WATER AND EFFLUENT MANAGEMENT OF BALMER LAKE TAILINGS MANAGEMENT SYSTEM

by

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Abstract

In recent years, environmental concerns have increased awareness in the mining industry resulting in more resources being devoted to minimizing the environmental impact of mining and its effluents. This study was carried out to assess the effectivenss of Balmer Lake tailing managment system in improving effluent and to generate data for the mine closure plan of the A.W. White Mine of Goldcorp Inc. located in Red Lake, Northwestern Ontario. At this mine, gold ore is treated using a cyanidation-Merrill-Crowe process and the fine tailings are discharged to a 3-pond tailings system.

A review of the main legislation affecting tailings management in Ontario revealed that the Mining Act, Fisheries Act, Environment Protection Act and the Ontario Water Resources Act (OWRA) are most relevant. Under the authority of OWRA, site-specific enforceable water quality parameters are specified in the Certificate of Approval.

The main objective of this work was to establish the effectiveness of Balmer Lake tailings management system in improving effluent quality. In order to achieve this, the study involved a hydrological assessment, water quality assessment and an evaluation of the effectiveness of the tailings ponds in improving effluent. A water and mass balance model for the system was also developed. The results can be used to improve or validate the existing water management system with quantifiable data.

The study was able to establish that catchment hydrology plays a very significant role in the Balmer Lake tailings system, with natural inflow accounting for 84% of the total inflow into Balmer Lake. The impact of hydrology on Pond 1 is that it reduces the retention time in the pond and does not allow, therefore, sufficient time for pond mechanisms such as volatilization, precipitation and sedimentation to effectively improve the effluent quality. In Pond 2, hydrology is not significant due to the fact that the catchment area is small. In Pond 3, the

excess runoff during late spring and early summer does not allow sufficient time for effluent improvement. This can possibly result in the discharge of non-compliant effluents relative to the Certificate of Approval, enforced by the Ontario Ministry of Environment under the legislative authority of the OWRA. To avoid this, the Certificate of Approval specifies that from May 1 to July 1 no discharge should be allowed from Balmer Lake without permission from the Ministry of Environment. The excess runoff, however, often forces discharge to protect the impoundment from being overtaxed.

The evaluation of the effectiveness of the tailings management system was carried out using total efficiency, mass removal efficiency and effluent improvement efficiency due to dilution. Pond 1 was found to be ineffective in improving effluent quality. Over the years, the accumulation of tailings in the pond has reduced its effectiveness by reducing the retention time. A decline in overall effluent improvement efficiency was observed over a 7 year period. Although the overall efficiency for all parameters was positive, it was found that it was mainly due to dilution for cyanide and totally due to dilution for copper and nickel. Unlike Pond 1, the mass removal efficiency for Pond 2 was positive for all the water quality parameters. Mass removal of cyanide was attributed to volatilization with pH at 7.8, while for copper and nickel, precipitation and sedimentation is the most likely removal mechanism. In Pond 3, both mass removal and dilution were significant in improving effluent quality.

The water and mass balance model was used to evaluate the effect of changing some of the water input parameters on the overall tailings management system. Using the model it was found that by diverting 20% of the catchment area, an extra 2 month retention period in Balmer Lake would result. This would significantly reduce the problem caused by the excess spring runoff into Balmer Lake and could be achieved by diverting Natural Drainage River 3 (NDR3) just before it enters Pond 1, hence reducing the Pond 1 catchment area as well. Diverting NDR3 would also result in a better performance for Ponds 1 and 2 due to increased retention times. This would ensure better water and waste water management for the Balmer Lake tailings system.

Table of Contents

Abstract ii

Table of Contents v

List of Figures x

List of Tables xii

Acknowledgments xiv

1.0 INTRODUCTION 1

1.1 General Overview 1

1.2 Objectives of the Study 3

1.3 Scope of the Study 4

1.3.1 Evaluation of the catchment hydrology 4

1.3.2 Study of effluent quality characteristics and the performance of the tailings system 4

1.3.3 Development of the water and mass balance model 6

2.0 THEORETICAL AND APPLIED ASPECTS OF TAILINGS MANAGEMENT SYSTEM 8

2.1 Introduction 8

2.2 Legislation Governing Tailings Effluent Quality 10

2.2.1 Introduction 10

2.2.2 Canadian Federal Legislation 10

2.2.3 Provincial Legislation - British Columbia 11

2.2.4 Provincial Legislation - Ontario 13

2.3 Water Management of a Tailings Pond 14
2.3.1 Introduction 14
2.3.2 Mill water use 15
2.3.3 Hydrology 15
2.3.4 Water control 16
2.4 Effluent Improvement Processes in a Tailings Pond 17
2.4.1 Introduction 17
2.4.2 Source of cyanide and heavy metals in mill effluent 18
2.4.3 Natural degradation of cyanide and removal of heavy metals 19
2.5 Water and Mass Balance Modeling of a Tailings Pond 21
2.5.1 Water balance 21
2.5.2 Mass balance evaluation 22
2.6 Summary 22
3.0 FIELD ASSESSMENT AND STUDY METHODS 24
3.1 Introduction 24
3.2 Topographical Assessment of the Catchment 24
3.2.1 Site description 24
3.2.2 Sub-catchment and pond area evaluations 25
3.3 Hydrological Data Collection 27
3.3.1 Flow measurement stations 27
3.3.2 Flow measurement methods 29
3.3.3 Flow measurement frequency 32
3.3.4 Precipitation and evaporation data 32

3.4 Water Quality Sampling 33
3.4.1 Sampling stations 33
3.4.2 Sampling method and procedure 34
3.4.3 Preservation, storage and transportation 35
3.4.4 Methods of analysis 35
3.4.5 Quality assurance 36

4.0 HYDROLOGICAL ASSESSMENT 37

4.1 Introduction 37

4.2 Presentation and Analysis of Flow Results 39
4.2.1 Stream flow characteristics (hydrographs) 39
4.2.2 Rainfall-flow relationships 42
4.2.3 Catchment area-flow relationships 46

4.3 Flow Volume Estimation 48
4.3.1 Rainfall-runoff relationship 48
4.3.2 Flow volume estimation 50

4.4 Summary of Flow Results 52

5.0 WATER QUALITY ASSESSMENT 54

5.1 Introduction 54

5.2 Water Quality Data Analysis 55
5.2.1 Influent and effluent quality 55
5.2.2 Evaluation of effluent improvement efficiency 60
5.2.3 Evaluation of mass removal efficiency 64
5.2.4 Evaluation of effluent improvement efficiency due to dilution 67

5.3 Summary of Data Analysis for Pond 1 73

6.0 WATER AND MASS BALANCE MODELING 77

6.1 Introduction 77

6.2 Model Definition 77

6.2.1 Pond 1 79

6.2.2 Pond 2 79

6.2.3 Pond 3 (Balmer Lake) 79

6.3 Model Input and Output Parameters 80

6.4 Model Solution Using Microsoft Excel 81

6.5 Model Results 81

6.5.1 Water balance 81

6.5.2 Mass balance 84

6.6 Sensitivity Analysis 91

6.6.1 Reduction in catchment area 92

6.6.2 Change in rainfall-runoff coefficient 93

6.6.3 Increase in mill discharge 94

6.7 Summary 95

6.7.1 Water balance 95

6.7.2 Mass balance 96

7.0. DISCUSSION AND APPLICATION OF RESULTS 98

7.1. Introduction 98

7.2. Hydrological Assessment 98

7.3. Water Quality Assessment 102

7.4. Water and Mass Balance Modeling 105

8.0 CONCLUSIONS AND RECOMMENDATIONS 109

8.1 Conclusions 109

8.2 Recommendations for Further Study 112

REFERENCES 116

APPENDIX I 120

A1.1 Photographs of the flow measuring stations 120

A1.2 Using a Current Meter 123

A1.3 Using an Open Channel Monitor II (OCM II) 128

A1.4 Precipitation and Evaporation Data 130

A1.4.1. Daily precipitation data for the field study period 130

A1.4.2. Monthly precipitation data 1990 to 1993 134

A1.4.3. Average monthly evaporation data (1957-1966) 135

APPENDIX II 136

A2.1 Measured Flow Data 136

A2.2 Evaluation of the Runoff Coefficient - 1992/3 144

A2.3 Evaluation of the Snow Runoff 145

List of Figures

Figure 1.1. Schematic overview of Balmer Lake tailings system 5

Figure 2.1. Factors and mechanisms affecting a tailings pond 9

Figure 2.2. In the first pond undergoing natural degradation, mill effluent concentration with . irregular variation results in effluent concentration with seasonal variation 20

Figure 2.3. In a second pond undergoing natural degradation with a shorter retention time, ... seasonal variation in influent concentration results in effluent concentration with . seasonal variation without a lag. 21

Figure 2.4. Water flow through a tailings pond (Modified from Swaisgood and Toland, 1973) 22

Figure 3.1. Balmer Lake Catchment 25

Figure 3.2. Balmer Lake Catchment showing the sub-catchments for each creek 26

Figure 3.3. Cross section of a uniform flow measurement station 30

Figure 3.4. Cross section of a culvert flow measurement station 31

Figure 3.5. Water quality sampling stations 33

Figure 4.1. Upper Balmer Creek and Pond 1 Effluent 1992 (May to July) 40

Figure 4.2a, b. Hydrographs of Upper Balmer Creek, Pond 1 Effluent, NDR3 and the Diversion Ditch 1993 (a) April to August and (b) April to July 25 42

.Figure 4.3. Total catchment rainfall volume (bars) vs. flow (line) for Upper Balmer Creek ..... (1992) 43

Figure 4.4. Total catchment rainfall volume (bars) vs. flow (line) for Upper Balmer Creek ..... (1993) 44

Figure 4.5. Total catchment rainfall volume (bars) vs. flow (line) for Pond 1 Effluent (1992)44

Figure 4.6. Total catchment rainfall volume (bars) vs. flow (line) for Pond 1 Effluent (1993)45

Figure 4.7. Total catchment rainfall volume (bars) vs. flow (line) for NDR3 (1993) 45

Figure 4.8. Total catchment rainfall volume (bars) vs. flow (line) for Diversion Ditch (1993)46

Figure 4.9. Upper Balmer Creek and Pond 1 Effluent 1992 (May to July) discharge per catchment area 47
Figure 4.10 a, b. Discharge per catchment are for Upper Balmer Creek, Pond 1 Effluent, NDR3 and Diversion Ditch 1993 (a) April to August and (b) April to July 25. 48
Figure 5.1. Influent and effluent quality for Pond 1 (CN) 56
Figure 5.2. Influent and effluent quality for Pond 1 (Cu) 56
Figure 5.3. Influent quality and effluent quality for Pond 2 (CN) 57
Figure 5.4. Influent quality and effluent quality Pond 3 (CN) 59
Figure 5.5. Influent quality and effluent quality for Pond 3 (Cu) 59
Figure 5.6. Effluent improvement efficiency for Pond 1 (1987-92) 60
Figure 5.7. Effluent improvement efficiency for Pond 2 62
Figure 5.8. Effluent improvement efficiency for Pond 3 63
Figure 5.9. Improvement efficiency due to dilution and actual (CN) 69
Figure 5.10. Improvement efficiency due to dilution and actual (Cu) 70
Figure 5.11. Effluent improvement efficiency due to dilution and the actual 71
Figure 5.12. Effluent improvement efficiency due to dilution and the actual 72
Figure 5.13. Effluent improvement efficiency due to dilution and the actual (CN) 73
Figure 5.14. Effluent improvement efficiency due to dilution and the actual (Cu) 73
Figure 6.1. Water balance model for the tailings management system 78

List of Tables

Table 2.1 Metal Mining Liquid Effluent Regulations (Reichenbach, 1994) 11

Table 3.1. Areas of sub-catchments and ponds 26

Table 4.1. Monthly runoff volumes for Upper Balmer Creek 50

Table 4.2. Monthly runoff volumes for Pond 1 Effluent 50

Table 4.3. Monthly runoff volumes for NDR3 (Beaver Creek) 51

Table 4.4. Monthly runoff volumes for the Diversion Ditch 51

Table 5.1. Average influent and effluent quality for Pond 1 (1987-1992) 56

Table 5.2. Influent and effluent quality for Pond 2 (1987-1992) 58

Table 5.3. Average Influent and effluent quality for Pond 3 (1987-1992) 59

Table 5.4. Annual average influent and effluent concentration and effluent improvement efficiency for Pond 1 (1987-1992). 61

Table 5.5 Annual average influent and effluent concentration and effluent improvement efficiency for Pond 2 (1987-1992). 62

Table 5.6. Annual average influent and effluent concentration and effluent improvement efficiency for Pond 3 (1987-1992). 64

Table 5.7. Mass removal efficiency evaluations for Pond 1 (cyanide) 65

Table 5.8. Mass removal efficiency evaluations for Pond 1 (copper and nickel) 65

Table 5.9. Mass removal efficiency evaluation for Pond 2 (cyanide) 66

Table 5.10 Mass removal efficiency evaluation for Pond 2 (copper and nickel) 66

Table 5.11 Mass removal efficiency evaluation for Pond 3 (cyanide) 67

Table 5.12 Mass removal efficiency evaluation for Pond 3 (copper and nickel) 67

Table 6.1. Summary of Pond 1 water balance model (m^3/year) 82

Table 6.2. Summary of Pond 2 water balance model 82

Table 6.3. Summary of Pond 3 water balance model 84

Table 6.4. Summary of Pond 1 mass balance model (cyanide) 85

Table 6.5. Summary of Pond 1 mass balance model (copper) 86

Table 6.6. Summary Pond 1 mass balance model (nickel) 86
Table 6.7. Summary of Pond 2 mass balance model (cyanide)..87
Table 6.8. Summary of Pond 2 mass balance model (copper) 87
Table 6.9. Summary of Pond 2 mass balance model (nickel) 88
Table 6.10. Summary of Pond 3 mass balance model (cyanide)..89
Table 6.11. Summary of Pond 3 mass balance model (copper) 90
Table 6.12. Summary of Pond 3 mass balance model (nickel) 91
Table 6.13. Pond 3 water balance model reduction in catchment area.................................93
Table 6.14. Pond 3 water balance model - change in runoff coefficient 94
Table 6.15. Pond 3 water balance model increase in mill outflow.......................................95

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1.0 INTRODUCTION

1.1 General Overview

In recent years, environmental concerns have increased awareness in the mining industry resulting in more resources being devoted to minimizing the environmental impact of mining and mining effluent. Mining companies have been under increasing pressure to keep up with changing regulations which are becoming significantly more stringent. If mining is to remain a competitive industry in Canada, it has to meet the challenges posed by these developments.

Regulations which have had the biggest impact on mining operations are related to mine closure which normally fall under the Mining Act of the particular jurisdiction. In the closure plan, the mine is required to demonstrate quantitatively, that the effluent will not have a significant impact on the receiving environment after closure. Before a mine can start to operate, it has to obtain various permits and licenses which should ensure that the environment is not adversely affected during its operations and after closure. One of these permits is specific to waste water management. In Ontario for example, the province where the present study was carried out, mines need to obtain a Certificate of Approval, which is enforceable under the Ontario Water Resources Act (OWRA), to ensure that the mine effluent does not impair the aquatic environment.

This study was carried out as part of the mine closure plan for the A.W. White Mine of Goldcorp Inc. located in Red Lake, Northwestern Ontario. At this mine, gold ore is treated using the cyanidation-Merrill-Crowe process and the fine tailings are discharged to a 3 pond system. The final polishing pond is a natural lake, Balmer Lake. At the time of the study the final polishing pond was shared with the adjacent Campbell Mine of Placer Dome Inc. In the pond system residual cyanide is removed by natural degradation, and heavy metals by both physical and chemical processes.

It is the long term goal of the Ministry of Environment of Ontario, to restore Balmer Lake to its natural state which prevailed before mining operations were initiated. The Ministry of Environment of Ontario is also concerned about the impact of the effluent from Balmer Lake on downstream aquatic life, especially fish which frequent the downstream waters. The most sensitive period is the early spring. At this time, it is possible that cyanide and heavy metal levels can exceed the permit requirements, while at the same time, this is the spawning period for fish. In this period, discharge is not allowed except in emergency cases, and then only with careful monitoring.

Hydrological and water quality assessment, and evaluation of the effectiveness of the tailings pond in improving effluent quality were conducted. A water and mass balance model for the system was also developed. The results can be used to improve or validate the existing water management plan to provide quantifiable data about the possible impact of any change on the system. Recognizing that tailings management is primarily a water management problem (Firlotte and Welch, 1989), a good water management plan is important for the development, operation and ultimate decommissioning of the site. Water management involves both qualitative and quantitative management. Qualitative management involves improving effluent quality to the acceptable regulatory standards, while quantitative management involves effectively managing water volumes.

The main contaminants in gold mill effluent are cyanide and heavy metals. Cyanide is used for gold recovery in the cyanidation process (Scott, 1989). Cyanide being a powerful solvent and non-selective for gold, a host of deleterious elements such as copper, nickel, zinc and iron simultaneously enter into solution during the process. In this study, the water quality parameters which will be considered in detail are cyanide, copper and nickel.

Cyanide in gold mill effluents has to be reduced to acceptable levels before discharge. Natural degradation is still the most commonly employed method for cyanide effluent improvement at Canadian gold mills (Scott, 1989) although the INCO SO_2/Air and hydrogen peroxide treatments are now commonly used for primary destruction. Even those mines which use these alternative primary treatment processes still partially rely on natural degradation for pre-treatment or final polishing. Natural degradation of cyanide is the most cost effective method of treatment (Wilson and Wilson, 1987) and is the process used at the study site.

The rate of the processes involved in natural degradation increase with increasing temperature. A pond undergoing natural degradation, therefore, is characterized by better performance during warmer months and poorer performance during colder months. This can produce distinct seasonal variations in the pond effluent quality. These seasonal variations have a significant effect on permit requirements, and on receiving waters. Both of these have specific threshold values which are independent of seasonal variations of the pond performance.

1.2 Objectives of the Study

The main objective of this work is to carry out a detailed hydrological and water quality assessment of the Balmer Lake tailings management system. The study will establish the effectiveness of the system in improving effluent quality and make suggestions on how it can be improved. In order to do this, the study had the following sub-objectives:

- Evaluation of the impact of the catchment hydrology on the tailings management system, especially the impact on the effluent quality and quantity;
- Evaluation of the water quality and the performance of the tailings system using pond parameters such as mass removal efficiency, improvement efficiency due to dilution, and total efficiency in order to establish the most significant mechanisms in each pond; and
- Development of a water and mass balance model for Balmer Lake tailings management system.

1.3 Scope of the Study

This section gives a detailed description of the above objectives.

1.3.1 Evaluation of the catchment hydrology

For an open tailings system such as Balmer Lake, the catchment hydrology has a significant impact on both the effluent quality and quantity. To assess this impact, the investigation involved the following:

- division of the catchment into sub-catchments, with a creek draining each sub-catchment;
- flow measurement at all accessible creeks to determine flow characteristics and volumes;
- quantifying total inflow into the tailings system;
- evaluating flow rates into the tailings system;
- evaluating extreme storm events and the possible impact on the tailings system;
- collection of precipitation and evaporation data; and
- evaluation of catchment runoff coefficients.

The hydrological assessment also involved a review of other previous studies carried out on the catchment. Any relevant data was used to expand the database and the understanding of the catchment hydrology.

1.3.2 Study of effluent quality characteristics and the performance of the tailings system

The schematic overview of Goldcorp tailings management system has 3 ponds in series (Figure 1.1). Effluent quality was monitored at the outflow from each pond. Assessment of the water quality at different discharge points through the system involved the following:

- regular effluent quality sampling; and
- analysis of effluent quality data to investigate any important trends in the data.

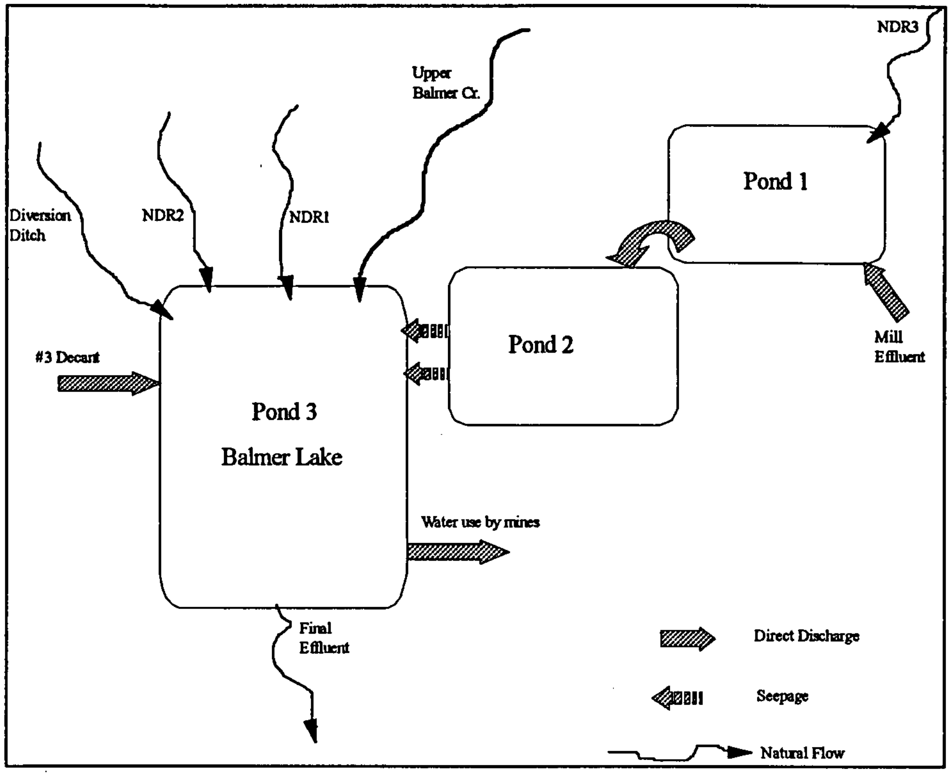


Figure 1.1. Schematic overview of Balmer Lake tailings system

The performance of a tailings management system undergoing natural degradation is influenced by a number of mechanisms such as: volatilization, sedimentation, precipitation, and dilution. Although this list is not exhaustive, it does include those mechanisms believed to have the most significant impact on the Balmer Lake tailings system.

