	24212	119.46	744

Table A.19: Sampling Location LM5E

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
3-Jun-91	19444	18.38	N/A
6-Jan-92	19270	7.79	N/A
29-Mar-93	21985	17.63	N/A
17-May-93	21520	32.9	N/A
16-Aug-93	21285	26.5	N/A
13-Sep-93	21400	29.1	N/A
8-Nov-93	21214	12.72	N/A
3-Jan-94	21348	7.34	N/A
9-Jan-95	19802	14.71	714
5-Jun-95	19942	47.5	772
10-Jul-95	20092	39.4	729
7-Aug-95	20267	48.25	771
2-Oct-95	20743	17.72	778
5-Feb-96	22012	14.21	681
1-Apr-96	22069	30.09	686
15-Apr-96	22039	41.85	716
20-May-96	21753	35.08	705
17-Jun-96	21666	83.81	781
9-Sep-96	21508	76.27	737
30-Sep-96	21613	46.1	699
8-Apr-97	22854	34.39	651
8-Jul-97	23349	37.39	650
2-Sep-97	23555	65.53	708
2-Dec-97	24834	27.4	630
10-Feb-98	25006	15.2	592
7-Apr-98	25021	74.26	693
18-May-98	24729	56.8	680
15-Jun-98	24665	76.7	656
7-Jul-98	24630	33.77	653
19-Oct-98	25195	45.18	663
7-Sep-99	24333	59.76	666
5-Jan-00	24861	23.65	481
4-Apr-00	24212	55.44	533

Table A.20: Sampling Location LM5M

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
25-Feb-91	20141	9.16	N/A
12-Mar-91	20060	12.36	N/A
9-Sep-91	19230	50.42	N/A
13-Jul-92	19340	20.97	N/A
8-Nov-93	21214	13.02	N/A
3-Jan-94	21348	9.8	N/A
5-Apr-94	21214	32.12	N/A
5-Jul-94	20059	54.72	N/A
1-May-95	20081	90.64	843
5-Jun-95	19942	114.56	886
10-Jul-95	20092	113.14	869
7-Aug-95	20267	108.325	885
5-Sep-95	20407	68.56	813
6-Nov-95	21028	41.62	712
5-Feb-96	22012	14.83	685
1-Apr-96	22069	29.68	693
9-Sep-96	21508	10.41	713
8-Apr-97	22854	41.92	695
8-Jul-97	23349	40.22	636
2-Dec-97	24834	28.5	635
10-Feb-98	25006	12	598
7-Apr-98	25021	31.49	657
7-Jul-98	24630	32.03	657
8-Sep-98	25169	18.24	978
3-Nov-98	25268	24.15	600
6-Apr-99	23020	25.39	605
8-Jun-99	23997	62.22	417
5-Jan-00	24861	17.65	388
4-Apr-00	24212	21.19	592

Table A.21: Sampling Location LM5H

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
9-Sep-91	19230	3.4	N/A
7-Jul-92	19340	11.32	N/A
13-Jul-92	19340	10.8	N/A
13-Sep-93	21390	7.79	N/A
8-Nov-93	21214	5.82	N/A
3-Jan-94	21348	55.12	N/A
5-Apr-94	21214	16.44	N/A
4-Jul-94	20068	8.96	N/A
1-May-95	20081	34.58	769
5-Jun-95	19942	9.03	730
10-Jul-95	20092	12.5	708
5-Sep-95	20407	1.69	766
2-Oct-95	20743	8.48	717
6-Nov-95	21028	7.68	720
5-Feb-96	22012	144.62	838
1-Apr-96	22069	92.96	775
9-Sep-96	21508	10.33	653
8-Apr-97	22854	17.66	648
8-Jul-97	23349	15.08	799
2-Sep-97	23555	70.32	638
2-Dec-97	24834	50.04	662
10-Feb-98	25006	96.91	742
7-Jul-98	24630	8.73	625
3-Nov-98	25268	6.03	610
6-Apr-99	23020	14.41	601
7-Sep-99	24333	14.25	605
5-Jan-00	24861	69.59	702
4-Apr-00	24212	96.49	735

Table A.22: Sampling Location LM8E

Date	Lake Storage (1000 ac-ft)	Perchlorate (ppb)	TDS (ppm)
26-Feb-91	20141	9.28	N/A
9-Sep-91	19230	0	N/A
13-Jul-92	19340	12.62	N/A
29-Mar-93	21985	0	N/A
16-Aug-93	21280	10.6	N/A
3-Jan-94	21348	7.39	N/A
21-Mar-94	20912	7.79	N/A
5-Jul-94	20059	3.52	N/A
1-May-95	20081	29	700
10-Jul-95	20220	5.0	677
17-Jul-95	20220	18.3	698
5-Sep-95	20407	23.06	741
2-Oct-95	20743	25.22	698
6-Nov-95	21028	5.76	693
5-Feb-96	22012	15.18	682
1-Apr-96	22069	13.34	678
12-Apr-96	22058	27.29	687
20-May-96	21753	16.72	668
17-Jun-96	21666	15.44	673
9-Sep-96	21508	19.7	671
30-Sep-96	21613	18.68	651
8-Apr-97	22854	12.78	637
8-Jul-97	23349	49.29	620
2-Sep-97	23555	26.16	639
2-Dec-97	24834	22.18	618
10-Feb-98	25006	0	602
7-Apr-98	25021	11.58	618
7-Jul-98	24630	18.62	622
21-Sep-98	25178	15.5	599
6-Apr-99	23020	6.51	577
8-Jun-99	23997	14.35	609
7-Sep-99	24333	20.21	619
3-Nov-99	24701	23.1	571
5-Jan-00	24861	13.92	495
4-Apr-00	24212	14.28	485

Table A.23: Sampling Location LM8M

Date	Lake Storage	Perchlorate (ppb)	TDS (ppm)
9-Sep-91	19230	6.21	N/A
13-Jul-92	19340	31.34	N/A
13-Sep-93	21390	13.69	N/A
8-Nov-93	21214	4	N/A
3-Jan-94	21348	9.61	N/A
5-Apr-94	21214	7.74	N/A
5-Jul-94	20059	10.71	N/A
1-May-95	20081	2.49	N/A
5-Jun-95	19942	12.5	714
10-Jul-95	20092	12.58	700
7-Aug-95	20267	2.19	693
5-Sep-95	20407	19.27	710
2-Oct-95	20743	4.77	627
11-Dec-95	21528	19.66	693
5-Feb-96	22012	11.98	675
1-Apr-96	22069	13.3	664
9-Sep-96	21508	8.81	598
8-Apr-97	22854	11.47	625
8-Jul-97	23349	18.61	619
2-Sep-97	23555	24.55	631
2-Dec-97	24834	32.71	625
7-Apr-98	25021	11.22	619
7-Jul-98	24630	9.68	563
6-Apr-99	24020	8.31	566
8-Jun-99	23997	16.68	545
7-Sep-99	24333	19.75	589
5-Jan-00	24861	15.98	510
4-Apr-00	24212	12.27	558

Table A.24: Sampling Location LM8H

Date	Lake Storage	Perchlorate (ppb)	TDS (ppm)
26-Feb-91	20141	3.9	N/A
3-Jun-91	19444	7.45	N/A
6-Jan-92	19877	0	N/A
2-Aug-93	21280	9.0	N/A
6-Dec-93	21320	5.0	N/A
6-Sep-94	19901	5.05	702
7-Nov-94	19777	0	693
5-Jun-95	20000	13.7	714
10-Jul-95	20246	10.4	678
4-Aug-95	20350	8.5	690
5-Feb-96	22012	12.3	667
1-Apr-96	22069	9.11	661
9-Sep-96	21508	3.45	633
8-Apr-97	22854	7.43	602
8-Jul-97	23349	18.15	596
2-Sep-97	23555	20.57	606
2-Dec-97	24834	22.59	635
10-Feb-98	25006	11.09	582
7-Apr-98	25021	24.45	618
7-Jul-98	24630	7.76	595
3-Nov-98	25268	19.37	579
7-Sep-99	24333	25.44	606
5-Jan-00	24861	4.59	418
4-Apr-00	24212	5.03	500

Table A.25: Sampling Location LM9H

Date	Lake Storage	Perchlorate (ppb)	TDS (ppm)
3-Jun-91	19444	5.62	N/A
2-Dec-91	19286	6.14	N/A
1-May-95	20081	11.01	680
10-Jul-95	20092	14.04	698
6-Nov-95	21028	19.52	637
9-Sep-96	21508	6.51	635
8-Jul-97	23349	12.33	627
2-Sep-97	23555	10.45	604
7-Jul-98	24630	25.47	602
3-Nov-98	25268	5.64	537
5-Jan-00	24861	6.11	542

APPENDIX B

STATISTICAL ANALYSES OF PERCHLORATE DATA

B.1 Comparison of perchlorate levels between LVW5 and LVW3K:

Paired T-Test and Confidence Interval : Data include all years

Paired T for lvw3k - lvw5

	N	Mean	StDev	SE Mean
lvw3k	21	979.1	274.7	59.9
lvw5	21	797.8	212.9	46.5
Difference	21	181.3	337.7	73.7

95% CI for mean difference: (27.5, 335.0)
T-Test of mean difference = 0 (vs > 0): T-Value = 2.46 P-Value = 0.012

Paired T-Test and Confidence Interval : Data before 1995

Paired T for LVW5-P - LVW3K-P

	N	Mean	StDev	SE Mean
LVW5-P	15	526.4	185.8	48.0
LVW3K-P	15	556.0	132.4	34.2
Difference	15	-29.6	234.7	60.6

95% CI for mean difference: (-159.5, 100.4)
T-Test of mean difference = 0 (vs < 0): T-Value = -0.49 P-Value = 0.316

Paired T-Test and Confidence Interval: Data from 1995

Paired T for LVW5-A - LVW3K-Dep

	N	Mean	StDev	SE Mean
LVW5-A	20	780.7	206.0	46.1
LVW3K-De	20	921.8	206.8	46.2
Difference	20	-141.1	282.4	63.2

95% CI for mean difference: (-273.3, -8.9)
T-Test of mean difference = 0 (vs < 0): T-Value = -2.23 P-Value = 0.019

B.2 Comparison of perchlorate levels before and from 1995, for sampling locations LVW5 and LVW3K:

```
Sampling Location : LVW3K

Two sample T for LVW3K-P vs LVW3K-A

           N      Mean     StDev   SE Mean
LVW3K-P   18       569       125        30
LVW3K-A   68       868       253        31

95% CI for mu LVW3K-P - mu LVW3K-A: ( -384,  -213)
T-Test mu LVW3K-P = mu LVW3K-A (vs <): T = -7.01  P = 0.0000  DF = 56
```

```
Sampling Location : LVW5

Two sample T for LVW5-P vs LVW5-A

          N      Mean     StDev   SE Mean
LVW5-P   15       526       186        48
LVW5-A   22       800       208        44

95% CI for mu LVW5-P - mu LVW5-A: ( -407,  -141)
T-Test mu LVW5-P = mu LVW5-A (vs <): T = -4.19  P = 0.0001  DF = 32
```

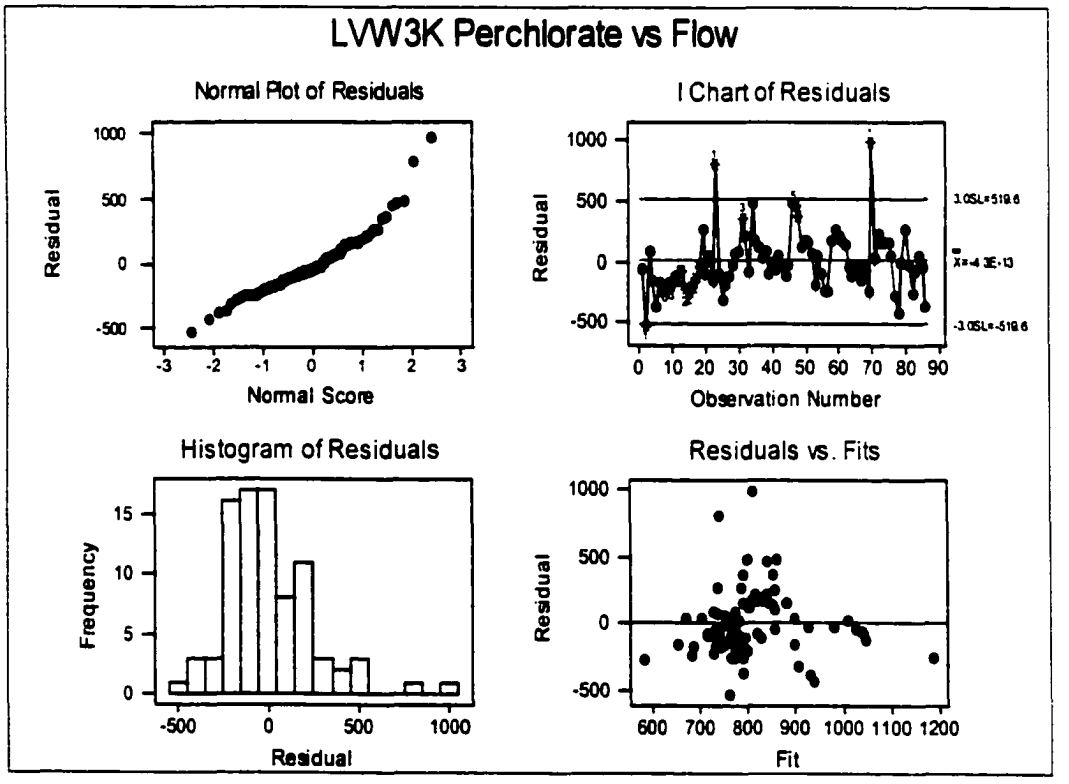
B.3 Correlation of Wash perchlorate concentrations with flow data:

Regression Analysis: LVW3K Perchlorate vs Wash Flow

The regression equation is
Perchlorate = 253 + 2.69 Flow

Predictor	Coef	StDev	T	P
Constant	253.3	153.2	1.65	0.102
Flow	2.6888	0.7354	3.66	0.000

S = 244.3 R-Sq = 13.7% R-Sq(adj) = 12.7%

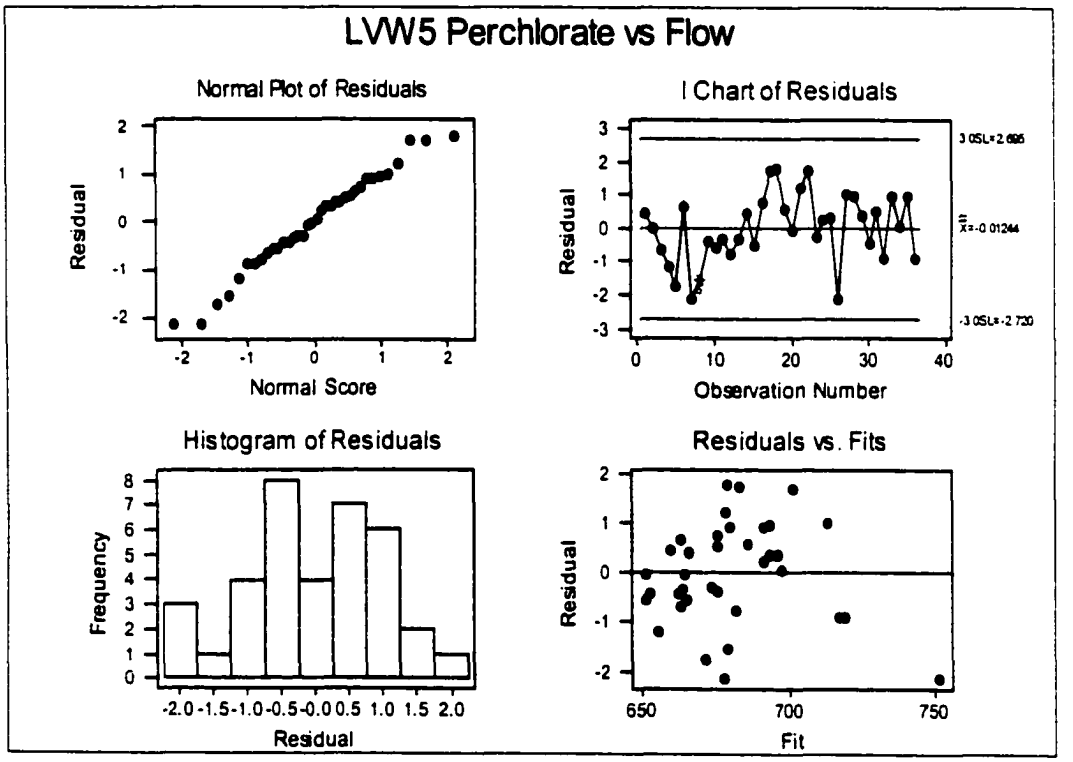


Regression Analysis: LVW5 Perchlorate vs Wash Flow

The regression equation is
Perchlorate = 535 + 0.72 Flow

Predictor	Coef	StDev	T	P
Constant	535.3	276.1	1.94	0.061
Flow	0.722	1.359	0.53	0.599

S = 239.0 R-Sq = 0.8% R-Sq(adj) = 0.0%



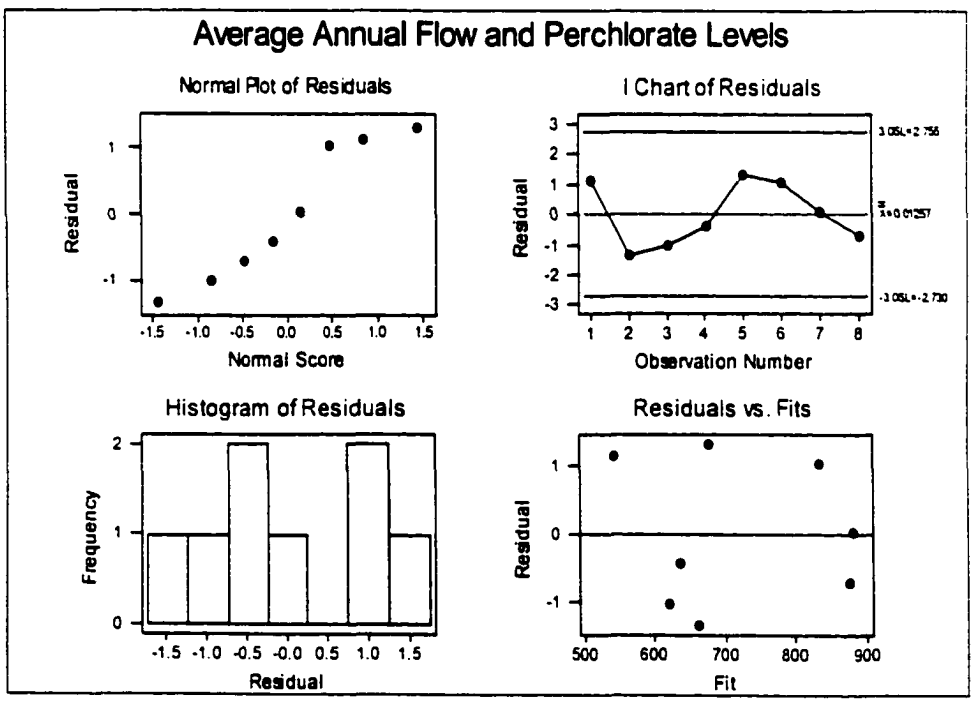
B.4 Correlation of Wash average annual perchlorate concentrations with average annual flow data:

Regression Analysis: Average Annual Flow vs Average Annual Perchlorate

The regression equation is
Perchlorate = - 340 + 5.19 Flow

Predictor	Coef	StDev	T	P
Constant	-339.9	367.1	-0.93	0.390
Flow	5.189	1.793	2.89	0.028

S = 117.6 R-Sq = 58.2% R-Sq(adj) = 51.3%



4.5. Comparison of perchlorate data for high-flow and typical-flow dates:

Paired T-Test and Confidence Interval : Perchlorate Concentration

Paired T for High-flow - Reg-flow

	N	Mean	StDev	SE Mean
High-flo	11	947	373	113
Reg-flow	11	921	187	56
Difference	11	26	411	124

95% CI for mean difference: (-249, 302)
T-Test of mean difference = 0 (vs > 0): T-Value = 0.21 P-Value = 0.418

Paired T-Test and Confidence Interval : Perchlorate Loading

Paired T for high-flow - reg-flow

	N	Mean	StDev	SE Mean
High-flow	11	718	578	174
Reg-flow	11	447	107	32
Difference	11	271	566	171

95% CI for mean difference: (-109, 652)
T-Test of mean difference = 0 (vs > 0): T-Value = 1.59 P-Value = 0.072

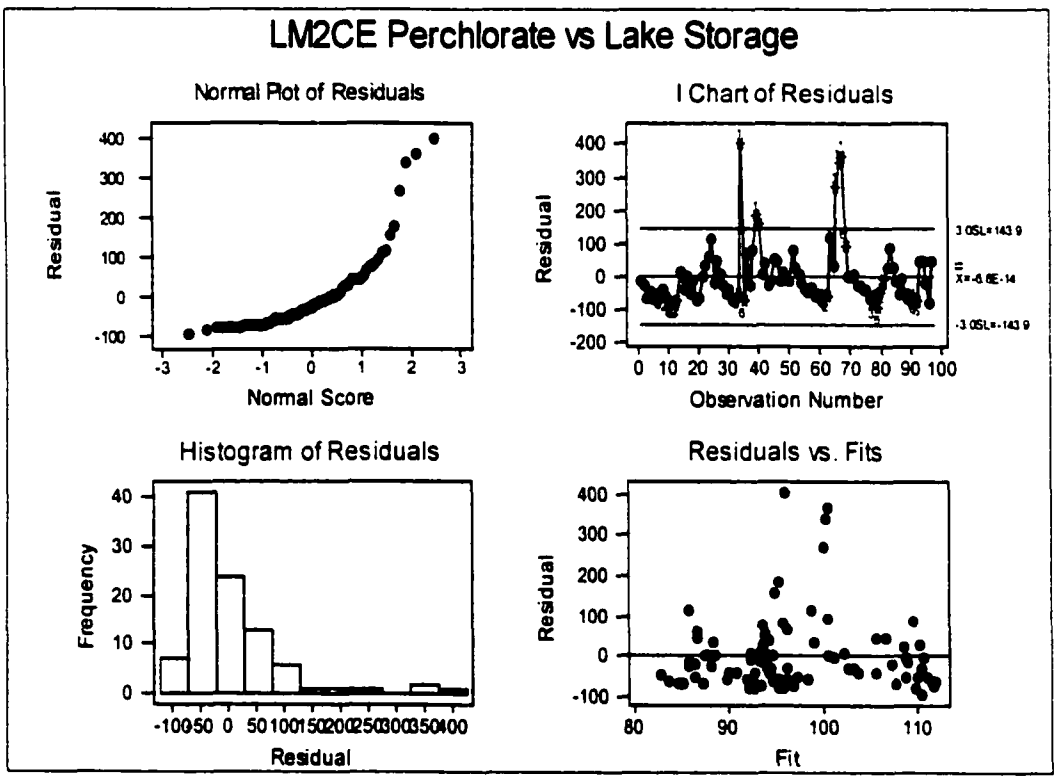
4.6 Correlation of Lake perchlorate concentrations with storage data:

Regression Analysis: LM2CE Perhchlorate vs Lake Storage

The regression equation is
Perchlorate = - 11 + 0.00486 Storage

Predictor	Coef	StDev	T	P
Constant	-11.0	125.8	-0.09	0.930
Storage	0.004862	0.005638	0.86	0.391

S = 91.83 R-Sq = 0.8% R-Sq(adj) = 0.0%

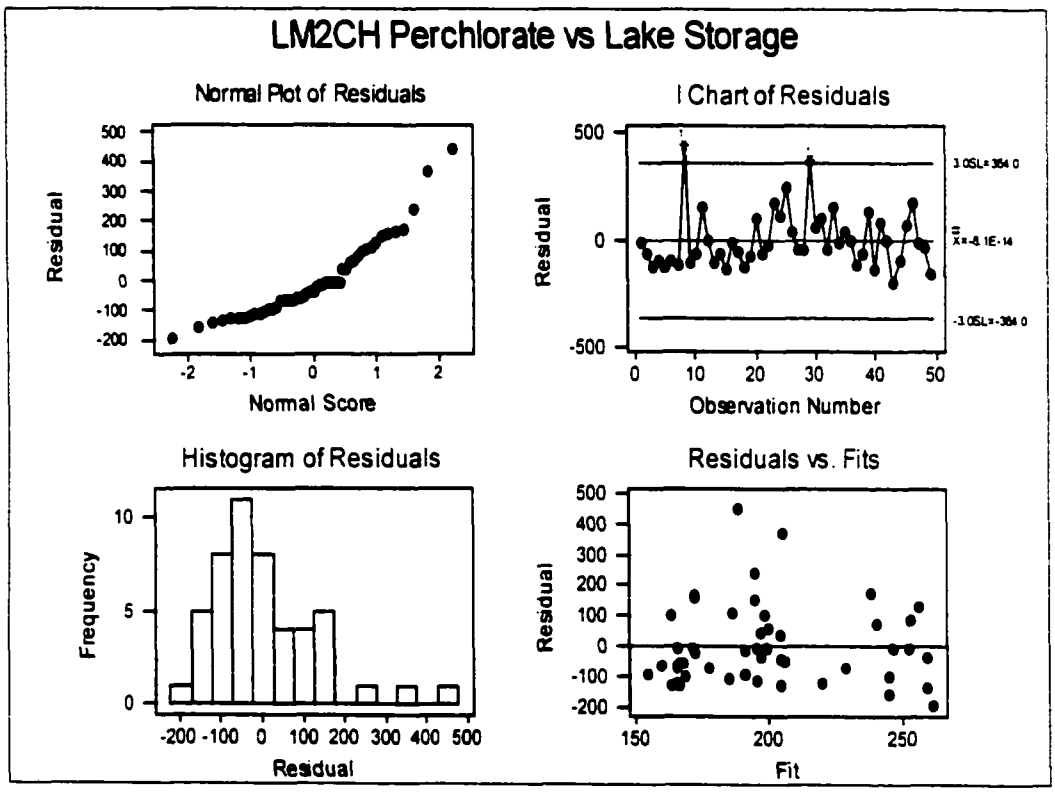


Regression Analysis LM2CH

The regression equation is
Perchlorate = - 197 + 0.0182 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-196.6	239.1	-0.82	0.415
Lake Sto	0.01821	0.01096	1.66	0.103