The overall effect of these mechanisms on the effluent quality can be assessed by determining the pond effluent improvement efficiency, which is the difference in the influent and effluent concentration expressed as a percentage of the influent concentration. However, the relative significance of the different mechanisms is not apparent. To assess the significance of the different mechanisms and identity the most dominant mechanisms, the following evaluations were undertaken:

- evaluation of the effluent improvement efficiency of each pond;
- evaluation of the impact of the dilution from natural water on the effluent quality; and

- mass removal efficiency evaluation to determine sedimentation, volatilization and re-suspension.

1.3.3 Development of the water and mass balance model

A water and mass balance evaluation was developed for each of the three ponds being studied. Ponds 1 and 2 were evaluated as sub-models and the Pond 3 (Balmer Lake) model accounted for the whole catchment. All significant water and mass inflows and outflows for each pond were identified and quantified.

The topographical, hydrological and water quality assessment data was used as input for the modeling process. The inputs for the water balance model were: monthly rainfall, snowfall for each hydrological year, monthly lake evaporation, surface area for each pond and sub-catchment area; runoff coefficient; mill effluent and water usage by the mines. The inputs for the mass balance model were: the monthly water inflow and outflow from the water balance model, and the effluent concentration of cyanide, copper and nickel.

The outputs from the water and mass balance model were the monthly water and mass inflows and outflows. The model results can be used for:

- identifying and quantifying the main water and mass input and output into each of the ponds;
- evaluating the significance of deposition and re-suspension in the ponds;
- evaluating the significance of dilution on the pond system; and
- evaluating the impact of any change in the system such as an increase in mill effluent quantity, decrease in catchment area through diversion, or a change in catchment characteristics resulting in a higher or lower runoff coefficient.

A water and mass balance model is an effective tool for evaluating the effectiveness of the existing system, while pointing to the most appropriate available options for increasing the effectiveness of the system. The increasing pressure on mining companies from the more stringent environmental regulations makes improvement to a tailings system inevitable. A water and mass balance model provides a good starting point for understanding and evaluating the effect of those improvements.

2.0 THEORETICAL AND APPLIED ASPECTS OF A TAILINGS MANAGEMENT SYSTEM

2.1 Introduction

In this chapter, a review of how a tailings management system functions is presented based on current knowledge and practice. The review focuses mainly on water and waste water management. The specific interrelated topics covered include:

- legislation governing tailings pond systems for Ontario, BC and Federal jurisdictions;
- water management of a tailings pond;
- effluent improvement mechanisms in a tailings pond system; and
- water and mass balance evaluation of a tailings pond.

For a mine to operate, it has to obtain several permits, one of which is the waste water management permit to ensure environmental protection from mine effluent. This permit specifies the requirements which the effluent has to meet before it can be discharged into the environment. The mine has to demonstrate that there is a strategy in place which will ensure that the waste water will be treated to the required regulatory standard. Acts which affect waste water management in Ontario include the Mining Act, Fisheries Act, Environmental Protection Act and Ontario Water Resources Act. Under the authority of the Ontario Water Resources Act (OWRA), site-specific enforceable water quality parameters are specified in the Certificate of Approval.

To ensure that the mine will meet regulatory requirements, it has to have a good water management strategy. A tailings system is one of the principal features of mine effluent water management. According to Ritcey (1989) and Water Pollution Control Directorate Staff (1975), a well designed tailings pond should perform some of the following functions:

- sedimentation of tailings solids;

- final retention of tailings residue and precipitate sludges;
- heavy metal precipitate formation and sedimentation;
- stabilization of constituents that require oxidation, e.g. cyanide to carbon dioxide and nitrogen;
- storage of seepage and runoff water;
- balancing influent quality and quantity; and
- storage prior to the recycling of quantities of water for re-use in the milling process.

Managing the quantity of water is of less significance if the quality is not improved to the required regulatory standards. Several factors and mechanisms affect effluent quality from a tailings pond (Figure 2.1). These include climatic factors such as temperature, precipitation, sunlight hours, wind, evaporation; hydrological factors such as runoff quality and quantity; human factors; mill effluent and pond geometry. Of these factors, temperature, sunlight hours, hydrology and retention time have been recognized to be the most significant (Simovic and Snodgrass, 1989).

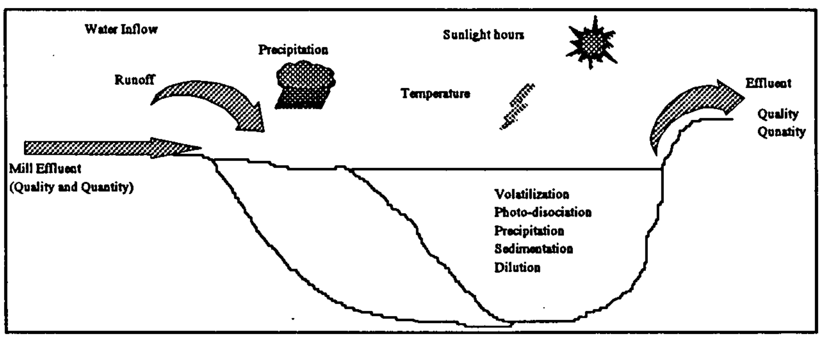


Figure 2.1. Factors and mechanisms affecting a tailings pond

An important management tool which gives a better understanding of the quantitative and qualitative management of a tailings system is water and mass balance evaluation. This takes into account all of the sources and sinks of both water and mass in the tailings system. This helps to identify the most important water and mass sources and sinks for the system. This information is vital for any optimization strategy the mine may consider implementing.

2.2 Legislation Governing Tailings Effluent Quality

2.2.1 Introduction

In Canada, non-enforceable water quality guidelines are the norm (Reichenbach, 1994). Non-enforceable guidelines do not have any legislative authority. Site specific enforceable parameters, based on the water quality guidelines are usually incorporated in the mine operation permits. The limit set in a permit for each water quality parameter takes into account background concentration and sensitivity of the receiving environment. The following sections will review Federal, BC and Ontario legislation relevant to waste water management.

2.2.2 Canadian Federal Legislation

The Federal legislation is triggered whenever a project affects Federal jurisdiction. Some of the Canadian Federal Legislation which is relevant to waste water management is given in the following section.

Canadian Environment Protection Act

This Act is administered by the Department of the Environment. It is a statute oriented towards prevention and outlines comprehensive schemes for the control and regulation of toxic chemicals. The aim of CEPA is to establish nationally consistent levels of environmental quality. For specific parameters, waste water quality is mostly regulated under the Fisheries Act.

The Fisheries Act

This Act is aimed at protecting fish, marine mammals, and their habitats. The Act falls under the jurisdiction of the Ministry of Environment and Fisheries and Oceans. The Act prohibits the deposit of any deleterious substance directly into water frequented by fish. Therefore this Act controls all watersheds which are fish-bearing. The Metal Mining Liquid Effluent Regulations and Guidelines (MMLER) (Table 2.1) contains enforceable effluent regulations under the authority of this Act for new, expanded and reopened mines and non-enforceable for existing mines (Reichenback, 1994).

Gold mines were not included in the regulations when they were passed in 1977 because cyanide treatment technology was not well advanced at that time (British Columbia Technical and Research Committee on Reclamation, 1992). According to the British Columbia Technical and Research Committee on Reclamation's Cyanide Guide, the current federal response to applications involving cyanide is to control the discharge using a combination of best available practiced technology, receiving water objectives, and effluent toxicity considerations.

Table 2.1 Metal Mining Liquid Effluent Regulations (Reichenbach, 1994)

Parameters mg/L	Maximum Monthly Arithmetic Mean Value	Maximum Value in a Composite Sample	Maximum Value in a Grab Sample
pH (unitless)	6.0	5.5	5.0
Total Suspended Matter	25.0	37.5	50.0
Arsenic	0.5	0.75	1.0
Copper	0.3	0.45	0.6
Lead	0.2	0.3	0.1
Nickel	0.5	0.75	1.0
Zinc	0.5	0.75	1.0

2.2.3 Provincial Legislation - British Columbia

Environmental Assessment Act - 1994

In British Columbia the Environmental Assessment Act which recently replaced the Mine Development Assessment Act provides the legal framework for comprehensive environmental assessments of proposed mine developments. For a mine development to fall under the Act, it has to be larger than the threshold sizes specified in the Act.

Application for a mine development certificate must contain an environmental protection plan for approval by the Minister of Energy, Mines and Petroleum Resources and the Minister of the Environment, Lands and Parks based on the recommendations from the project committee. The two cabinet ministers may also refer an application to the Environmental Assessment Board for a public hearing.

Once a development certificate has been obtained, mines are regulated under the Mines Act and Waste Management Act through mine plan approvals, reclamation permits, waste and water management approvals permits and licenses. All of these approvals, permits, and licenses are issued subject to monitoring and confirmation of predictions (Price and Errington, 1994).

Mines Act of 1989

The Mines Act governs all mining activities including waste disposal and site reclamation. Before commencing work, a work plan and program for the protection and reclamation of the land and watercourses affected by a mine must be submitted for approval to obtain a reclamation permit. Disturbed land and water resources must be reclaimed to a level of productivity not less than that which existed previously. Water released from the minesite must meet long term water quality standards.

According to the Health, Safety and Reclamation Code for Mines in British Columbia, 1992, a producing mine should have particulars of the nature and present uses of the land with reference to:

- surface water and groundwater, including drainage, water quality, licensed water rights, hydrology and fisheries;
- waste disposal, including tailings waste rock and overburden;
- protection of watercourses, including prediction of effluent quality for all disturbances;
- drainage control, monitoring and maintenance;

- source of any water required in the operation ; and
- a program for the protection and reclamation of the land and watercourses during construction and operational phase of the mine.

<u>Waste Management Act</u>

The Waste Management Act regulates the discharge of waste water from mining operations in BC. This Act which is administered by the Ministry of Environment, Lands and Parks, specifies that permits are required in all cases involving the discharge of gaseous, liquid and solid materials. Waste water discharge permits are issued with site-specific criteria for discharge.

BC Environment develops objectives on a site-specific basis using scientific guidelines or criteria. Criteria and objectives are not based on legislation, and are therefore, non-enforceable.

2.2.4 Provincial Legislation - Ontario

<u>Mining Act amended in 1991</u>

Part VII of the Mining Act and its accompanying Regulation 114/91 addresses mine closure and rehabilitation. The Act is administered by the Ontario Ministry of Northern Development and Mines. Based on the Mining Act, the Ministry came up with guidelines entitled "Rehabilitation of Mines Guidelines for Proponents" which include detailed suggestions on: closure plans, regulations, closure technology, closure components, monitoring, costing and financial assurance (Ontario Ministry of Northern Development and Mines, 1992).

With respect to water management issues, the closure plan should include:

- details of the overall water balance of the waste water management system;
- data to predict seasonal flows in each watercourse after closure;
- data to allow estimation of receiving streams flows, lake volumes and drainage patterns;
- data on mineralogy and AMD potential of the ore and host rock;

- data to allow the Ministry to predict water quality impacts adjacent to and downstream from the site, which should be compared with Provincial Water Quality Objectives; and
- details on the chemical monitoring program to be carried out during closure including the location of the monitoring points, parameters to be measured and sampling frequency.

Environmental Protection Act (EPA) of 1980

The purpose of this Act is to protect and conserve the air, land and water of Ontario by prohibiting discharge that contaminates the environment. Under the legislative authority of the Environmental Protection Act (EPA), the Municipal Industrial Strategy for Abatement (MISA) was formulated. MISA was initiated by the Ministry of Environment to tighten standards that must be met by mines and other industries that discharge effluent into surface water. Effluent limits set are attainable by using the "best available technology economically achievable." The purpose of MISA is "to virtually eliminate the discharge of all persistently toxic materials from liquid effluents directed to natural water bodies in Ontario" (Hawley, 1989).

Ontario Water Resources Act (OWRA) of 1980

This Act prohibits discharges of materials that may impair the water quality. The general purpose of the Act is to protect and conserve the lakes, rivers, streams and ground water of Ontario. Under the authority of this Act, mines have to obtain a Certificate of Approval which sets the limits of discharge for each parameter.

2.3 Water Management of a Tailings Pond

2.3.1 Introduction

It is recognized that tailings management is primarily a water management problem and that the solids are relatively easy to dispose of, particularly if they are non-acid producing (Firlotte and Welch, 1989). Minimizing water inflow into the tailings management system usually minimizes the tailings management problem. Several methods are used to reduce water inflow into the tailings system including, diversion of natural inflow and reuse and recycle of tailings water for mill use. Water management is of primary importance to the mining operation for the successful development, operation and ultimate decommissioning of the site.

2.3.2 Mill water use

Water is the major and most important commodity in the processing of ores (Ritcey, 1989). Most processes in ore processing, require water. Water of varying quality is required depending on the specific nature of the mill and its processes. Within the mill there are normally the following water streams, process water, boiler water, service water, and potable water.

Most plants incorporate recycling and reuse of tailings water in the process circuits and thus minimize the environmental impact of effluent discharge (Ritcey, 1989). Recycling can also result in reagent conservation, water conservation and help meet possible zero discharge goals. Before recycling can be implemented in mill processes, the water must be compatible with the metallurgical process, otherwise water treatment may be required. In certain cases, recycling or reuse of tailings water may be only be suitable for some part of the mill water requirements.

Recycling of mine, mill and processing plant effluents can provide economic returns to the mine/mill operations as well as reduce the impact on the downstream environment. In certain cases removal of constituents might be necessary to prevent buildup in concentration which could adversely affect the metallurgy of the process. This results in discharge of some of the treated effluent into the environment and the use of fresh water to meet the process requirements.

2.3.3 Hydrology

Water management of a tailings pond system is site specific. Hydrology is one of the most important factors to be considered in selecting a site for tailings impoundment. A tailings basin has to operate within a range of operating and hydrological conditions. These hydrological conditions have to be understood and evaluated in order to achieve effective tailings management. A hydrological evaluation should involve:

- quantifying total inflow into the tailings system;
- evaluating flow rates into the tailings system;
- evaluating extreme events and their possible impact on the tailings system;
- measurement or collection of precipitation and evaporation data

These factors are evaluated and investigated in detail in Chapter 4.

2.3.4 Water control

A mine effluent water control plan should involve qualitative and quantitative controls. The qualitative control involves improving effluent quality to the acceptable regulatory standards and this is considered in the next section. Quantitative control involves effectively managing water volumes and this is considered in this section.

In most cases quantitative water control involves building a water control structure such as a dam which will accommodate mill effluent (water and solids) and the natural runoff from the surrounding catchment. As already discussed, tailings management is primarily a water management problem. The less water there is to manage the smaller the environmental problem. Therefore limiting the catchment area is one of the most common methods of controlling water inflow into the tailings area. It is recommended by Ritcey, 1989 that sections of streams where the catchment area is larger than 13 km^2 (5 square miles) should be excluded, unless stream diversion can be done so that it will be effective in the long term.

The other common water control strategy involves effluent recycle and water reuse. This has been discussed in Section 2.3.2.

2.4 Effluent Improvement Processes in a Tailings Pond

2.4.1 Introduction

Qualitative water control in the tailings pond is achieved by various effluent improvement processes. Determining the effectiveness of a tailings pond in improving effluent is essential to tailings management. However, it is extremely difficult to predict with any degree of certainty the performance of a tailings basin involving the complex interaction of many factors such as climatic factors: temperature, precipitation, sunlight hours, wind, evaporation; hydrological factors: runoff quantity and characteristics; human factors: mill effluent quality and quantity, regulatory constraints, pond geometry and effluent quality and quantity.

The most realistic approach in evaluating the performance of a tailings pond is to select the most significant factors and mechanisms. Temperature, sunlight hours, hydrology and retention time have been recognized to be the most significant (Simovic and Snodgrass, 1985).

Temperature and sunlight hours have a great impact on most chemical and biological mechanisms in the tailings pond such as volatilization, oxidation and precipitation. These factors can also be related to the effluent quality, in particular to seasonal variations in the effluent quality.

Surface runoff and precipitation will cause dilution in the tailings pond. Both the qualitative and quantitative evaluation of total inflow is required to calculate the dilution capacity. It is important to establish the flow rates into each pond from both the natural and effluent inflow.

Usually the longer the retention time the better the effluent quality. In a case where natural degradation is the only process responsible for improvement of effluent, new basins are designed with as much pond space as possible to maximize the retention. Minimizing runoff will also help increase the retention time.

2.4.2 Source of cyanide and heavy metals in mill effluent

The most common process for the recovery of gold from ore deposits is that of cyanidation, in which gold is leached from the ore in a weak cyanide solution, usually NaCN. Gold is then recovered from solution either by adsorption unto carbon in the case of Carbon-In-Leach or Carbon-In-Pulp or by precipitation with zinc dust, in the case of the Merrill-Crowe process.

The chemical equation for the dissolution of gold is:

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_4 + 4NaOH$$

The zinc precipitation step can be represented as follows:

$$2NaAu(CN)_2 + Zn \rightarrow Na_2Zn(CN)_4 + 2Au$$

Cyanide is a powerful solvent which is non-selective for gold. Therefore depending on the mineralogy of the ore being treated, other ions may enter solution in lesser or greater amounts. These ions include metals such as copper, iron, nickel and zinc and at times antimony and molybdenum, which form complexes with cyanide. Thiocyanate $(CNS)^-$, cyanate $(CNO)^-$, thiosulphate $(S_2O_3)^{-2}$ and ammonia are also frequently present in gold mill effluents (Scott, 1989).

In the Merrill-Crowe process cyanide exists in the mill with the washed and repulped leach solids. In addition, it is necessary to bleed off a portion of the barren (gold-free) solution from the mill to avoid the build-up of deleterious metals, such as copper, iron, nickel, zinc, arsenic and antimony which dissolve simultaneously with gold, and would subsequently interfere with the further dissolution and precipitation of gold. In the Carbon In Pulp (CIP) or Carbon In Leach (CIL) process only a single waste stream of tailings slurry is discharged from the mill.

2.4.3 Natural degradation of cyanide and removal of heavy metals

Natural degradation was the only form of cyanide waste treatment used by the mining industry in Canada before the mid-1970's. Though this historical method is the most common and economical method for treatment of gold mill effluent (Wilson and Wilson, 1987), it is increasingly found to be inadequate to meet water quality standards. The introduction of federal and provincial environmental regulations in the late 1970s forced many new and existing mining operations to seek additional treatment systems. This led to the development and extensive use of hydrogen peroxide and SO2-air process for cyanide destruction, however, some of the mines which have introduced these additional treatment systems, still use natural degradation as part of their treatment systems. It is being used either as a pre-treatment process or as a final process in series with the chemical treatment system. Therefore, natural degradation will continue to play a very significant role in gold mill effluent treatment.

Natural degradation of cyanide held in a tailings pond for extended periods involves removal of cyanide and associated cyanide-metal complexes by naturally occurring processes. Processes responsible for degradation of cyanide and metal-cyanide complexes result from a combination of physical, chemical and biological processes. These processes include volatilization, chemical and photo-chemical decomposition, chemical and microbial oxidation, precipitation of metals, hydrolysis and adsorption on to solids (Scott, 1989). Sedimentation of solid particles, can further remove cyanide from the water. Of these processes, volatilization of hydrogen cyanide (HCN) and chemical dissociation of the cyanide-metal complexes have been shown to be the most important mechanisms in cyanide removal (Simovic and Snodgrass, 1985). Through these natural processes and dilution in the tailings impoundment the concentration of pollutants in the mill waste waters can be reduced considerably but concentration might not be reduced to desired levels for discharge to the environment.

Some of the factors which influence natural degradation are the species of cyanide present, influent concentration of the various species of cyanide, metal concentrations, pH, temperature, sunlight (UV), aeration, pond dimensions and conditions (area, depth, turbidity, turbulence, ice cover, retention time) and the presence of bacteria (Palaty and Horokova-Jakubu, 1959). As metal-cyanide complexes decompose, cyanide is removed mainly through volatilization, concurrently metals are removed as precipitates in the form of hydroxide, insoluble metal-cyanide complexes and adsorbed cations on suspended solids which usually settle out.

Natural degradation of cyanide is rapid during warmer months but extremely slow or perhaps non-existent during the late fall and winter months. For a stand-alone natural degradation system, it will require a retention time of 9-10 months (Scott, 1989). The tailings pond must, therefore have the capacity to store water from October through to the following July or August.

The composition of mill effluent, which is the influent into a tailings pond tends to vary irregularly. After passing through a tailings pond, a certain pattern emerges reflecting the dominant factors and mechanisms in the tailings pond. What is particularly evident are the seasonal variations in the concentration of water quality parameters (Figure 2.2).

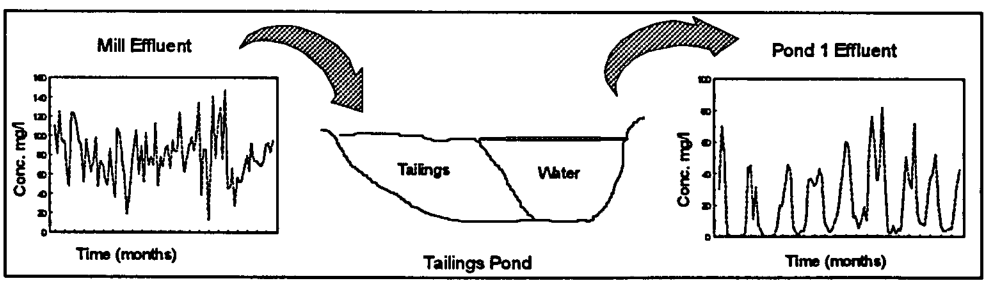


Figure 2.2. In the first pond undergoing natural degradation, mill effluent concentration with irregular variation results in effluent concentration with seasonal variation

In a multiple-pond tailings management system, the effluent from one pond becomes the influent into the next pond. In this case, the pattern of effluent quality in the second pond is doubly affected by seasonal factors since the input has seasonal variations and the pond mechanisms are also undergoing seasonal variations. A similar pattern between the input and output is observed in the pond with a short retention period (Figure 2.3).

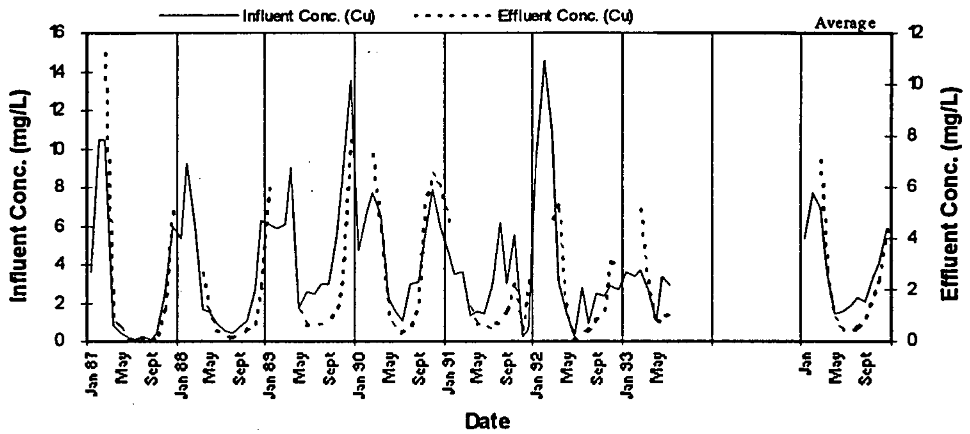


Figure 2.3. In a second pond undergoing natural degradation with a shorter retention time, seasonal variation in influent concentration results in effluent concentration with seasonal variation without a lag.

2.5 Water and Mass Balance Modeling of a Tailings Pond

2.5.1 Water balance

A water balance evaluation of a tailings pond takes into account all the water inflows and losses on a periodic basis. A typical evaluation for water management purposes will use a set of average data, taking into account precipitation, tailings water, and miscellaneous inflow such as: mine water minus evaporation; water retained in the tailings; seepage and recirculation to the mill. For some design purposes, extreme data might be used.

The main sources of water in a tailings area are the mill effluent, direct precipitation, surface runoff from the pond shores and inflow from creeks. Water leaves the impoundment area as free water (effluent discharged or recycled water), seepage water, evaporation and water reused by the mine plant. Figure 2.4 shows a representation of the influent and effluent sources together with a graphical representation of their relative amounts.

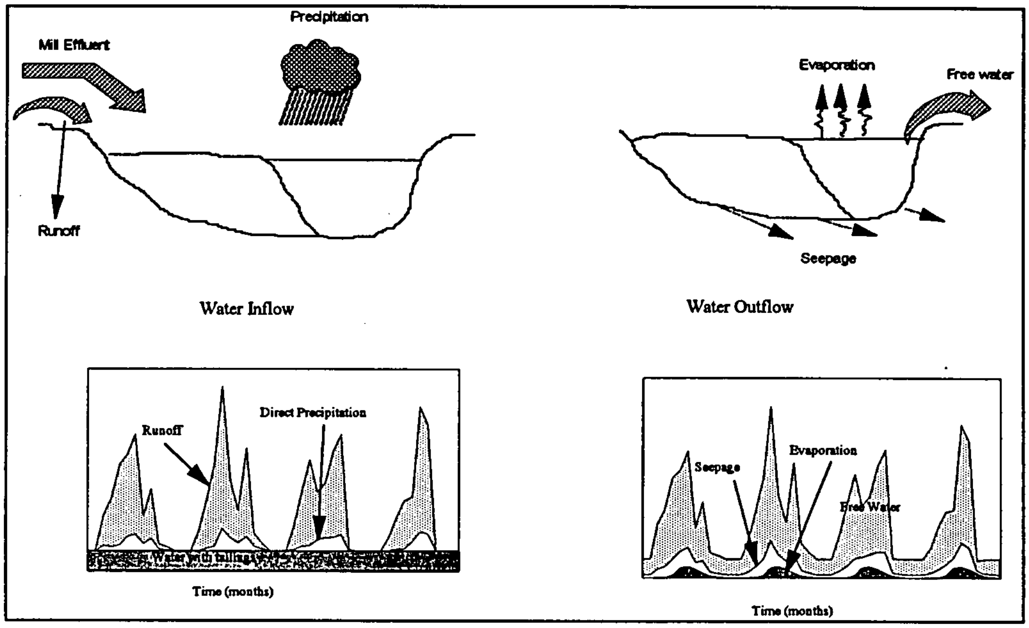


Figure 2.4. Water flow through a tailings pond (Modified from Swaisgood and Toland, 1973)

2.5.2 Mass balance evaluation

A mass balance evaluation is based on the water balance evaluation. The masses of specific parameters (e.g. cyanide) are calculated by multiplying the average effluent concentration for each water source or sink for the pond being evaluated. This is also covered in detail in Chapter 6.

2.6 Summary

This chapter has reviewed the main legislation which governs tailings effluent management in Canada, Ontario and BC. The most important federal legislation which affects tailings effluent management is the Fisheries Act, which seeks to protect waters frequented by fish. In BC, the

Waste Management Act regulates discharge from mining operations through a permit issued to the mine. In Ontario, the Certificate of Approval specific to a mine regulates waste water discharge under the legislative authority of Ontario Water Resources Act. The Mining Act of a particular jurisdiction is crucial in determining the waste water management for the purpose of mine closure and reclamation.

Water management is a vital part of tailings management. Quantitative management considered the following factors: mill water use; hydrology; and water control. Qualitative evaluation presented the source of cyanide and heavy metal in the mill effluent and the main mechanisms responsible for improvement of effluent in a tailings pond.

Water and mass balances take into account all the water and mass sources and sinks in a tailings system. These balances provide the bases for any improvement to the system.

3.0 FIELD ASSESSMENT AND STUDY METHODS

3.1 Introduction

In this chapter, the details of the field study and the methods used for data collection are given. The main components of the field study included topographical assessment of the catchment, hydrological sampling, and effluent quality and quantity sampling. The field study also covered the review of existing studies on Balmer Lake. The study was conducted from May to July, 1992 and April to August, 1993.

3.2 Topographical Assessment of the Catchment

3.2.1 Site description

The Balmer Lake tailings management system drains a catchment area of about 32.5 km^2 which includes the tailings systems of the A.W. White Mine of Goldcorp Inc. and Campbell Mine of Placer Dome Inc. Most of this area is forest cover with some breaks resulting from road construction, timber harvesting and mining exploration. The major drainage route of the catchment is Upper Balmer Creek which drains an area of about 12.7 km^2. Three other smaller creeks drain the rest of the catchment which for the purpose of this study will be referred to as NDR1, NDR2 and NDR3. Upper Balmer Creek, NDR1 and NDR2 discharge into Balmer Lake, while NDR3 discharges into Pond 1 of the Goldcorp tailings system. The catchment area is shown in Figure 3.1, which was modified from the MacLaren Plansearch report of 1991. Balmer Lake has a surface area of 2.6 km^2 with an average depth of 3 m. Balmer Lake discharges into Balmer Creek which is a tributary of the Chikuni River, an important fishery. Balmer Creek is also used for fish spawning during spring.

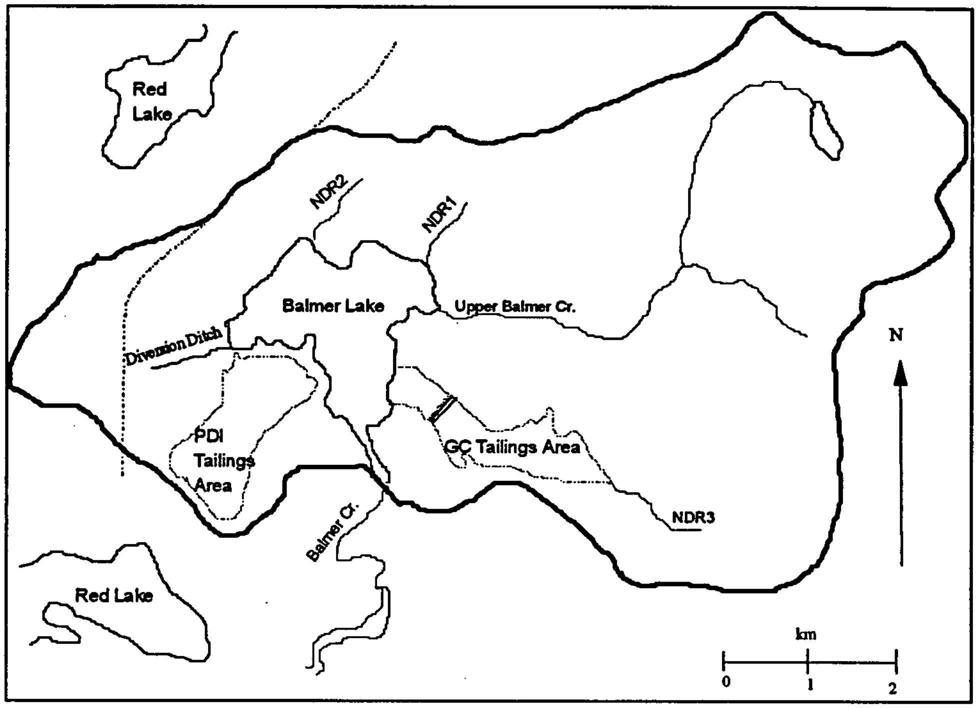


Figure 3.1. Balmer Lake Catchment

3.2.2 Sub-catchment and pond area evaluations

The catchment area was divided into sub-catchments based on local watersheds and the location of flow monitoring stations. Each sub-catchment is drained by a creek, ditch or discharges into a pond. This helped to compare measured flow and estimated flow in Section 4.3.2. The sub-catchment areas are presented in Figure 3.2 as follows:

1 Upper Balmer Creek

2 NDR3 (Beaver Creek)

3 Tailings Ponds Catchment Area (Goldcorp)

4 Diversion Ditch (Placer Dome)

5 Tailings Ponds Catchment Area (Placer Dome)

6 Pond Catchment Area (Balmer Lake)

7 NDR1

8 NDR2

Sub-catchment and pond areas are given in Table 3.1.

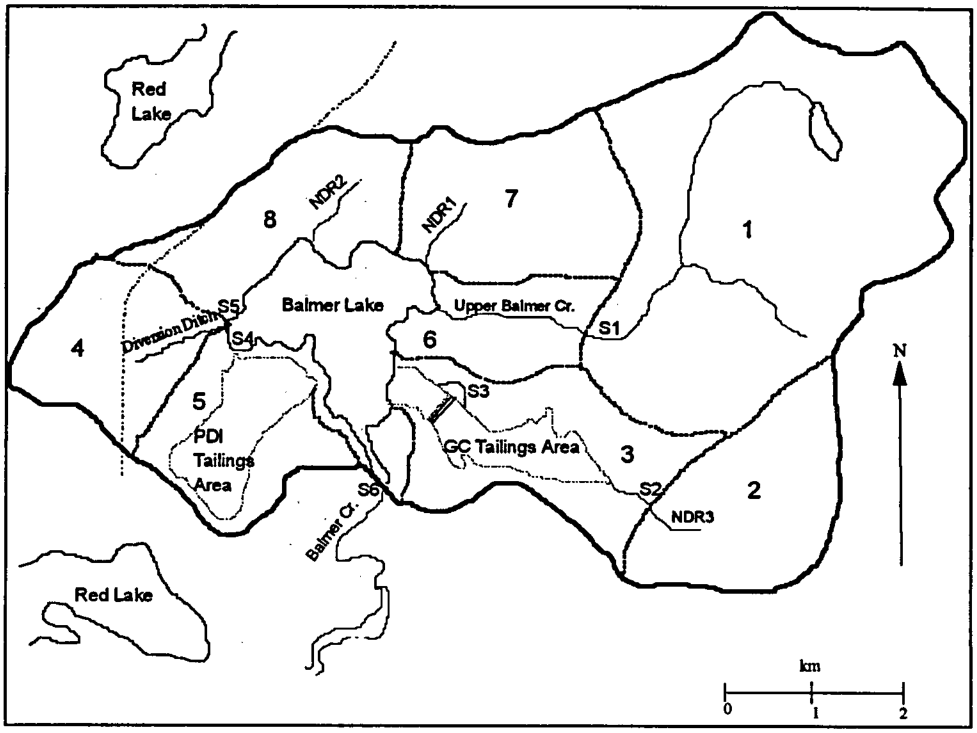


Figure 3.2. Balmer Lake Catchment showing the sub-catchments for each creek

Table 3.1. Areas of sub-catchments and ponds

Sub-catchment areas	**Area size (m²)**
1. Upper Balmer Creek	12,700,000
2. NDR3 (Beaver Creek)	4,500,000
3. Tailings ponds catchment area (Goldcorp)	3,800,000
4. Diversion Ditch (Placer Dome)	2,900,000
5. Tailings Ponds Catchment Area (Placer Dome)	
6. Pond Catchment Area (Balmer Lake)	1,300,000
7. NDR1	3,800,000
8. NDR2	4,100,000
Pond areas	
Pond 1	800,000
Pond 2	200,000
Balmer Lake	2,600,000

3.3 Hydrological Data Collection

Several flow measurement stations were established around the catchment as shown in Figure 3.2. Flow measurement was conducted over two spring and summer seasons, 1992 (May to July) and 1993 (April to August). NDR1 and NDR2 were inaccessible for flow measurement, their inflow volumes were estimated from the hydrograph of Upper Balmer Creek, based on the comparison of catchment areas.

3.3.1 Flow measurement stations

Station #1 Upper Balmer Creek

Station #1 is located on Upper Balmer Creek. Upper Balmer Creek discharges into Balmer Lake. This station intercepts inflow from the largest single segment of the catchment. It drains an area of 12.7 km^2 which is over 1/3 of the total area of the catchment.

This station was selected because it is easily accessible by road and a circular culvert which conveyed flow across the road provided a uniform section for measuring flow using the current meter and the stage discharge curve developed during the field study. A photograph of the station is shown in Appendix I.

Station #2 NDR3

Station #2 is located on NDR3, which discharges into Pond 1. The station intercepts inflow from the upper part of the sub-catchment. It drains an area of 4.48 km^2.

Like station #1 flow monitoring at this station was facilitated by a circular culvert which conveys flow across the access road. Flow monitoring at this station was only carried out in the spring and summer of 1993. A photograph of the station is shown in Appendix I.

Station #3 Pond 1 Effluent

Station #3 was used to monitor discharge from Pond 1. Pond 1 receives inflow from the mill effluent, NDR3, runoff from surrounding area and direct rainfall. The discharge from Pond 1 into Pond 2 is through a spillway.

Flow measurement was carried out in the spillway, which channels flow around Pond 1 dam. The channel is about 150 m long. Flow was quite uniform for most parts of the channel and Station #3 was located about 50 m from the spillway. Flow was measured using the current meter method and the stage discharge curve. A photograph of the station is shown in Appendix I.

Station #4 Diversion Ditch

Station #4 was used to monitor flow in the diversion ditch. The ditch diverts excess flow from the surrounding area away from Placer Dome tailings system. The diversion ditch discharges into Balmer Lake. It drains an area of about 2.87 km^2.

Like station #3, flow was measured at a uniform section of the channel. Flow was monitored using the current meter method and the stage discharge curve. A photograph of the station is shown in Appendix I.

Station #5 #3 Decant

Station #5 was used to monitor discharge from the Placer Dome tailings system into Balmer Lake. Flow monitoring for this station was conducted by Placer Dome personnel.

Station #6 Control Weir

This is the final discharge point, which controls the discharge from Balmer Lake. The discharge is regulated by a Certificate of Approval from the Ministry of Environment (MOE), Ontario. At present, this stipulates that discharge will not be permitted between 01 May and 01 July of each year without prior MOE approval.

Discharge was measured using the weir installed at the station. From July 14, 1993, flow was measured using the OCM II installed at the weir. This was calibrated using the current meter method. A photograph of the station is shown in Appendix I.

3.3.2 Flow measurement methods

The current meter method

The current meter method was used to measure flow for a uniform channel and a circular shaped channel, as presented below. Details of the specific type of current meter used and how it works are given in Appendix I.

For a uniform channel

In this method the stream is divided into sections, as shown in Figure 3.3. The average flow velocity of the stream in each section is typically determined by placing the current meter at 0.2 and 0.8 of the depth of the stream and averaging the velocities to determine the average for the section (Linsley et al, 1982). However when the flow depth is less than 1 meter, as was the case for all the stations in the study, the average velocity can be approximated by measuring velocity at 0.6 of the depth.

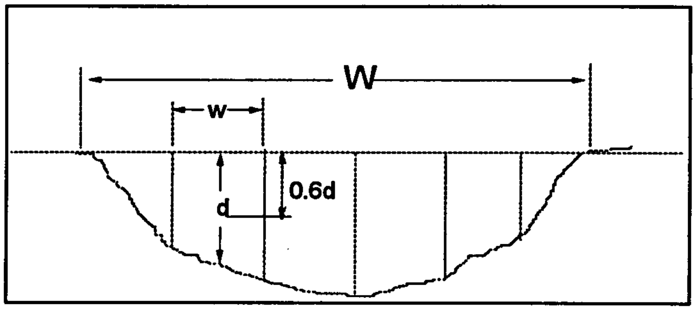


Figure 3.3. Cross section of a uniform flow measurement station

The total flow is calculated by summing the flow through all the segments. The following equation was used to determine flow:

$$Q = \sum_{i=1}^{i=n} v_i a_i$$

where, Q is the total flow in the channel

n is the number of equi-distant points across the channel selected for velocity and depth measurements

v_i is the velocity at the selected equi-distant points across the channel

a_i is the area of each segment of the channel, evaluated by multiplying depth by the width of each segment

For a circular shaped channel (culverts)

Taking advantage of the shape of the culvert, velocity was measured at 2 or 3 points across the culvert from which the average wascalculated. To determine the cross-sectional area of flow only the depth at the center of the culvert was required. The culvert diameter was predetermined and was used in the calculation of the area of flow (see Figure 3.4). The following relationship was used to evaluate flow:

Diameter of the culvert = D

Water depth = d

Water level to the center of the culvert = R-d = b

1/2 cord length	=	$\sqrt{R^2 - b^2} = \frac{l}{2}$
Angle subtended at the center	=	$Cos^{-1}(R-d)/(R) = a$
Area of the segment	=	$\frac{2a}{360} * \Pi R^2 = s$
Area subtended by the chord	=	s-(R-d)*l/2 = Area
Velocity	=	v
Q	=	Area*v*2

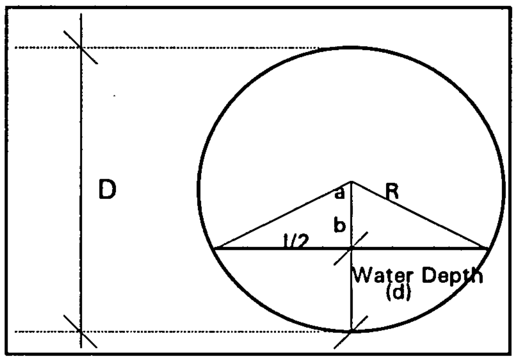


Figure 3.4. Cross section of a culvert flow measurement station

Flow-discharge curves

The flow measurements from the current meter method and simultaneous stage or depth observations provided data for the calibration curves also called rating curves or stage-discharge relationships. These relationships were used to determine flow, directly from the depth of flow. The stage-discharge curve for Upper Balmer Creek, NDR3, Pond 1 Effluent and Diversion Ditch are given in Appendix I.

Flow measuring weir

This method was used for flow measurement at Station #6 (the control weir). A rectangular weir was installed to control discharge from Balmer Lake into Balmer Creek, and to measure the flow. The relationship that exists between head and flow, for any particular type of weir may be expressed as:

$$Q = Kh^x$$

where, h - the height of water above the weir

K - scaling factor and is a function of the width

x - exponential constant (for a rectangular channel it is usually 1.5)

An Open Channel Monitor (OCM II) was installed at the control weir. For a particular weir, the only variable is the height of water above the crest of the weir. Using a transducer, the flow height above the weir was determined. The OCM II was calibrated using the current meter method. Details of the OCM II used and how it functions are given in Appendix I.

3.3.3 Flow measurement frequency

Flow measurement was carried out 3 to 4 times a week. However, after a major storm flow measurements were conducted more frequently, up to two times a day. The flows on days when no measurements were taken were estimated by linear interpolation.

3.3.4 Precipitation and evaporation data

Daily and monthly precipitation (snow and rainfall) data was collected from Red Lake Weather Station which is located 4.5 km from Balmer Lake. Daily precipitation data for the field study months are given in Tables A1 to A4 in Appendix I. Monthly precipitation data are also given in Appendix I in Table A5 from 1990 to 1994. The long term total annual precipitation average for the area was given as 509.4 mm (1941 -1970). In a typical year the ground is under snow cover from November to April.

The evaporation data was not available from the Red Lake Weather Station. The evaporation data used in the study were estimated from hydrological maps (Department of Transport Meteorological Branch Climatic Maps, 1970). Monthly averages are given in Appendix I.

3.4 Water Quality Sampling

3.4.1 Sampling stations

The schematic diagram of the sampling stations is given in Figure 3.5. The sampling stations were chosen so that the influent and effluent of each pond was monitored. In order to assess the water quality of natural inflow, water quality sampling conducted for Upper Balmer Creek and NDR3. All the effluent data collected during the various studies and by the mine have been compiled from 1987 to 1994 and are presented in Chapter 5.

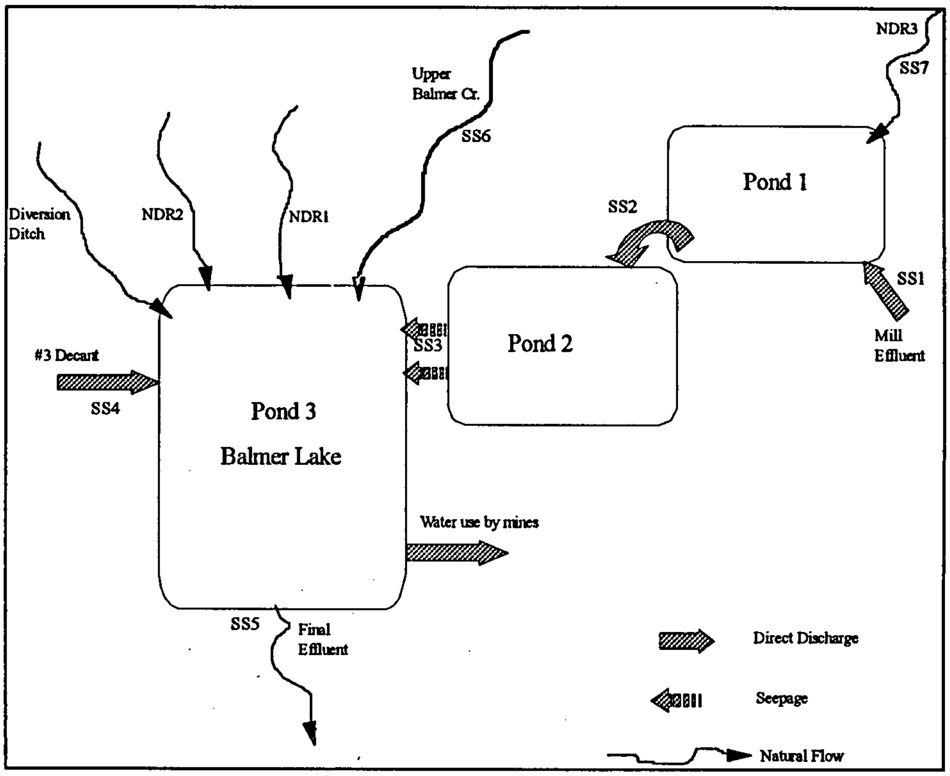


Figure 3.5. Water quality sampling stations

Mill Effluent - SS1

The mill effluent was sampled to assess the quality of the influent into Pond 1. Samples were collected monthly.