S = 133.8 R-Sq = 5.5% R-Sq(adj) = 3.5%

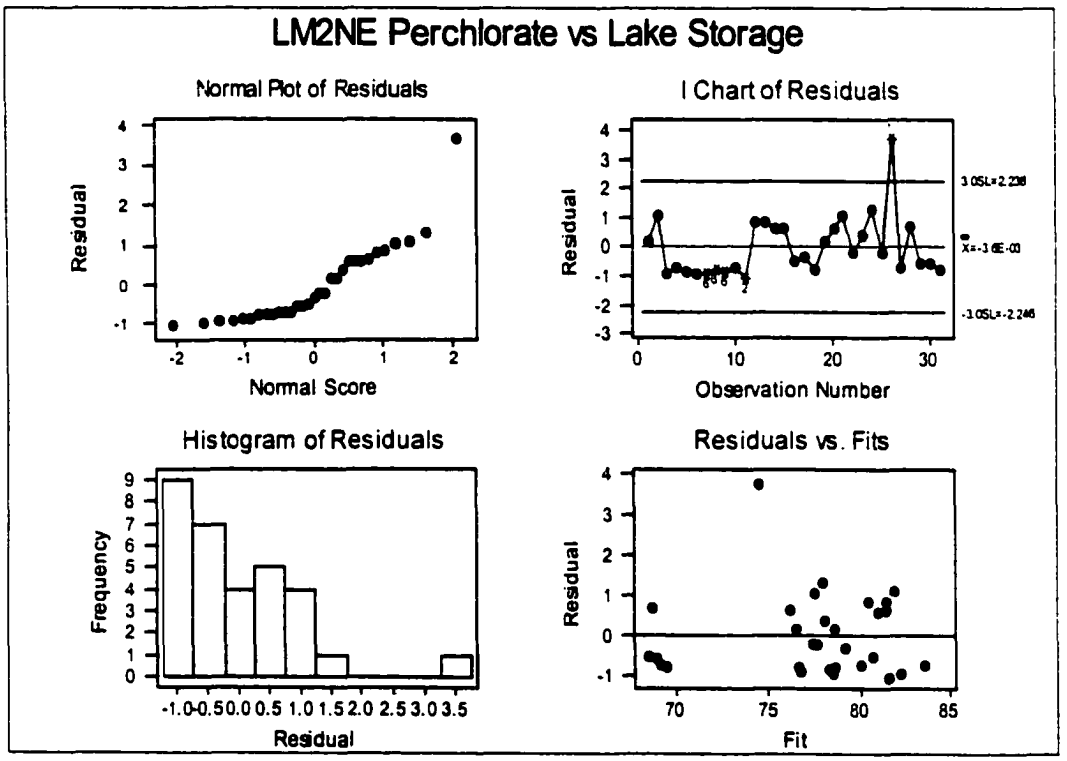


Regression Analysis: LM2NE

The regression equation is
Perchlorate = 132 - 0.00251 Lake Storage

Predictor	Coef	StDev	T	P
Constant	132.0	159.6	0.83	0.415
Lake Sto	-0.002514	0.007329	-0.34	0.734

S = 68.65 R-Sq = 0.4% R-Sq(adj) = 0.0%

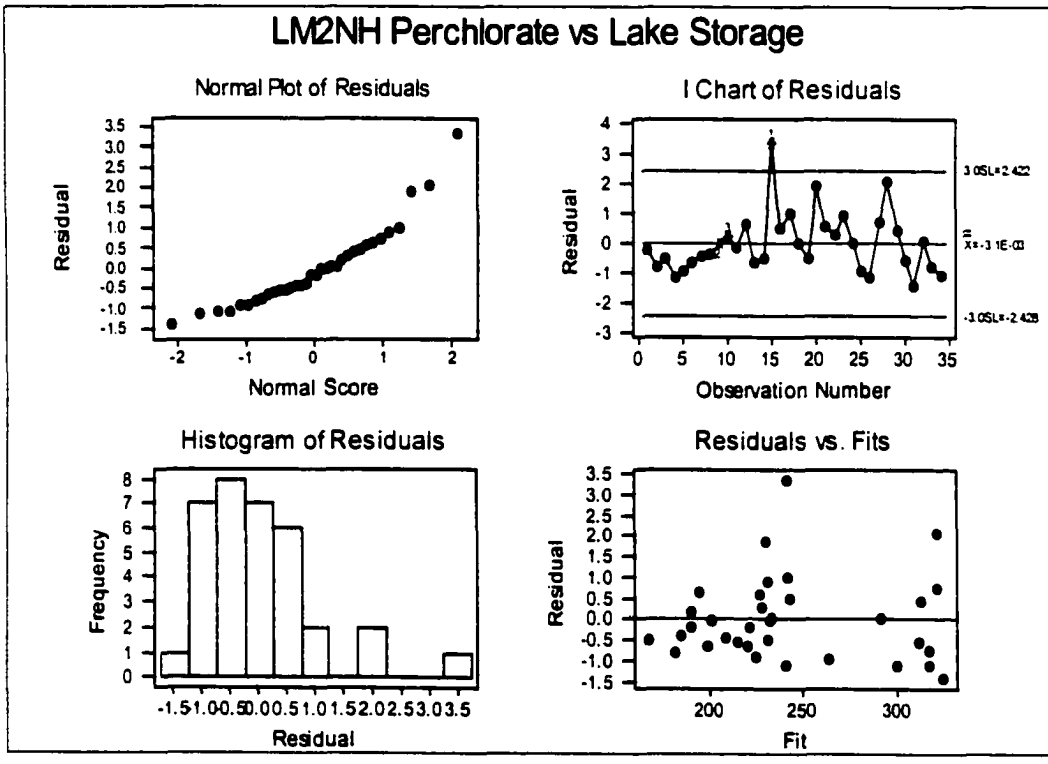


Regression Analysis : LM2NH

The regression equation is
Perchlorate = - 352 + 0.0270 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-352.1	441.0	-0.80	0.431
Lake Sto	0.02695	0.01992	1.35	0.186

S = 203.5 R-Sq = 5.4% R-Sq(adj) = 2.5%

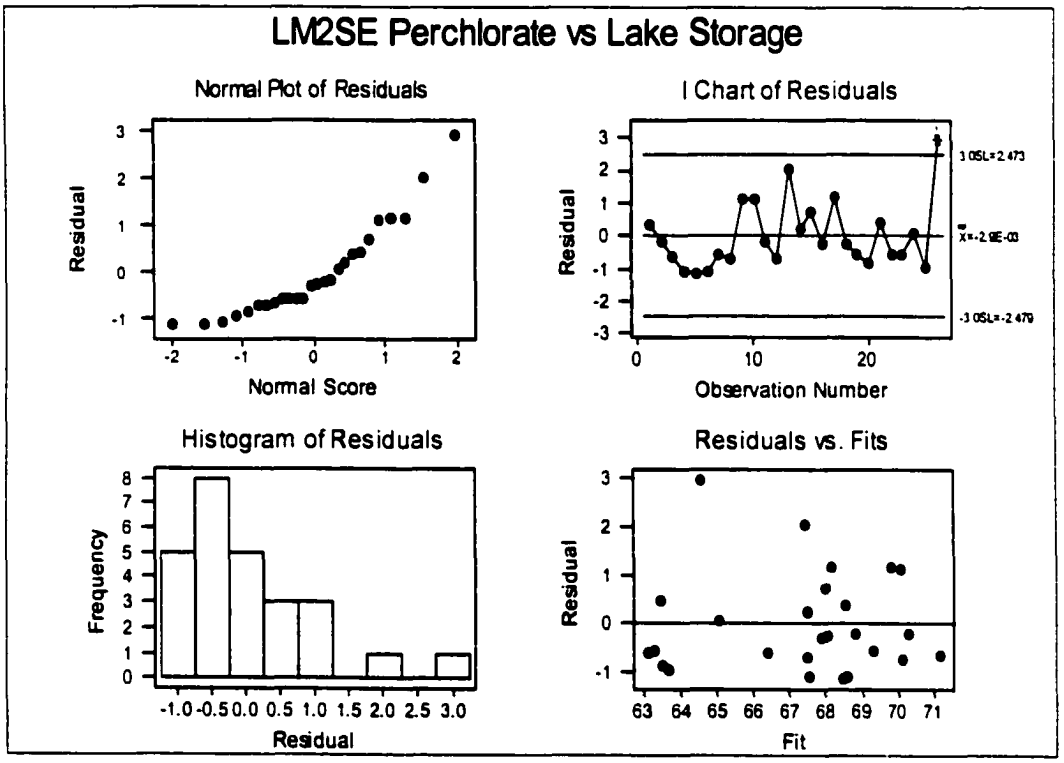


Regression Analysis: LM2SE

The regression equation is
Perchlorate = 97 - 0.00134 Lake Storage

Predictor	Coef	StDev	T	P
Constant	97.0	127.6	0.76	0.455
Lake Sto	-0.001340	0.005743	-0.23	0.817

S = 52.32 R-Sq = 0.2% R-Sq(adj) = 0.0%

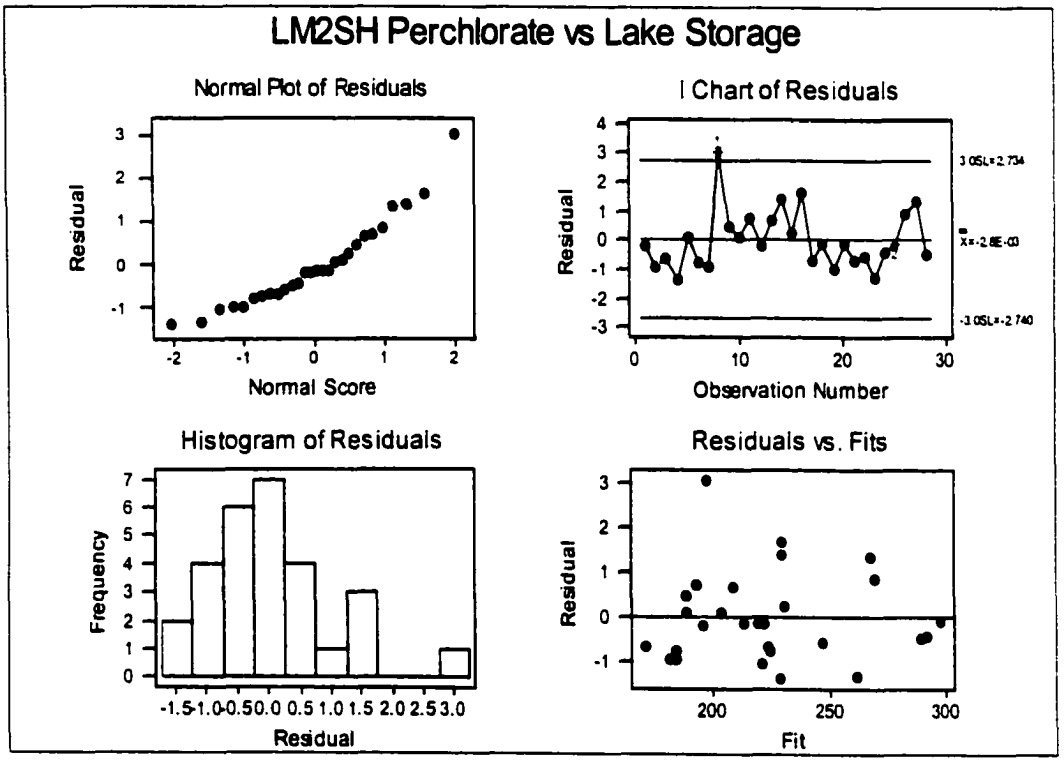


Regression Analysis: LM2SH

The regression equation is
Perchlorate = - 233 + 0.0210 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-232.5	379.5	-0.61	0.545
Lake Sto	0.02097	0.01740	1.21	0.239

S = 152.3 R-Sq = 5.3% R-Sq(adj) = 1.6%

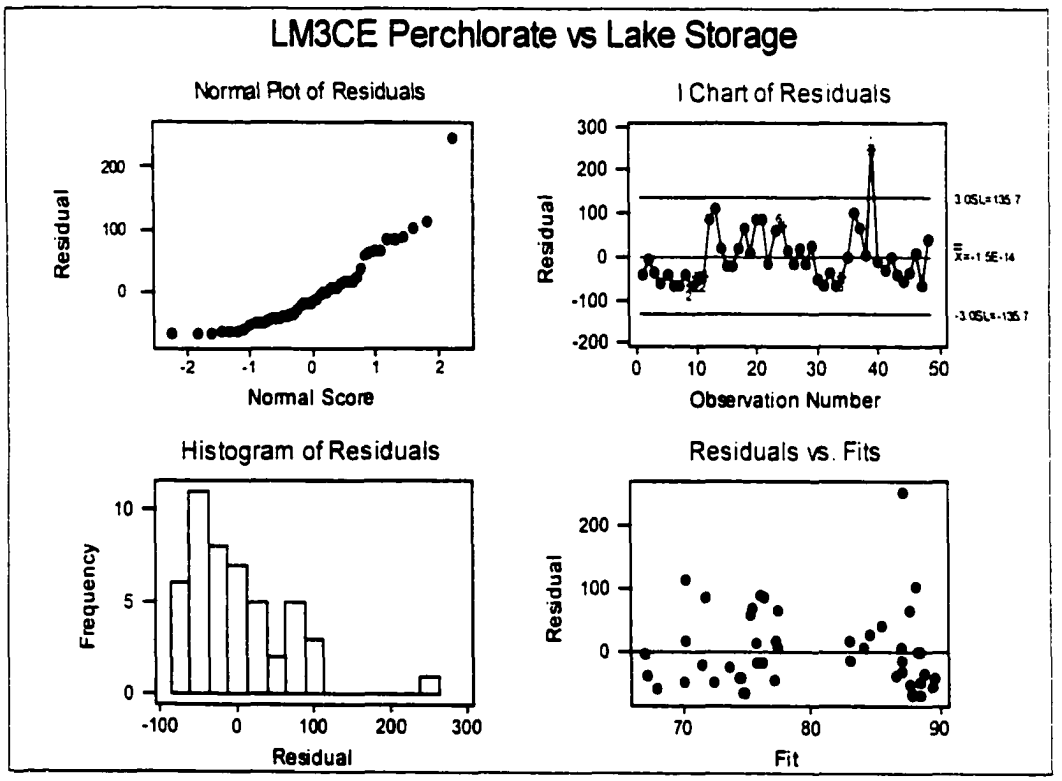


Regression Analysis LM3CE

The regression equation is
Perchlorate = - 5 + 0.00372 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-4.6	107.6	-0.04	0.966
Lake Sto	0.003719	0.004724	0.79	0.435

S = 63.59 R-Sq = 1.3% R-Sq(adj) = 0.0%

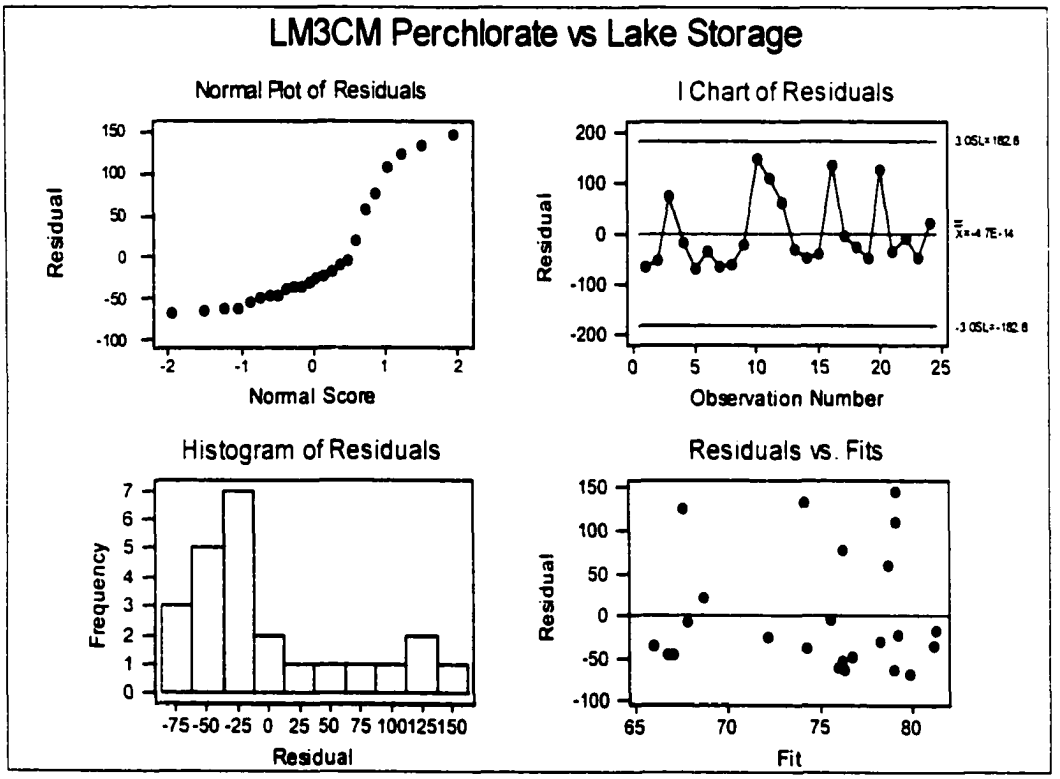


Regression Analysis LM3CM

The regression equation is
Perchlorate = 130 - 0.00253 Lake Storage

Predictor	Coef	StDev	T	P
Constant	130.0	163.6	0.79	0.435
Lake Sto	-0.002533	0.007489	-0.34	0.738

S = 70.67 R-Sq = 0.5% R-Sq(adj) = 0.0%

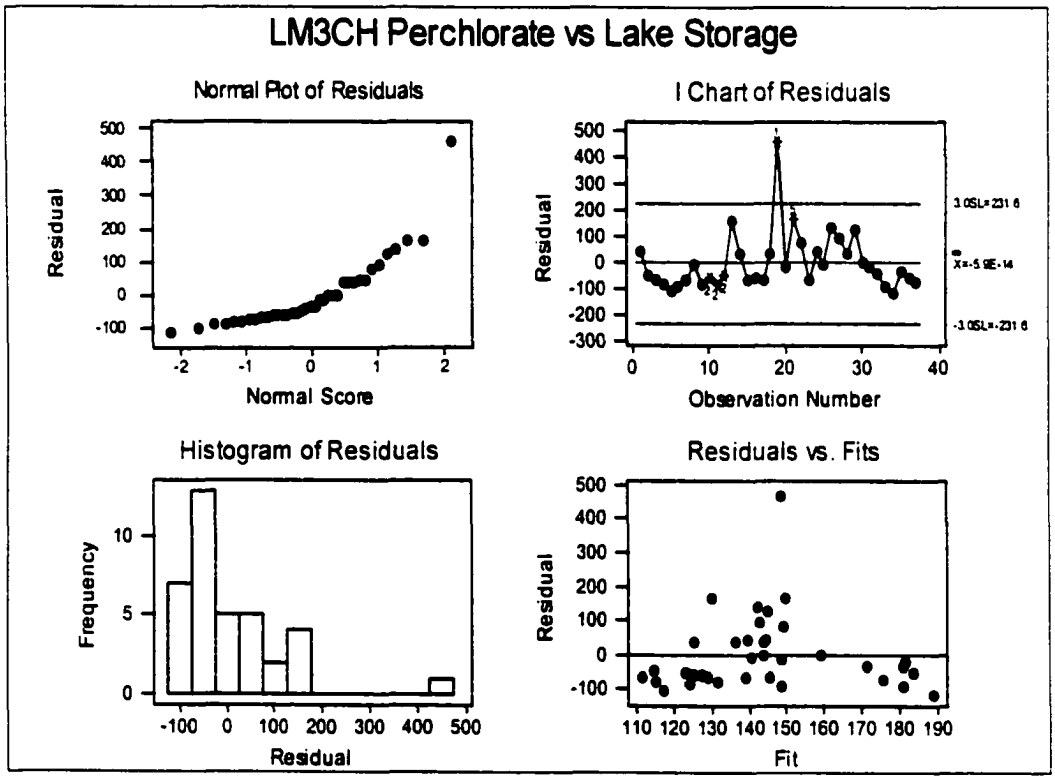


Regression Analysis : LM3CH

The regression equation is
Perchlorate = - 122 + 0.0123 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-121.7	233.6	-0.52	0.606
Lake Sto	0.01229	0.01077	1.14	0.262

S = 111.4 R-Sq = 3.6% R-Sq(adj) = 0.8%

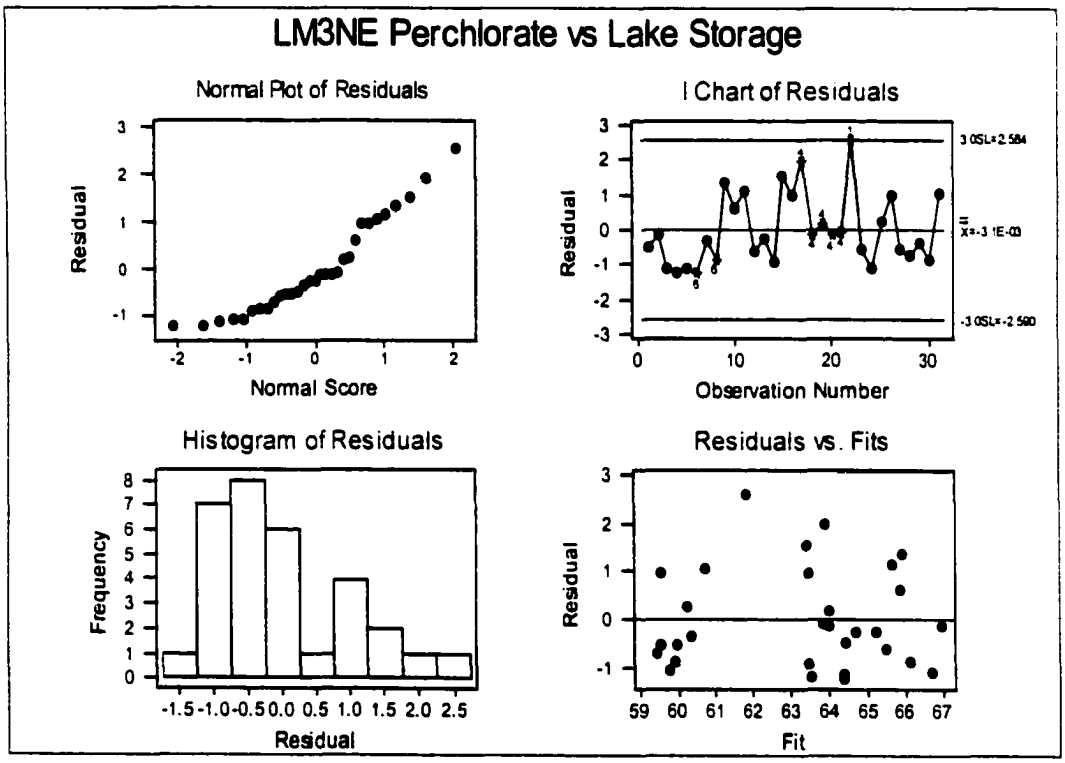


Regression Analysis : LM3NE

The regression equation is
Perchlorate = 90.9 - 0.00125 Lake Storage

Predictor	Coef	StDev	T	P
Constant	90.92	95.09	0.96	0.347
Lake Sto	-0.001247	0.004268	-0.29	0.772

S = 45.05 R-Sq = 0.3% R-Sq(adj) = 0.0%

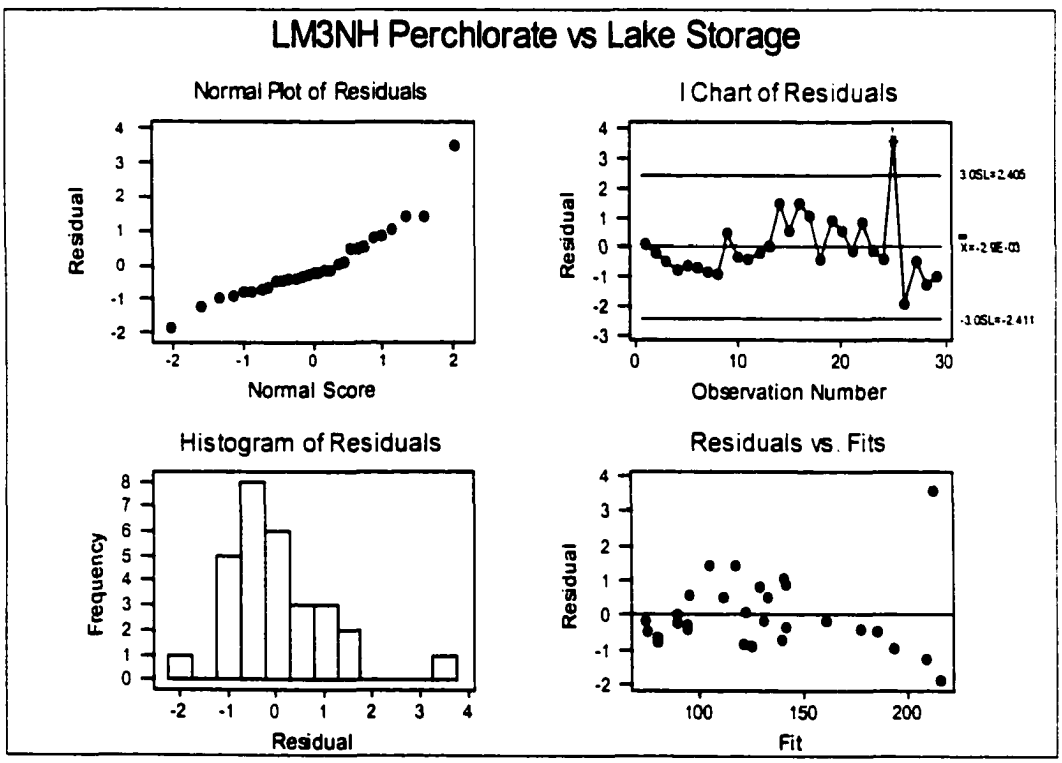


Regression Analysis: LM3NH

The regression equation is
Perchlorate = - 386 + 0.0239 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-385.8	220.2	-1.75	0.091
Lake Sto	0.02391	0.01017	2.35	0.026

S = 95.62 R-Sq = 17.0% R-Sq(adj) = 13.9%

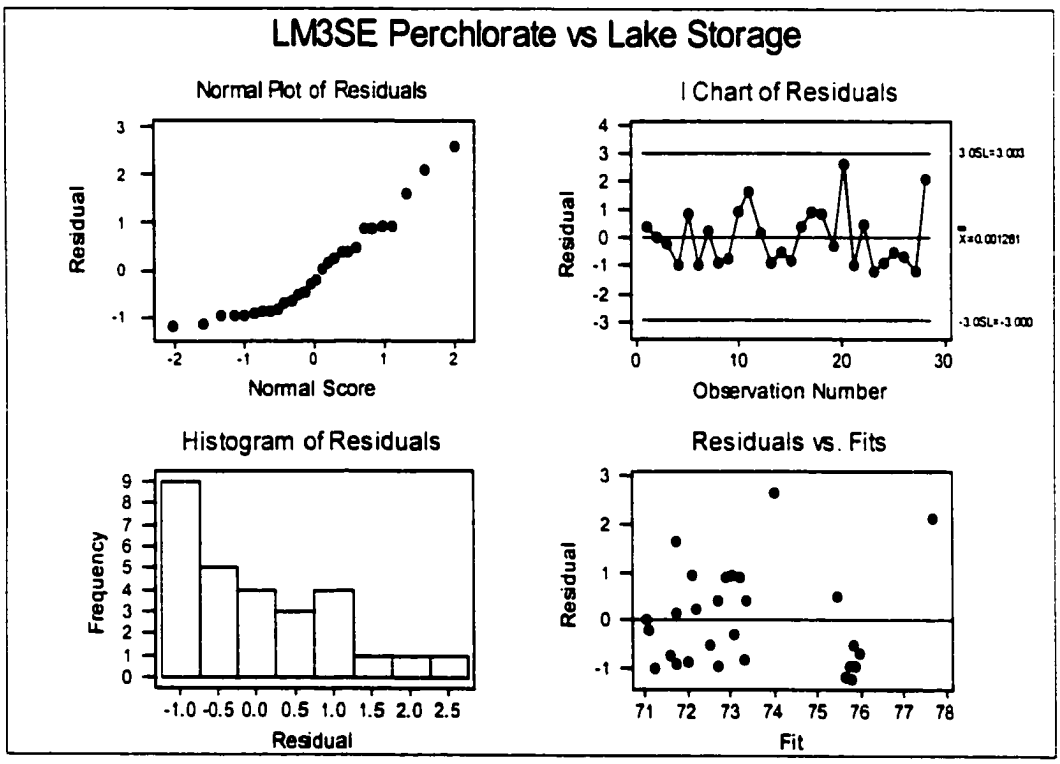


Regression Analysis : LM3SE

The regression equation is
Perchlorate = 55 + 0.00081 Lake Storage

Predictor	Coef	StDev	T	P
Constant	55.4	114.5	0.48	0.633
Lake Sto	0.000814	0.005151	0.16	0.876