Pond 1 Effluent - SS2

The effluent samples from Pond 1 were collected at the spillway. Effluent samples were collected every week during the study period.

Pond 2 Effluent - SS3

This pond does not have a spillway. Effluent flows through the permeable dam into Balmer Lake. The effluent samples were collected at the upstream side of the dam.

#3 Decant (Placer Dome) - SS4

Effluent discharge into Balmer Lake from Placer Dome was monitored at this station. All the data for this station were collected by mine personnel or from other independent studies.

Pond 3 Effluent - SS5

This is the most important sampling station since the final effluent is monitored here before being discharged into the environment. Effluent monitoring at this station was more frequent. Daily monitoring was done during spring runoff. During the zero discharge period no sampling was done. During the rest of the year sampling was carried out about 3 times a week.

Upper Balmer Creek - SS6 and NDR3 - SS7

During 1993 field study period sampling was done at these station at the frequency of once per week for two months.

3.4.2 Sampling method and procedure

Clean sampling bottles were pre-labeled. Information on the labels included sampling station identification, the parameter being analyzed, the type of preservative to be used and the date. Samples were collected in 250 ml, 500 ml or 1 liter polyethylene bottles depending on the sample size requirement. The sample bottles were rinsed at least once with the sample before finally completely filling it. To ensure that the sample was as representative as possible, the sample was collected at the center of the discharge point by the sampler who was dressed in waders. The sample was collected upstream from where he/she was standing to avoid any contamination or disturbance of the sample.

For the mill effluent, the sample was collected using a 20 liter bucket. The sample was allowed to stand until most of the suspended solids had settled out and a supernatant sample was collected in the polyethylene bottles.

3.4.3 Preservation, storage and transportation

After the samples were collected, they were transported to the mill laboratory within 1 hour. For cyanide samples, 4 pearls of sodium hydroxide were added to a 500 ml sample, to raise the pH above 11 to prevent loss of cyanide through volatilization of hydrogen cyanide. For the heavy metals, 1 ml of nitric acid was added to a 250 ml sample, to lower the pH to below 2, to ensure that the metals remained soluble.

After the preservatives were added, the samples were stored in a refrigerator at 4°C. The samples were than transported to the analytical laboratory within 1 week. The samples were transported in a cooler with ice blocks to keep the samples around 4°C.

3.4.4 Methods of analysis

Sample analysis was done by the Thunder Bay Analytical Laboratory in Thunder Bay, Ontario. Analysis were carried out according to the Standard Method for the Examination of Water and Waste Water, American Public Health Association (APHA) manual. A brief review of the methods is given below:

Total cyanide

Total cyanide includes free cyanide, simple cyanides and metallocyanide complexes. The analyses method involves reflux distillation of the sample using heat and mineral acid (1:1 sulphuric acid), resulting in the release of hydrogen cyanide gas, which is then absorbed by dilute sodium hydroxide. The resulting solution is analyzed for sodium cyanide using a calorimetric method or titrimetric method.

Copper and nickel

Copper was determined using an atomic absorption spectrometer. The principle behind the method is that each metal has its own characteristic absorption wavelength. A source lamp composed of the element is used. The amount of energy at the characteristic wavelength absorbed in the flame is proportional to the concentration of the element in the sample over a limited concentration range.

3.4.5 Quality assurance

The US EPA defines Quality Assurance (QA) as "the total program for assuring the reliability of monitoring data". This takes care of any possible sources of misrepresentation of the results through contamination during sample collection, handling, transportation and analysis. Quality Assurance also ensures that the right sample is being analyzed for a particular station.

To ensure that the right sample is being analyzed, sample bottles were pre-labeled. Also a chain of custody form accompanied each sample shipment. This form was filled out by each party who accepted responsibility during handling. The information on the form included the sampling station, parameters sampled, sampling data and initial of the sampler.

4.0 HYDROLOGICAL ASSESSMENT

4.1 Introduction

In this chapter the hydrological results are presented and analyzed. The flow results are presented in tables and in graphical form as hydrographs. The analysis of results involves:

- comparing hydrographs of the different creeks;
- comparing precipitation and flow peaks;
- calculation of catchment runoff coefficients;
- estimation of monthly flow volumes into the tailings system; and
- analysis of rainfall data for extreme events.

A tailings management system is constantly subjected to changing hydrological conditions due to human and natural interference. These necessitate periodic modifications and improvements to the system. A clear hydrological assessment forms a base line for any consequent changes and helps point to the most appropriate solutions such as diversion, recycling or water re-use. The hydrological study of a system identifies and quantifies all the significant natural inflows and outflows of the tailings management system. All this hydrological data are required for the mine closure plan (Rehabilitation of Mines Guidelines for Proponents, 1992).

The schematic diagram of the Goldcorp Inc. tailings management system is presented in Figure 3.5. The main inflows and outflows for each of the 3 ponds in the system are presented below.

Pond 1

Inflows	**Outflows**
Natural Drainage River 3 (NDR 3)	Evaporation
Mill Effluent	Outflow to Pond 2
Pond 1 Runoff	
Direct Precipitation	

Pond 2

Inflows	**Outflows**
Pond 1 Effluent	Evaporation
Pond 2 Runoff	Outflow to Balmer Lake
Direct Precipitation	

Pond 3 (Balmer Lake)

Inflows	**Outflows**
Upper Balmer Creek	Evaporation
Natural Drainage River 1 (NDR1)	Placer Dome Water Use
Natural Drainage River 2 (NDR 2)	Goldcorp Water Use
Diversion Ditch (Placer Dome)	Outflow to Balmer Creek
Secondary Pond Effluent (Goldcorp)	
#3 Decant (Placer Dome)	
Balmer Lake Runoff	
Direct Precipitation	

Hydrological assessment included flow measurements at selected stations in the catchment (see Sections 3.3). This was done during spring and summer of 1992 and 1993. The flow results are presented in the next section.

4.2 Presentation and Analysis of Flow Results

4.2.1 Stream flow characteristics (hydrographs)

One of the most informative ways of presenting stream flow characteristics is through a hydrograph. A hydrograph represents variation in stream flow with time. As stated in Section 3.3 some of the creeks were inaccessible for flow measurement hence hydrographs for these creeks are not presented here or discussed.

Hydrographs of Upper Balmer Creek, NDR3, Pond 1 Effluent and the Diversion Ditch are presented in Figures 4.1 and 4.2. Figure 4.1 presents the hydrographs for Upper Balmer Creek and Pond 1 Effluent for the 1992 field study period. Figure 4.2 presents the hydrographs of Upper Balmer Creek, NDR3, Pond 1 Effluent and the Diversion Ditch for the 1993 field study period, which has two parts, a and b. Figure 4.2a covers the whole field study period, while Figure 4.2b covers the period from April to July 27 (just before a major storm). An unusually high peak occurred between July 25 and August 4, 1993. Rainfall of about 82.2 mm was received in a period of about 5 days. This caused very high flow, with as much as 800,000 m^3/day of inflow into Balmer Lake.

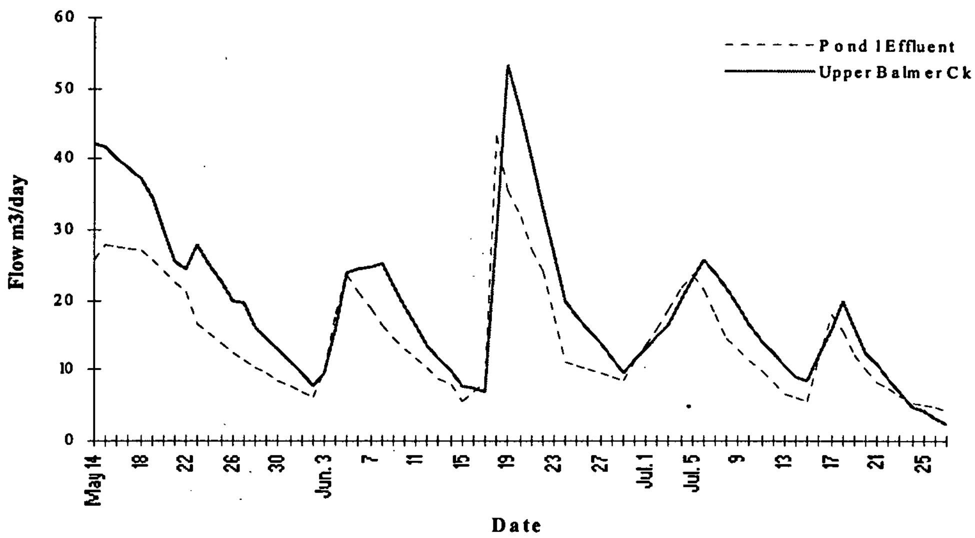
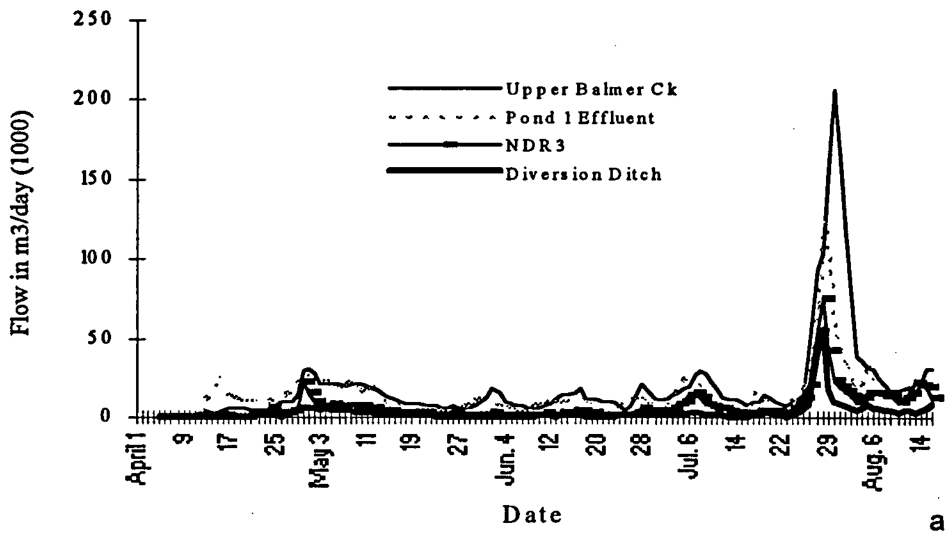


Figure 4.1. Upper Balmer Creek and Pond 1 Effluent 1992 (May to July)

Figures 4.1 and 4.2 allow comparison of the hydrographs for all the measuring stations. Similarities in the characteristics of the hydrographs are observed. The peaks and troughs occur at the same time, subject to small lags between different creeks. This suggests that uniform distribution of precipitation over the catchment was received. The small lags between the different creeks are a result of the differences in the concentration time, which is the time required for the whole catchment to start contributing to the flow at the flow measuring station. This is dependent on how far the furthest point is from the measuring point. In general, the larger the catchment area, the longer the concentration time. As can be observed from Figures 4.1 and 4.2, the peak of Upper Balmer Creek, which is the largest sub-catchment, lags all the other peaks.

It can also be observed from the hydrographs that the flows in spring and summer have different characteristics. In the spring season (April to May), the flows are influenced by both rainfall and snow melt. This causes longer peaks in the hydrographs. For instance, after the peaks which occurred between April 29 to May 3, 1993 (Figure 4.3b), it took about 20 days before the hydrographs dropped to base flow levels, but for the peaks after the end of May, a maximum of only 10 days was required before the hydrographs dropped to base flow levels after a storm event (Masala et al, 1993). The spring period is also characterized by dissimilarities in the hydrographs, because the snow melt over the whole catchment is not uniform.

The second period is the summer season (June to August) in which only rainfall influences the hydrographs. This period is generally characterized by shorter peaks and close similarity in the hydrographs.



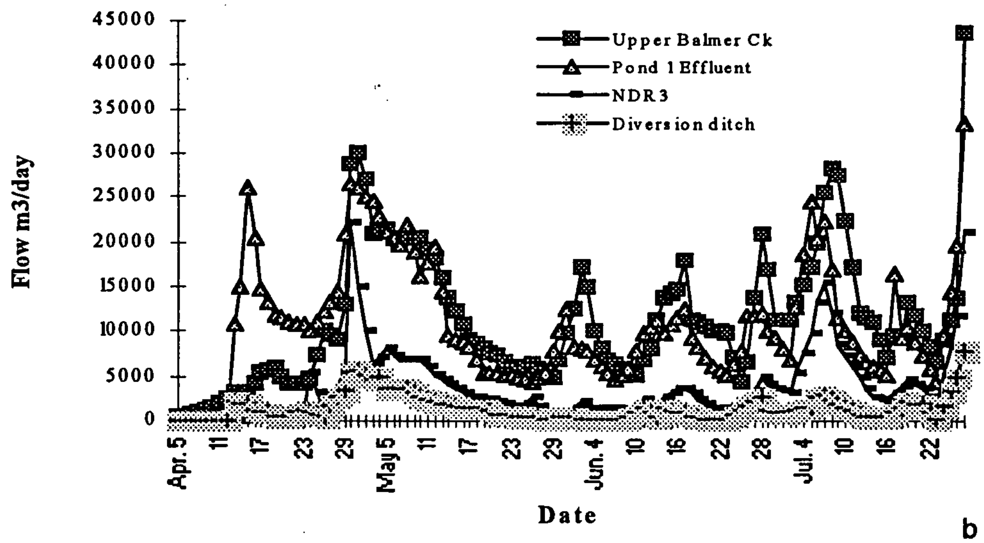
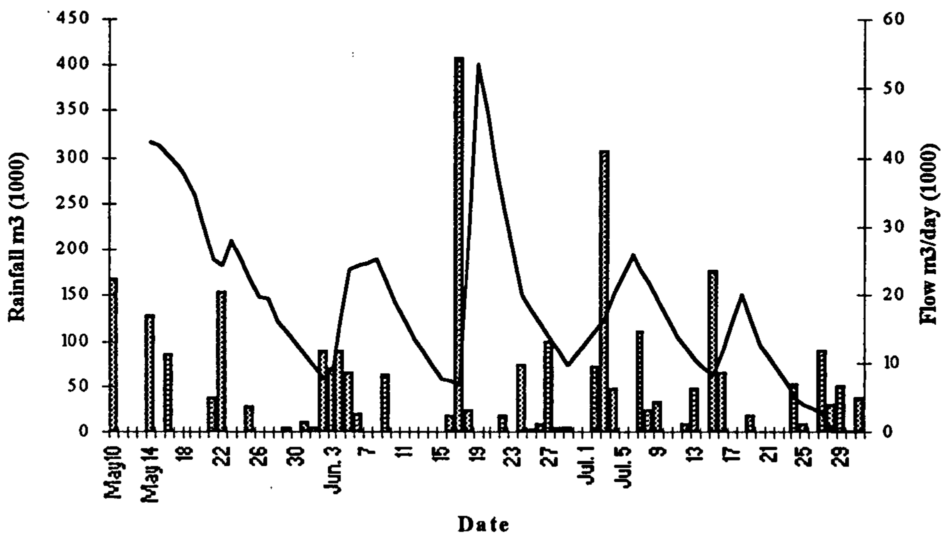


Figure 4.2a, b. Hydrographs of Upper Balmer Creek, Pond 1 Effluent, NDR3 and the Diversion Ditch 1993 (a) April to August and (b) April to July 25

4.2.2 Rainfall-flow relationships

Figures 4.3 to 4.8 give the hydrographs of each of the stations with their respective total rainfall volume received for the sub-catchment after a storm event. It can be observed that in certain cases the magnitude of the flow peaks does not necessarily correspond to the magnitude of the rainfall. This is due to other factors which influence runoff volume such as antecedent catchment conditions (Vardavas, 1988). The antecedent catchment condition determines how much rainfall ends up as interception store, surface store and soil store. After these components are filled, the excess ends up as runoff.

By comparing the rainfall received and the measured runoff volumes it was found that over the two years of study, about 51 % of the total rainfall received ended up in the tailings system.



.Figure 4.3. Total catchment rainfall volume (bars) vs. flow (line) for Upper Balmer Creek (1992)

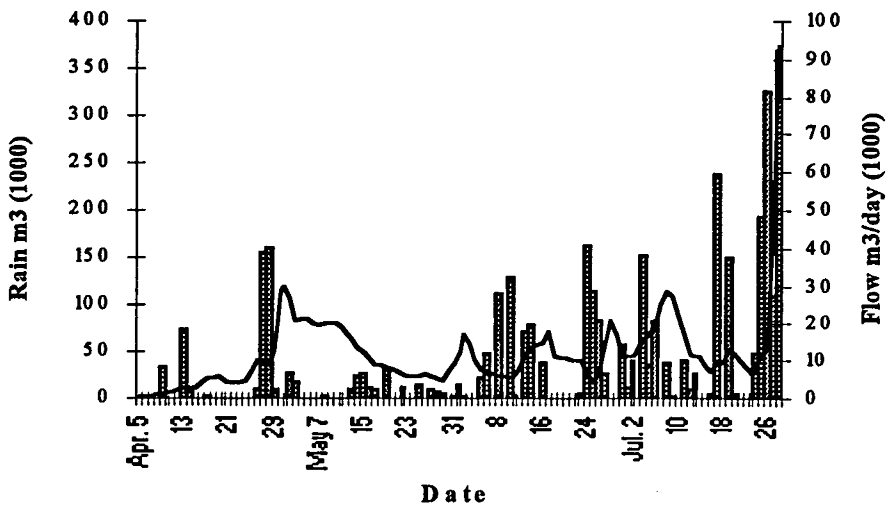


Figure 4.4. Total catchment rainfall volume (bars) vs. flow (line) for Upper Balmer Creek (1993)

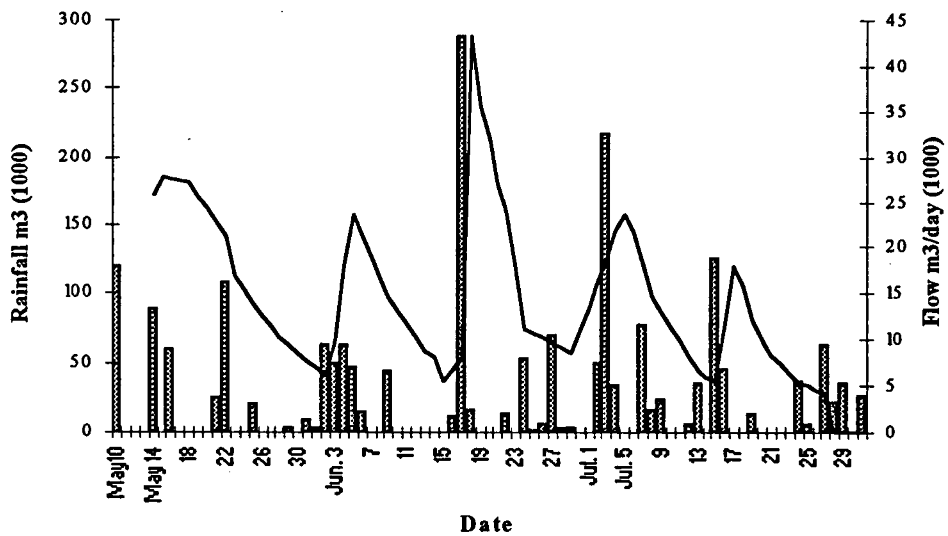


Figure 4.5. Total catchment rainfall volume (bars) vs. flow (line) for Pond 1 Effluent (1992)

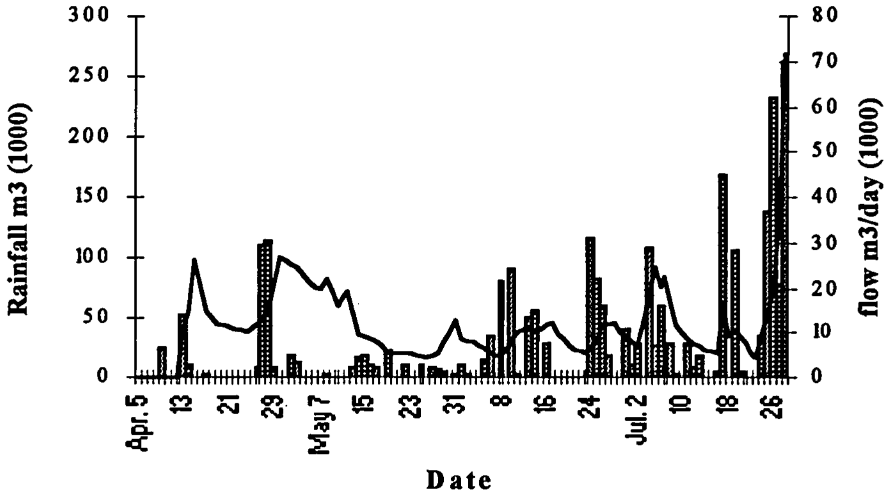


Figure 4.6. Total catchment rainfall volume (bars) vs. flow (line) for Pond 1 Effluent (1993)

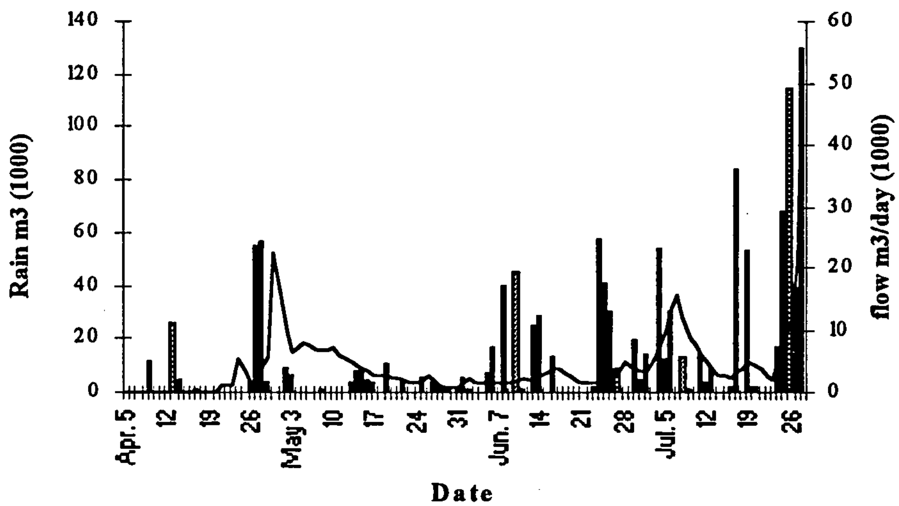


Figure 4.7. Total catchment rainfall volume (bars) vs. flow (line) for NDR3 (1993)

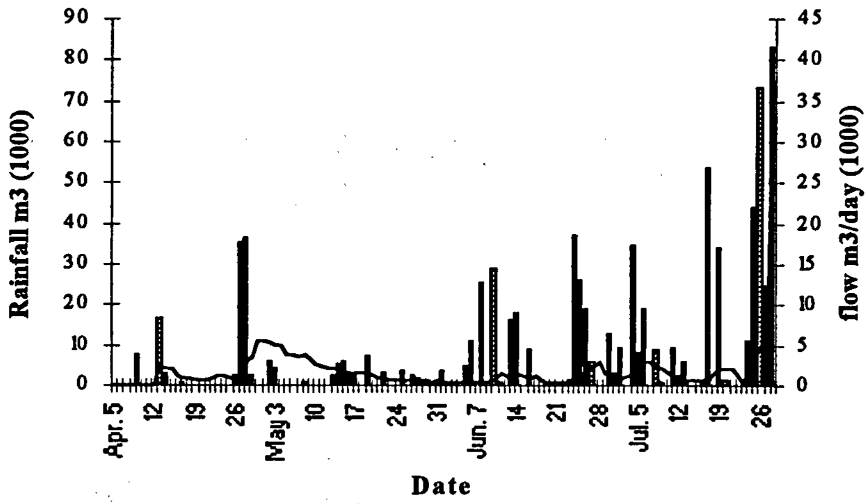


Figure 4.8. Total catchment rainfall volume (bars) vs. flow (line) for Diversion Ditch (1993)

4.2.3 Catchment area-flow relationships

Different catchments have different characteristics affecting the quantity of runoff. Examples of different characteristics include: degree of tree cover, water cover, rock outcrops and slope of the catchment. A comparison of the characteristics of each sub-catchment and how they affect runoff quantity was made. In order to do this the hydrographs of each creek were divided by the area of the catchment. Figures 4.9 to 4.11 give the flow for each creek per unit area per day. If the catchment characteristics were similar for all the sub-catchments, the hydrographs per unit area would be identical.

Figure 4.9 gives the runoff per unit area per day for Upper Balmer Creek and Pond 1 Effluent in 1992. The hydrographs are almost identical for the most part, except that Pond 1 Effluent peaks are higher than the Upper Balmer Creek peaks. The average runoff per unit area for Pond 1 Effluent is 1600 $m^3/km^2/day$, while that of Upper Balmer Creek is 1500 $m^3/km^2/day$. The higher average runoff per unit area for Pond 1 Effluent is partly due to the higher water covered area, since Pond 1 area is included in the sub-catchment area.

Figures 4.10 a and b give the runoff per unit area for Upper Balmer Creek, Pond 1 Effluent, NDR3 and the Diversion Ditch for the 1993 season. On average Pond 1 Effluent shows the highest runoff per unit area (1600 $m^3/km^2/day$), followed by Upper Balmer Creek (1500 $m^3/km^2/day$), then NDR3 (1500 $m^3/km^2/day$) and then the Diversion Ditch (1000 $m^3/km^2/day$). However during some peaks, NDR3 and the Diversion Ditch show higher runoff per unit area.

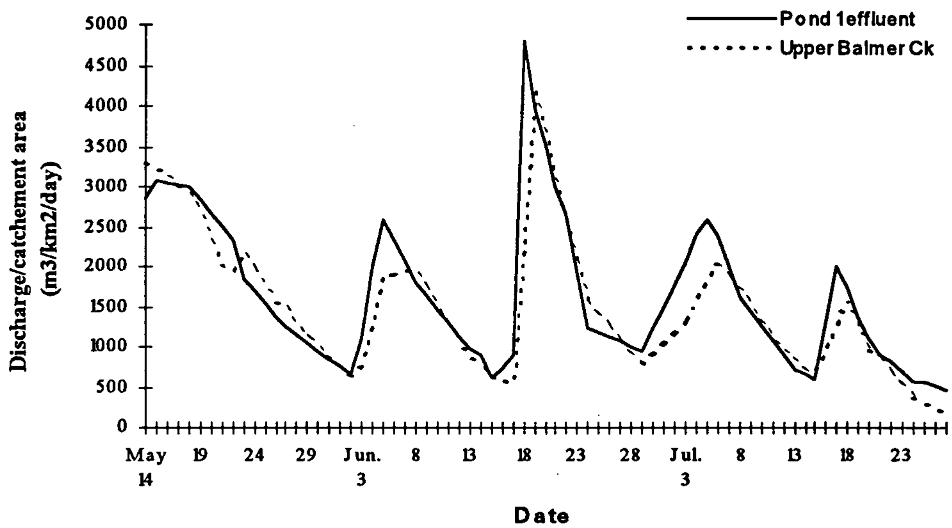
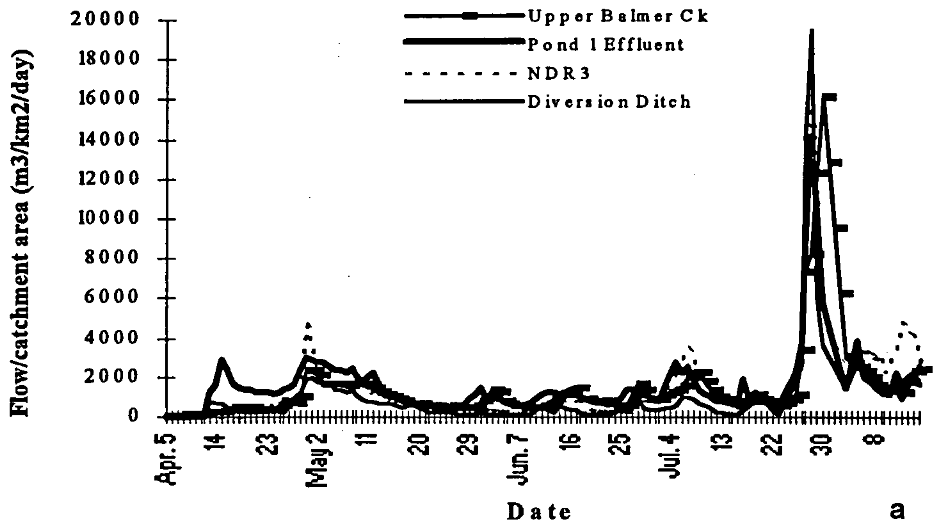


Figure 4.9. Upper Balmer Creek and Pond 1 Effluent 1992 (May to July) discharge per catchment area



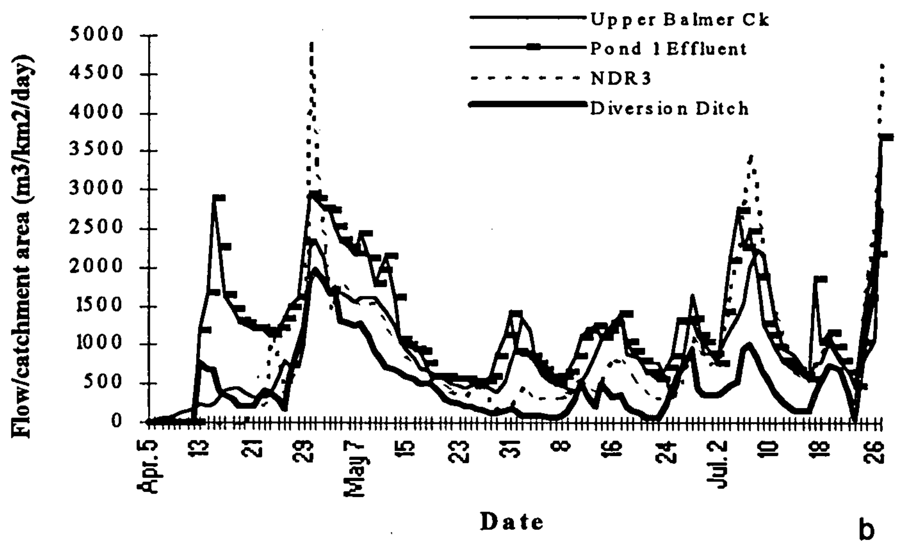


Figure 4.10 a, b. Discharge per catchment are for Upper Balmer Creek, Pond 1 Effluent, NDR3 and Diversion Ditch 1993 (a) April to August and (b) April to July 25.

4.3 Flow Volume Estimation

4.3.1 Rainfall-runoff relationship

The method used for estimating runoff volumes from each sub-catchment is based on the rational method (Linsley et al., 1982). This method is based on a precipitation-runoff relationship. The precipitation-runoff relation gives a simple way of predicting runoff volumes. This is particularly applicable for estimating monthly, seasonal, or annual runoff volumes . The application of this method in this study is based on the following assumptions:

- uniform distribution of rainfall over the catchment (one rainfall station was used);
- uniform runoff coefficients over the catchment area; and
- negligible base flows.

The monthly runoff volumes were evaluated using estimated catchment runoff coefficients. The runoff coefficient is the fraction of the total rainfall which contributes to runoff volume from the catchment.

The runoff coefficient was evaluated by dividing total measured runoff at Balmer Lake control weir by total rainfall volume received for catchment for 1990 to 1992. The average annual runoff from Balmer Lake catchment was found to be 11,900,000 m^3. This figure takes into account the water inflow from the mill effluent, water use and evaporation from the lake. The total precipitation over the 3 years was 702 mm, which amounted to 23,200,000 m3 for the catchment. The overall catchment runoff was found to be 0.51.

Snow runoff was assumed to take place in March, April and May, based on calculation of the excess runoff during this period above the precipitation received, using 1992 and 1993 data. The total snow runoff was estimated at 25 % of the total annual snowfall received. Detailed evaluations are given in Appendix II. The distribution of this runoff over the three month period was estimated as:

- March 8 % of total annual snow runoff;
- April 32 % of total annual snow runoff; and
- May 60 % of total annual snow runoff.

4.3.2 Flow volume estimation

Measured monthly runoff volumes and those estimated using the runoff coefficient are given in Tables 4.1 to 4.4. Measured daily flow volumes for the field study period, Spring and Summer of 1992 and 1993 are presented in Appendix II. As discussed in Section 4.3.1 the runoff calculations are based on a simple precipitation-runoff relationship. The relationship has the advantage of being simple to apply because it requires less input data and yet gives adequate prediction for most tailings management purposes.

Table 4.1. Monthly runoff volumes for Upper Balmer Creek

Month	1992 Estimated (m^3)	1992 Measured (m^3)	1993 Estimated (m^3)	1993 Measured (m^3)
Apr.			273,000	142,000
May	759,000	968,000	428,000	417,000
Jun.	423,000	584,000	386,000	324,000
Jul.	485,000	368,000	1,100,000	1,123,000
Aug.			959,000	1,107,000
Total	**1,667,000**	**1,902,000**	**3,146,000**	**3,113,000**

Table 4.2. Monthly runoff volumes for Pond 1 Effluent

Month	1992 Estimated (m^3)	1992 Measured (m^3)	1993 Estimated (m^3)	1993 Measured (m^3)
Apr.			316,000	396,000
May	637,000	670,000	400,000	393,000
Jun.	391,000	458,000	360,000	255,000
Jul.	432,000	316,000	888,000	716,000
Aug.			799,000	610,000
Total	**1,460,000**	**1,445,000**	**2,763,000**	**2,370,000**

Table 4.3. Monthly runoff volumes for NDR3 (Beaver Creek)

Month	1992 Estimated (m^3)	1992 Measured (m^3)	1993 Estimated (m^3)	1993 Measured (m^3)
Apr.			106,000	143,000
May	293,000	356,000	167,000	137,000
Jun.	165,000	243,000	151,000	68,000
Jul.	189,000	168,000	429,000	394,000
Aug.			375,000	469,000
Total	**647,000**	**767,000**	**1,228,000**	**1,210,000**

Table 4.4. Monthly runoff volumes for the Diversion Ditch

Month	1992 Estimated (m^3)	1992 Measured (m^3)	1993 Estimated (m^3)	1993 Measured (m^3)
Apr.			62,000	58,000
May	169,000	119,000	97,000	64,000
Jun.	95,000	42,000	87,000	24,000
Jul.	109,000	39,000	247,000	181,000
Aug.			216,000	160,000
Total	**264,000**	**162,000**	**492,000**	**327,000**

In certain cases, the monthly estimated flow volumes may show significant discrepancies from the measured flow volumes. This can be due to the overlap of storm events at the end of the month. The runoff coefficient provide a better estimate of the total volumes for the whole study, since the effects of month-end overlap are eliminated.

The runoff coefficients were estimated to represent the whole catchment. Therefore, runoff volume estimations are better for the creeks with larger sub-catchment areas than those with smaller sub-catchment areas. For instance, for the Diversion Ditch, which has a small catchment area, the estimated volumes tended to be an overestimate of the actual.

The runoff volume estimates are adequate for most hydrological applications such as:

- reservoir storage capacity estimation;

- pond retention period estimation;
- estimation of dilution capacity of the pond; and
- water recycle volume estimation.

4.4 Summary of Flow Results

In this chapter a hydrological evaluation of the Balmer Lake Catchment has been carried out. Important hydrological factors for a tailings pond management system such as runoff flow patterns, rainfall-runoff coefficients, impact of catchment characteristics on runoff, measured and estimated flow volumes have been analyzed.

From the hydrographs of the main creeks in the catchment, it was found that the rainfall is uniform over the catchment area. The hydrographs represented two quite distinct periods, spring and summer. For the spring period, the runoff in the creeks was due to both rainfall and snow melt. Flow peaks after a storm event were observed to be longer than in summer. Similarities were also observed among the hydrographs of the different creeks, although the peaks of Upper Balmer Creek tended to lag the other peaks.

Runoff volumes per unit area were determined as follows:

Pond 1 Effluent	1600 $m^3/km^2/day$
Upper Balmer Creek	1500 $m^3/km^2/day$
NDR3	1500 $m^3/km^2/day$
Diversion Ditch	1000 $m^3/km^2/day$

The average rainfall-runoff coefficient for the catchment was found to be 0.51. About 25% of the total snow fall results in runoff, which took place mainly in March (8%), April (32%), and May (60%).

An unusual storm event was received over 5 days at the end of July in 1993 which resulted in peak runoff into Balmer Lake of 800,000 m3/day accounting for 5% of the total annual flow.

5.0 WATER QUALITY ASSESSMENT

5.1 Introduction

This chapter gives a detailed water quality assessment of the Balmer Lake tailings management system. The water quality parameters investigated are total cyanide, total copper and total nickel. The effluent quality of these parameters is dependent upon a number of processes taking place within the tailings pond, such as volatilization, oxidation, precipitation, sedimentation and dilution. The dominance of any one of these processes is both pond and site specific and is dependent on several seasonal factors such as temperature, sunlight hours, precipitation, hydrology and wind as well as influent quality and retention time.

In order to try to isolate some of the dominant mechanisms in the tailings pond, several pond parameters should be defined. These parameters are also used in evaluating the effectiveness of each pond in the system. The pond parameters evaluated are:

- Effluent quality - this defines the characteristics of effluent from each pond;
- Pond improvement efficiency - the difference in the influent and effluent concentration expressed as a percentage of the influent concentration and this takes into account the effect of all mechanisms in the tailings ponds on the quality of effluent;
- Mass removal efficiency - the difference between the mass into the pond and mass out of the pond expressed as a percentage of mass of the pond and this accounts for the mass lost or gained in the pond. Mass lost might be due to volatilization in the case of cyanide and precipitation and sedimentation in the case of heavy metals. Mass gain might be due to re-suspension in the pond;
- Effluent improvement due to dilution - this takes into account the effect of natural water in diluting the effluent in the pond.

Data used in this study includes historical data collected by the mine (1987-92) and data collected during the field study period (spring and summer of 1992 and 1993).

5.2 Water Quality Data Analysis

5.2.1 Influent and effluent quality

In this section a qualitative evaluation of the influent and effluent characteristics is carried out. This evaluation looks only at the general behavior. The quantitative evaluation will be done in the following sections. For example, the graphical presentation of effluent and influent quality are not on the same scale, they are presented to facilitate comparing seasonal variations between effluent and influent.

Pond 1

Figures 5.1 and 5.2 show a comparison between monthly influent and effluent concentrations in Pond 1 for cyanide and copper respectively from 1987 to 1992 and the monthly averages over the 6 years. Although data for nickel is provided in tables, it is not shown graphically here and in all other sections in this chapter due to the similarity with the behavior of the data for copper. Table 5.1 gives the average influent and effluent concentration of the whole period. The mill effluent concentration of cyanide averaged over 6 years was 79.7 mg/l. This is within the typical 40-80 mg/l cyanide concentration in mill discharge (Scott, 1989).

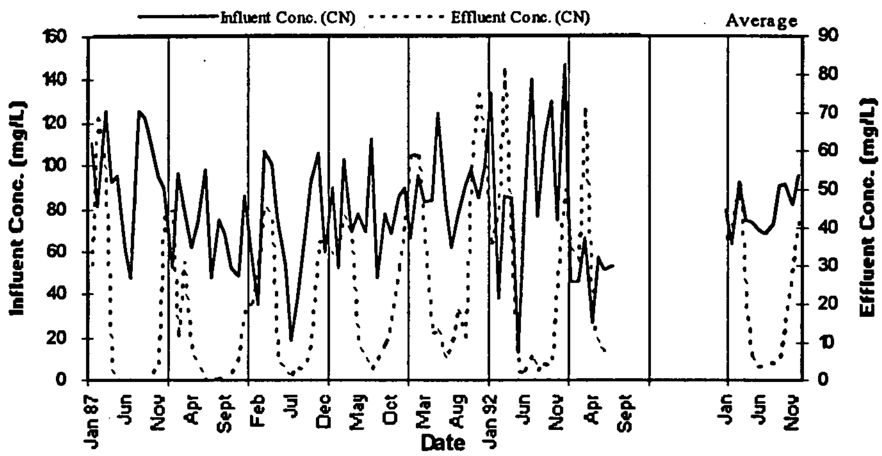


Figure 5.1. Influent and effluent quality for Pond 1 (CN)

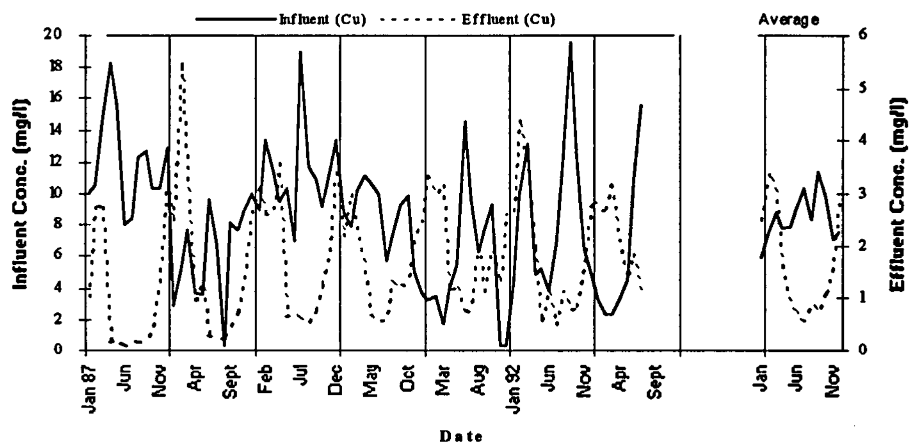


Figure 5.2. Influent and effluent quality for Pond 1 (Cu)

Table 5.1. Average influent and effluent quality for Pond 1 (1987-1992)

Parameters	Influent Concentration (mg/l)		Effluent Concentration (mg/l)	
	Average	Range	Average	Range
Cyanide	79.7	13.1 - 146.6	21.7	0.1 - 82.0
Copper	8.5	0.4 - 19.5	3.8	0.1 - 14.6
Nickel	3.5	1.3 - 6.9	1.7	0.1 - 5.5

The influent to Pond 1 is the mill effluent which is independent of any seasonal variations. As a result, no relationship should be expected between the influent and effluent quality in Pond 1 for all the parameters (cyanide, copper and nickel). Figures 5.1 and 5.2 confirm this and show that the effluent quality exhibits seasonal patterns.

High effluent concentrations are observed from October to April with the peak occurring in December or January, while lower effluent concentrations are observed between April and October with the minimum occurring in June. There is a similarity in the behavior of the two parameters. This suggests that these parameters are affected in a similar way by seasonal factors. This is investigated in more detail in Section 5.2.4.

Pond 2

Figures 5.3 show a comparison between influent and effluent concentration behavior in Pond 2 for cyanide from 1987 to 1992 and the monthly averages over the 6 year period. Table 5.2 gives the averages and the ranges of the influent and effluent concentration over the whole period.

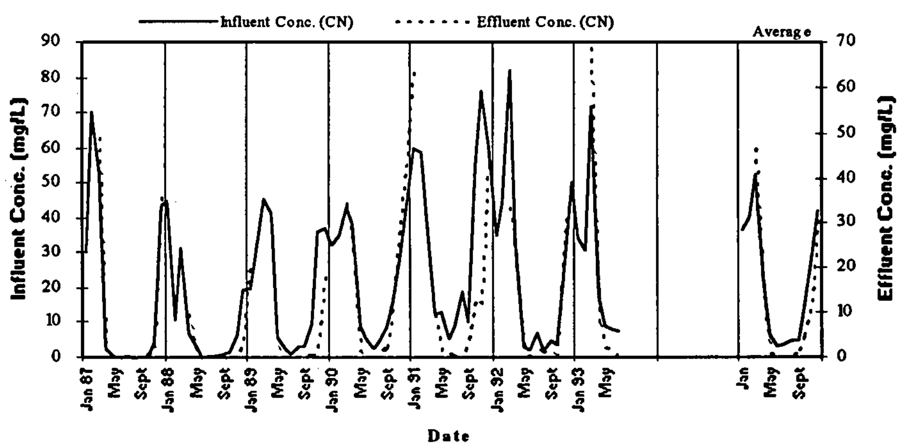


Figure 5.3. Influent quality and effluent quality for Pond 2 (CN)

Table 5.2. Influent and effluent quality for Pond 2 (1987-1992)

Parameters	Influent Concentration (mg/l)		Effluent Concentration (mg/l)	
	Average	Range	Average	Range
Cyanide	21.7	0.1 - 82.0	9.8	0.1-68.8
Copper	3.8	0.1 - 14.6	2.0	0.1-11.2
Nickel	1.7	0.1 - 5.5	0.9	0.1-3.8

A very distinct seasonal pattern is observed for both the influent and effluent concentration. The two show close similarity with the peaks and the troughs almost completely coinciding. A very slight lag of the effluent on the up turn can be observed, probably due to retention in the pond.