S = 60.83 R-Sq = 0.1% R-Sq(adj) = 0.0%

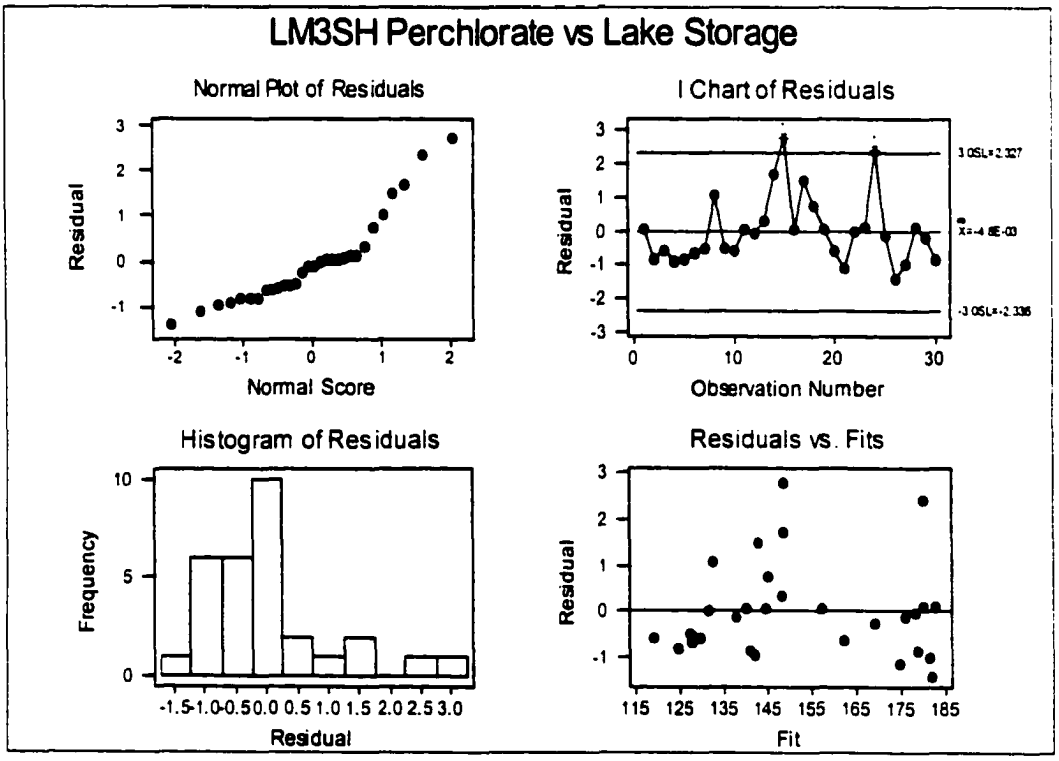


Regression Analysis : LM3SH

The regression equation is
Perchlorate = - 86 + 0.0106 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-85.6	246.3	-0.35	0.731
Lake Sto	0.01062	0.01097	0.97	0.341

S = 117.4 R-Sq = 3.2% R-Sq(adj) = 0.0%

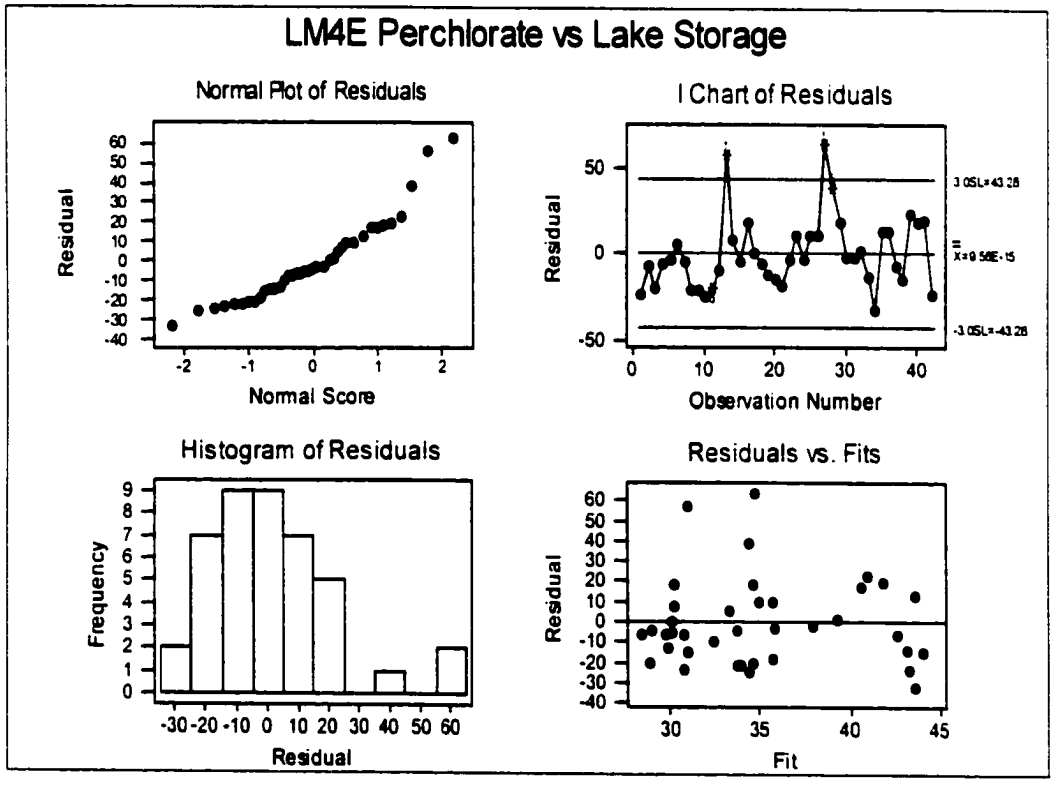


Regression Analysis : LM4E

The regression equation is
Perchlorate = - 22.4 + 0.00264 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-22.39	38.74	-0.58	0.567
Lake Sto	0.002638	0.001763	1.50	0.142

S = 20.99 R-Sq = 5.3% R-Sq(adj) = 2.9%

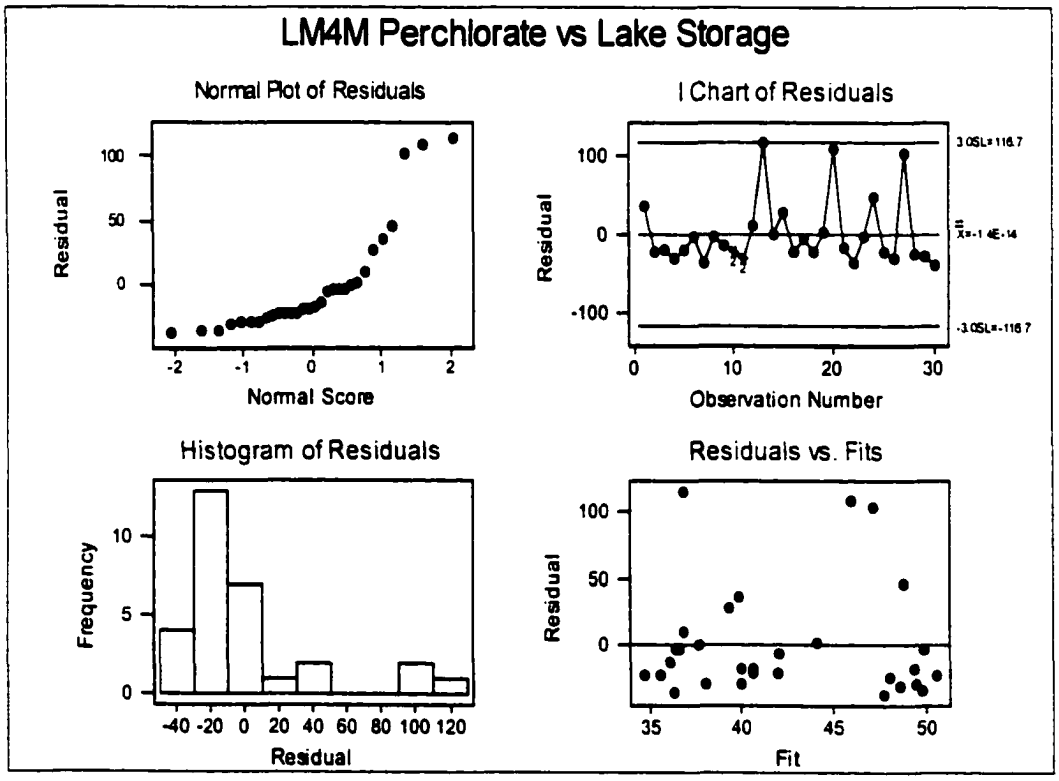


Regression Analysis LM4M

The regression equation is
Perchlorate = - 16.1 + 0.00263 lake storage

Predictor	Coef	StDev	T	P
Constant	-16.05	87.25	-0.18	0.855
Lake Sto	0.002632	0.003922	0.67	0.508

S = 43.19 R-Sq = 1.6% R-Sq(adj) = 0.0%

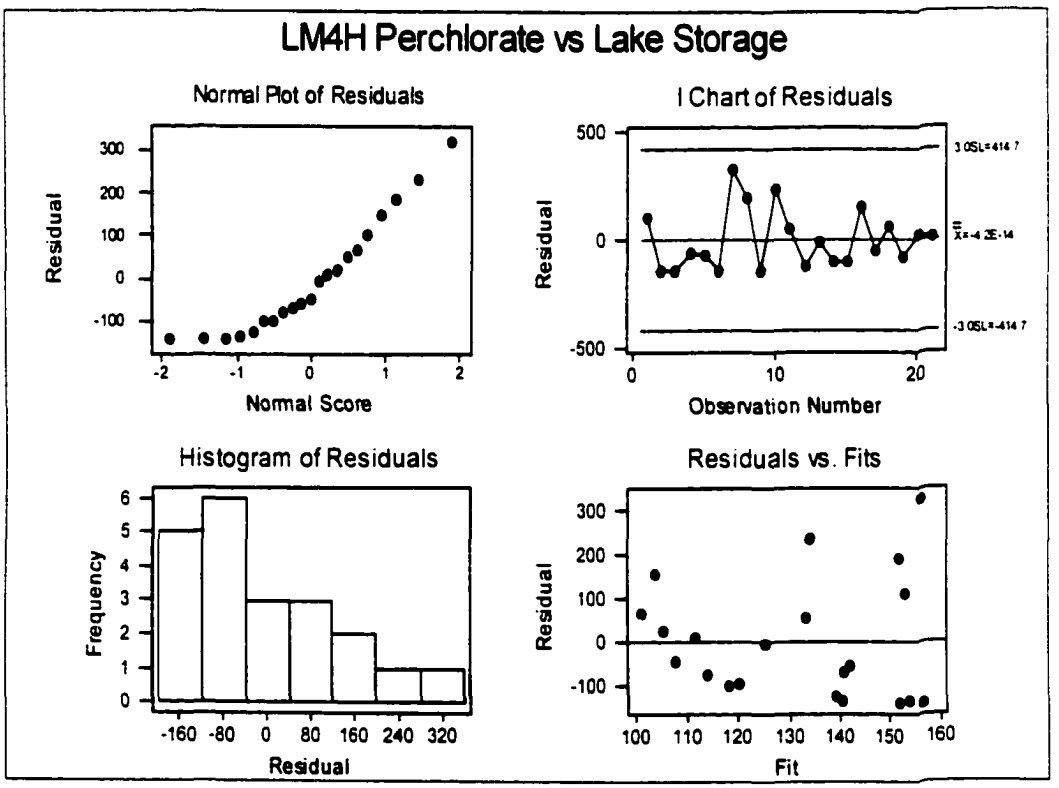


Regression Analysis : LM4H

The regression equation is
perchlorate = 356 - 0.0101 lake storage

Predictor	Coef	StDev	T	P
Constant	356.3	367.6	0.97	0.345
Lake Sto	-0.01010	0.01646	-0.61	0.546

S = 139.6 R-Sq = 1.9% R-Sq(adj) = 0.0%

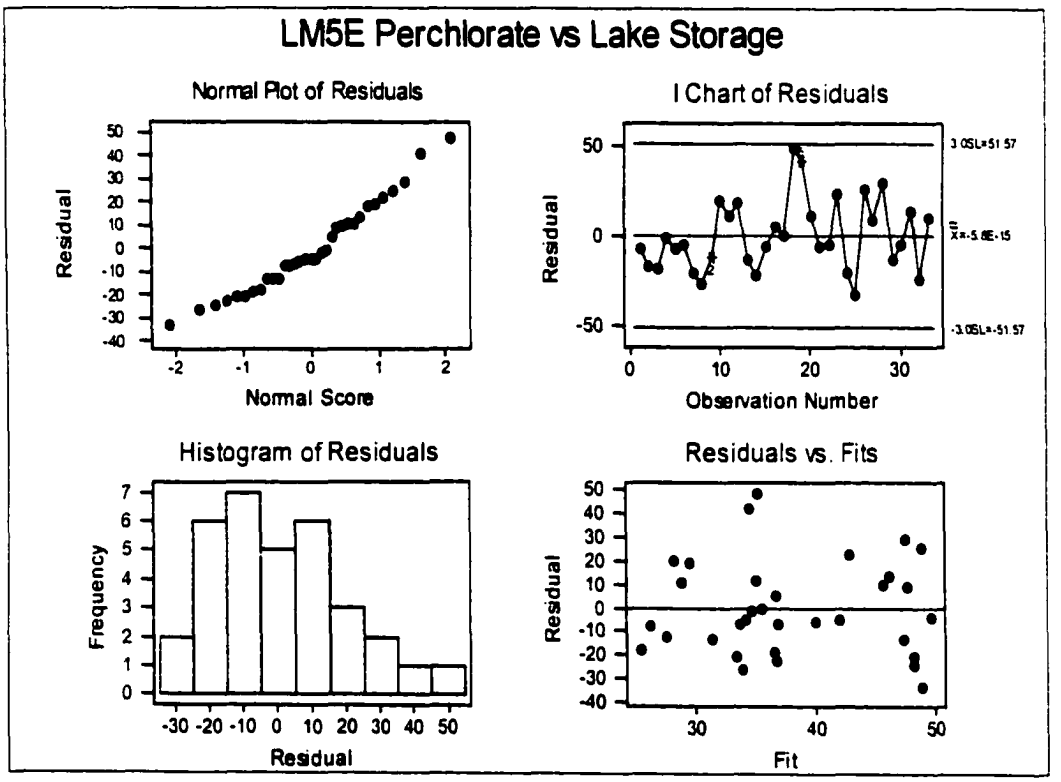


Regression Analysis : LM5E

The regression equation is
Perchlorate = - 53.5 + 0.00409 lake storage

Predictor	Coef	StDev	T	P
Constant	-53.50	43.21	-1.24	0.225
Lake Sto	0.004089	0.001925	2.12	0.042

S = 20.26 R-Sq = 12.7% R-Sq(adj) = 9.9%

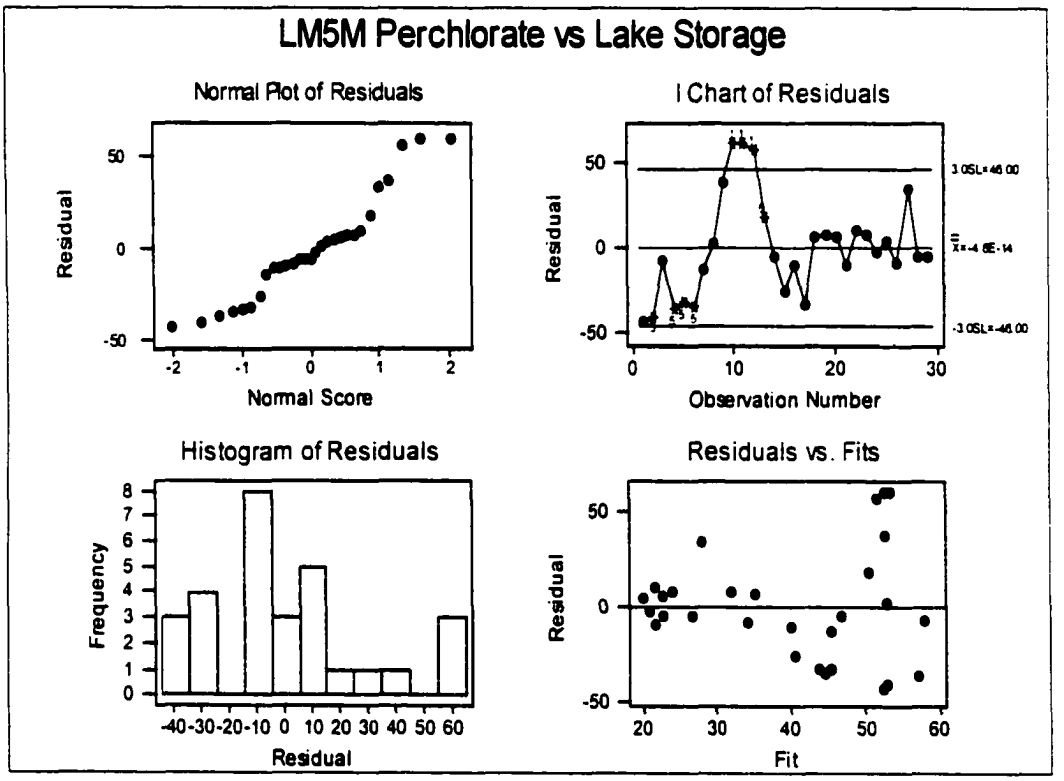


Regression Analysis: LM5M

The regression equation is
Perchlorate = 178 - 0.00625 lake storage

Predictor	Coef	StDev	T	P
Constant	178.12	59.80	2.98	0.006
Lake Sto	-0.006253	0.002689	-2.33	0.028

S = 29.40 R-Sq = 16.7% R-Sq(adj) = 13.6%

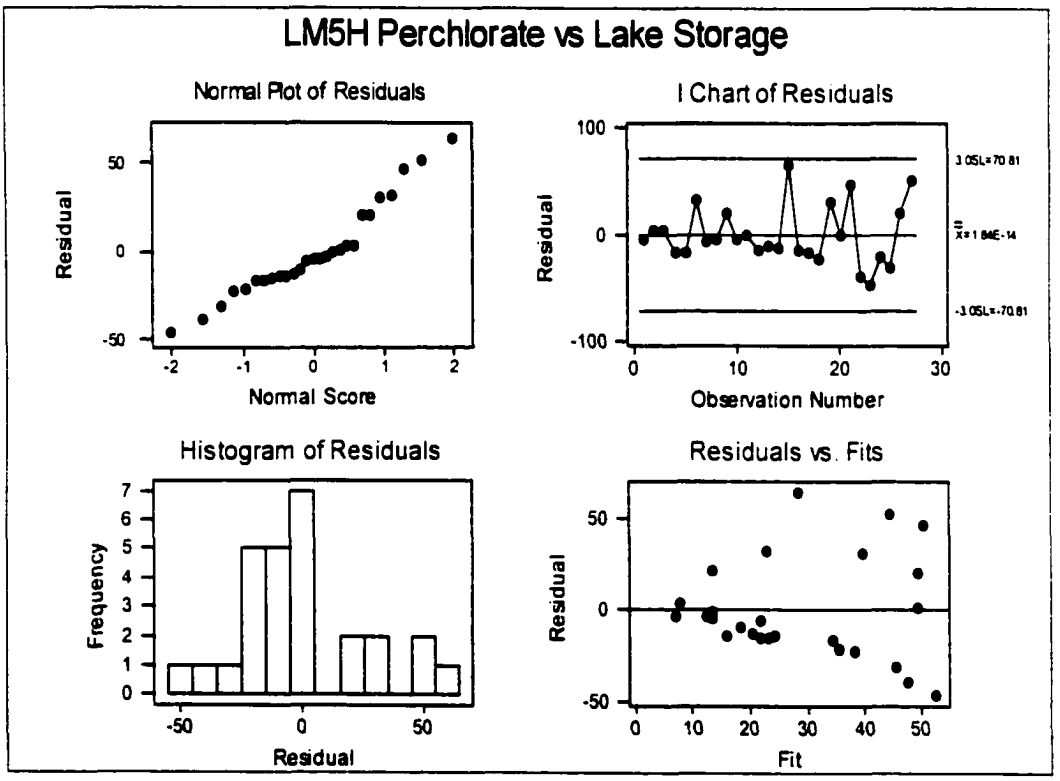


Regression Analysis: LM5H

The regression equation is
Perchlorate = - 138 + 0.00755 lake storage

Predictor	Coef	StDev	T	P
Constant	-138.45	59.92	-2.31	0.029
Lake Sto	0.007555	0.002709	2.79	0.010

S = 27.57 R-Sq = 23.7% R-Sq(adj) = 20.7%

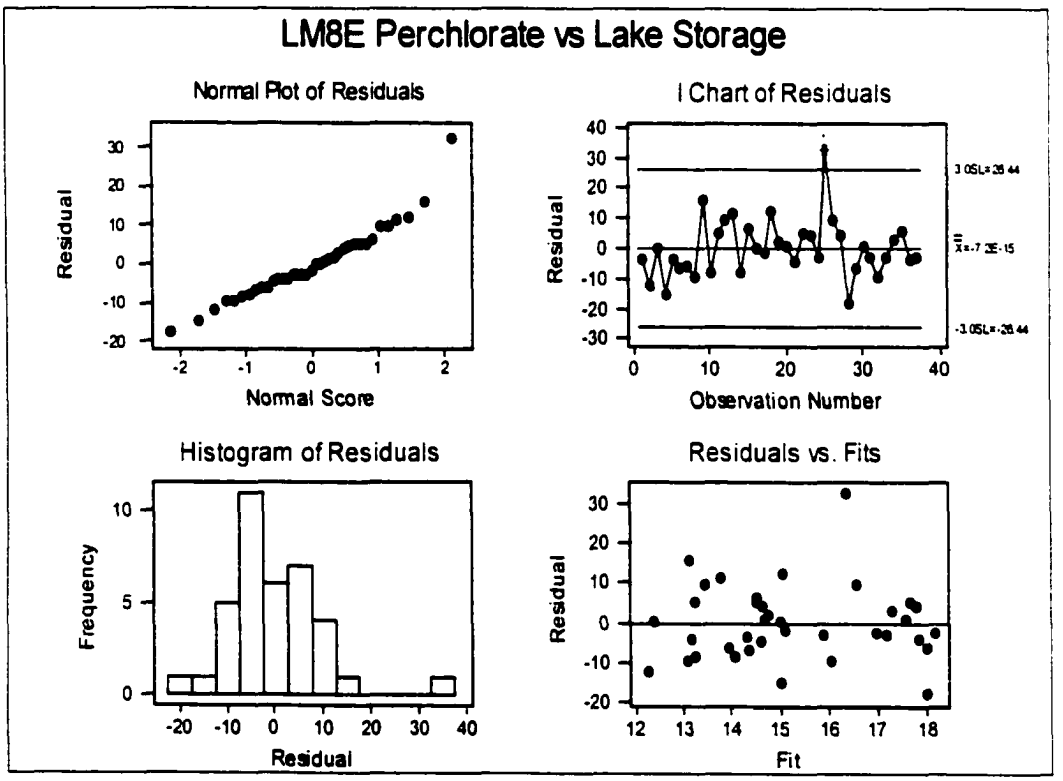


Regression Analysis : LM8E

The regression equation is
Perchlorate = - 6.8 +0.000990 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-6.78	19.75	-0.34	0.734
Lake Sto	0.0009898	0.0008860	1.12	0.272

S = 9.597 R-Sq = 3.4% R-Sq(adj) = 0.7%

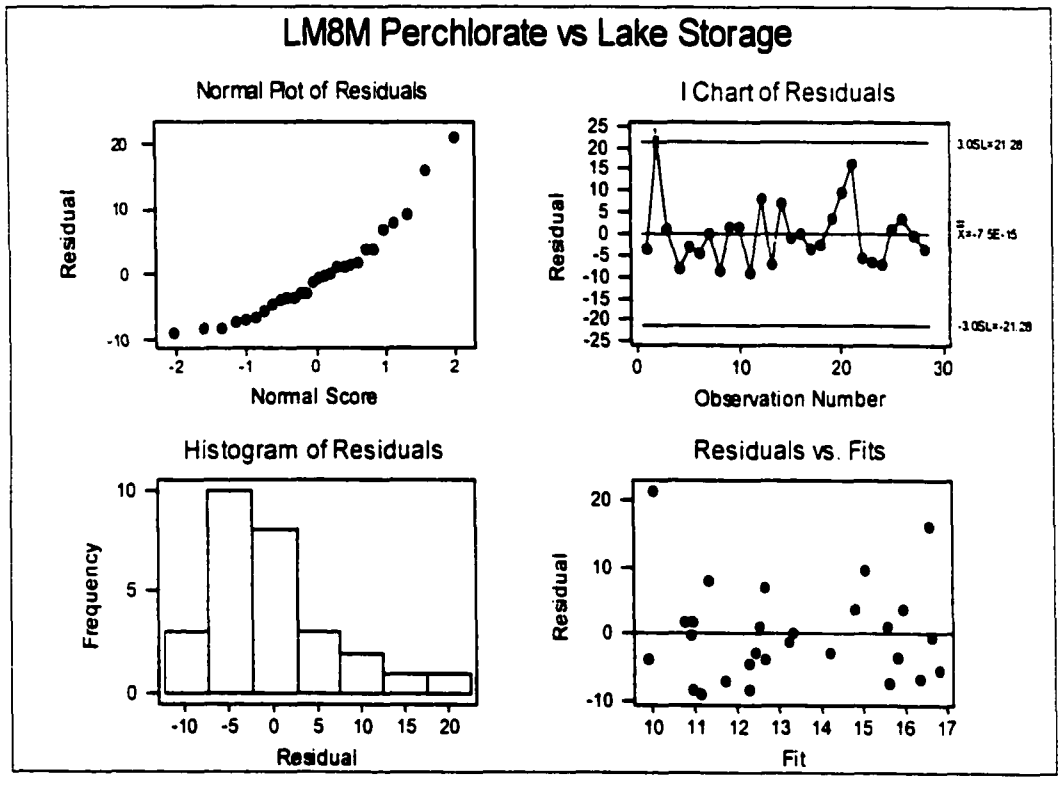


Regression Analysis : LM8M

The regression equation is
Perchlorate = - 13.0 + 0.00119 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-13.01	16.84	-0.77	0.447
Lake Sto	0.0011913	0.0007600	1.57	0.129