Pond 3

Figures 5.4 and 5.5 show a comparison between influent and effluent concentration in Pond 3 for cyanide and copper respectively from 1987 to 1992 and the monthly averages over the 6 year period. Table 5.3 gives the averages and the ranges of the influent and effluent concentration over the whole period.

In contrast to Pond 1 and Pond 2 data, a distinct lag is observed between the influent and effluent concentration. The peaks of the influent occur in January or February while the peaks of the effluent occur in April or May.

The lag of effluent peaks in Balmer Lake might be due to either the freeze/thaw cycle or to the retention period in the pond. This presents an interesting phenomenon, which requires further investigation. The occurrence of peak concentrations in April or May has a significant practical implication, since it coincides with the spawning period for fish in the downstream waters. In order to protect the fish during this period, the Certificate of Approval allows no discharge from

Balmer Lake from May 01 to July 01, except with the approval of the Ministry of Environment, and even then, only with careful monitoring.

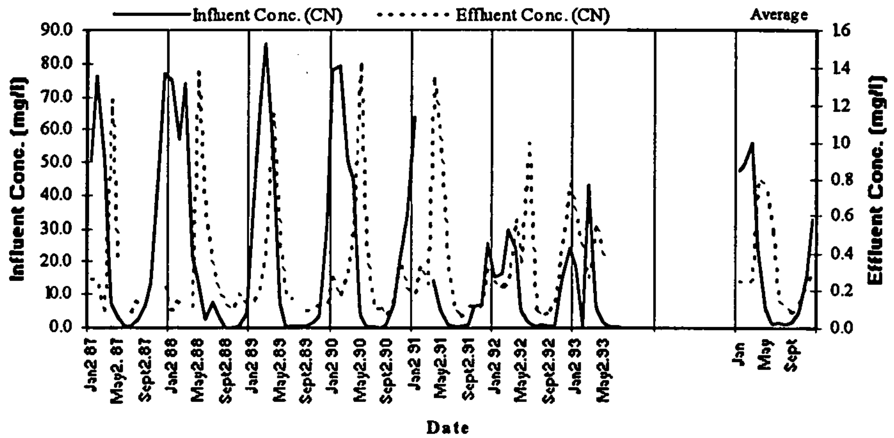


Figure 5.4. Influent quality and effluent quality Pond 3 (CN)

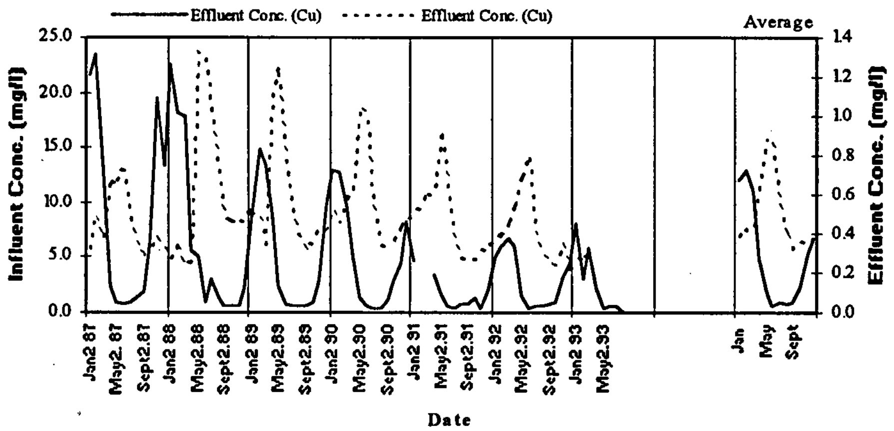


Figure 5.5. Influent quality and effluent quality for Pond 3 (Cu)

Table 5.3. Average Influent and effluent quality for Pond 3 (1987-1992)

	Influent Concentration (mg/l)		Effluent Concentration (mg/l)	
Parameters	Average	Range	Average	Range
Cyanide	20.2	0.2-86.0	0.3	0.1-1.4
Copper	5.0	0.1-23.5	0.5	0.2-1.3
Nickel	3.4	0.3-13.6	0.6	0.2-1.2

5.2.2 Evaluation of effluent improvement efficiency

The effluent improvement efficiencies for all ponds and for all elements studied have been calculated as follows:

$$\eta = \frac{(C_i - C_e)x100}{C_i}$$

Where, η - is % effluent improvement

C_i - is concentration of influent

C_e - is concentration of effluent

Pond 1

The effluent improvement efficiencies of Pond 1 for cyanide, copper and nickel from 1987 to 1992 are presented in Figure 5.6. Monthly averages over the 6 years are also shown. The effluent improvement efficiency of the two parameters follow a similar trend. High efficiency is observed from April to October with the peak occurring in July. This coincides with the lowest effluent concentration in Figure 5.1 and 5.2. Cyanide exhibits a higher efficiency than copper and it is positive throughout the year. The evaluation of mass removal efficiency in Section 5.2.3 indicates why this is so.

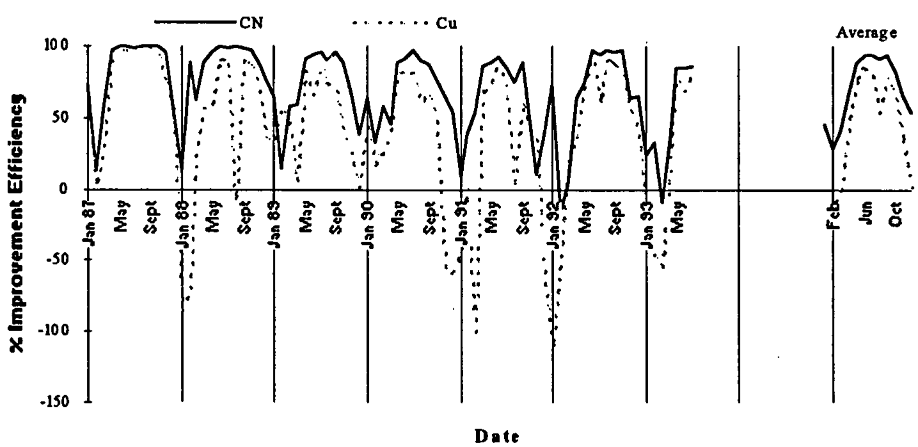


Figure 5.6. Effluent improvement efficiency for Pond 1 (1987-92)

Table 5.4 gives the annual average influent and effluent concentration and effluent improvement efficiency for Pond 1 from 1987 to 1992. The effluent concentration of cyanide over the period increases, while the effluent improvement efficiency decreases. A similar trend is observed for copper and nickel, though not as evident as for cyanide. This is probably due to the fact that as a pond ages, its effluent improvement efficiency decreases due to accumulation of sediments, which reduces the pond capacity to hold effluent. The reduced retention time in the pond does not allow sufficient time for the pond processes to improve effluent.

Table 5.4. Annual average influent and effluent concentration and effluent improvement efficiency for Pond 1 (1987-1992).

Year	Influent Quality (mg/l)				Effluent Quality (mg/l)				Effluent Improvement Efficiency (%)		
	pH	CN	Cu	Ni	pH	CN	Cu	Ni	CN	Cu	Ni
1987	10.3	97.1	11.9	3.4	7.9	14.7	2.7	0.8	85	77	74
1988	9.2	70.1	6.2	3.6	8.5	10.6	3.0	1.6	84	36	54
1989	10.5	67.8	11.4	3.3	8.6	19.8	5.6	1.8	72	49	41
1990	10.6	78.5	8.3	3.1	8.9	22.3	4.7	1.6	71	36	45
1991	9.7	87.2	5.5	3.1	8.7	34.8	2.9	1.9	59	19	37
1992	10.5	92.9	8.6	4.3	8.3	24.3	4.5	1.8	68	40	49
Average	**10.1**	**82.3**	**8.6**	**3.5**	**8.5**	**21.1**	**3.9**	**1.6**	**73**	**43**	**50**

Pond 2

Figure 5.7 gives the effluent improvement efficiency for cyanide and copper in Pond 2 over 6 years (1987-1992). The average monthly effluent improvement efficiencies are also shown. December to February data is missing since the pond is frozen during this time and no sampling is done.

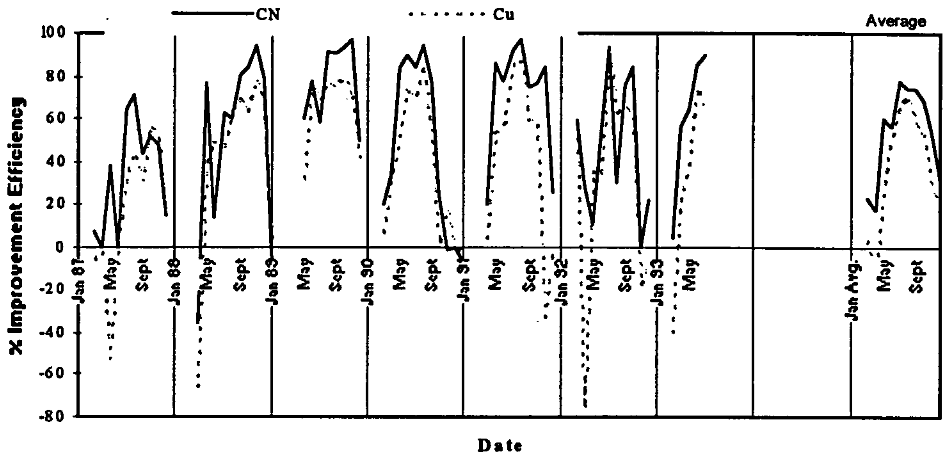


Figure 5.7. Effluent improvement efficiency for Pond 2

Pond 2 is similar to Pond 1 the effluent improvement efficiency of the two parameters follow a similar trend, with high efficiencies observed during the warmer months of the year (April to October) with the peak occurring in July. This coincides with low effluent concentration, which is expected. In this pond also, cyanide exhibits a higher efficiency than the two metals.

Table 5.5 gives the annual average influent and effluent concentration and effluent improvement efficiency for Pond 2 from 1987 to 1992. Unlike Pond 1 there is no particular trend in the average concentration of cyanide, copper or nickel over the period.

Table 5.5 Annual average influent and effluent concentration and effluent improvement efficiency for Pond 2 (1987-1992).

Year	Influent Quality (mg/l)				Effluent Quality (mg/l)				Effluent Improvement Efficiency (%)		
	pH	CN	Cu	Ni	pH	CN	Cu	Ni	CN	Cu	Ni
1987	7.9	17.1	2.9	1.0	7.8	9.2	2.0	0.8	34	17	20
1988	8.5	10.5	3.0	1.6	7.9	1.7	0.9	0.6	57	45	28
1989	8.6	19.7	5.6	1.8	7.8	5.1	2.4	0.8	68	58	47
1990	8.9	22.2	4.6	1.6	7.7	14.8	3.3	1.1	51	38	33
1991	8.7	34.7	2.9	1.9	7.8	15.0	1.5	1.3	63	41	29
1992	8.3	24.3	4.5	1.8	7.8	12.9	2.0	1.1	46	30	34
Average	**8.5**	**21.5**	**3.9**	**1.6**	**7.8**	**9.8**	**2.0**	**0.9**	**53**	**38**	**32**

Pond 3

Figure 5.8 shows the effluent improvement efficiency for cyanide and copper for Pond 3, from 1987 to 1992. The average monthly efficiencies for the 6 years are also given.

Low effluent improvement efficiency is observed from April to June, while high efficiency is observed from August to February. This is very unusual and unexpected behavior. It is quite different from the first two ponds.

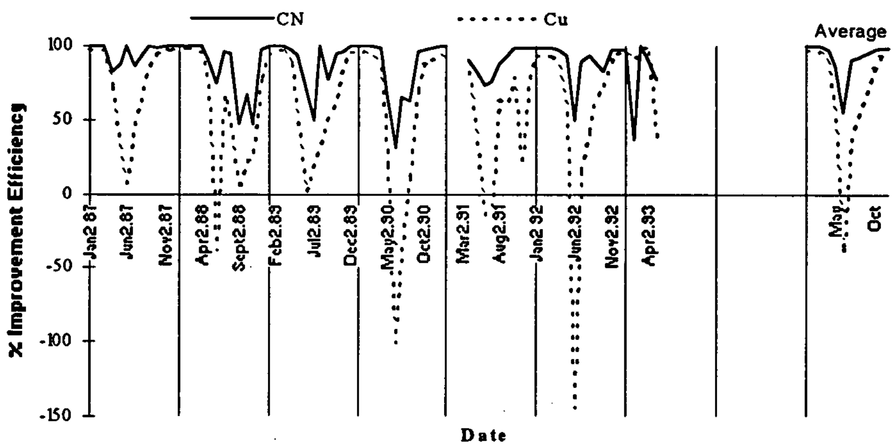


Figure 5.8. Effluent improvement efficiency for Pond 3

Table 5.6 gives the annual average influent and effluent concentration and effluent improvement efficiency for Pond 3 from 1987 to 1992.

Table 5.6. Annual average influent and effluent concentration and effluent improvement efficiency for Pond 3 (1987-1992).

Year	Influent Quality (mg/l)				Effluent Quality (mg/l)				Effluent Improvement Efficiency (%)		
	pH	CN	Cu	Ni	pH	CN	Cu	Ni	CN	Cu	Ni
1987	7.8	28.1	8.8	5.3	7.3	0.3	0.5	0.5	96	74	81
1988	7.9	21.8	6.5	4.9	7.6	0.3	0.6	0.8	84	56	47
1989	7.8	23.5	5.4	3.2	7.5	0.3	0.6	0.7	90	64	61
1990	7.7	26.8	5.0	3.1	7.6	0.3	0.6	0.6	85	51	71
1991	7.8	12.7	1.6	1.9	7.6	0.4	0.5	0.6	90	48	52
1992	7.8	11.4	3.0	2.6	7.4	0.4	0.4	0.5	91	55	71
Average	**7.8**	**20.7**	**5.1**	**3.5**	**7.5**	**0.3**	**0.5**	**0.6**	**89**	**58**	**64**

5.2.3 Evaluation of mass removal efficiency

Mass removal efficiency is calculated as:

$$\eta = \frac{(M_i - M_o)x100}{M_i}$$

Where, η is the % mass removal

M_i is the mass in

M_o is the mass out

Pond 1

Cyanide

Table 5.6 gives the year by year mass balance for cyanide for Pond 1 from 1990 to 1993 and the average mass removal efficiency over the period. The mass in is greater than mass out for each year. This indicates that there is mass removal or loss in the pond. This is probably due to volatilization.

Table 5.7 Mass removal efficiency evaluations for Pond 1 (cyanide)

	Mass in (kg)	Mass out (kg)	Removal %
1990	115	75	35
1991	127	107	16
1992	136	76	44
Average	**126**	**86**	**32**

Copper and nickel

Table 5.7 gives a year by year mass in and out for copper and nickel for Pond 1 from 1990 to 1993 and the average mass removal efficiency over the period. The mass out is greater than mass in for both copper and nickel. This indicates that there is some re-suspension taking place in the pond.

Table 5.8 Mass removal efficiency evaluations for Pond 1 (copper and nickel)

Year	Copper			Nickel		
	Mass in (kg)	Mass out (kg)	Removal %	Mass in (kg)	Mass out (kg)	Remova l %
1990	12.2	16.6	-36	4.4	5.3	-20
1991	8	12.2	-53	4.4	6.4	-45
1992	12.6	14.0	-16	6.2	6.1	2
Average	**10.9**	**14.3**	**-34**	**5.0**	**5.9**	**-18**

Pond 2

Cyanide

Table 5.8 gives the year by year mass in and mass out for cyanide for Pond 2 from 1990 to 1993 and average mass removal efficiency over the period. The mass in is greater than mass out indicating again that there is some mass loss, probably due to volatilization.

Table 5.9 Mass removal efficiency evaluation for Pond 2 (cyanide)

Year	Mass in (kg)	Mass out (kg)	Removal (%)
1990	75	47.4	37
1991	107	32.8	69
1992	76	39.6	48
Average	**86**	**39.9**	**54**

Table 5.9 gives the year to year comparison between mass in and mass out for copper and the mass removal efficiency for Pond 2. There is more mass in than mass out hence positive mass removal efficiency. Indicating that there is mass removal in this pond, probably due to sedimentation.

Table 5.10. Mass removal efficiency evaluation for Pond 2 (copper and nickel)

Year	Copper Mass in (kg)	Copper Mass out (kg)	Copper Remova l (%)	Nickel Mass in (kg)	Nickel Mass out (kg)	Nickel Removal (%)
1990	16.6	11.6	30	5.3	3.8	28
1991	12.2	4.9	60	6.4	3.9	39
1992	14.0	7.8	44	6.1	3.9	36
Average	**14.3**	**8.1**	**43**	**5.9**	**3.9**	**34**

Pond 3

Cyanide

Table 5.10 gives the year by year mass in and mass out for cyanide for Pond 3 from 1990 to 1993 and average mass removal efficiency over the period. As with ponds 1 and 2, the mass in is much greater than mass out. The average mass removal efficiency over the period is 95%.

Table 5.11. Mass removal efficiency evaluation for Pond 3 (cyanide)

Year	Mass in (kg)	Mass out (kg)	Removal (%)
1990	115.1	10.7	91
1991	60.0	8.5	86
1992	68.7	7.8	89
Average	**81.3**	**9.0**	**89**

Copper and nickel

Table 5.11 gives the year by year comparison between mass in and mass out for copper and the mass removal efficiency for Pond 3. The mass removal efficiency for copper is positive, while that of nickel is negative.

Table 5.12. Mass removal efficiency evaluation for Pond 3 (copper and nickel)

Year	Copper			Nickel		
	Mass in (kg)	Mass out (kg)	Removal (%)	Mass in (kg)	Mass out (kg)	Removal (%)
1990	24.2	15.1	38	11.7	13.1	-12
1991	8.3	11.3	-36	8.0	14.7	-84
1992	15.5	10.5	32	10.8	12.2	-13
Average	**16.0**	**12.3**	**23**	**10.2**	**13.3**	**-30**

5.2.4 Evaluation of effluent improvement efficiency due to dilution

In order to evaluate the effect of dilution on the effluent improvement efficiency, the effluent improvement due to dilution alone is evaluated. It is assumed that there is complete mixing between the mill effluent and the natural inflow (runoff and precipitation).

The following equation is used to evaluate the effect of dilution on the effluent quality:

$$C_d = \frac{Q_n x C_n + Q_i x C_i}{Q_n + Q_i}$$

Where, C_d is concentration of effluent after dilution

Q_n is natural inflow

C_n is concentration of natural inflow

C_i is concentration of mill effluent

Q_i is mill inflow

The percentage improvement due to dilution is calculated as:

$$\eta_d = \frac{(C_i - C_d) x 100}{C_i}$$

Where, η_d is % effluent improvement due to dilution.

The detailed water quality assessment for each pond is now presented.

Pond 1

Cyanide

Figure 5.9 shows a comparison between actual effluent improvement efficiency and that which is due to dilution in Pond 1 for cyanide from 1990 to 1992 and the monthly averages over the 3 year period. The improvement of effluent quality due to dilution is quite substantial. Using the formula shown above an average of about 45% of the effluent improvement in the pond can be attributed to dilution. The average actual effluent improvement efficiency as defined in Section 5.2.2, over the period is 63%. Dilution has the highest effect from March to October and reduces to zero from December to February.

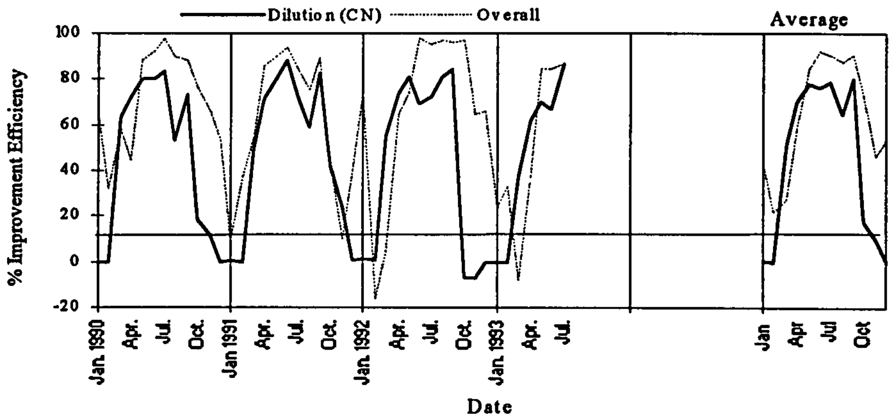


Figure 5.9. Improvement efficiency due to dilution and actual (CN)

There is great similarity between the effluent improvement efficiency due to dilution and the overall effluent improvement efficiency. Furthermore, it is evident that most of the improvement in effluent quality is due to dilution.

Copper

Figure 5.10 shows a comparison between actual effluent improvement efficiency and that which is due to dilution in Pond 1 for copper from 1990 to 1992 and the monthly averages over the 3 year period. The average improvement of effluent due to dilution is the same for all the parameters at 45%. The average actual effluent improvement efficiency for copper is 38% (Table 5.5). The average improvement efficiency is less than that which is due to dilution. This strongly suggests that there is re-suspension occurring in the pond. During the period from December to February when dilution capacity is zero, the overall effluent improvement shows negative efficiency.

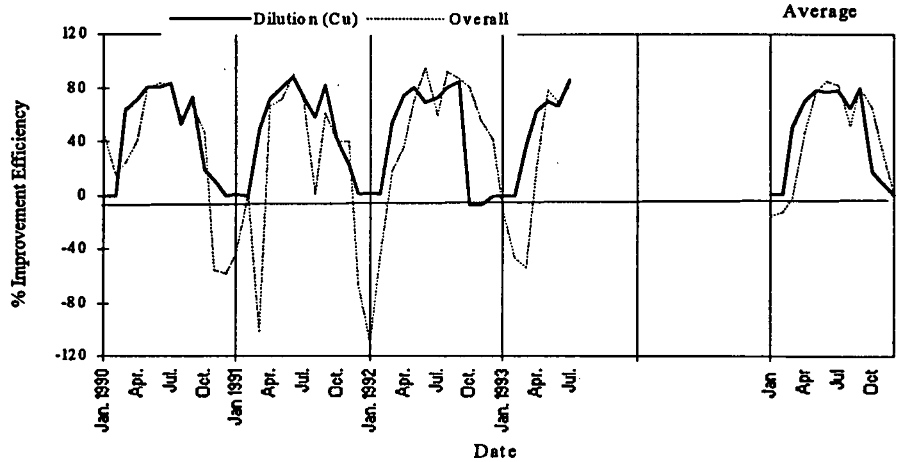


Figure 5.10. Improvement efficiency due to dilution and actual (Cu)

It is evident from Figure 5.10, that there is a close similarity between the effluent improvement attributable to dilution and the overall efficiency value for copper. This further supports the argument that dilution is the dominant mechanism responsible for improvement of effluent quality.

Pond 2

Cyanide

Figure 5.11 shows a comparison between the effluent improvement due to dilution in Pond 2 and the actual effluent improvement efficiency. In contrast to Pond 1 data, only 6% of the effluent improvement can be attributed to dilution. The actual effluent improvement efficiency is about 52%. This shows that in this pond mechanisms other than dilution are dominant in effluent improvement, such as volatilization.

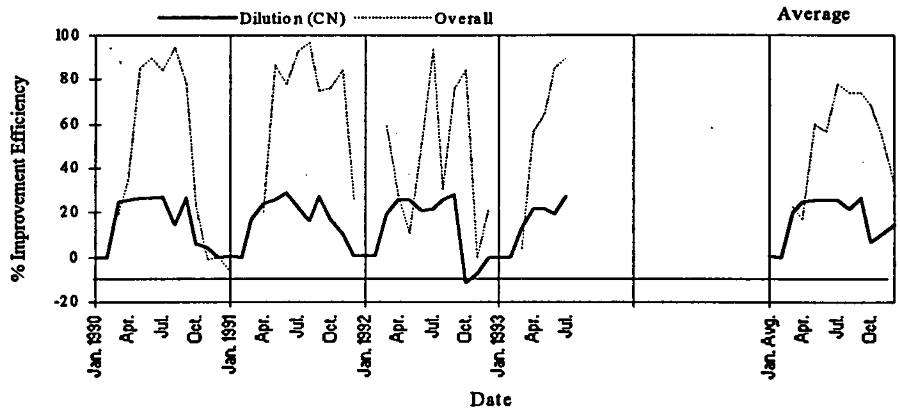


Figure 5.11. Effluent improvement efficiency due to dilution and the actual

Copper

Figure 5.12 shows the effluent improvement efficiency due to dilution and the actual value in Pond 1 for copper. As with cyanide, only 6% effluent improvement for Cu is attributable to dilution. The overall improvement efficiency is 35%. Indicating that other mechanisms such as precipitation and sedimentation are therefore quite significant.

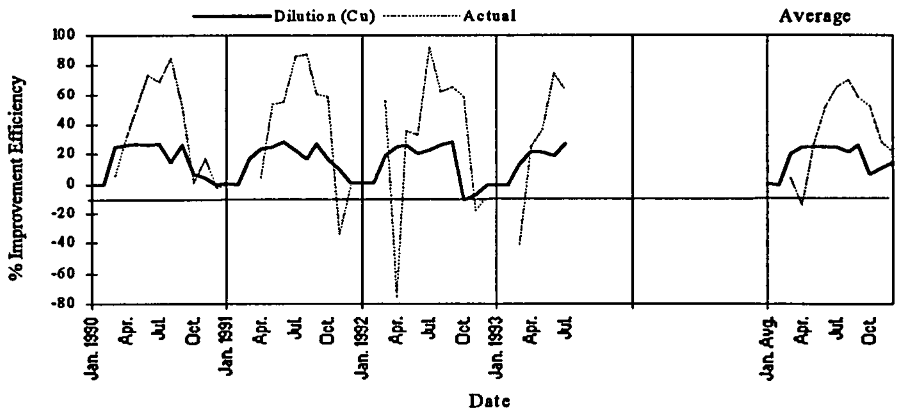


Figure 5.12. Effluent improvement efficiency due to dilution and the actual

Pond 3

Cyanide and copper

Figures 5.13 and 5.14 show a comparison between the actual effluent improvement efficiency and that which is due to dilution in Pond 3 for cyanide and copper respectively from 1990 to 1992 and the monthly averages over the 6 year period.

For this pond, the percentage improvement due to dilution can be calculated to be 42%. The overall effluent improvement efficiencies are 89% for cyanide and 58% for copper (Table 5.6). Although dilution is quite a significant mechanism in this pond, it does not seems to have an effect on the positioning of the peaks. This suggests that other mechanisms such as volatilization in case of cyanide and precipitation and sedimentation in case of copper are also significant.

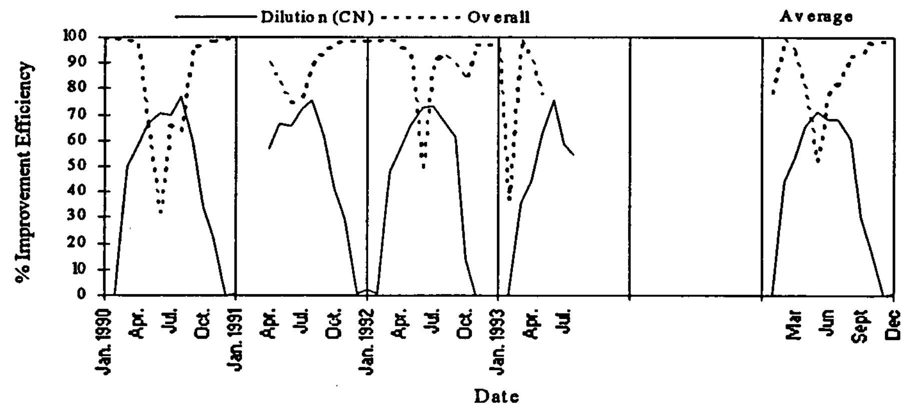


Figure 5.13. Effluent improvement efficiency due to dilution and the actual (CN)

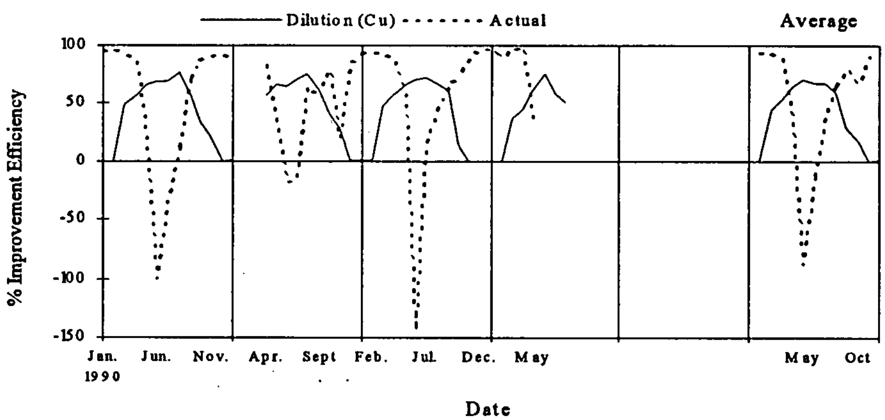


Figure 5.14. Effluent improvement efficiency due to dilution and the actual (Cu)

5.3 Summary of Data Analysis for Pond 1

<u>Pond 1</u>

- Although influent concentration is irregular, effluent concentrations follow a seasonal pattern.

- Effluent concentration follows the expected seasonal pattern with low effluent concentration in warmer months and higher effluent concentration during colder months. Effluent improvement efficiency, therefore, is higher in the warmer months.
- The annual average effluent improvement efficiency for cyanide in Pond 1 from 1987 to 1992 was 70%. The effluent improvement efficiency ranged from 29 to 95%.
- Average effluent improvement efficiency due to dilution in Pond 1 from 1990 to 1992 was 45%. During the same period the overall average effluent improvement for cyanide was 63%. This indicates that dilution is a significant mechanism in effluent improvement in this pond. Other mechanisms such as volatilization also contribute to the effluent improvement efficiency in the pond.
- Average mass removal efficiency in Pond 1 for cyanide from 1990 to 1992 was 40%.
- For copper, the annual average effluent improvement efficiency from 1987 to 1992 was 41%. The range was from 16 to 84%.
- From 1990 to 1992 the effluent improvement efficiency was 29%. This is less than the effluent improvement due to dilution which was 45%, suggesting that other processes such as re-suspension might be taking place in the pond.

<u>Pond 2</u>

- The seasonally influenced influent concentrations result in effluent maintaining a similar pattern.
- Effluent quality follows the expected seasonal pattern with low effluent concentration in warmer months and higher effluent concentration during colder months. As expected the effluent improvement efficiency behaves in an opposite manner.
- The annual average effluent improvement efficiency ranges from 23 to 78% with an average of 48%, for cyanide in Pond 2 from 1987 to 1992.
- Average effluent improvement efficiency due to dilution for Pond 2 from 1990 to 1992 was 6%. During the same period the average effluent improvement for cyanide was 52%. This

indicates that dilution was not the main mechanism responsible for effluent improvement. Other mechanisms such as volatilization are more significant in the effluent improvement efficiency in the pond.

- For copper, the effluent improvement efficiency ranged from -14 to 70% with an annual average of 33%.
- From 1990 to 1992 the effluent improvement efficiency was 35%. This is greater than the effluent improvement due to dilution which is 6%, suggesting that other processes, such precipitation and sedimentation, are taking place in the pond.

<u>Pond 3</u>

- Seasonally influenced influent concentration result in a seasonally influenced effluent, but with the effluent concentration lagging the influent concentration.
- Effluent quality does not follow the expected seasonal pattern. Instead, peaks occur during the spring time (April/May) and a low effluent concentration is observed for the rest of the year.
- The temporal behavior of the effluent improvement efficiency curve is quite different from curves for the other two ponds. High efficiency is observed from July to April, while high efficiency in the other ponds low effluent concentration is observed from March to May.
- The annual average effluent improvement efficiency for cyanide in Pond 3 from 1987 to 1992 is 89%. The effluent improvement efficiency ranges from 31 to 99%.
- Average effluent improvement efficiency due to dilution for Pond 3 from 1990 to 1992 was 42%. During the same period, the average effluent improvement was 87%. This indicates that dilution is not the only significant mechanism responsible for effluent improvement. Other mechanisms such as volatilization are more significant.
- For copper, the annual average effluent improvement efficiency for the years is 60%. The range is from -40 to 97%.

- From 1990 to 1992, the effluent improvement efficiency was 56%. This is more than effluent improvement due to dilution, suggesting that other processes such as re-suspension might be taking place in the pond.

6.0 WATER AND MASS BALANCE MODELING

6.1 Introduction

This chapter presents the water and mass balance evaluation of Balmer Lake tailings system. A model was developed which covered the whole of the Balmer Lake catchment area, accounting for all the important inflows and outflows of the lake.

Water and mass balance modeling involves carrying out a quantitative and qualitative evaluation of the tailings management system. This is essential for determining the consequences of any changes in the tailings management system or for improving the performance of the system through diversion, recycling and reuse.

The Balmer Lake Tailings System receives natural runoff from several creeks and tailings from the mines (Section 4.1). It is necessary in tailings management to know how much water is flowing into the tailings management system from the different sources. This involves identifying and quantifying the most important water sources for the tailings management system.

The other factors to be evaluated and quantified are:

- the significance of deposition and re-suspension in the ponds
- the significance of different sources of mass loading into the tailings pond
- the significance of dilution on the effluent quality

6.2 Model Definition

The basic equation of conservation of mass was applied, as presented below:

$$Q_{in} - Q_{out} = \Delta_{storage}$$

where,

Q_{in}	is the rate of water or mass inflow into the pond
Q_{out}	is the rate of water or mass outflow from the pond
$\Delta_{storage}$	is the rate of water or mass lost or gained in the pond

The various ponds in the tailings management are used as control volumes for water balancing. Therefore, the model is composed of sub-models representing each tailings pond. The total inflow and outflow of Balmer Catchment is accounted for in the Balmer Lake sub-model. The model does not take into account ground water flow. It is assumed that the inflow and outflow from ground water sources cancel each other and therefore have a negligible impact on the water model (Golder Model, 1985).

Figure 6.1 gives the schematic presentation of the water and mass balance model. It shows all the major inflow and outflows in each of the ponds.

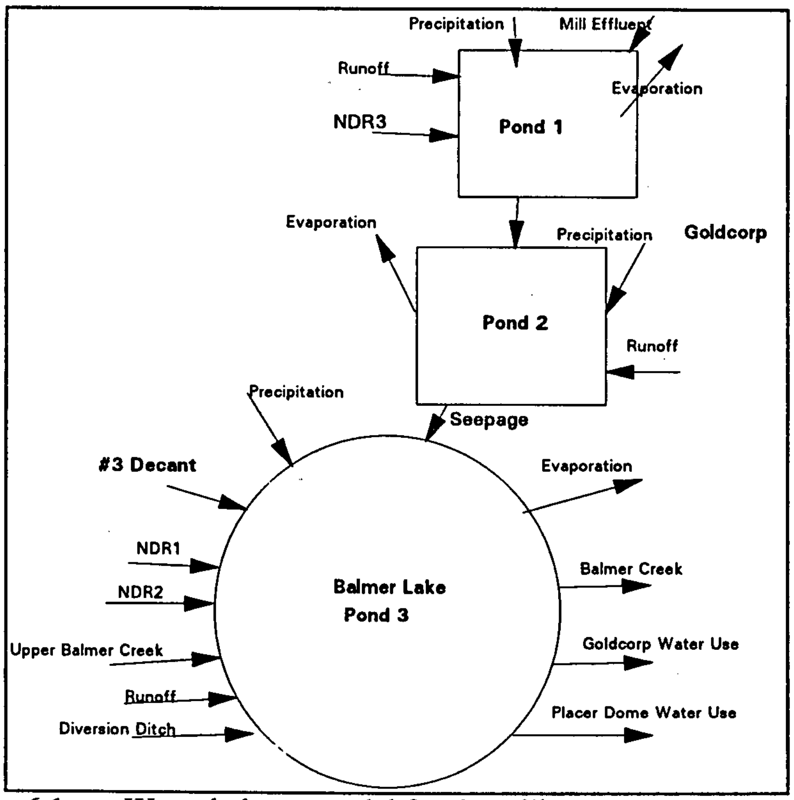


Figure 6.1. Water balance model for the tailings management system

The principal components of flow in and out of the ponds used in the model are as follows:

6.2.1 Pond 1

<u>Qin</u>

i) Natural Drainage River 3 (NDR3)

ii) Direct catchment runoff

iii) Mill effluent

iv) Direct precipitation

<u>Qout</u>

i) Outflow to Pond 2

ii) Evaporation

6.2.2 Pond 2

<u>Qin</u>

i) Pond 1 inflow

ii) Direct catchment runoff

iii) Direct precipitation

<u>Qout</u>

i) Seepage to Balmer Lake

ii) Evaporation

6.2.3 Pond 3 (Balmer Lake)

<u>Qin</u>

i) Natural drainage river 1 (NDR1)

ii) Natural drainage river 2 (NDR2)

iii) Upper Balmer creek (UBC)

iv) Precipitation

v) Runoff from shores

vi) Diversion ditch

vii) Pond 2 effluent

viii) #3 Decant

Qout

i) Evaporation

ii) Balmer Creek

iii) Goldcorp water use

iv) Placer Dome water use

6.3 Model Input and Output Parameters

Inputs

1. Rainfall (monthly)
2. Snowfall (for each hydrological year)
3. Monthly lake evaporation data
4. Surface area of the ponds
5. Sub-catchment area of each pond
6. Runoff coefficient of the catchment area
7. Mill effluent
8. Water uses, Goldcorp and Placer Dome

Outputs

1. Monthly water and mass inflow from each source
2. Monthly total water and mass inflow and outflow for each pond

6.4 Model Solution Using Microsoft Excel

Microsoft Excel version 5.0 was used to solve the model. A workbook was set up with several sheets, which are explained below:

- Water balance - This sheet included data input and the evaluation of the water balance model
- WQdata - This sheet contained all the effluent quality input data. This included data from Goldcorp mill effluent, Pond 1 effluent, Pond 2 effluent, Natural inflow, #3 Decant and Balmer Lake effluent
- MasbCN - This sheet was used for mass balance evaluation for cyanide for all the ponds
- MasbCu - This sheet was used for mass balance evaluation for copper for all the ponds
- MasbNi - This sheet was used for mass balance evaluation for nickel for all the ponds

6.5 Model Results

6.5.1 Water balance

The summaries of the water balance model for Pond 1, Pond 2 and Balmer Lake are given in Tables 6.1 to 6.3 below. The tables present all the sources and sinks of the water inflow and outflow for each pond from 1990 to 1992. The averages over the period are also provided, along with the percentage contribution of each inflow or outflow to the total.

Pond 1

This pond received a substantial amount of natural inflow from NDR3, Pond 1 catchment runoff and direct precipitation, and accounted for more than 2/3 of the total inflow. This results in a higher volume of water to be managed although, this water helps to improve the water quality through dilution. The main outflow from this pond is into Pond 2.

Table 6.1. Summary of Pond 1 water balance model (m^3/year)

Inflows	1990 (m^3/year)	1991 (m^3/year)	1992 (m^3/year)	Average (m^3/year)	% of total
NDR 3	1,830,000	1,660,000	1,670,000	1,720,000	35
Mill Effluent	1,460,000	1,460,000	1,460,000	1,460,000	29
Pond 1 Runoff	1,330,000	1,210,000	1,210,000	1,250,000	25
Direct Precipitation	540,000	570,000	560,000	560,000	11
Total inflow	**5,160,000**	**4,900,000**	**4,900,000**	**4,990,000**	**100**
Outflows					
Evaporation	280,000	280,000	280,000	280,000	5
Outflow to Pond 2	4,890,000	4,620,000	4,630,000	4,710,000	95
Total Outflow	**5,160,000**	**4,900,000**	**4,900,000**	**4,990,000**	**100**

Pond 2

The natural inflow is quite insignificant in this pond, accounting for less than 6% (Table 6.2). The rest is the effluent from Pond 1. The outflow from this pond is mainly into the Balmer Lake.

Table 6.2. Summary of Pond 2 water balance model

Inflows	1990 (m^3/year)	1991 (m^3/year)	1992 (m^3/year)	Average (m^3/year)	% of total
Pond 1 Effluent	4,890,000	4,620,000	4,630,000	4,710,000	94
Pond 2 Runoff	190,000	170,000	170,000	180,000	4
Direct Precipitation	110,000	120,000	120,000	120,000	2
Total inflow	**5,190,000**	**4,910,000**	**4,920,000**	**5,010,000**	**100**
Outflows					
Evaporation	60,000	60,000	60,000	60,000	1
Outflow to Balmer Lake	5,130,000	4,860,000	4,860,000	4,950,000	99
Total Outflow	**5,190,000**	**4,910,000**	**4,920,000**	**5,010,000**	**100**

Pond 3

Balmer Lake water balance accounts for the total water inflow and outflow of the whole catchment. Like Pond 1, natural inflow is very significant in this pond, accounting for nearly 60% of the total inflow (Table 6.3). This is very important in that it will help the long term rehabilitation of Balmer Lake, considering that this is a natural lake. The dilution from the natural inflow also helps to improve the quality of water recycled to the mill processes at both mines.

The main outflow from this pond is the discharge into the Balmer Creek, accounting for over 70% of the total outflow. This discharge point is the final discharge before the effluent goes into the environment. The other outflows are the water used by the two mines and water lost due to evaporation.

Table 6.3. Summary of Pond 3 water balance model

Inflows	**1990 (m^3/year)**	**1991 (m^3/year)**	**1992 (m^3/year)**	**Average (m^3/year)**	**% of total**
Upper Balmer Creek	4,690,000	4,260,000	4,270,000	4,410,000	25
NDR1	1,430,000	1,290,000	1,300,000	1,340,000	8
NDR 2	1,550,000	1,410,000	1,420,000	1,460,000	8
Diversion Ditch (Placer Dome)	1,060,000	960,000	960,000	990,000	6
Secondary Pond Effluent (Goldcorp)	5,130,000	4,860,000	4,860,000	4,950,000	28
#3 Decant (Placer Dome)	2,560,000	2,560,000	2,560,000	2,560,000	14
Balmer Lake Runoff	470,000	420,000	430,000	440,000	2
Direct Precipitation	1,780,000	1,860,000	1,840,000	1,820,000	10
Total inflow	**18,660,000**	**17,620,000**	**17,640,000**	**17,970,000**	**100**
Outflows					
Evaporation	900,000	900,000	900,000	900,000	5
Placer Dome Water Use	2,560,000	2,560,000	2,560,000	2,560,000	14
Goldcorp Water Use	1,460,000	1,460,000	1,460,000	1,460,000	8
Outflow to Balmer Creek	13,740,000	12,700,000	12,720,000	13,060,000	73
Total Outflow	**18,660,000**	**17,620,000**	**17,640,000**	**17,970,000**	**100**

The reliability of the water balance model is based on the estimation of runoff volumes from the creeks and surrounding catchment (Section 4.3) and the estimated average flow from other sources. A sensitivity analysis is carried out in Section 6.6 to determine the effect of diversion from the model parameters

6.5.2 Mass balance

The mass balance model is based on the flow volumes estimated using the water balance model and the actual measured water quality data. The data are presented in Tables 6.4 to 6.12. The tables present mass balance evaluations for each pond for the parameters cyanide, copper and nickel.

Pond 1

The mass balance evaluation for Pond 1 for cyanide, copper and nickel are presented in Tables 6.4 to 6.6. Although the natural inflow accounts for 2/3 of the total water inflow into the pond (Section 6.5.1), it accounts for less than 1% of the total mass inflow into the pond for all the parameters. This confirms the fact that the natural water inflow plays a very significant role in diluting the effluent quality in the pond. The effect of dilution on the effluent quality is quantified in Chapter 5. For cyanide, on average, over 30% of the total mass inflow into the pond is removed in the pond. Again, this subject is dealt with in detail in Chapter 5. The main outflow of cyanide from the pond is the effluent into Pond 2, which accounts for up to 58% of the total mass outflow.

The results for copper and nickel are unexpected. They both show higher mass outflow than inflow. This means that there is re-suspension taking place in the pond.