S = 7.414 R-Sq = 8.6% R-Sq(adj) = 5.1%

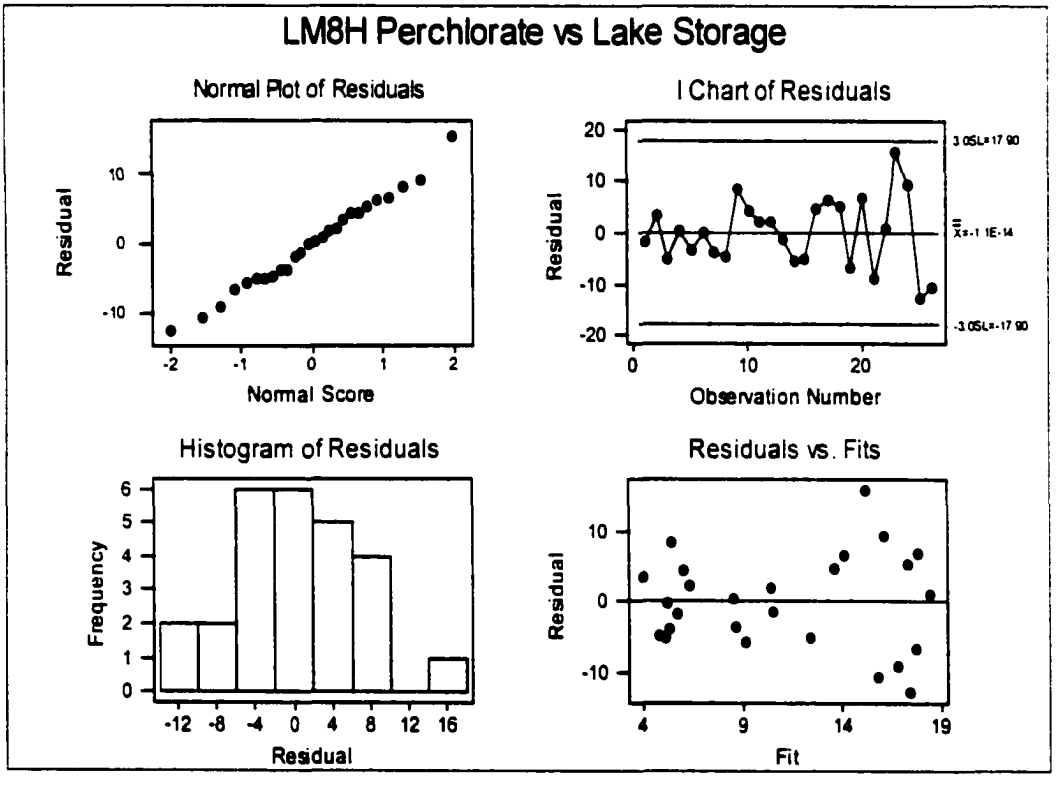


Regression Analysis : LM8H

The regression equation is
Perhclorate = - 44.1 + 0.00247 Lake Storage

Predictor	Coef	StDev	T	P
Constant	-44.06	14.73	-2.99	0.006
Lake Sto	0.0024703	0.0006579	3.75	0.001

S = 6.838 R-Sq = 37.0% R-Sq(adj) = 34.4%

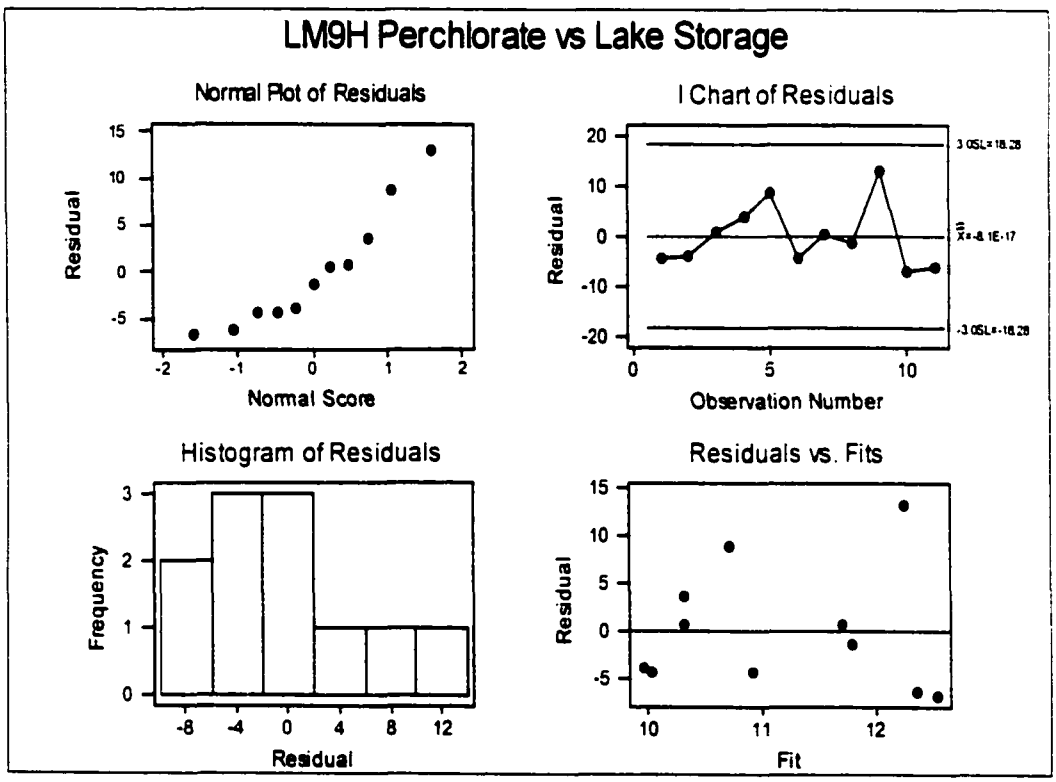


Regression Analysis : LM9H

The regression equation is
Perchlorate = 1.7 +0.000427 Lake Storage

Predictor	Coef	StDev	T	P
Constant	1.72	20.69	0.08	0.935
Lake Sto	0.0004273	0.0009318	0.46	0.657

S = 6.740 R-Sq = 2.3% R-Sq(adj) = 0.0%



B.7 Comparison of perchlorate data for stratified and non-stratified periods:

Paired T-Test and Confidence Interval : Epilimnion-Initial Mixing Zone

Paired T for stratified - non-stratifid

	N	Mean	StDev	SE Mean
stratifi	79	110.93	73.04	8.22
non-stra	79	55.50	67.74	7.62
Difference	79	55.4	94.7	10.6

95% CI for mean difference: (34.2, 76.6)
T-Test of mean difference = 0 (vs > 0): T-Value = 5.21 P-Value = 0.000

Paired T-Test and Confidence Interval : Epilimnion-Middle Zone

Paired T for Stratified - non-stratified

	N	Mean	StDev	SE Mean
Stratifi	25	47.71	27.69	5.54
non-stra	25	19.10	9.36	1.87
Difference	25	28.61	30.50	6.10

95% CI for mean difference: (16.02, 41.20)
T-Test of mean difference = 0 (vs > 0): T-Value = 4.69 P-Value = 0.000

Paired T-Test and Confidence Interval : Epilimnion-Interior Zone

Paired T for Stratified - non-stratified

	N	Mean	StDev	SE Mean
Stratifi	10	19.45	12.03	3.80
non-stra	10	12.19	8.64	2.73
Difference	10	7.26	11.77	3.72

95% CI for mean difference: (-1.16, 15.69)
T-Test of mean difference = 0 (vs > 0): T-Value = 1.95 P-Value = 0.041

Paired T-Test and Confidence Interval: Hypolimnion- Initial Mixing Zone

Paired T for Stratified - Non-Stratified

	N	Mean	StDev	SE Mean
Stratifi	62	178.5	108.5	13.8
Non-Stra	62	219.6	188.3	23.9
Difference	62	-41.2	184.5	23.4

95% CI for mean difference: (-88.0, 5.7)
T-Test of mean difference = 0 (vs < 0): T-Value = -1.76 P-Value = 0.042

Paired T-Test and Confidence Interval: Hypolimnion- Middle Zone

Paired T for Stratified - Non-Stratified

	N	Mean	StDev	SE Mean
Stratifi	25	20.6	20.3	4.1
Non-Stra	25	125.5	121.0	24.2
Difference	25	-104.8	128.9	25.8

95% CI for mean difference: (-158.0, -51.6)
T-Test of mean difference = 0 (vs < 0): T-Value = -4.07 P-Value = 0.000

Paired T-Test and Confidence Interval: Hypolimnion- Interior Zone

Paired T for Stratified - Non-Stratified

	N	Mean	StDev	SE Mean
Stratifi	13	13.58	8.12	2.25
Non-Stra	13	9.34	7.31	2.03
Difference	13	4.24	11.38	3.16

95% CI for mean difference: (-2.64, 11.12)
T-Test of mean difference = 0 (vs < 0): T-Value = 1.34 P-Value = 0.898

B.8 Comparison of hypolimnion and epilimnion perchlorate levels at selected sampling stations

Paired T-Test and Confidence Interval

Paired T for lm2ce - lm2ch

	N	Mean	StDev	SE Mean
lm2ce	26	108.0	110.7	21.7
lm2ch	26	210.6	125.1	24.5
Difference	26	-102.6	176.2	34.5

95% CI for mean difference: (-173.8, -31.5)
T-Test of mean difference = 0 (vs < 0): T-Value = -2.97 P-Value = 0.003

Paired T-Test and Confidence Interval

Paired T for lm3ce - lm3ch

	N	Mean	StDev	SE Mean
lm3ce	31	85.7	69.3	12.5
lm3ch	31	139.6	81.2	14.6
Difference	31	-53.9	79.8	14.3

95% CI for mean difference: (-83.2, -24.7)
T-Test of mean difference = 0 (vs < 0): T-Value = -3.76 P-Value = 0.000

Paired T-Test and Confidence Interval

Paired T for LM4E - LM4H

	N	Mean	StDev	SE Mean
LM4E	15	38.8	36.3	9.4
LM4H	15	161.0	149.1	38.5
Difference	15	-122.2	171.4	44.3

95% CI for mean difference: (-217.1, -27.3)
T-Test of mean difference = 0 (vs < 0): T-Value = -2.76 P-Value = 0.008

Paired T-Test and Confidence Interval

Paired T for LM5E - LM5H

	N	Mean	StDev	SE Mean
LM5E	18	31.8	20.4	4.8
LM5H	18	43.3	42.8	10.1
Difference	18	-11.4	49.1	11.6

95% CI for mean difference: (-35.8, 13.0)
T-Test of mean difference = 0 (vs < 0): T-Value = -0.99 P-Value = 0.169

Paired T-Test and Confidence Interval

Paired T for LM8E - LM8H (E greater than H)

	N	Mean	StDev	SE Mean
LM8E	13	18.96	10.26	2.85
LM8H	13	12.67	8.38	2.32
Difference	13	6.29	10.48	2.91

95% CI for mean difference: (-0.05, 12.62)
T-Test of mean difference = 0 (vs > 0): T-Value = 2.16 P-Value = 0.026

Appendix C

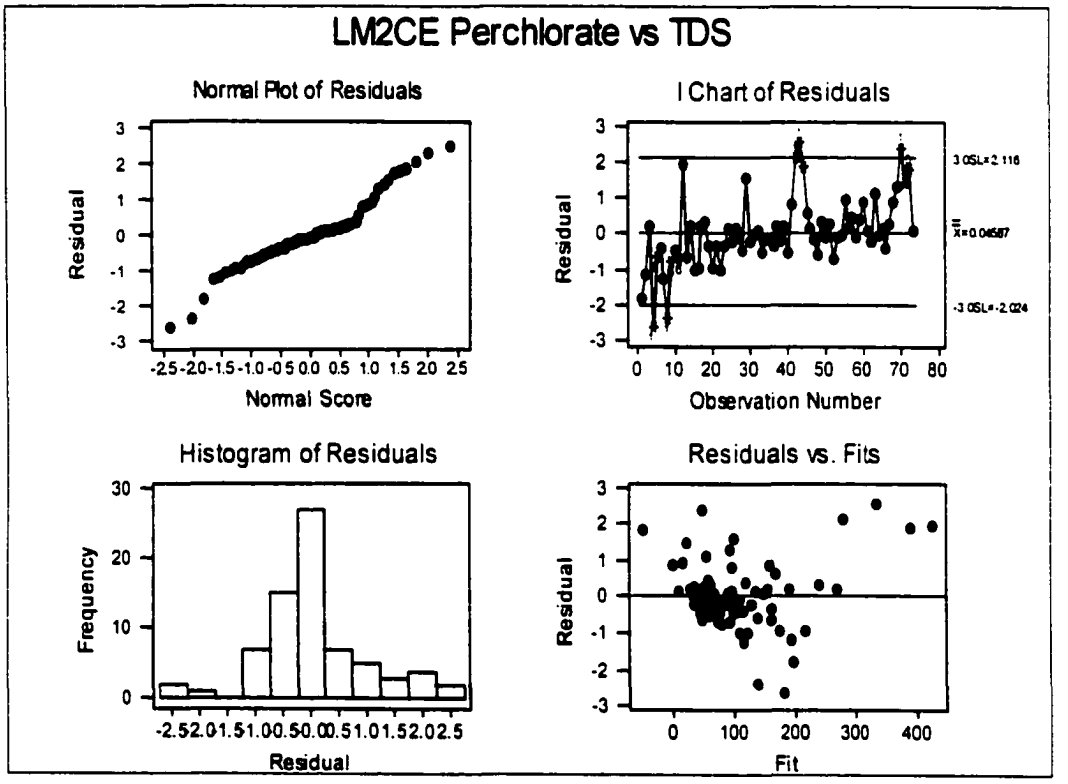
Comparison of Perchlorate and TDS Levels

Regression Analysis : LM2CE

The regression equation is
Perch = - 332 + 0.573 tds

Predictor	Coef	StDev	T	P
Constant	-332.34	26.65	-12.47	0.000
tds	0.57295	0.03364	17.03	0.000

S = 44.01 R-Sq = 80.1% R-Sq(adj) = 79.8%

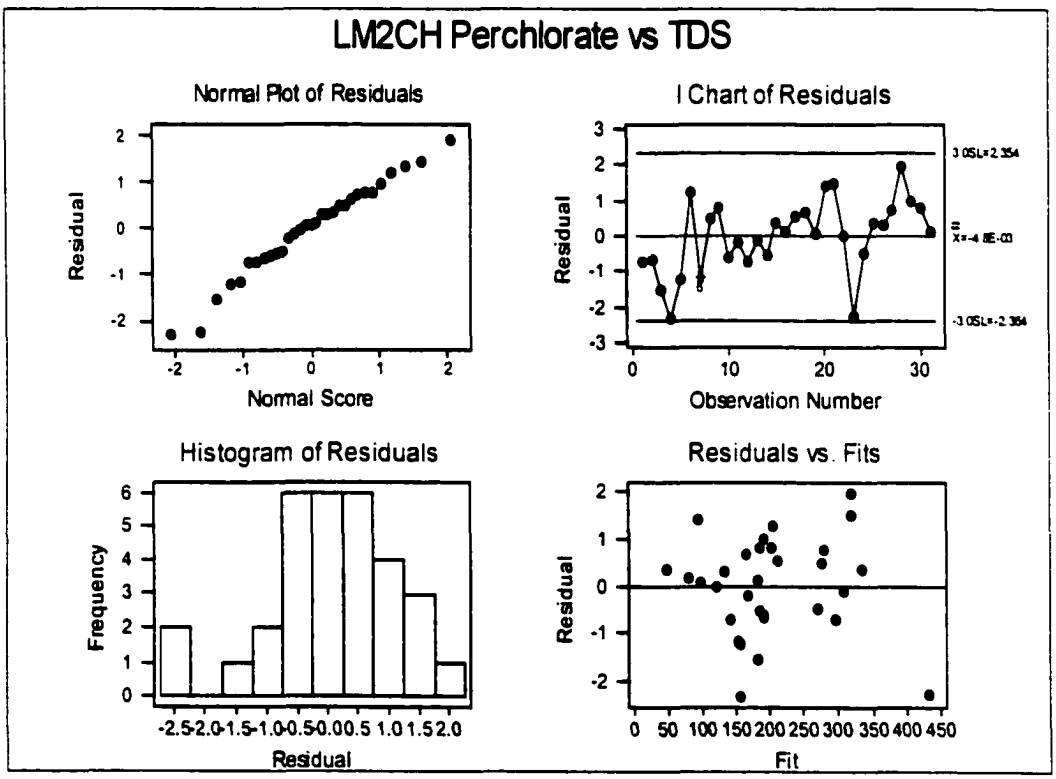


Regression Analysis : LM2CH

The regression equation is
Perch = - 322 + 0.559 tds

Predictor	Coef	StDev	T	P
Constant	-322.04	55.65	-5.79	0.000
tds	0.55856	0.05867	9.52	0.000

S = 49.55 R-Sq = 75.8% R-Sq(adj) = 74.9%

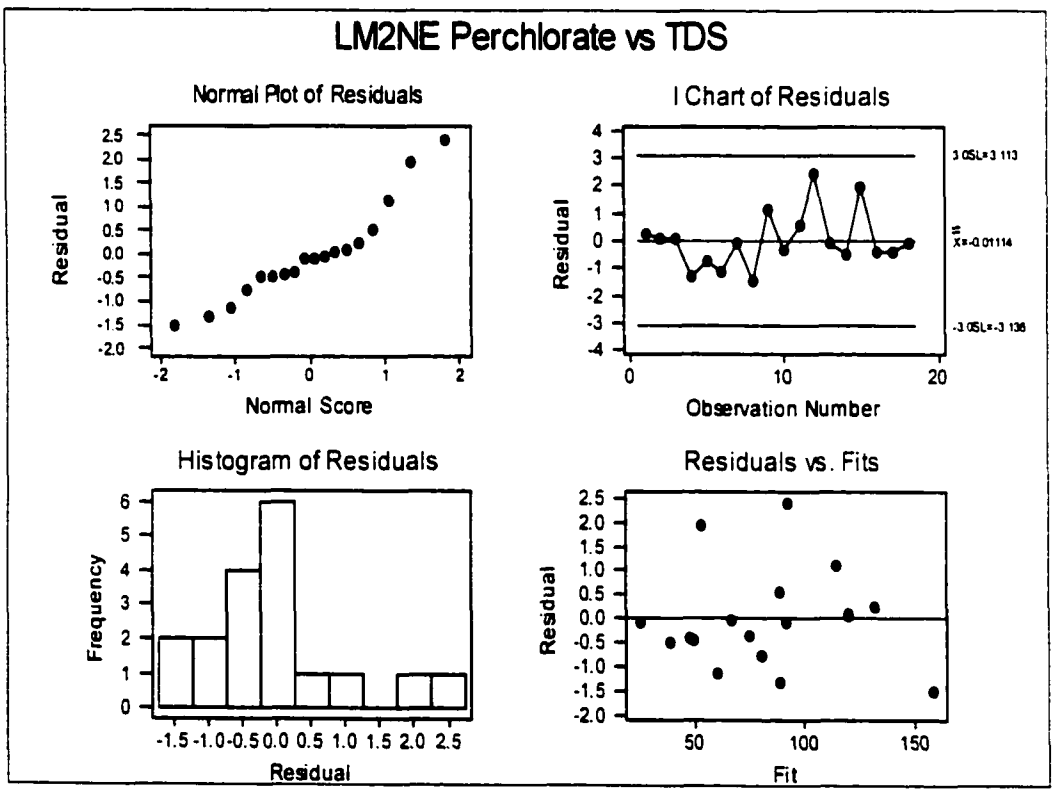


Regression Analysis : LM2NE

The regression equation is
perch = - 133 + 0.277 tds

Predictor	Coef	StDev	T	P
Constant	-133.05	46.79	-2.84	0.012
tds	0.27700	0.05921	4.68	0.000

S = 31.52 R-Sq = 57.8% R-Sq(adj) = 55.1%

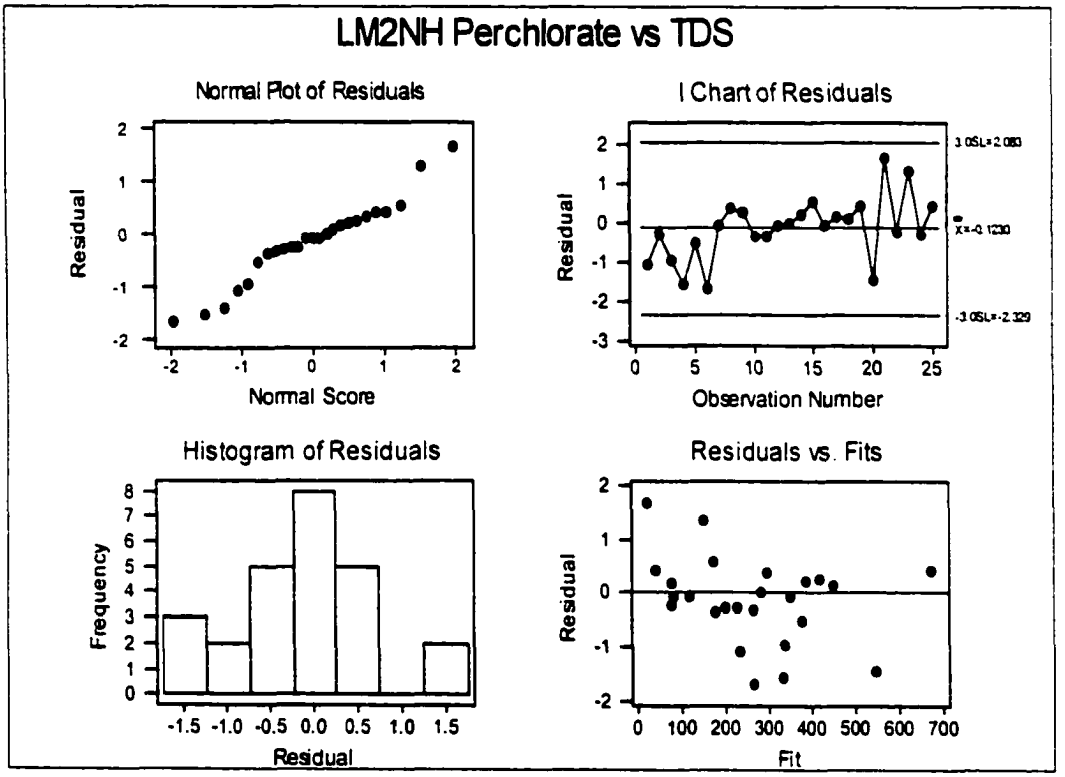


Regression Analysis : LM2NH

The regression equation is
perch = - 297 + 0.538 tds

Predictor	Coef	StDev	T	P
Constant	-297.38	74.02	-4.02	0.001
tds	0.53830	0.07114	7.57	0.000

S = 86.36 R-Sq = 71.3% R-Sq(adj) = 70.1%

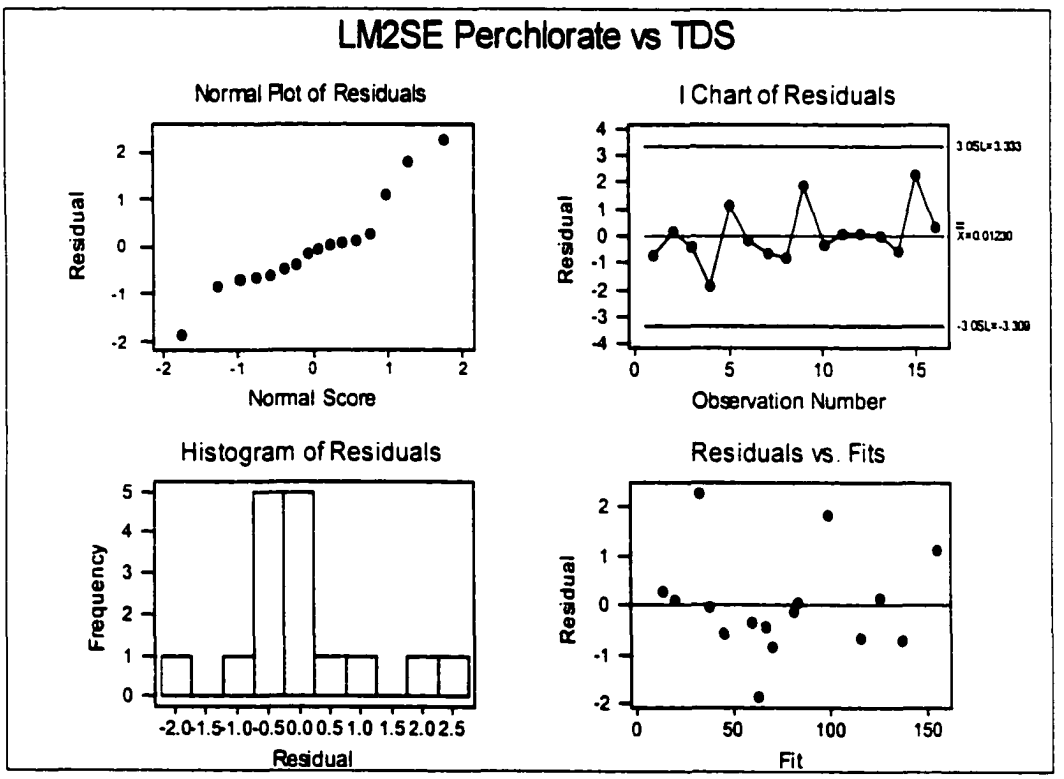


Regression Analysis : LM2SE

The regression equation is
perch = - 189 + 0.346 tds

Predictor	Coef	StDev	T	P
Constant	-188.51	27.69	-6.81	0.000
tds	0.34593	0.03592	9.63	0.000

S = 16.94 R-Sq = 86.9% R-Sq(adj) = 85.9%

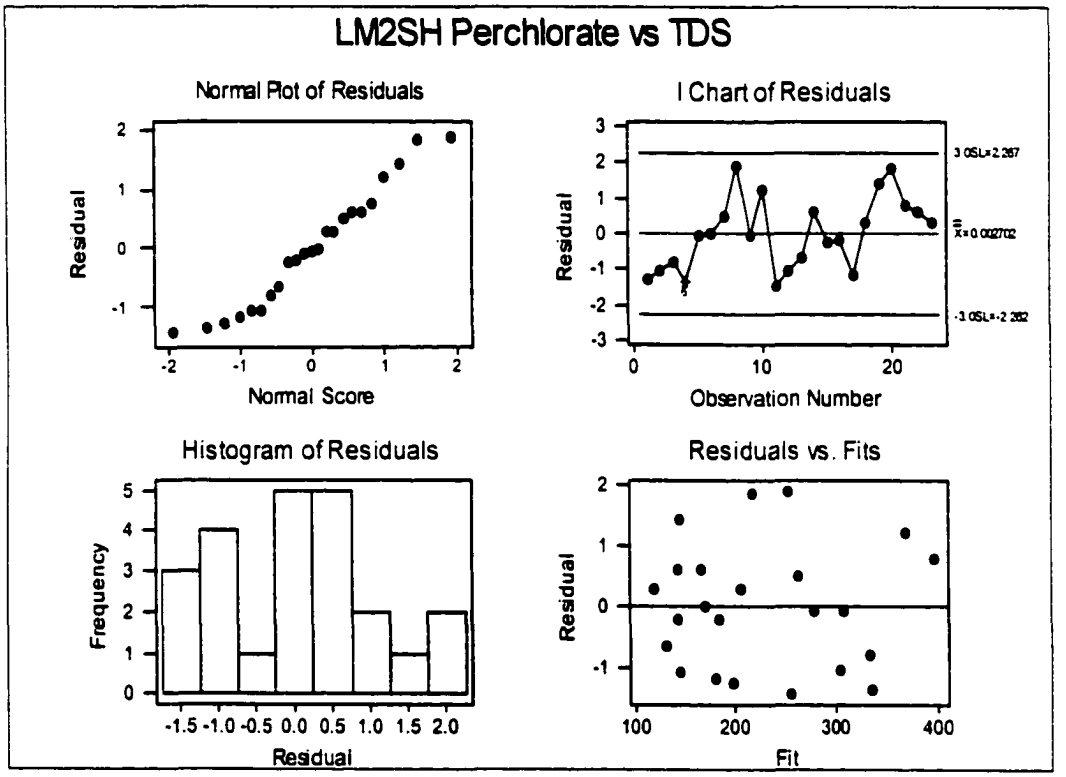


Regression Analysis : LM2SH

The regression equation is
perch = - 262 + 0.506 tds

Predictor	Coef	StDev	T	P
Constant	-261.8	127.1	-2.06	0.052
tds	0.5057	0.1298	3.90	0.001

S = 99.74 R-Sq = 41.9% R-Sq(adj) = 39.2%

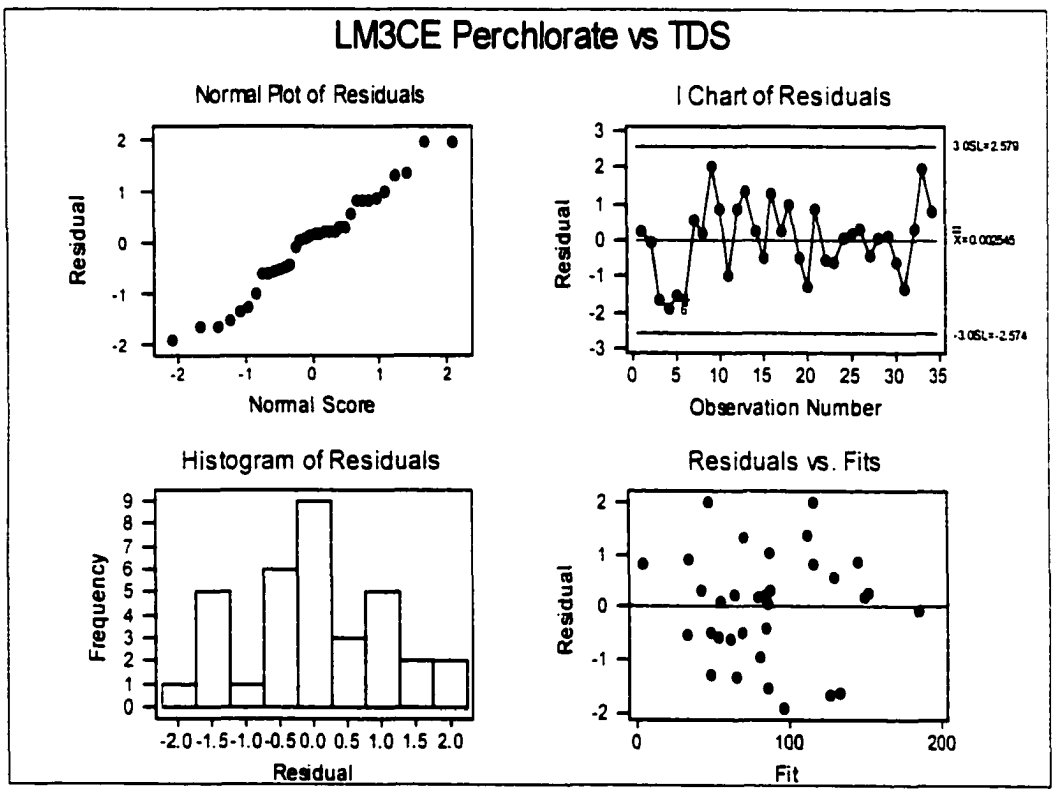


Regression Analysis : LM3CE

The regression equation is
perch = - 207 + 0.390 tds

Predictor	Coef	StDev	T	P
Constant	-207.14	30.12	-6.88	0.000
tds	0.38966	0.03976	9.80	0.000

S = 23.46 R-Sq = 75.0% R-Sq(adj) = 74.2%

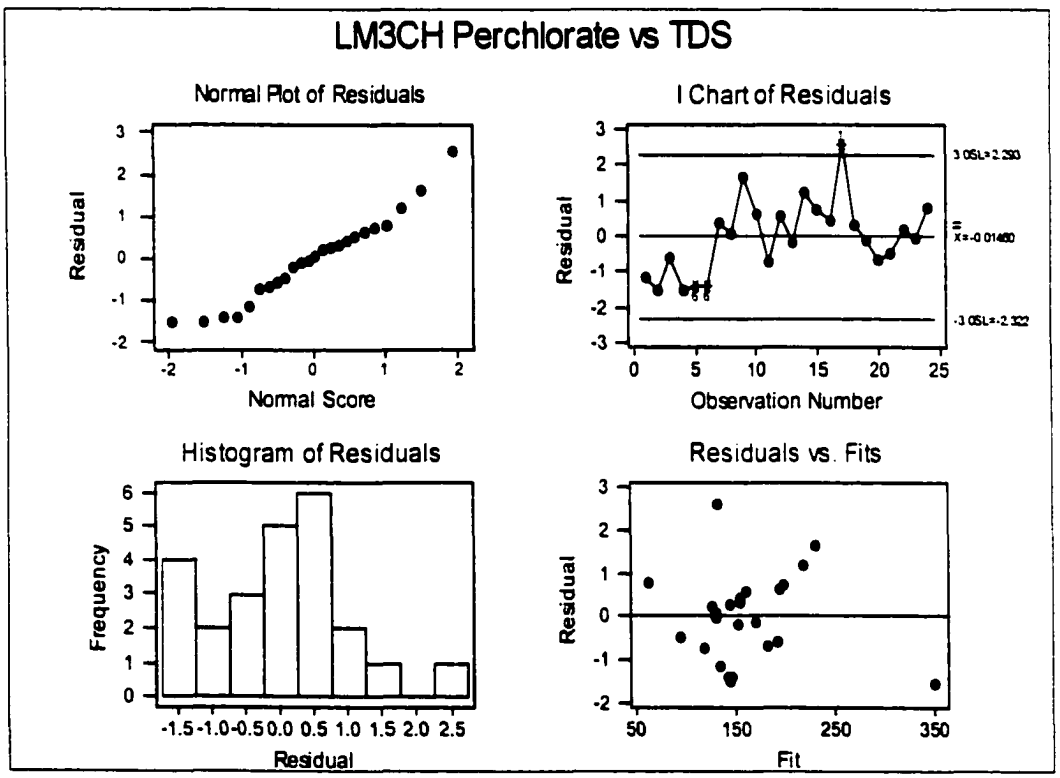


Regression Analysis : LM3CH

The regression equation is
perch = - 195 + 0.396 tds

Predictor	Coef	StDev	T	P
Constant	-195.39	74.82	-2.61	0.016
tds	0.39589	0.08230	4.81	0.000

S = 55.00 R-Sq = 51.3% R-Sq(adj) = 49.1%

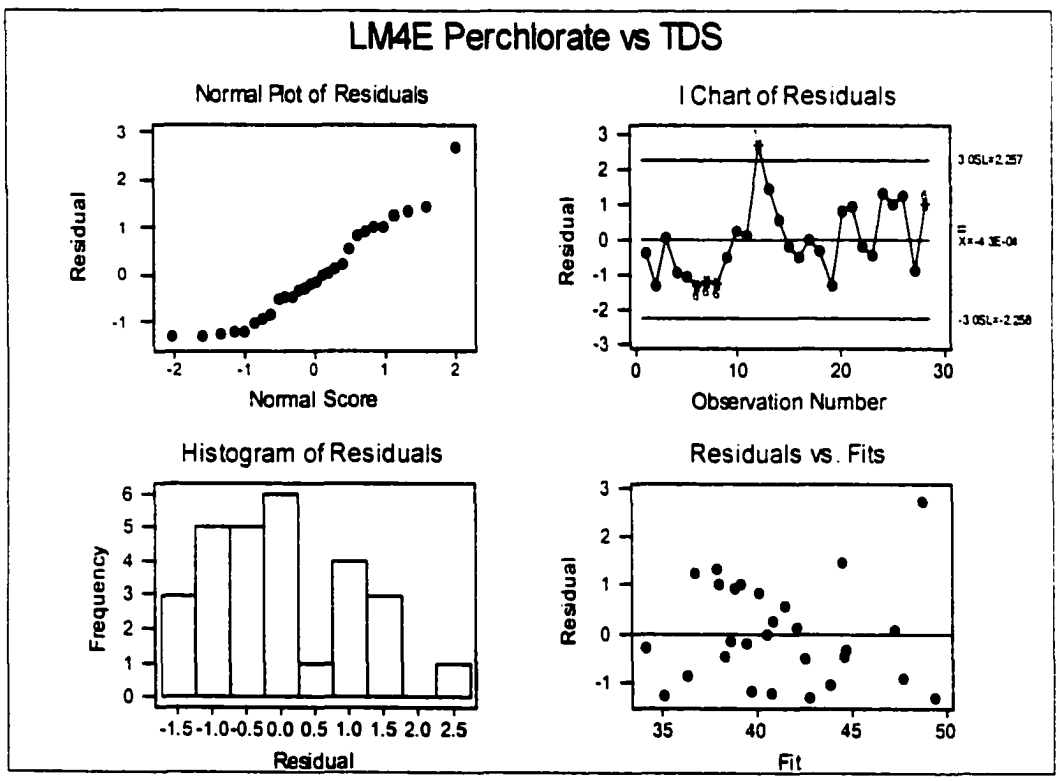


Regression Analysis : LM4E

The regression equation is
perch = - 3.6 + 0.0637 tds

Predictor	Coef	StDev	T	P
Constant	-3.60	43.47	-0.08	0.935
tds	0.06367	0.06153	1.03	0.310

S = 20.10 R-Sq = 4.0% R-Sq(adj) = 0.3%

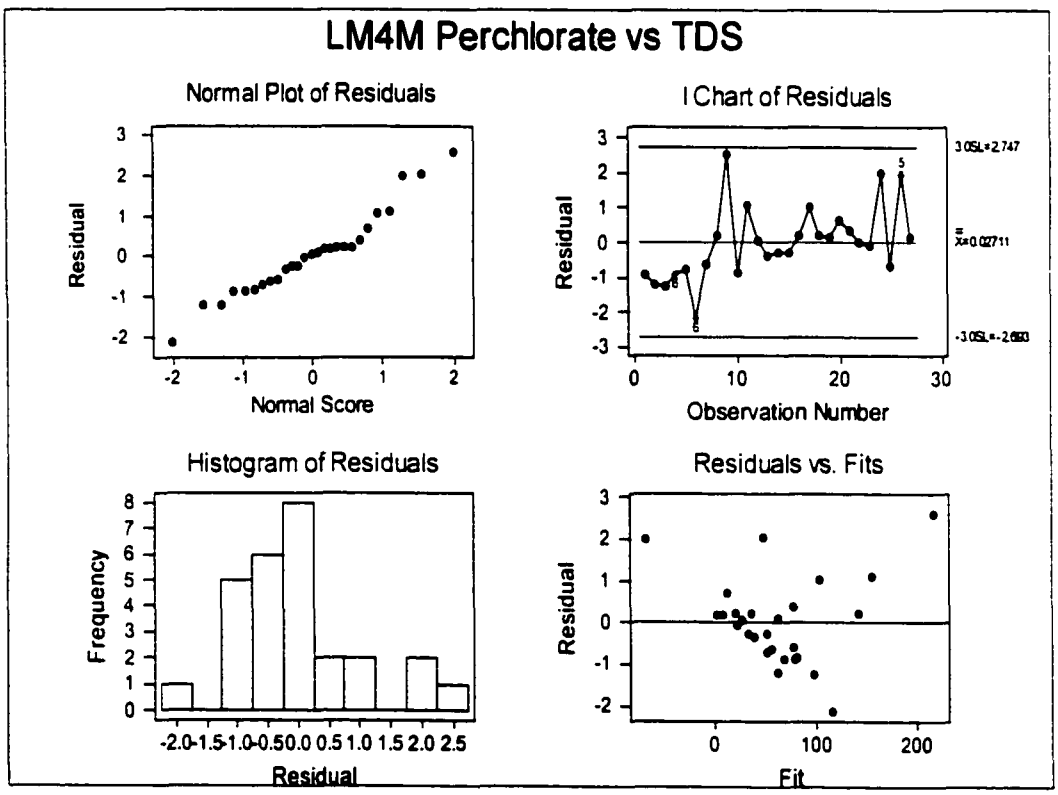


Regression Analysis : LM4M

The regression equation is
perch = - 237 + 0.409 tds

Predictor	Coef	StDev	T	P
Constant	-236.72	55.55	-4.26	0.000
tds	0.40858	0.07484	5.46	0.000

S = 52.01 R-Sq = 54.4% R-Sq(adj) = 52.6%

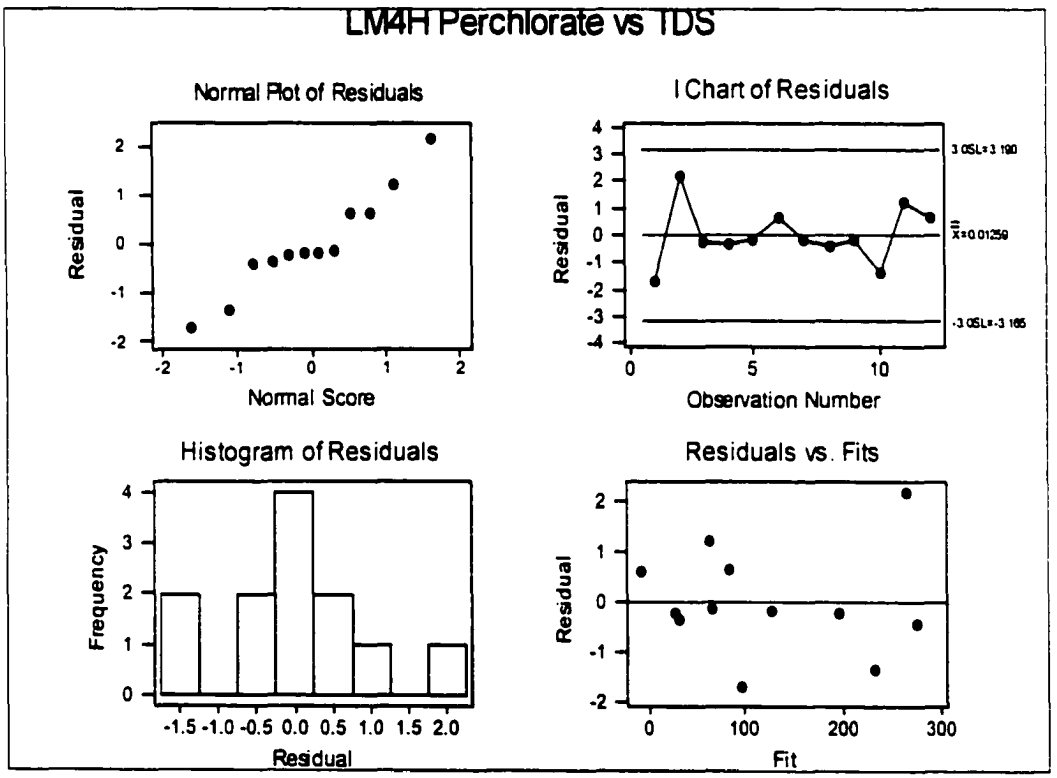


Regression Analysis : LM4H

The regression equation is
perch = - 507 + 0.796 tds

Predictor	Coef	StDev	T	P
Constant	-507.2	106.8	-4.75	0.001
tds	0.7962	0.1338	5.95	0.000

S = 54.33 R-Sq = 78.0% R-Sq(adj) = 75.8%

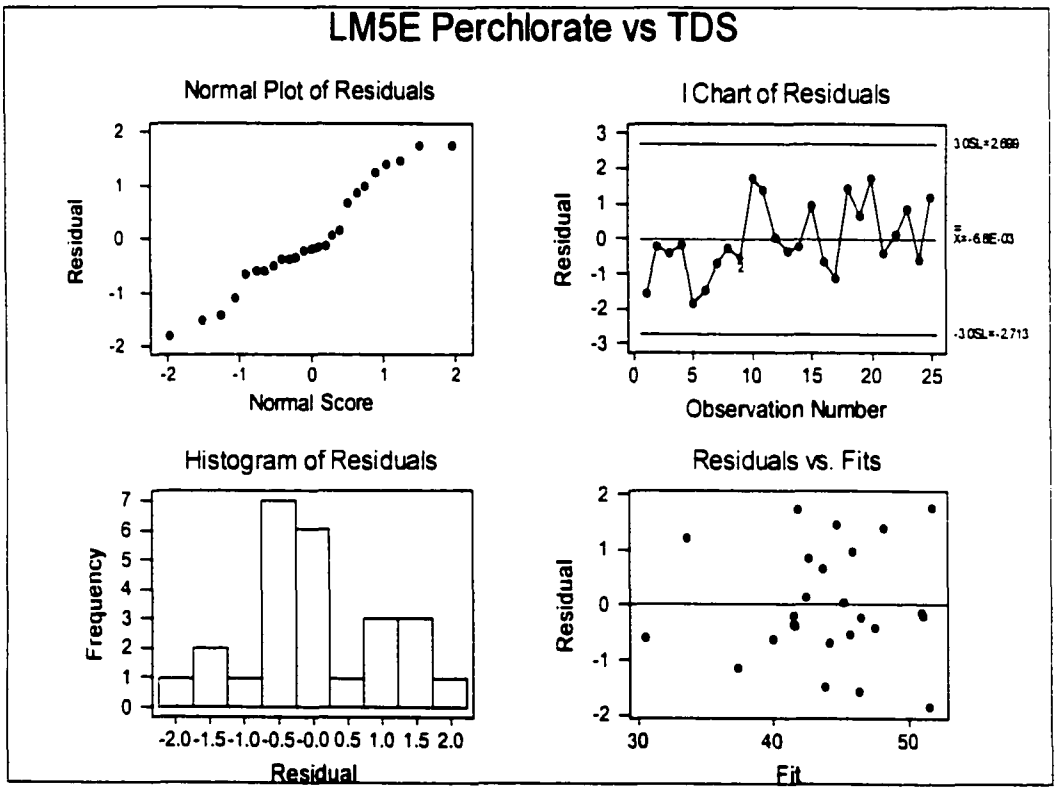


Regression Analysis : LM5E

The regression equation is
ln (perch) = 2.55 + 0.00164 tds

Predictor	Coef	StDev	T	P
Constant	2.549	1.036	2.46	0.022
tds	0.001636	0.001514	1.08	0.291

S = 0.5279 R-Sq = 4.8% R-Sq(adj) = 0.7%

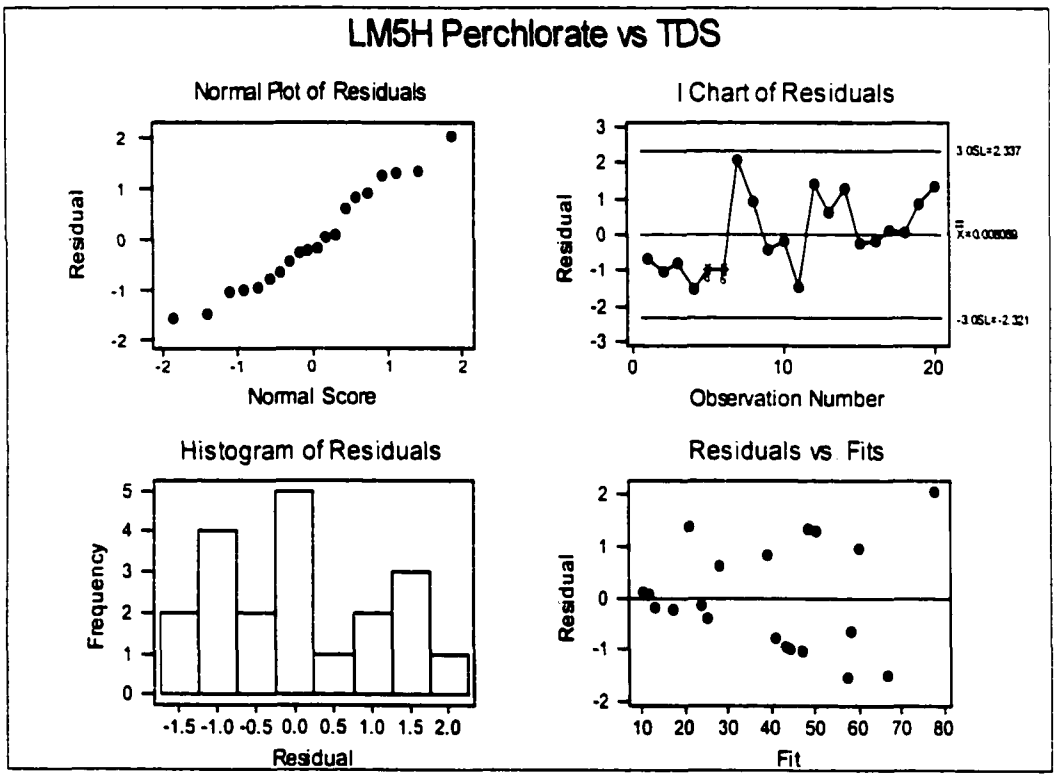


Regression Analysis : LM5H

The regression equation is
perch = - 161 + 0.284 tds

Predictor	Coef	StDev	T	P
Constant	-160.64	87.90	-1.83	0.084
tds	0.2844	0.1246	2.28	0.035

S = 37.57 R-Sq = 22.4% R-Sq(adj) = 18.1%

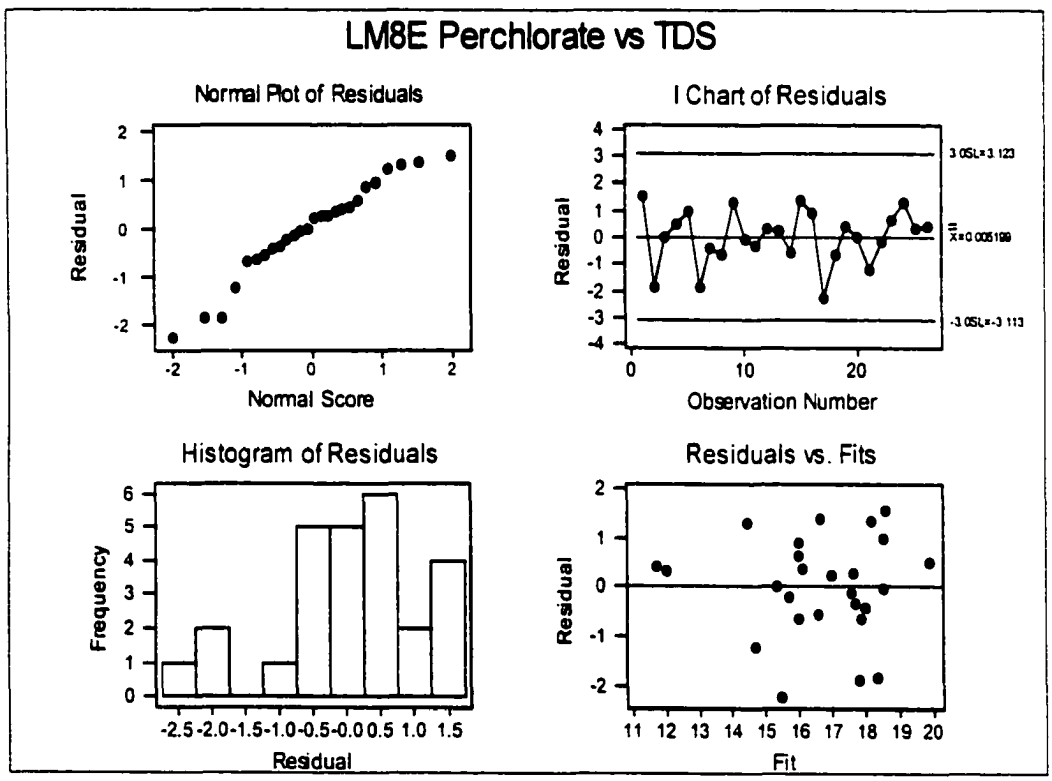


Regression Analysis : LM8E

The regression equation is
perch = - 3.7 + 0.0319 tds

Predictor	Coef	StDev	T	P
Constant	-3.75	14.85	-0.25	0.803
tds	0.03187	0.02314	1.38	0.181

S = 7.044 R-Sq = 7.3% R-Sq(adj) = 3.5%

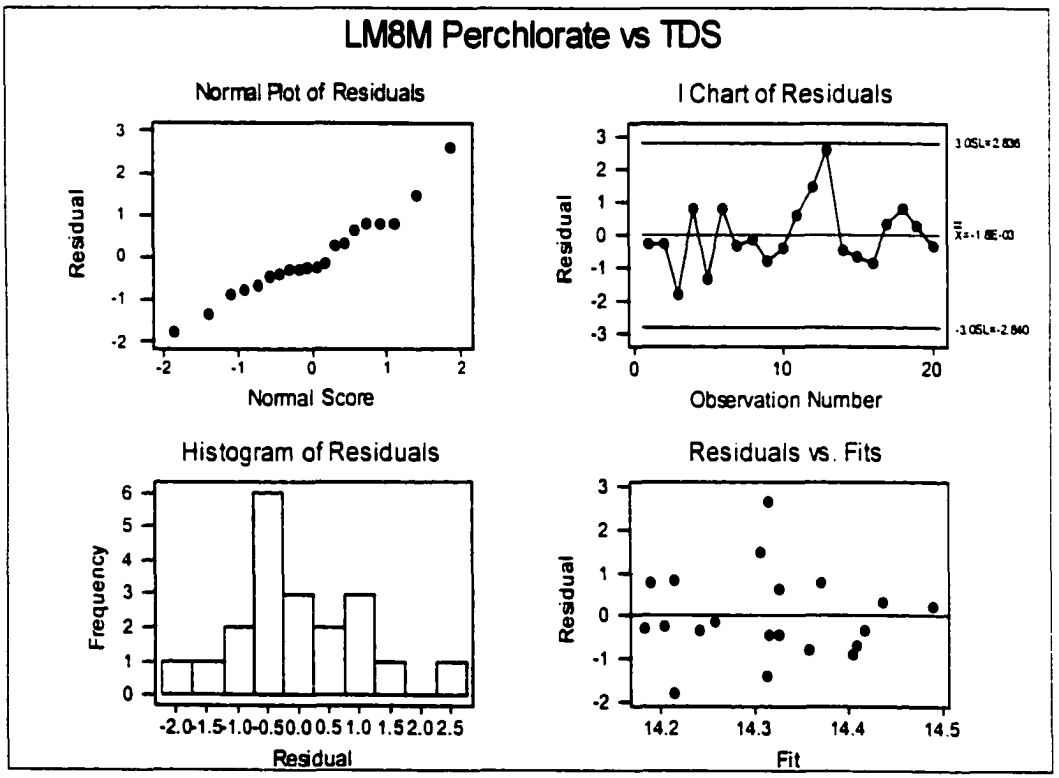


Regression Analysis : LM8M

The regression equation is
perch = 15.3 - 0.0015 tds

Predictor	Coef	StDev	T	P
Constant	15.26	17.23	0.89	0.388
tds	-0.00151	0.02740	-0.05	0.957

S = 7.122 R-Sq = 0.0% R-Sq(adj) = 0.0%

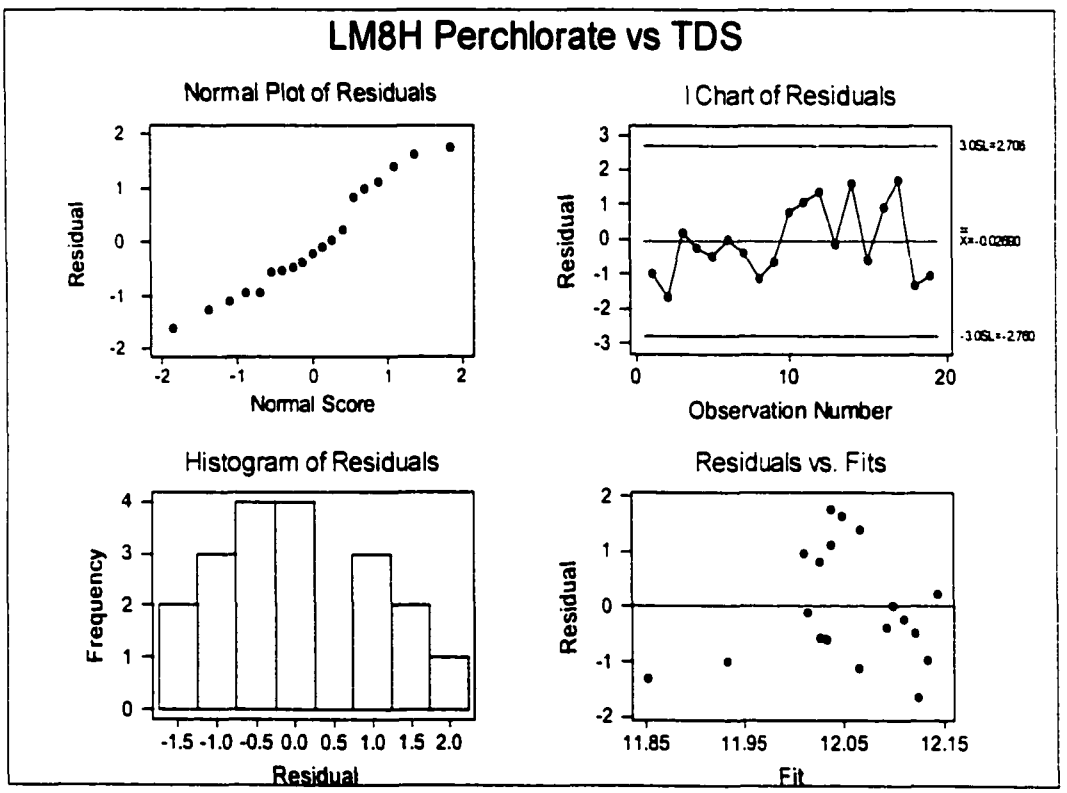


Regression Analysis : LM8H

The regression equation is
perch = 11.4 + 0.0010 tds

Predictor	Coef	StDev	T	P
Constant	11.44	16.00	0.71	0.484
tds	0.00099	0.02565	0.04	0.970

S = 7.851 R-Sq = 0.0% R-Sq(adj) = 0.0%

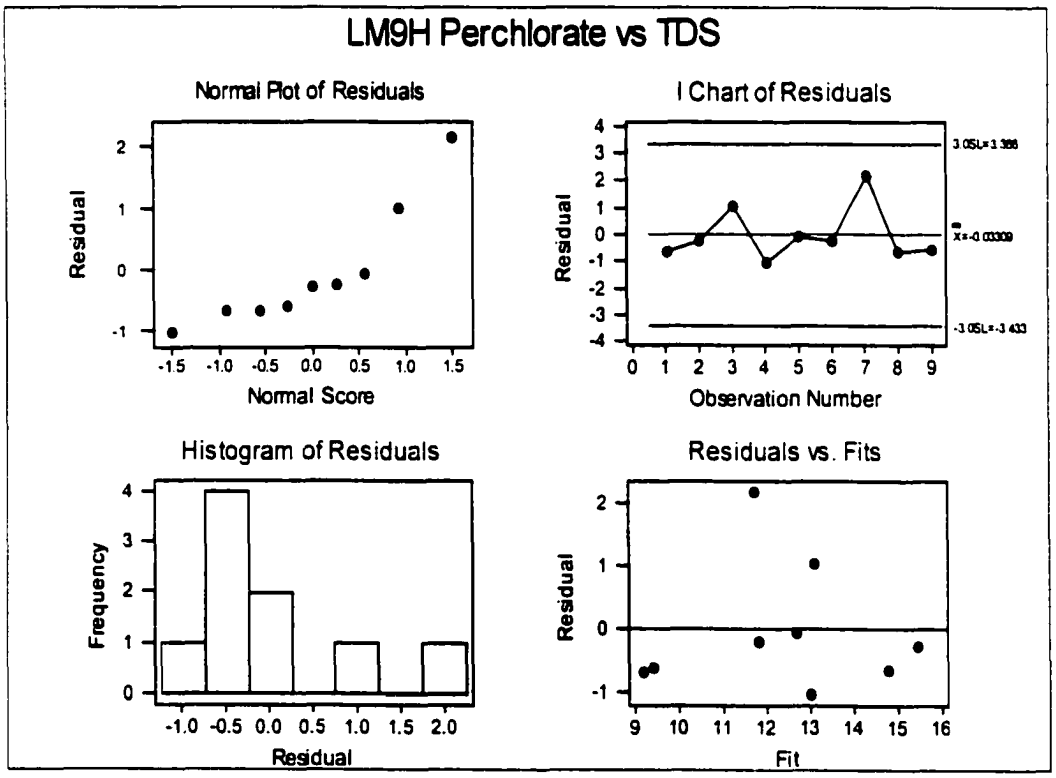


Regression Analysis: LM9H

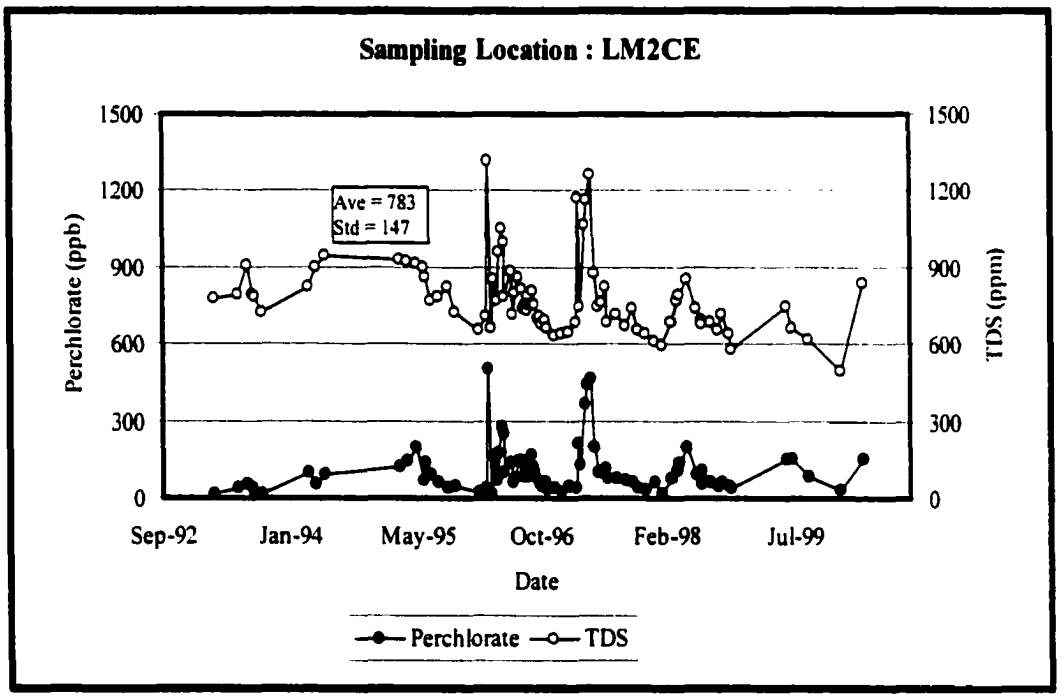
The regression equation is
perch = - 11.7 + 0.0389 tds

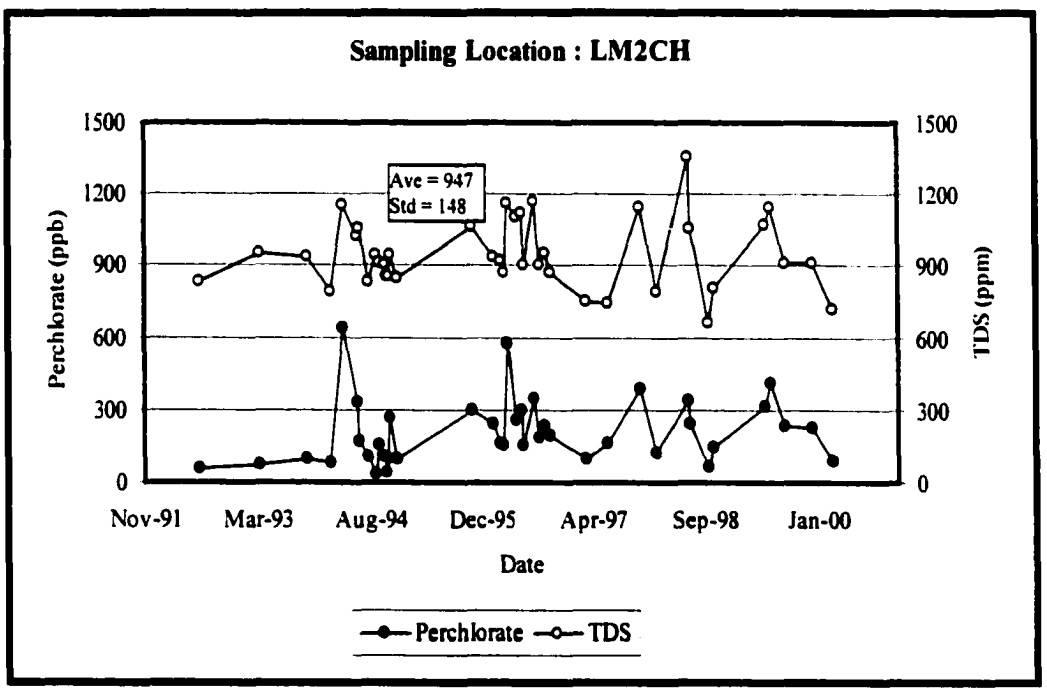
Predictor	Coef	StDev	T	P
Constant	-11.67	26.94	-0.43	0.678
tds	0.03885	0.04345	0.89	0.401

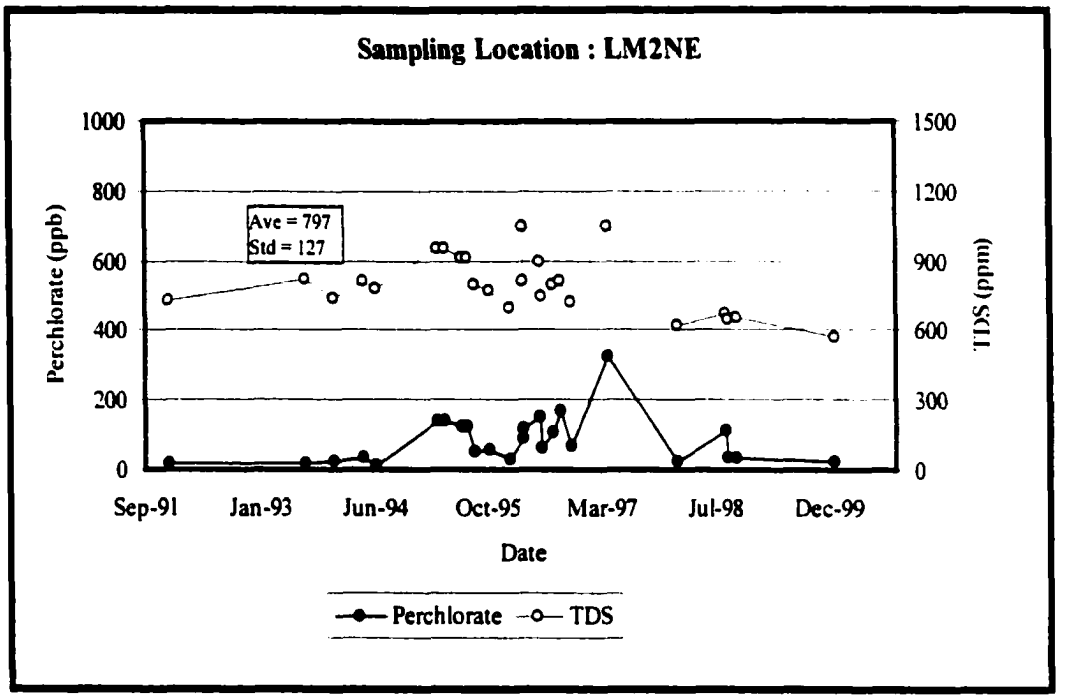
S = 6.698 R-Sq = 10.3% R-Sq(adj) = 0.0%

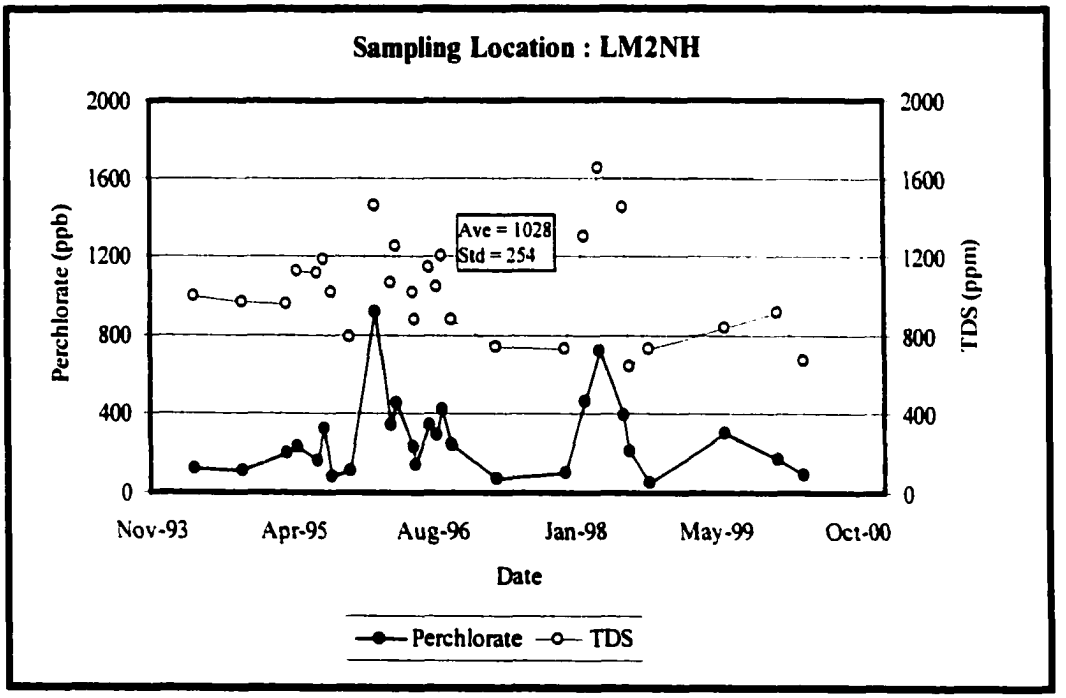


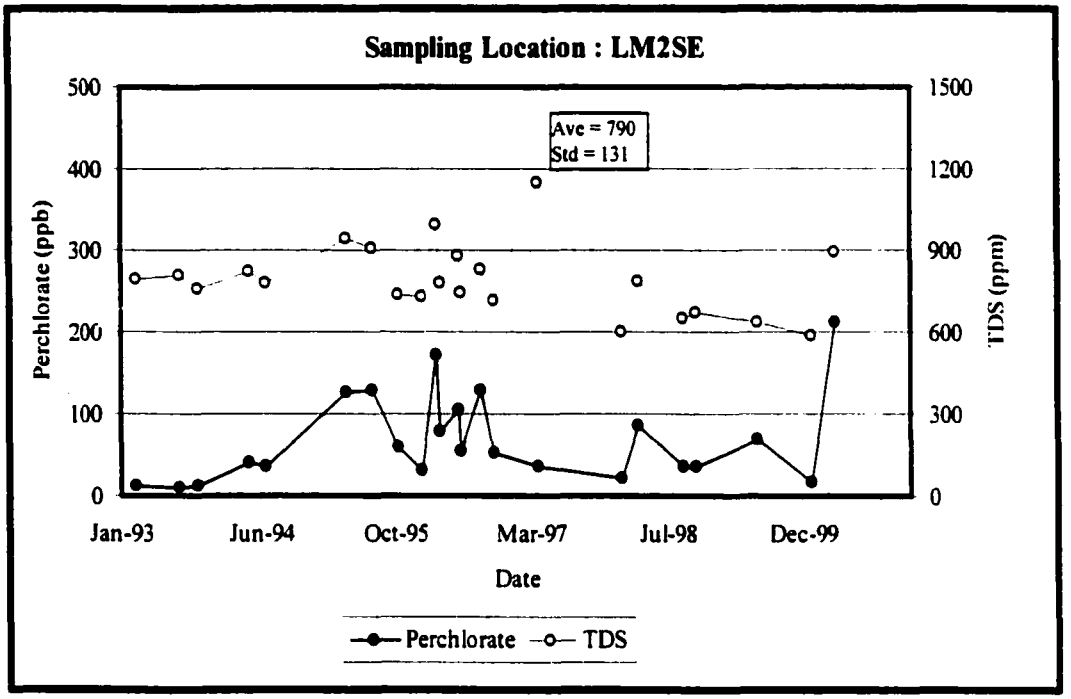
TDS Levels in the Lake:

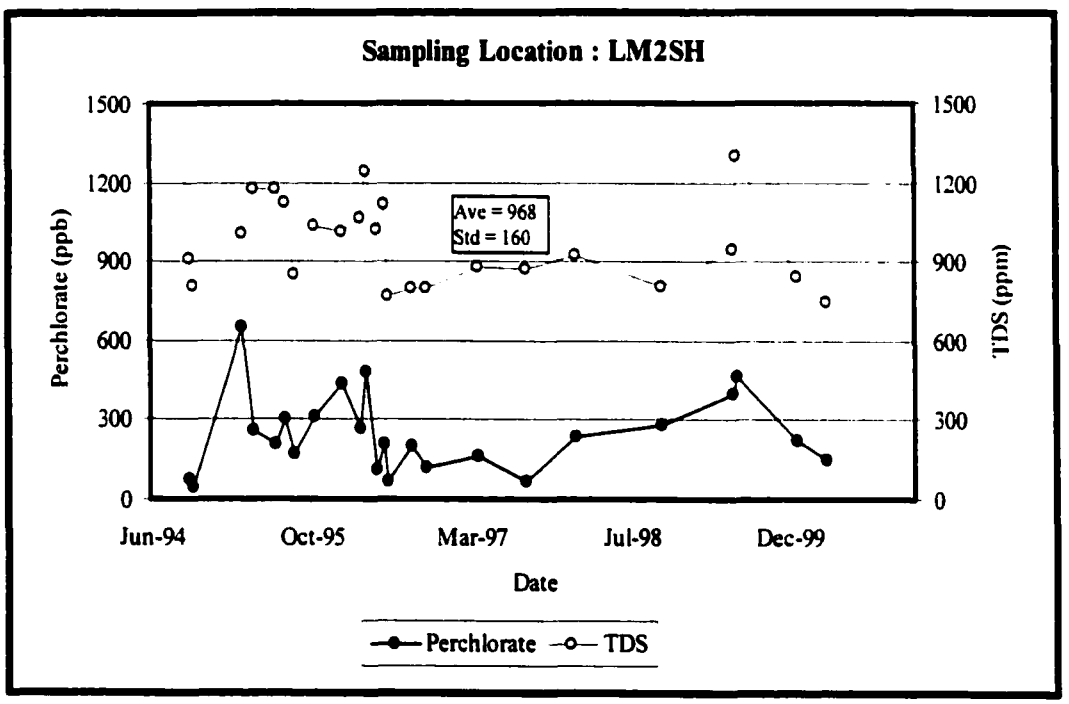


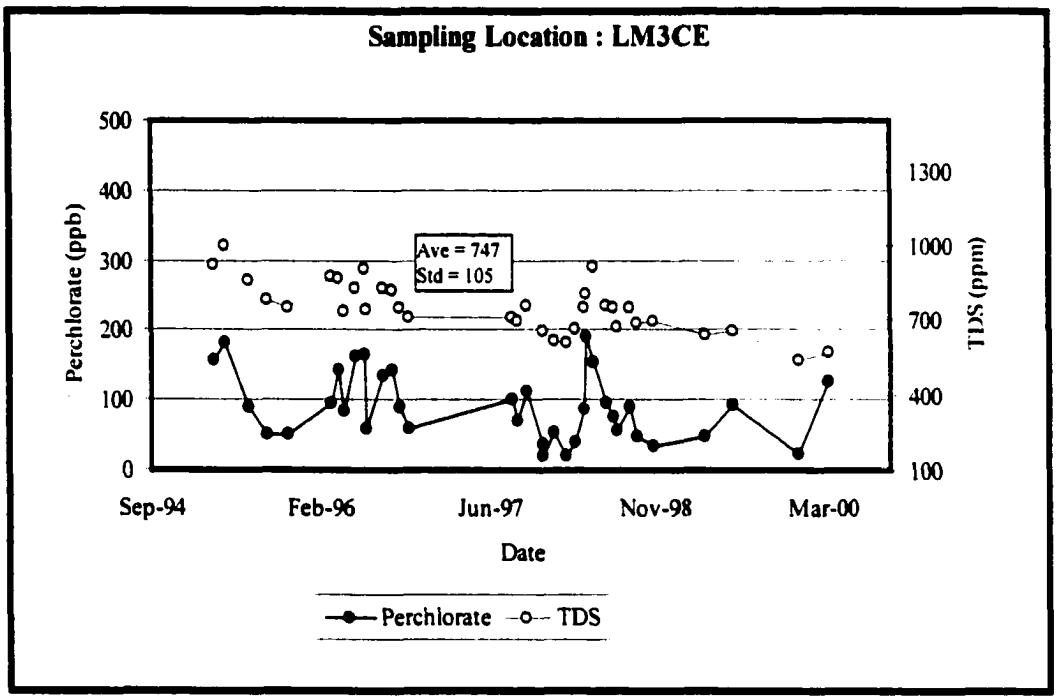


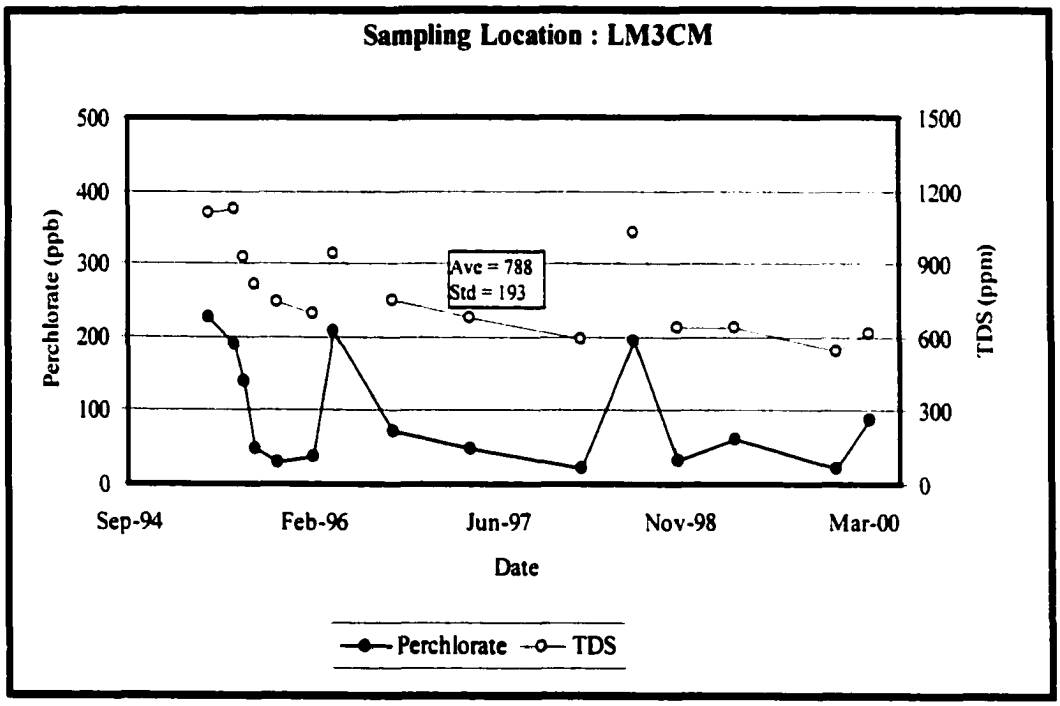


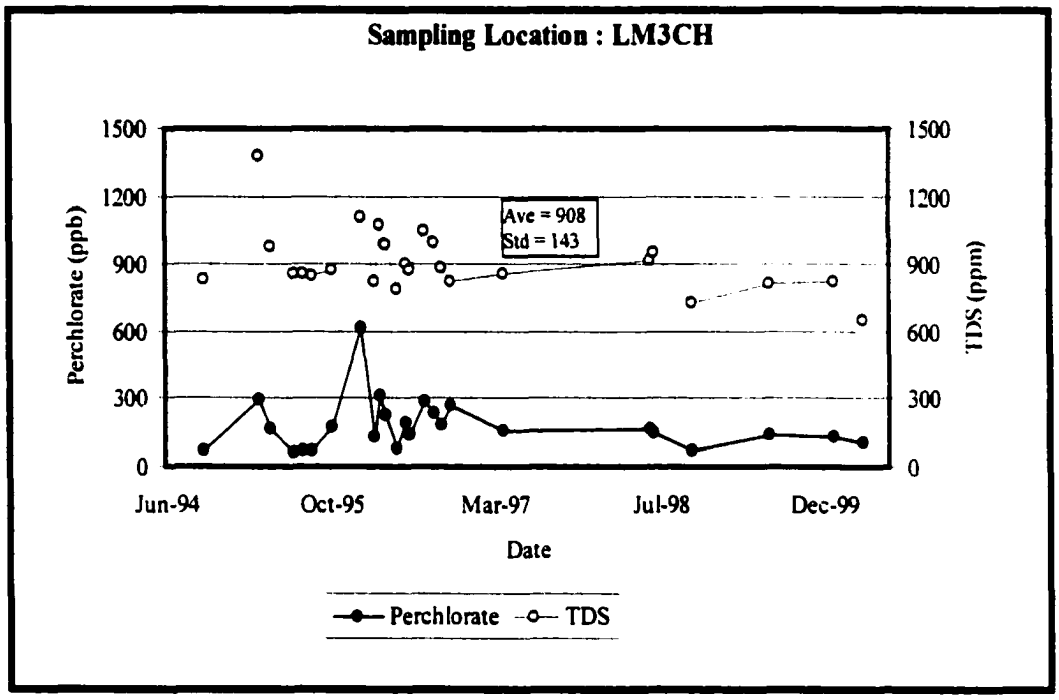


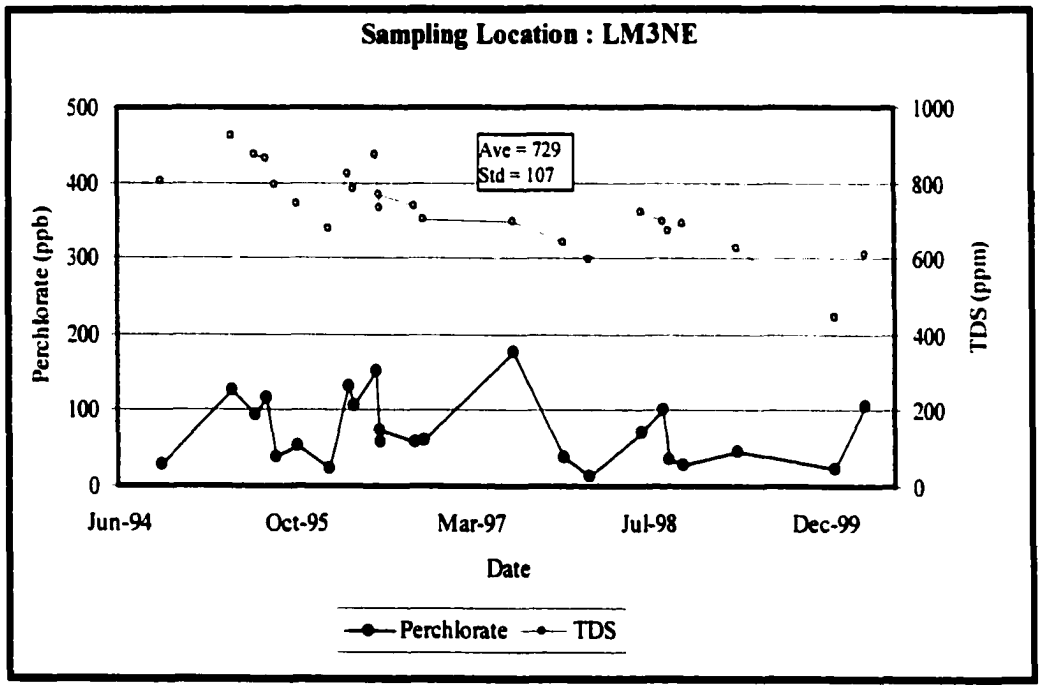


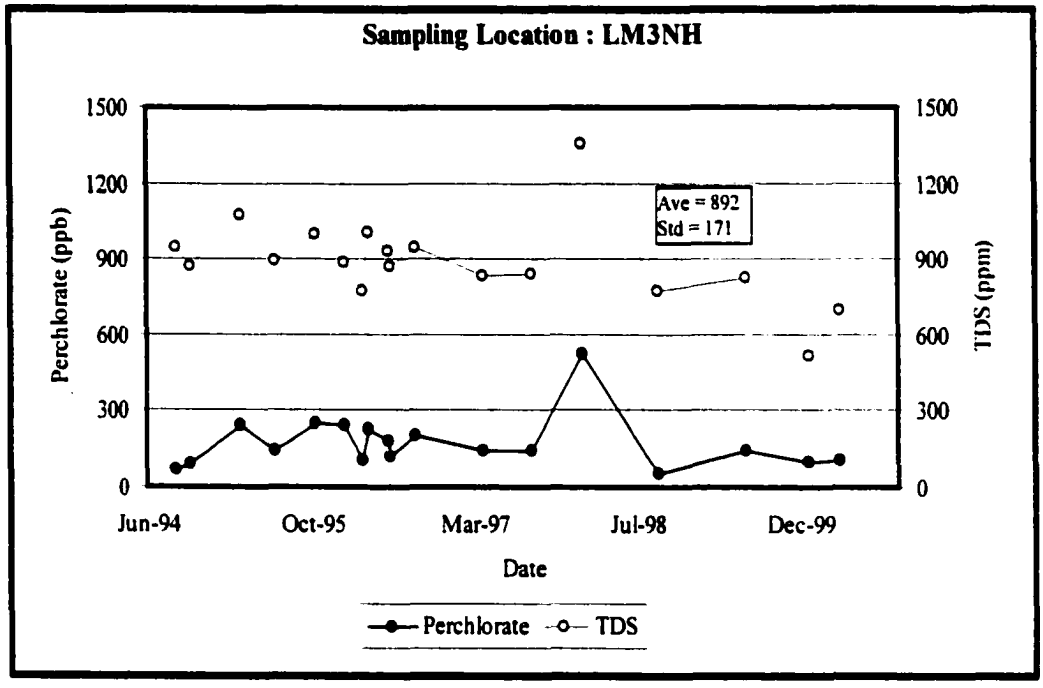


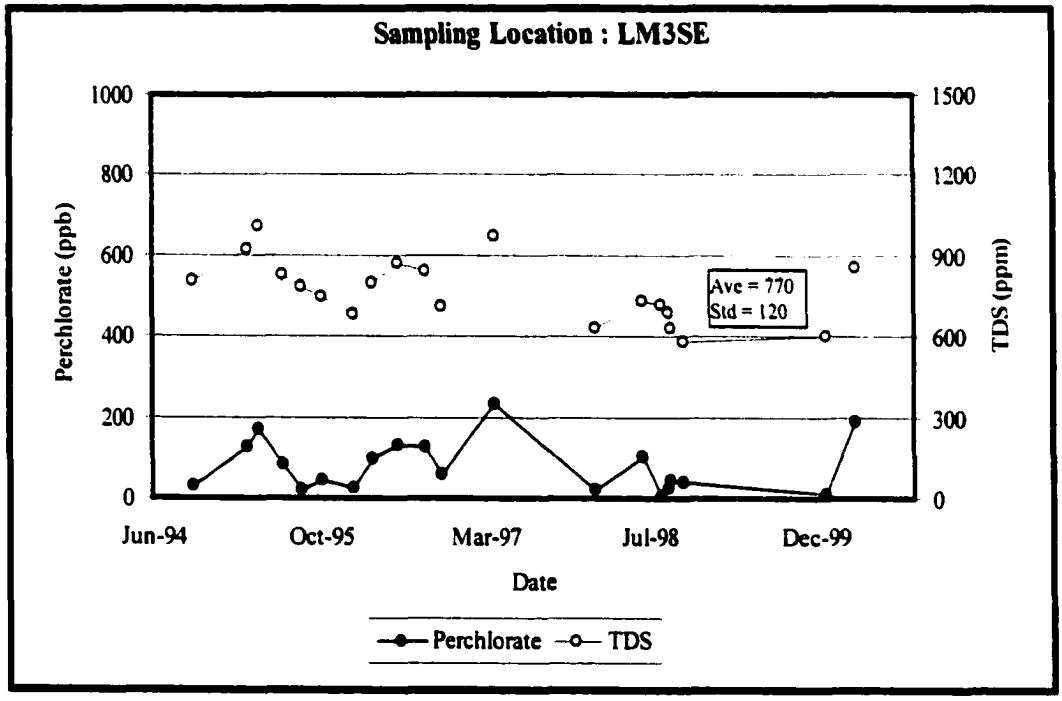


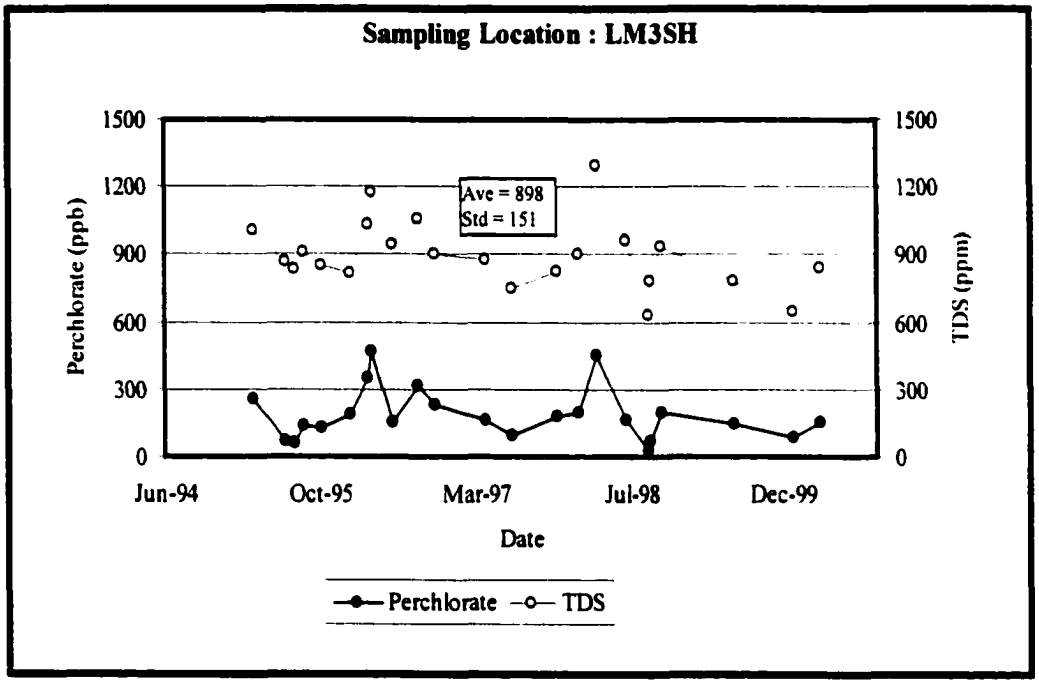


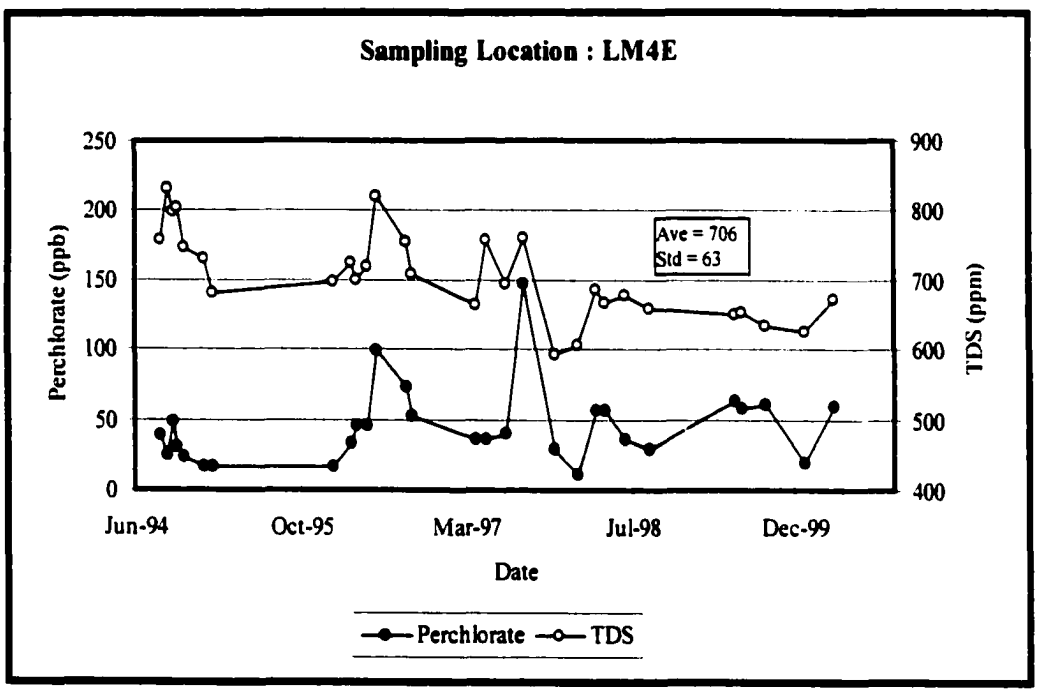


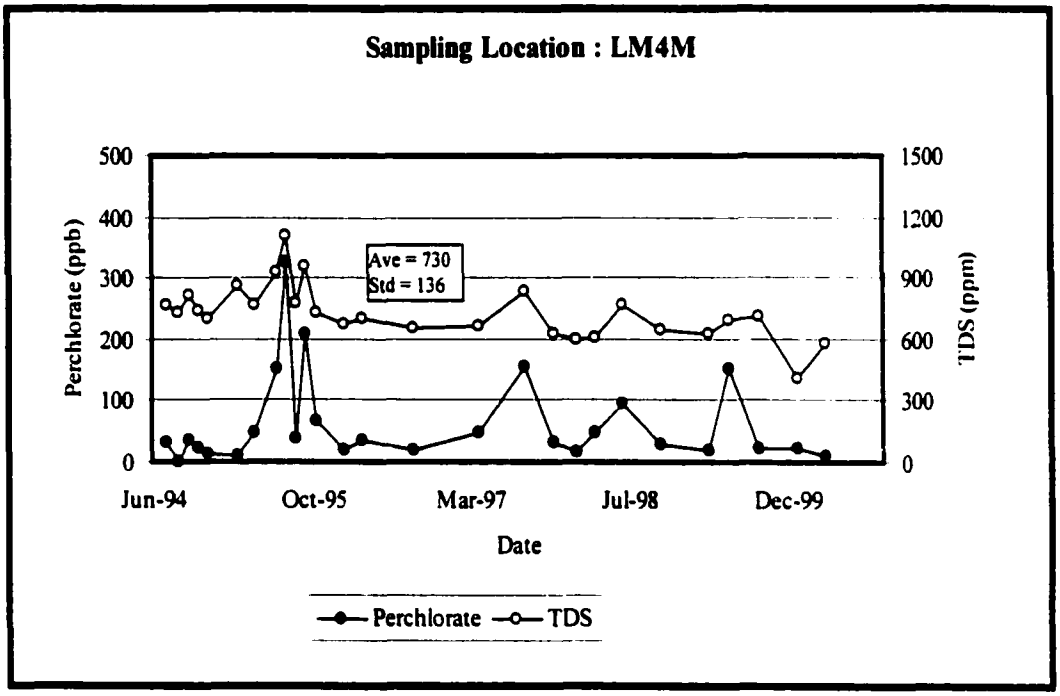


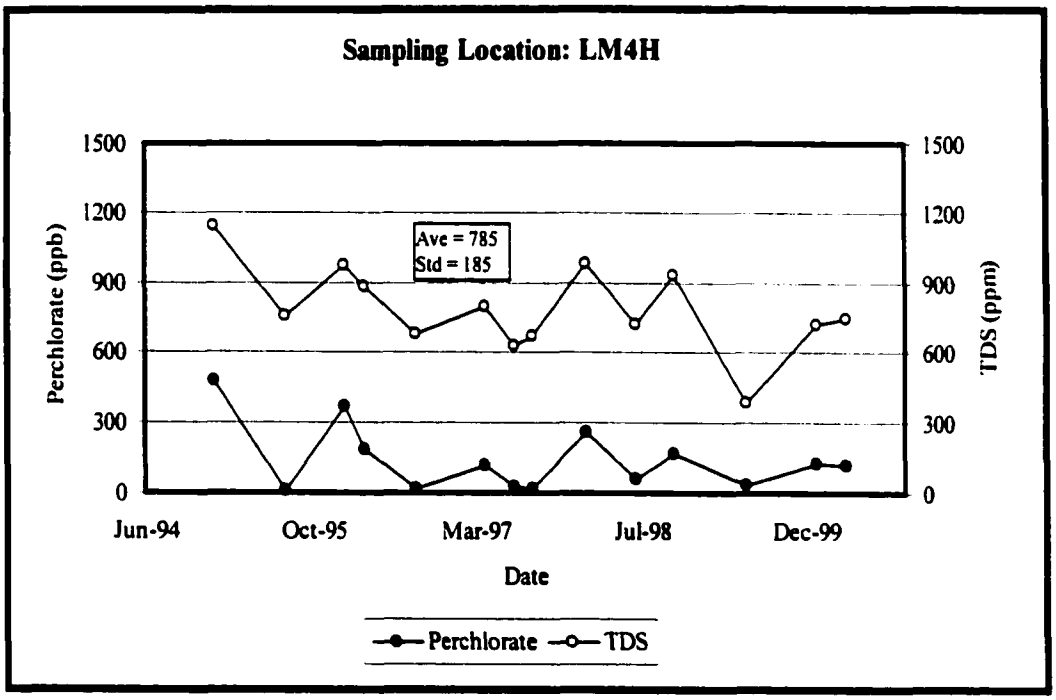


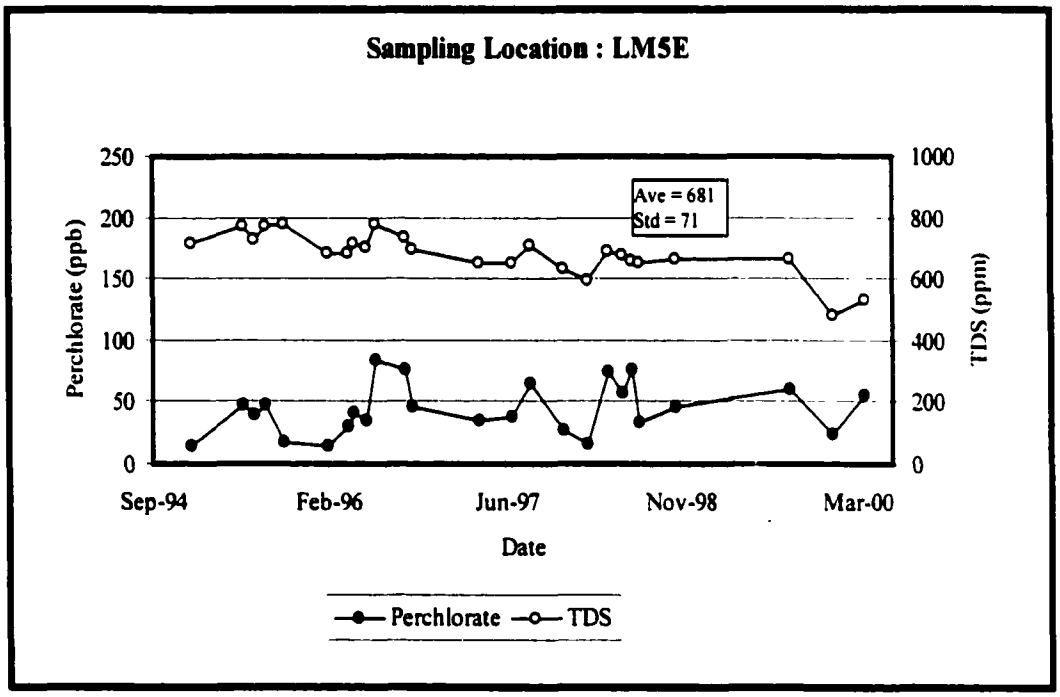


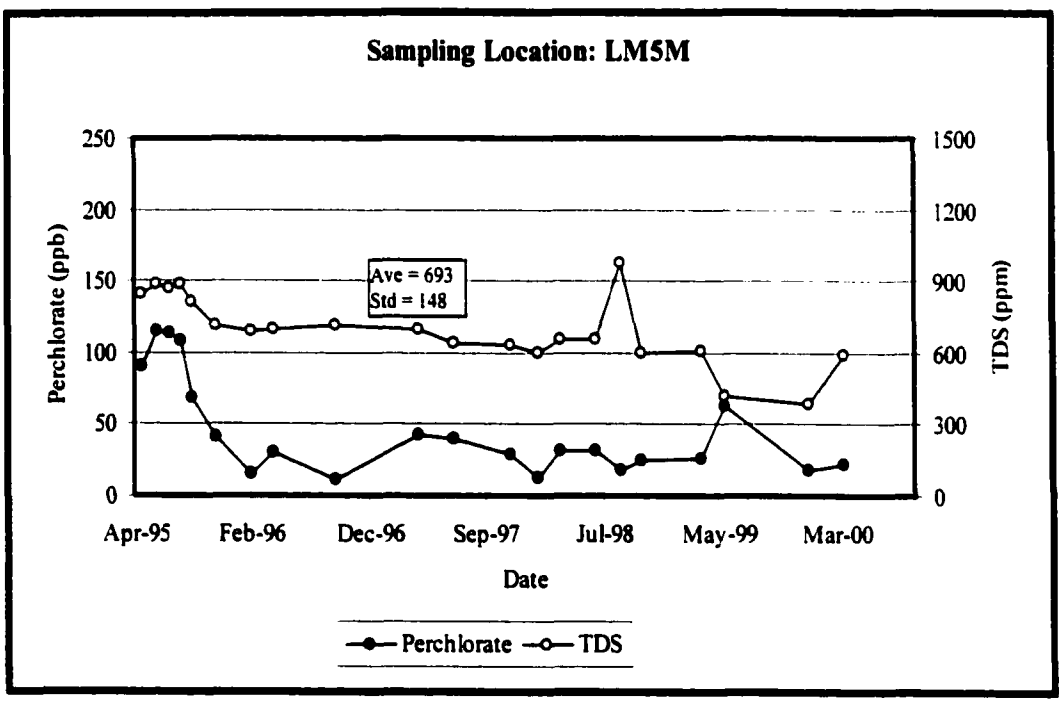


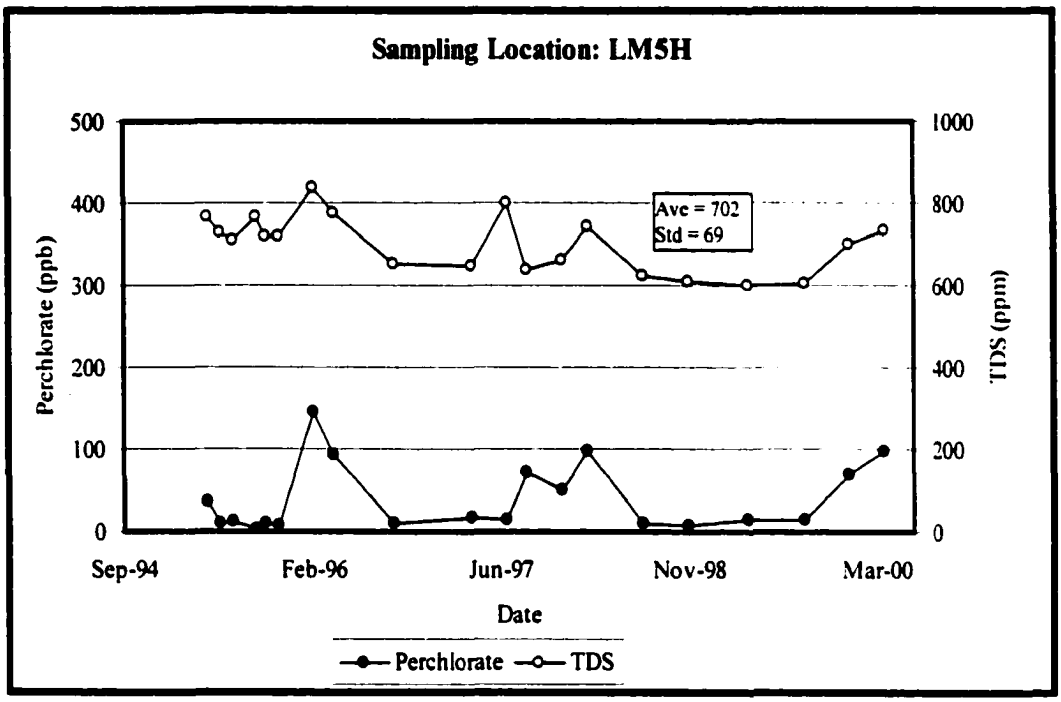


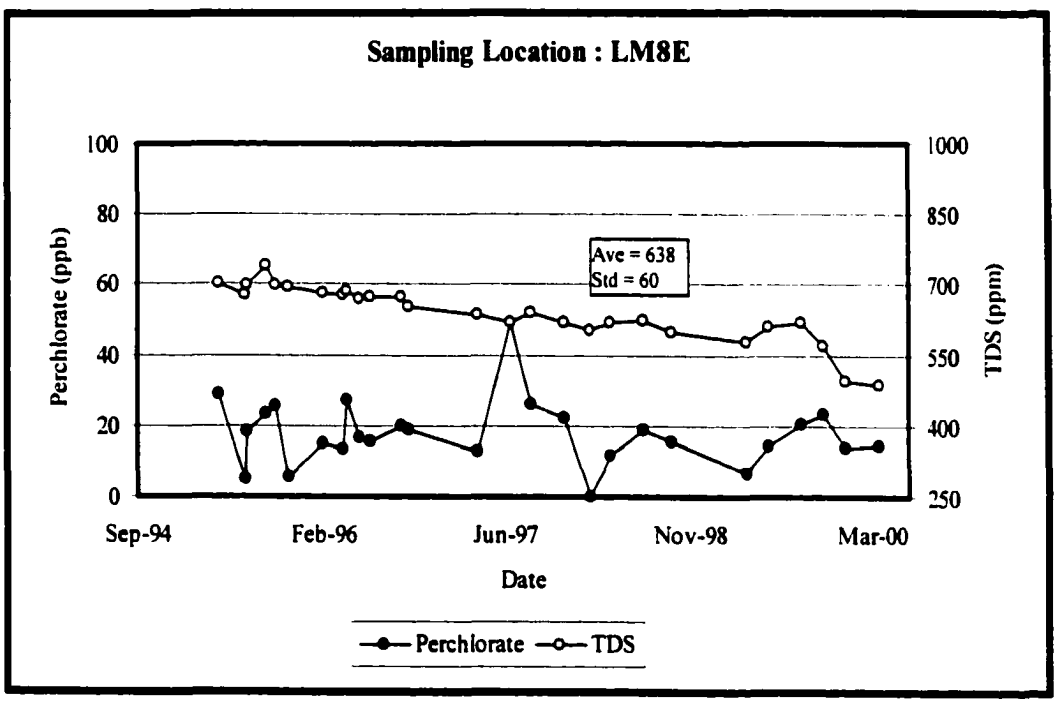


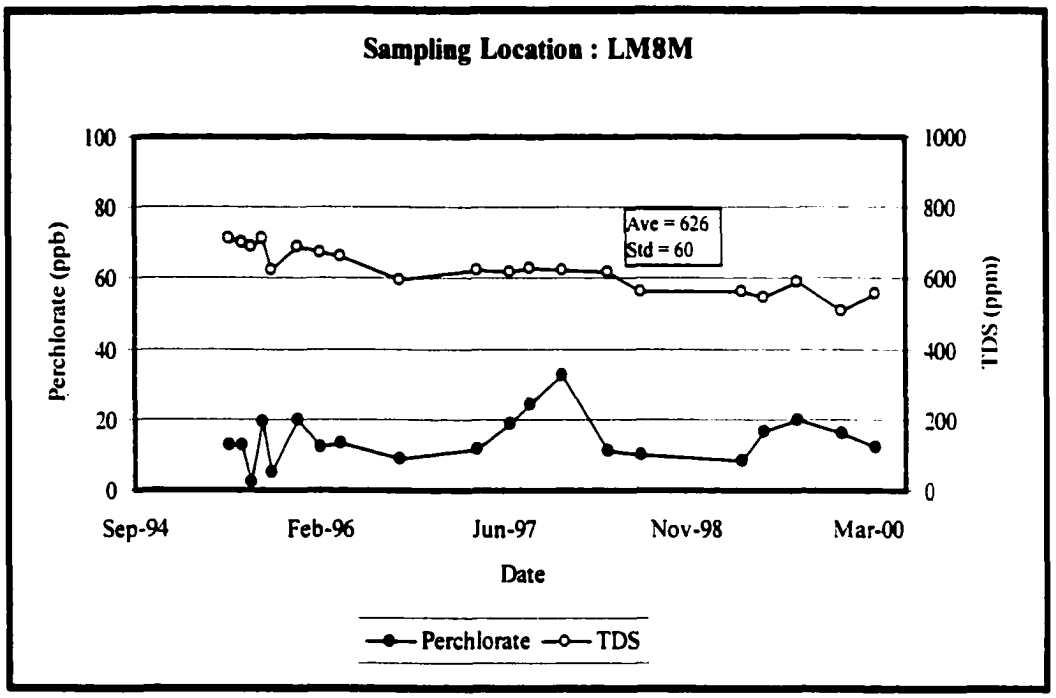


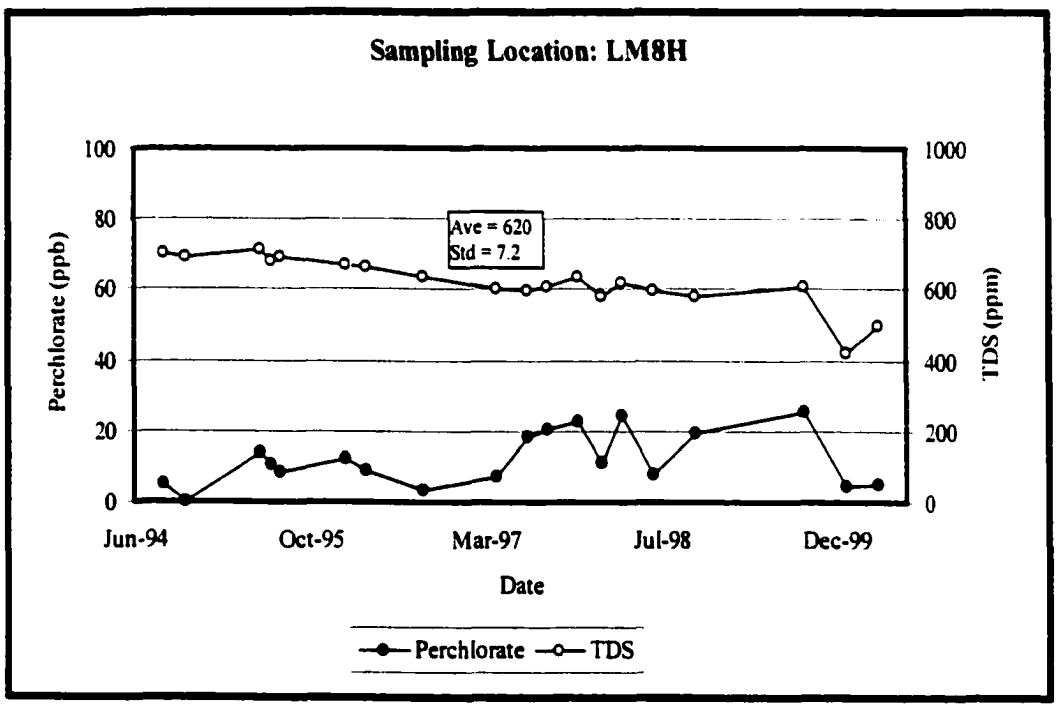


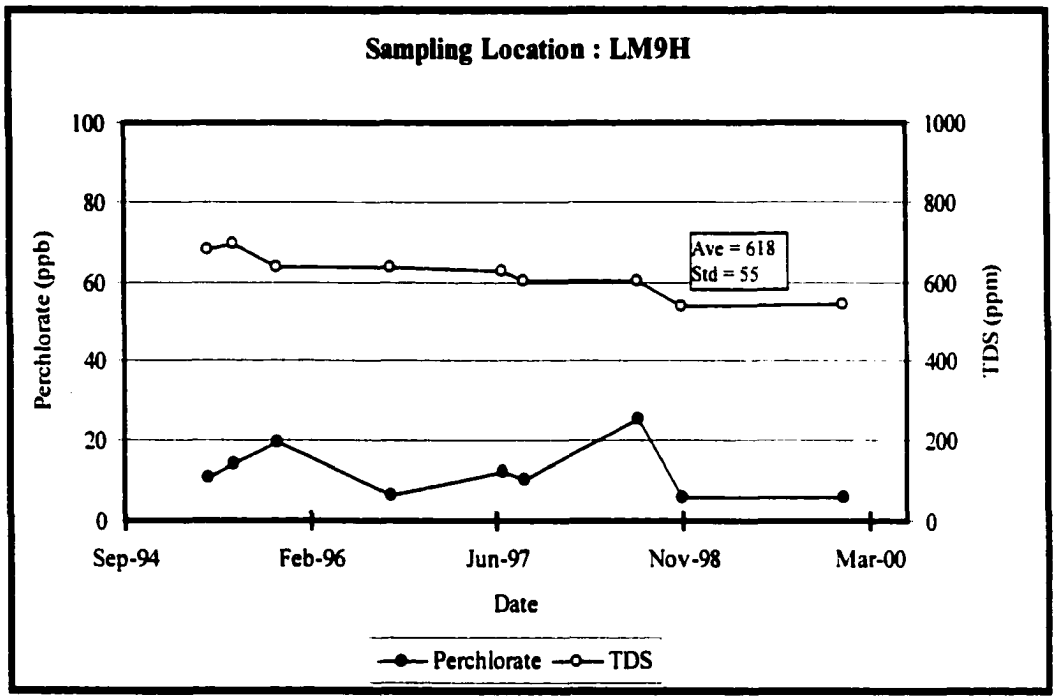












APPENDIX D

FINITE ELEMENT ANALYSES COMPUTER CODE

```
'Program BODDOV14.BAS
'Revision Date: 10/14/1996 & 4/18/2000
'Programmers: Rob Howard & D. James
'
'Purpose: Program solves partial differential equations by the explicit
'          finite difference method.
'          The program computes Biochemical Oxygen Demand (BOD) and
Disolved
'          Oxygen DO profiles in a river.  The  algorithm based on
p.172-179
'          of "Introduction to Water Quality Modelling" edited by A.
James-
'          Wiley and Sons 1993.
'          The program is written in MS-DOS Qbasic.
'
'*************************************************************************
****
CLS 'clears the screen

main:
        GOSUB screenout ' Screen output describing the program
        GOSUB manage.files 'opens input and output files
        startTime! = TIMER
        GOSUB computation 'computation portion of the program
        endTime! = TIMER
        PRINT endTime! - startTime!; "seconds elapsed.  Have a nice
day."
        CLOSE 'closes files
END

computation:
'
' Input intitial conditions
molecular.diffusion = .000176'molecular diffusion coefficient of O2 in
water
                              'at 20 degrees Celsius
 BEEP
 PRINT "Provide Initial Conditions for the analysis." PRINT
 INPUT "Enter the initial temperature (Celsius): "; temperature
 BEEP
 INPUT "Enter the Saturation Oxygen concentration in mg/liter: "; sox
 BEEP
 INPUT "Enter the Dispersion Coefficient in m^2/day: "; E
 BEEP
 INPUT "Enter the BOD Decay Constant in day^-1: "; k1
 BEEP
 INPUT "Enter the Nitrification Coefficient in day^-1: "; k3
 BEEP
 INPUT "Enter the Benthal Demand (BD) in mg/liter:  "; benthal.demand
 BEEP
 INPUT "Enter the Plant Respiration in mg/liter:  "; respire
 BEEP
 INPUT "Enter the photosynthesis in mg/liter:  "; photosynth
 BEEP
 INPUT "Enter the stream velocity in m/day: "; velocity
 BEEP
 INPUT "Enter the stream depth in meters: "; depth
```

```
BEEP
INPUT "Enter the stream width in meters: "; wide
BEEP
INPUT "Enter the length of reach in meters:  "; reach.length
BEEP
INPUT "Enter total time for pollutant transport in days: "; total.time
BEEP
INPUT "Enter the grid size in the x-direction:  "; dx
' Compute time step size
   dt = dx / velocity
' BEEP
' INPUT "Enter the time step size in days:  "; dt
' Compute the value of lambda, used to check for stability of the
solution
  lambda = E * dt / dx ^ 2
BEEP
INPUT "Enter the number of discharges along the reach:  ";
number.discharge
PRINT : PRINT : PRINT :
'=============================================================
'define the number of steps and number of time increements
   ns = reach.length / dx
   time.increment = total.time / dt
'=============================================================
'dimension variables
DIM BOD(ns, time.increment + 1), BOD.prime(ns, time.increment + 1)
DIM DO.val(ns, time.increment + 1), DO.prime(ns, time.increment + 1)
DIM LA(ns), mdot(ns)
'Calculate B and k2 values
  B = benthal.demand + respire - photosynth
'compute k2, reaeration rate constant from Metcalf & Eddy
  k2 = ((molecular.diffusion * velocity) ^ .5) / (depth ^ 1.5)'
reaeration
'=============================================================
'Print headings into output file
PRINT #1, "Temperature = "; temperature; " deg. Celsius   Saturated
Oxygen Concentration= "; sox; " mg/liter"
PRINT #1, "Dispersion Coefficient = "; E; " m^2/day   "
PRINT #1, "BOD Decay Coefficient (k1)= "; k1; " day^-1   Reaeration
rate constant (k2) = "; k2; " day^-1"
PRINT #1, "Nitrification Coefficient (k3) =  "; k3; "day^-1  "
PRINT #1, "Benthal Demand = "; benthal.demand; " mg/liter"
PRINT #1, "Plant Respiration = "; respire; " mg/liter   Photosynthesis=
"; photosynth; " mg/liter"
PRINT #1, "Stream Velocity =  "; velocity; " meters/day"
PRINT #1, "Stream Depth = "; depth; " meters"
PRINT #1, "Stream Width = "; wide; " meters"
PRINT #1, "Reach Length = "; reach.length; " meters"
PRINT #1, "Element cell volume = "; dx * depth * wide; " meters^3"
PRINT #1, "Lambda = "; lambda; "  -- if > 0.25, solution may oscillate
or blow up"

'=============================================================
'loop to initialize
FOR J = 0 TO time.increment
        FOR I = 0 TO ns
                BOD(I, J) = 0
```

```
                DO.val(I, J) = sox
                mdot(I) = 0
                LA(I) = 0
        NEXT I
NEXT J
'============================================================
'calculate the rate of addition of material at the point of discharge
FOR I = 1 TO number.discharge
        BEEP
        INPUT "Enter the point of discharge (model gridpoint)";
discharge.point
        BEEP
        INPUT "Enter the mass addition rate in g/day): ";
mdot(discharge.point)
        ' Compute LA for this mdot and print it out
        LA(discharge.point) = mdot(discharge.point) / (dx * wide *
depth)
        BEEP
        PRINT "Your LA for discharge point "; discharge.point; " is ";
LA(discharge.point); " g/m3/day"
        PRINT #1, " Mass addition rate at point "; discharge.point; "
is "; mdot(discharge.point); " gram/day"
        PRINT #1, " Mass rate normalized to cell volume is ";
LA(discharge.point); " gram/m3/day"
        PRINT
        INPUT " Press <enter> to proceed"; dud$
NEXT I
' Put a blank line in the output file before starting to print results
PRINT #1, ""
PRINT : PRINT

'================================================================
'Calculate the finite difference approximation
gamma = 0
FOR J = 0 TO time.increment
        time.point = time.point + dt
        PRINT "Time  = "; time.point; "days"
        PRINT TAB(3); "Grid point"; TAB(15); "Location"; TAB(28);
"BOD(mg/liter)"; TAB(43); "DO mg/liter"
        PRINT #1, "Time  = "; time.point; "days"
        PRINT #1, TAB(3); "Grid point"; TAB(15); "Location"; TAB(28);
"BOD(mg/liter)"; TAB(43); "DO mg/liter"
        gamma = gamma + 1    'This line doesn't do anything. (**D.J.
looks like a debugging variable)
        'two step explicit method approach

         'advect downstream one step
        FOR I = 1 TO ns        'loop modified from original version to
                          'index arrays in I rather than N
                BOD.prime(I, J) = BOD(I - 1, J)
                DO.prime(I, J) = DO.val(I - 1, J)
                NEXT I
'calculate BOD and DO profiles
                location = 0  'initialize location counter
'compute the value at the next time step
             BOD.denom = 1 + (dt * (k1 + k3) / 2)
             DO.denom = 1 + (dt * k2 / 2)
```

```
FOR I = 1 TO (ns - 1)
                location = location + dx

                BOD.term1 = BOD.prime(I - 1, J) * (dt * E / dx ^ 2)
                BOD.term2 = BOD.prime(I, J) * ((1 - (dt * ((k1 + k3) /
2)) - (2 * dt * E / dx ^ 2)))
                BOD.term3 = BOD.prime(I + 1, J) * (dt * E / dx ^ 2)
                BOD.term4 = dt * LA(I)
                BOD(I, J + 1) = (BOD.term1 + BOD.term2 + BOD.term3 +
BOD.term4) / BOD.denom

                DO.term1 = DO.prime(I - 1, J) * (dt * E / dx ^ 2)
                DO.term2 = DO.prime(I, J) * ((1 - (dt * k2 / 2) - (2 *
dt * E / dx ^ 2)))
                DO.term3 = DO.prime(I + 1, J) * (dt * E / dx ^ 2)
                DO.term4 = (dt * k2 * sox) - (dt * B)
                DO.term5 = (BOD(I, J) + BOD(I, J + 1)) * (dt * k1 / 2)
                DO.val(I, J + 1) = (DO.term1 + DO.term2 + DO.term3 +
DO.term4 - DO.term5) / DO.denom
                GOSUB print.results
        NEXT I
        GOSUB boundary.conditions
NEXT J
RETURN

print.results:
'=================================================================
=========
'print out results
PRINT TAB(3); I, TAB(15); location; TAB(28); BOD(I, J); TAB(43);
DO.val(I, J)
PRINT #1, TAB(3); I, TAB(15); location; TAB(28); BOD(I, J); TAB(43);
DO.val(I, J)
RETURN

boundary.conditions:
        BOD(0, J) = 0
'        BOD(2, J) = 0
        BOD(ns - 1, J) = 0
        BOD(ns, J) = 0
'        DO.val(1, J) = 0
'        DO.val(2, J) = 0
'        DO.val(ns - 1, J) = 0
'        DO.val(ns, J) = 0
RETURN
manage.files:
        BEEP
        INPUT "Enter the name of the file for the output data";
output.file$
        BEEP
        OPEN output.file$ FOR OUTPUT AS #1
        PRINT #1, "Filename: "; output.file$; "  Created : "; DATE$; "
at "; TIME$
        PRINT #1, "Output Data for BODDOVD14.BAS"
        PRINT #1,
RETURN
```

```
screenout:

'Screen Description of program

PRINT
"*************************************************************************
****"
PRINT "*
*"
PRINT "*          Welcome to BODDOV14.BAS
*"
PRINT "*          Revision Date: 10/09/96 and 4/18/2000
*"
PRINT "*          Programmers: Rob Howard & D. James
*"
PRINT "*          Today is "; DATE$; "
*"
PRINT "*   This program calculates the Biochemical Oxygen Demand (BOD)
and      *"
PRINT "*   Disolved Oxygen profiles in a river.
*"
PRINT "*    "
PRINT "*   The solution is obtained using an explicit finite difference
algorithm* "; ""
PRINT "*   based on p.172-177 of 'An Introduction to Water Quality
Modeling'              * "
PRINT "*   by A. James: Wiley & Sons 1993.
* "
PRINT "*   The program is written in MS-DOS QBasic and will run on an
INTEL X86 *"
PRINT "*   machine running under MS-DOS.
*"
PRINT "*
*"
PRINT "*
*"
PRINT
"*************************************************************************
****"
PRINT
INPUT " Press <enter> to proceed"; dud$
CLS 'clears the screen
PRINT
"*************************************************************************
***"
PRINT

 RETURN
```

APPENDIX E

Accuracy of the USGS Streamflow Data Records

Accuracy of the Records

The statement on the accuracy of our records as published in our annual report "Water Resources Data--Nevada, Water Year 1999," is provided below. The accuracy of stream-flow records depends primarily on:

(1) the stability of the stage-discharge relation or, if the control is unstable, the frequency of discharge measurements; and

(2) the accuracy of measurements of stage, measurements of discharge, and interpretation of records.

The accuracy attributed to the records is indicated under "REMARKS."

- "Excellent" means that about 95 percent of the daily discharges are within 5 percent of their true values;
- "good," within 10 percent; and
- "fair," within 15 percent.
- Records that do not meet the criteria mentioned are rated "poor."

Different accuracies may be attributed to different parts of a given record. Daily mean discharges in this report are given to the nearest hundredth of a cubic foot per second for values less than 1 ft3/s; to the nearest tenth between 1.0 and 10 ft3/s; to whole numbers between 10 and 1,000 ft3/s; and to three significant figures for more than 1,000 ft3/s. The number of significant figures used is based solely on the magnitude of

the discharge value. The same rounding rules apply to discharges listed for partial-record stations and miscellaneous sites.

Discharge at many stations, as indicated by the monthly mean, may not reflect natural runoff due to the effects of diversion, consumption, regulation by storage, increase or decrease in evaporation due to artificial causes, or to other factors. For such stations, figures of cubic feet per second per square mile and of runoff, in inches, are not published unless satisfactory adjustments can be made for diversions, for changes in contents of reservoirs, or for other changes incident to use and control. Evaporation from a reservoir is not included in the adjustments for changes in reservoir contents, unless it is so stated. Even at those stations where adjustments are made, large errors in computed runoff may occur if adjustments or losses are large in comparison with the observed discharge. The accuracy of our records as published in "Water Resources Data--Nevada, Water Year 19xx," is listed below:

Water Year	Accuracy: LVW3K	Accuracy: LVW5
1988	Fair	----
1989	Fair	----
1990	Fair except for estimated daily discharges, which are poor.	----
1991	Poor	----
1992	Poor	Poor
1993	Poor	Poor
1994	Poor	Fair except for estimated daily discharges, which are poor.
1995	Poor	Fair except for estimated daily discharges, which are poor.
1996	Fair	Fair
1997	Fair	Fair
1998	Fair	Fair
1999	----	Poor

APPENDIX F

Procedure for the Analyses of Low Concentration of Perchlorate in Water by Ion Chromatography

DIONEX

Application Note 12

Analysis of Low Concentrations of Perchlorate in Drinking Water and Ground Water by Ion Chromatography

INTRODUCTION

Perchlorate (as ammonium perchlorate), which is widely used in solid rocket propellants, has recently been found in drinking water wells in areas where aerospace materials and munitions have been manufactured and tested.[1] Perchlorate is a health concern, as it interferes with the production of thyroid hormones. Current data suggest that an exposure level range of 4 to 18 µg/L (ppb) is acceptable.[2] Although perchlorate is not yet regulated in the U.S. under the Federal Safe Drinking Water Act, the State of California requires remedial action for drinking water sources containing greater than 18 µg/L of perchlorate.

This Application Note details a new method developed to quantify low levels of perchlorate. A large loop injection (1000 µL) is used with an IonPac® AS11 column and suppressed conductivity detection to quantify perchlorate in drinking water down to approximately 2.5 µg/L.

EQUIPMENT

Dionex DX-500 Ion Chromatography system consisting of:
- GP40 Gradient Pump
- CD20 Conductivity Detector
- AS40 Automated Sampler
- LC20 Chromatography Enclosure with a rear-loading valve

4-L Plastic bottle assemblies (two for external water mode)

PeakNet Chromatography Workstation

REAGENTS AND STANDARDS

Deionized water (DI H_2O), Type I reagent grade, 18 MΩ-cm resistance or better

Sodium hydroxide, 50% (w/w) aqueous solution (Fisher Scientific or other)

Sodium perchlorate, 99% ACS reagent grade or better (Aldrich or other)

Potassium sulfate, 1000 mg/L aqueous solution (Ultra Scientific or other)

CONDITIONS

Columns:	IonPac AS11 Analytical, 4 x 250 mm (P/N 44076) IonPac AG11 Guard, 4 x 50 mm (P/N 44078)
Eluent:	100 mM Sodium hydroxide
Run Time:	12 min
Flow Rate:	1.0 mL/min
Sample Volume:	1000 µL
Detection:	Suppressed conductivity, ASRS® (4 mm AutoSuppression® external water mode
System Backpressure:	600–900 psi (3.95–5.93 MPa)
Background Conductance:	2–5 µS

PREPARATION OF SOLUTIONS AND REAGENTS

Standard Solution

Stock perchlorate standard solution (1000 mg/L)

Dissolve 1.231 g of sodium perchlorate in 1000 mL of deionized water to prepare a 1000 mg/L standard. Standard is stable for at least one month when stored at 4 °C.

Working Standard Solutions

Dilute 1000 mg/L standard solution as required with deionized water to prepare the appropriate working standards.

Eluent Solution

100.0 mM Sodium hydroxide

Weigh 992.0 g of deionized water into an eluent bottle. Degas water for approximately 5 minutes. Carefully add 8.0 g of 50% sodium hydroxide directly to the bottle. Mix then quickly transfer the eluent bottle to the instrument and pressurize the bottle with helium at 8 psi (0.055 MPa).

RESULTS AND DISCUSSION

For the best perfomance at low-ppb levels, it is critical that baseline noise be kept to a minimum. To minimize baseline noise, it is necessary to use the ASRS in external water mode rather than the recycle mode. An equilibrated system will produce a background conductance between 2–5 µS. Peak-to-peak noise is typically 10 nS and system backpressure is 600–900 psi (3.95–5.93 MPa). A system blank is determined by using deionized water as a sample. This blank establishes the baseline and confirms the lack of contamination in the system. The linear concentration range was determined to ensure accurate quantification of perchlorate in the 2.5–100 µg/L range. Figure 1 shows the results of a linearity study.

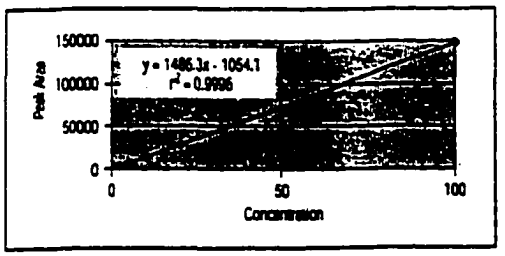


Figure 1 Perchlorate calibration

This plot demonstrates that calibration of perchlorate is linear in the low-ppb range. Figure 2 shows a typical chromatogram of a 20 µg/L perchlorate standard. To determine the method detection limit (MDL), seven injections of the 2.5 µg/L perchlorate standard were made. Table 1 shows the results of a method detection limit study. The 1000 µL injection is large enough to achieve the desired detection limit without overloading the column. Note that this method is not intended for use with high (ppm) levels of perchlorate. The calculated MDL equals 254 ng/L (ppt).

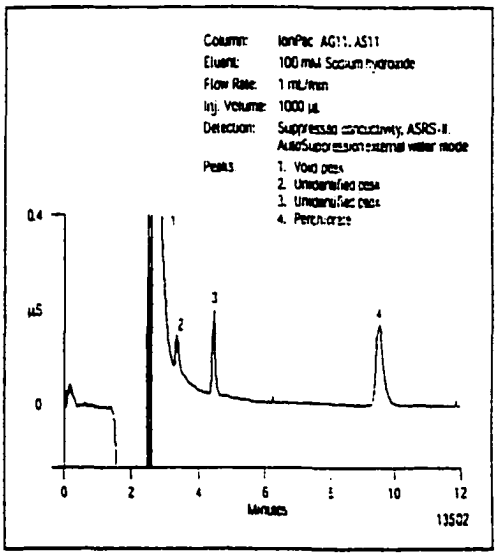


Figure 2 20 µg/L Perchlorate standard

Injection #	Area counts	Retention time (min)
1	3391	9.48
2	3405	9.57
3	3504	9.50
4	3503	9.45
5	3435	9.47
6	3301	9.52
7	3315	9.43
Average	3408	9.49
SD	81	0.05
RSD	2.38	0.49

MDL=254 ng/L (ppt). MDL=SD*$t_{(n)}$ where $t_{(n)}$=3.14 for n=7

Figures 3 through 5 show chromatograms obtained for 2.5 µg/L perchlorate in three different matrices. Figure 3 shows the chromatogram of 2.5 µg/L perchlorate in deionized water. Figure 4 shows 2.5 µg/L perchlorate in tap water. Note that all other anions present in tap water elute in the void volume and do not interfere with perchlorate determination. Some environmental samples may contain low levels of perchlorate in the presence of a large amount of sulfate. Figure 5 shows the determination of 2.5 µg/L perchlorate in the presence of 700 mg/L sulfate. The high concentration of sulfate does not affect perchlorate recovery or the detection limit.

SUMMARY

The method outlined in this Application Note allows the determination of low-µg/L (ppb) levels of perchlorate. Linear concentration ranges have been established to accurately quantify perchlorate in drinking water and ground water samples.

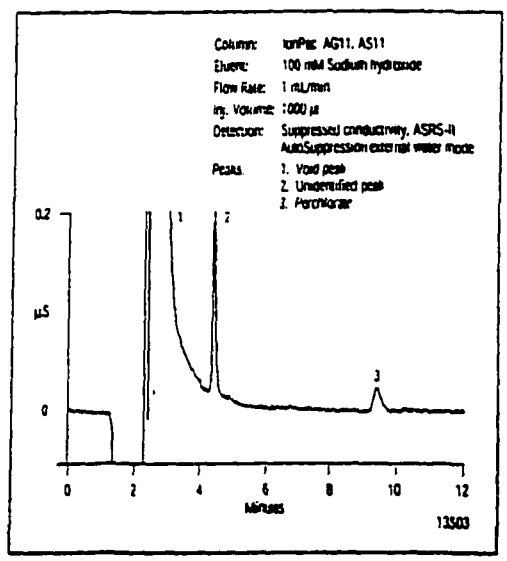


Figure 3 2.5 µg/L Perchlorate standard

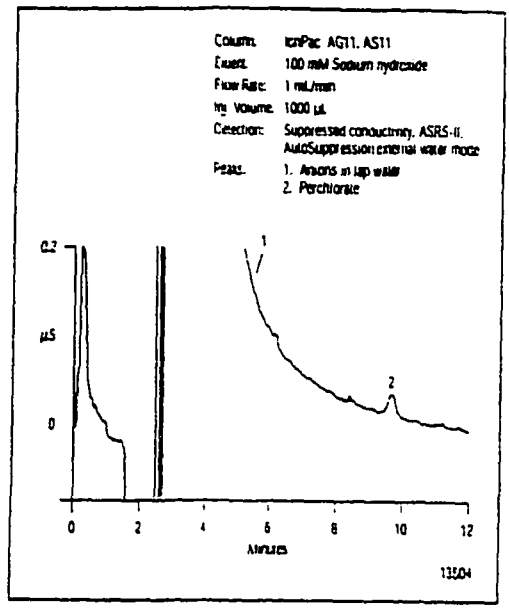


Figure 4 2.5 µg/L Perchlorate in tap water

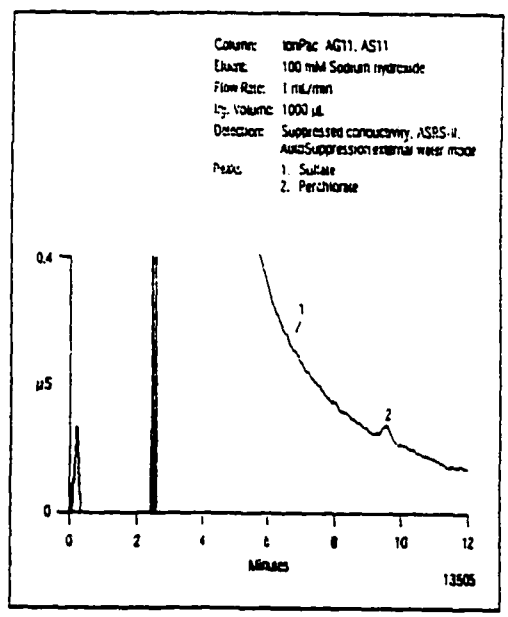


Figure 5 2.5 µg/L Perchlorate and 700 mg/L Sulfate

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2. Correspondence from Joan S. Dollarhide, National Center for Environmental Assessment, Office of Research and Development, to Mike Girrard, Chairman, Perchlorate Study Group, U.S. EPA, 1995.

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Aldrich Chemical Company, Inc., 1001 West Saint Paul Avenue, P.O. Box 355, Milwaukee, Wisconsin, 53233, USA. Tel: 1-800-558-9160.

Fisher Scientific, 711 Forbes Ave., Pittsburgh, Pennsylvania, 15219-4785, USA. Tel: 1-800-766-7000.

Ultra Scientific, 250 Smith Street, North Kingstown, Rhode Island, 02852, USA. Tel: 401-294-9400.

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VITA

The Graduate College
University of Nevada, Las Vegas

Manjula Roshan Boralessa

Home Address:
1895 N. Green Valley Parkway, # 1912
Henderson, Nevada 89014

Degree:
Bachelor of Science, Agricultural and Biological Engineering 1994
Cornell University, Ithaca, New York 14853, USA
Masters of Engineering, Agricultural and Biological Engineering 1995
Cornell University, Ithaca, New York 14853, USA

Publications
Boralessa, M.R., Batista, J.R., Historical Perchlorate Levels in the Las Vegas Wash and Lake Mead, Paper presented at the 2000 AWWA Inorganic Contaminants Conference, February 27-29, 2000, Albuquerque, New Mexico.

Thesis Title: Transport of Perchlorate in Las Vegas Wash and Lake Mead.

Thesis Examination Committee:
Chairperson, Dr. Jacimaria Ramos Batista, Ph.D.
Committee Member, Dr. David Earl James, Ph.D.
Committee Member, Dr. Thomas Piechota, Ph.D.
Graduate Faculty Representative, Dr. Malvane Ananda, Ph.D.