Table 6.4. Summary of Pond 1 mass balance model (cyanide)

Inflow	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of total**
NDR 3	13	12	12	12	0
Mill Effluent	114,995	127,300	136,393	126,223	100
Pond 1 Runoff	9	8	8	9	0
Direct Precipitation	4	4	4	4	0
Total inflow	**115,021**	**127,324**	**136,418**	**126,254**	**100**
Outflows					
Evaporation	1,852	4,046	1,068	2,322	3
Outflow to Pond 2	73,744	102,613	75,325	83,894	97
Total Outflow	**75,597**	**106,659**	**76,392**	**86,216**	**100**

Table 6.5. Summary of Pond 1 mass balance model (copper)

Inflow	1990 (g/year)	1991 (g/year)	1992 (g/year)	Average (g/year)	% of total
NDR 3	16	15	15	15	0.1
Mill Effluent	12,140	8,059	12,600	10,933	99.7
Pond 1 Runoff	12	11	11	11	0.1
Direct Precipitation	5	5	5	5	0.1
Total inflow	**12,174**	**8,089**	**12,632**	**10,965**	**100.0**
Outflows					
Evaporation	640	867	435	647	4.3
Outflow to Pond 2	16,613	12,201	14,045	14,287	95.7
Total Outflow	**17,253**	**13,068**	**14,480**	**14,934**	**100.0**

Table 6.6. Summary Pond 1 mass balance model (nickel)

Inflow	1990 (g/year)	1991 (g/year)	1992 (g/year)	Average (g/year)	% of total
NDR 3	15	13	13	14	0.3
Mill Effluent	4,463	4,502	6,239	5,068	99.4
Pond 1 Runoff	11	10	10	10	0.2
Direct Precipitation	4	5	4	4	0.1
Total inflow	**4,492**	**4,530**	**6,267**	**5,096**	**100.0**
Outflows					
Evaporation	238	328	197	254	4.1
Outflow to Pond 2	5,314	6,462	6,119	5,965	95.9
Total Outflow	**5,553**	**6,790**	**6,316**	**6,219**	**100.0**

<u>Pond 2</u>

For this pond like Pond 1 there is no significant mass inflow from the natural water inflow for all the parameters. However, dilution is not a major factor in this pond since it receives less than 6% of the total water inflow as natural inflow. As expected, the main source of mass is Pond 1 effluent. A significant mass loss in the pond is observed for all the parameters ranging from 35% to 55%. The rest of the mass is transported into Pond 3 with the effluent.

Table 6.7. Summary of Pond 2 mass balance model (cyanide)

Inflow	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of total**
Pond 1 Effluent	73,744	102,613	75,325	83,894	100.0
Pond 2 Runoff	1	1	1	1	0.0
Direct Precipitation	0.8	0.8	0.8	0.8	0.0
Total inflow	**73,746**	**102,615**	**75,327**	**83,896**	**100.0**
Outflows					
Evaporation	103	128	75	102	0.3
Outflow to Balmer Lake	47,325	32,639	39,590	39,852	99.7
Total Outflow	**47,429**	**32,767**	**39,665**	**39,954**	**100.0**

Table 6.8. Summary of Pond 2 mass balance model (copper)

Inflow	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of the total**
Pond 1 Effluent	16,613	12,201	14,045	14,287	100.0
Pond 2 Runoff	2	2	2	2	0.0
Direct Precipitation	1	1	1	1	0.0
Total inflow	**16,616**	**12,204**	**14,047**	**14,289**	**100.0**
Outflows					
Evaporation	61	48	28	46	0.6
Outflow to Balmer Lake	11,507	4,853	7,791	8,050	99.4
Total Outflow	**11,568**	**4,901**	**7,819**	**8,096**	**100.0**

Table 6.9. Summary of Pond 2 mass balance model (nickel)

Inflow	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of total**
Pond 1 Effluent	5,314	6,462	6,119	5,965	100.0
Pond 2 Runoff	2	1	1	1	0.0
Direct Precipitation	1	1	1	1	0.0
Total inflow	**5,317**	**6,465**	**6,121**	**5,968**	**100.0**
Outflows					
Evaporation	25	33	22	27	0.7
Outflow to Balmer Lake	3,751	3,913	3,902	3,855	99.3
Total Outflow	**3,775**	**3,945**	**3,924**	**3,882**	**100.0**

Pond 3

Like Pond 1, Pond 3 also receives less than 1% of its mass inflow from the natural inflow for all the parameters. This also signifies great dilution capacity considering that up of 60% of the total water inflow is from the natural runoff. The main source of mass inflow into this pond is the effluent from Pond 2 and effluent from #3 Decant.

For cyanide, almost 90% of the total mass inflow is removed in the pond. For copper, however, only about 25% of the total mass inflow is removed in the pond. Nickel indicates more mass outflow than inflow, suggesting that re-suspension is also taking place in the pond.

Table 6.10. Summary of Pond 3 mass balance model (cyanide)

Inflow	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of total**
Upper Balmer Creek	33	30	30	31	0
NDR1	10	9	9	9	0
NDR2	11	10	10	10	0
Diversion Ditch (Placer Dome)	7	7	7	7	0
Secondary Pond Effluent (Goldcorp)	47,325	32,639	39,590	39,852	49
#3 Decant (Placer Dome)	67,715	27,300	28,991	41,336	51
Balmer Lake Runoff	3	3	3	3	0
Direct Precipitation	12	13	13	13	0
Total inflow	**115,117**	**60,011**	**68,653**	**81**	**100**
Outflows					
Evaporation	372	269	306	315	4
Placer Dome Water Use	888	901	896	895	10
Goldcorp Water Use	508	515	512	512	6
Outflow to Balmer Creek	8,935	6,811	6,052	7,266	81
Total Outflow	**10,703**	**8,496**	**7,767**	**8,989**	**100**

Table 6.11. Summary of Pond 3 mass balance model (copper)

Inflows	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of total**
Upper Balmer Creek	42	38	38	40	0.2
NDR1	13	12	12	12	0.1
NDR2	14	13	13	13	0.1
Diversion Ditch (Placer Dome)	10	9	9	9	0.1
Secondary Pond Effluent (Goldcorp)	11,507	4,853	7,791	8,050	50.2
#3 Decant (Placer Dome)	12,671	3,341	7,659	7,890	49.2
Balmer Lake Runoff	4	4	4	4	0.0
Direct Precipitation	16	17	17	16	0.1
Total inflow	**24,277**	**8,286**	**15,542**	**16,035**	**100.0**
Outflows					
Evaporation	597	448	448	498	4.0
Placer Dome Water Use	1,435	1,202	1,063	1,233	10.0
Goldcorp Water Use	820	687	607	705	5.7
Outflow to Balmer Creek	12,260	9,000	8,335	9,865	80.2
Total Outflow	**15,114**	**11,337**	**10,453**	**12,301**	**100.0**

Table 6.12. Summary of Pond 3 mass balance model (nickel)

Inflows	**1990 (g/year)**	**1991 (g/year)**	**1992 (g/year)**	**Average (g/year)**	**% of total**
Upper Balmer Creek	37	34	34	35	0.3
NDR1	11	10	10	11	0.1
NDR2	12	11	11	12	0.1
Diversion Ditch (Placer Dome)	8	8	8	8	0.1
Pond 2 Effluent (Goldcorp)	3,751	3,913	3,902	3,855	38.1
#3 Decant (Placer Dome)	7,919	4,014	6,595	6,176	61.1
Balmer Lake Runoff	4	3	3	4	0.0
Direct Precipitation	14	15	15	15	0.1
Total inflow	**11,757**	**8,008**	**10,579**	**10,115**	**100.0**
Outflows					
Evaporation	477	609	523	536	4.0
Placer Dome Water Use	1,434	1,588	1,311	1,444	10.8
Goldcorp Water Use	819	907	749	825	6.2
Outflow to Balmer Creek	10,349	11,577	9,658	10,528	79.0
Total Outflow	**13,079**	**14,682**	**12,242**	**13,334**	**100.0**

6.6 Sensitivity Analysis

Since the values used for the various parameters are averages, it is necessary to find out how the water discharge or the final effluent will be affected by changes in each of the parameters involved. Sensitivity analysis also gives an insight into the expected impact on the water balance or mass balance should one parameter change. Extreme events are of particular interest. The water balance is likely to be affected by the following factors:

- a reduction in the catchment area, possibly due to runoff diversion;
- an unusual storm event;
- a change in the rainfall-runoff coefficient;

- increasing the discharge of the mill effluent;
- increasing the recycle of the tailings water to the mill;
- increasing the size of the tailings pond; and
- decreasing or increasing the effluent concentration.

The sensitivity analysis will only be done on the dominant parameters or a combination of parameters, in the event that two parameters change simultaneously. For the purpose of this study the following parameters will be evaluated in the sensitivity analysis:

- reduction in catchment area;
- change in rainfall-runoff coefficient; and
- increase in mill discharge.

6.6.1 Reduction in catchment area

A reduction in the catchment area could be achieved by diverting runoff and/or by diverting a creek. Assuming that Upper Balmer Creek has been diverted, this would results in about 12,000 m2, reduction of the catchment area which is more than 1/3 of the total area. The impact of the diversion on the water inflow into Pond 3 is given in Table 6.13. Table 6.13 shows that although 1/3 of the catchment has be diverted, the resulting reduction in water inflow into Balmer Lake is only 25 % due to the unchanged contribution of the mill effluents.

Table 6.13. Pond 3 water balance model reduction in catchment area

Inflow	Actual Flow 1992 (m^3)	Reduced (m^3)	Reduction %
Upper Balmer Creek	4,270,000	250,000	90
NDR1	1,300,000	1,300,000	0
NDR2	1,420,000	1,420,000	0
Diversion Ditch (Placer Dome)	960,000	960,000	0
Pond 2 Effluent (Goldcorp)	4,860,000	4,360,000	10
#3 Decant (Placer Dome)	2,560,000	2,560,000	0
Balmer Lake Runoff	430,000	430,000	0
Direct Precipitation	1,840,000	1,840,000	0
Total inflow	**17,640,000**	**13,100,000**	**25**
Outflows			
Evaporation	900,000	900,000	0
Placer Dome Water Use	2,560,000	2,560,000	0
Goldcorp Water Use	1,460,000	1,460,000	0
Outflow to Balmer Creek	12,720,000	8,200,000	40
Total Outflow	**17,640,000**	**13,110,000**	**25**

6.6.2 Change in rainfall-runoff coefficient

The average rainfall-runoff coefficient can vary with changing catchment conditions, such as tree cover or water cover. Also it is possible that the coefficient was over estimated or underestimated. Table 6.14 presents the effect of changing the rainfall-runoff coefficient on the catchment water balance. Two rainfall-runoff coefficients were evaluated, reducing the runoff coefficient by 40% to 0.3 and increasing the runoff coefficient by 40% to 0.7. They are compared with the rainfall-runoff coefficient determined from flow measurement which was about 0.5. Reducing the rainfall-runoff coefficient by 40% results in reduction of inflow into Balmer Lake of about 30%, while increasing the rainfall-runoff coefficient by 40% results in increase of total inflow into the pond of about 20%.

Table 6.14. Pond 3 water balance model - change in runoff coefficient

Inflow	Flow (m3/Year)			Change in Flow (%)	
	*RC = 0.5	RC = 0.3	RC = 0.7	RC = 0.3	RC = 0.7
Upper Balmer Creek	4,400,000	2,560,000	5,980,000	40	40
NDR1	1,340,000	780,000	1,820,000	40	40
NDR2	1,460,000	850,000	1,980,000	40	40
Diversion Ditch (Placer Dome)	990,000	580,000	1,350,000	40	40
Pond 2 Effluent (Goldcorp)	4,950,000	3,410,000	5,320,000	30	10
#3 Decant (Placer Dome)	2,560,000	2,560,000	2,560,000	0	0
Balmer Lake Runoff	440,000	260,000	600,000	40	40
Direct Precipitation	1,820,000	1,840,000	1,840,000	0	0
Total inflow	**17,970,000**	**12,830,000**	**21,450,000**	**30**	**20**
Outflows					
Evaporation	900,000	900,000	900,000	0	0
Placer Dome Water Use	2,560,000	2,560,000	2,560,000	0	0
Goldcorp Water Use	1,460,000	1,460,000	1,500,000	0	0
Outflow to Balmer Creek	13,060,000	7,920,000	16,500,000	40	30
Total Outflow	**17,970,000**	**12,830,000**	**21,450,000**	**30**	**20**

Note: RC = Runoff Coefficient * RC = 0.5 is the calculated value

6.6.3 Increase in mill discharge

Table 6.15 presents the impact on the water balance on Balmer Lake if the mill effluent is increased by 50%. It should be noted that although the Goldcorp mill effluent value has been increased by 50 %, Pond 2 effluent increases by 10 % due to the high proportion of natural inflow into Pond 1. The total inflow increases only by 9%.

Table 6.15. Pond 3 water balance model increase in mill outflow

Inflow	Actual 1992 (m^3/year)	Incr. in Mill (m^3/year)	% increase
Upper Balmer Creek	4,270,000	4,270,000	0
NDR1	1,300,000	1,300,000	0
NDR2	1,420,000	1,420,000	0
Diversion Ditch (Placer Dome)	960,000	960,000	0
Pond 2 Effl. (Goldcorp)	4,860,000	5,090,000	10
#3 Decant (Placer Dome)	2,560,000	3,830,000	50
Balmer Lake Runoff	430,000	430,000	0
Direct Precipitation	1,840,000	1,840,000	0
Total inflow	**17,640,000**	**19,150,000**	**10**
Outflows			
Evaporation	900,000	900,000	0
Placer Dome Water Use	2,560,000	3,830,000	50
Goldcorp Water Use	1,460,000	2,190,000	50
Outflow to Balmer Creek	12,720,000	12,220,000	0
Total Outflow	**17,637,799**	**19,147,308**	**10**

6.7 Summary

6.7.1 Water balance

- Total runoff volumes into Pond 1 averaged about 4,990,000 m^3/year during the 1990-1992 period. Natural inflow into this pond was about 67% of the total inflow.

- Total runoff volumes into Pond 2 averaged about 5,010,000 m^3/year during the 1990-1992 period. Natural inflow into this pond is less than 6% of the total inflow.

- Total runoff volumes into Pond 3 averaged about 17,970,000 m^3/year during the 1990-1992 period. Natural inflow for the pond is 60 % of the total inflow.

- Reduction of the catchment area by 1/3 would result in about 25% reduction in water inflow into Pond 3.

- Reducing the rainfall-runoff coefficient by 40% results in reduction of inflow in Pond 3 of about 30%, while increasing the rainfall-runoff coefficient by 40% results in an increase of total inflow into the pond of about 20%.

- Increasing the mill effluent by 50% results in an increase of only 9% of the total inflow into Pond 3.

6.7.2 Mass balance

The mass balance model was based on the flow volumes estimated using the water balance model and the actual measured water quality data

Pond 1

- Although the natural inflow accounts for 2/3 of the total water inflow into the pond (Section 6.5.1), it accounts for less than 1 % of the total mass inflow in to the pond for all the parameters.
- 60% of the cyanide in the mill discharge entering Pond 1 is in the effluent into Pond 2
- Copper and nickel present unexpected results. They both show higher mass outflow than inflow. This means that there is re-suspension taking place in the pond.

Pond 2

- A significant mass loss in the pond is observed for all the parameters ranging from 35% to 55%. The rest of the mass is transported into Pond 3 with the effluent.

Pond 3

- Pond 3 also receives less than 1% mass inflow from the natural inflow for all the parameters.
- For cyanide, almost 90% of the total mass inflow is reduced in the pond. For copper, only about 25% of the total mass inflow is reduced in the pond.
- For nickel, more mass outflow than inflow is indicated, suggesting that re-suspension is also taking place in the pond.

7.0. DISCUSSION AND APPLICATION OF RESULTS

7.1. Introduction

In this chapter the results of the study will be discussed in reference to the objectives stated in Chapter 1. The chapter is divided into three sections, the first section discusses the effect of hydrology on the catchment, the second section discusses the qualitative and quantitative evaluation of the performance of the 3 ponds in improving effluent quality and the third section discusses the water and mass balance model developed for the tailings system.

7.2. Hydrological Assessment

This study has established the characteristics of the natural flow patterns into the Balmer Lake tailings management system over a hydrological year. During late fall, winter and early spring there are no records of flow in the creeks. During this time most of the precipitation is in the form of snow and the temperature is mainly below zero. Flow was therefore, assumed to be insignificant or non-existent. Most of the flow occurs during late spring and summer, during which time flow measurement was conducted. Late spring and early summer runoff volumes are due to both rainfall and the melting of snow on the ground.

Since the Balmer Lake tailings management system is an open system and receives excess natural inflow, hydrology has a very significant impact on both the effluent quality and quantity. The study established that Pond 1 and Pond 3 have very high natural inflow volumes. The natural inflow accounts for about 67% for Pond 1 and 58% for Pond 3 of the total inflow into the ponds. In Pond 2, only 6% of the total water inflow is natural runoff. Once this natural inflow mixes with the mill effluent, it becomes part of the effluent.

The negative impact of excess natural inflow is that it increases the waste water volume to be managed, resulting in a reduced retention time for the effluent in the pond. This does not allow enough time for processes such as volatilization, precipitation and sedimentation to fully improve the effluent quality. Excess natural inflow has a significant impact on the regulation of Balmer Lake from May 1 to July 1. According to the current Certificate of Approval, discharge from Balmer Lake into Balmer Creek is not allowed during this time except with the approval of the Ministry of Environment. This is in order to protect downstream aquatic life such as fish, which spawns during this period. The rationale for this is that based on historical data effluent concentrations of cyanide and heavy metals are likely to be above the maximum specified in the permit during this time. The excess natural inflow occurring during this period makes this provision very difficult to adhere to. Almost every year the mines have been forced to discharge during this time in order to avoid overtaxing the physical design of the Balmer Lake impoundment.

For Pond 1, it has also been established that the net mass removal is negative for copper and nickel, meaning that more mass leaves the pond than comes in. The most likely explanation for this unexpected behavior is that re-suspension occurs in the pond due to the velocity of natural inflow from NDR3.

The positive effect of natural inflow into the tailings system is that it contributes to the improvement of effluent quality through dilution. This is discussed in detail in the next section. The impact of dilution is very significant for Balmer Lake for two reasons. Firstly, Balmer Lake being a natural lake, it is the long term objective of the Ministry of Environmental Ontario to fully rehabilitate this lake to its natural state especially once the mines cease to operate. There is a long term intention that, Balmer Lake will cease to be part of the mines tailings management system, making it part of the receiving environment. The excess natural water reduces retention time in Balmer Lake, so that less time is required to flush that lake. This will be able to speed up the rehabilitation of Balmer Lake after mine closure. The second reason that dilution is significant is that the Lake is used as a water supply source for the mill water. The natural inflow helps in improving the water quality for the mill processes.

In order to establish the main factors affecting flow patterns of the catchment hydrology, several evaluations were conducted. Firstly, the hydrographs of Upper Balmer Creek, Pond 1 Effluent, NDR3 and the Diversion Ditch were evaluated and compared. During spring, it was observed that there were dissimilarities in the hydrographs of the different creeks, and that some volume peaks did not necessary correspond to storm events. These anomalies are expected since, during this period, the hydrographs are responding to both rainfall and snow melt. Snow melt is not necessarily uniform over the catchment. A storm event of less magnitude in late Spring will introduce more water into the system due to snow melt accompanying the storm, which can easily cause failure to the physical structures of the tailings system.

In summer, the hydrographs of all the creeks showed close similarities, with the peaks and troughs occurring at the same time, subject to small lags between different creeks. This indicates uniform distribution of precipitation over the catchment (Masala et al., 1994). However, a slight lag is noticed between hydrographs, which is due to the difference in concentration time. Concentration time is the time required for the whole catchment to start contributing to the flow at the gauging station. A larger catchment area, has a longer concentration time. The peak of Upper Balmer Creek, which is the largest sub-catchment, lagged all the other peaks. The significance of this observation is that it indicates that flow measurement is consistent with theoretical expectation.

The study also made a quantitative comparison between inflows from the different catchment areas in order to evaluate the impact of catchment characteristics. If catchment characteristics were similar for all the sub-catchments, the hydrographs per unit area would be identical. Different catchments have different characteristics affecting the quantity of runoff from the catchment. Examples of different characteristics include: degree of tree cover, water cover, rock outcrops soil conditions and slope of the catchment. Flow per unit area per day for Pond 1 Effluent was higher for both years, 1992 and 1993, than Upper Balmer Creek. This is due to the fact that a larger part of the Pond 1 Effluent catchment area is covered by water than that of the Upper Balmer Creek catchment area. The Pond 1 Effluent catchment area includes the Pond 1 area which is covered by water. For an area covered by water, the contribution of rainfall to runoff is almost 100%.

The overall rainfall-runoff coefficient of the catchment was found to be 0.51. This was evaluated by comparing the total rainfall volume received and the total inflow into Balmer Lake for the 1992 and 1993 study periods. This is an average value of the whole catchment rainfall-runoff characteristics over the whole year. It might not, therefore be exact in predicting runoff from sub-catchments over a shorter period of time but it generally gives adequate predictions for estimating water volumes.

The excess runoff during late spring and early summer above the received precipitation was considered to be snow melt. For 1992 and 1993, this estimated to be 25% of the total snow received in the hydrological year. Snow runoff was found to take place mainly in March (8%), April (32%), and May (60%), based on the excess runoff received during this time.

Study of catchment hydrology is significant for protecting physical structures against damage in case of an extreme event. The most significant peak was observed at the end of July in 1993 when a total inflow of over 800,000 m^3/day was recorded. This is the highest flow on record for a single day and it accounts for about 5% of the total annual inflow into the system.

Although this storm event did not cause any physical damage to the tailings structures, it caused a lot of concern.

7.3. Water Quality Assessment

In order to meet this objective, the study evaluated qualitatively and quantitatively, the performance of the tailings system, using effluent quality characteristics, mass removal efficiency, improvement efficiency due to dilution and total efficiency. These parameters have also been used to determine the dominant mechanisms quantitatively.

The qualitative evaluation of effluent quality showed a seasonal pattern for each pond. Pond 1 and Pond 2 effluent followed a simiiar pattern with high concentration during winter months and low concentration during summer months for the parameters cyanide, copper and nickel. The effluent improvement efficiency curve showed higher performance in summer and lower performance in winter, which would be expected.

The effluent concentration of Pond 3 also exhibits a seasonal pattern, but the peaks lagged the influent concentration peaks by about 2 months for cyanide and by about 4 months for copper. The occurrence of the peaks during this period causes a major problem in the management of Balmer Lake tailings management system. The peaks occur when there is excess flow due to spring runoff resulting from snow melt. This can easily exceed the physical limitation of the control weir of the lake, thus not allowing sufficient retention. The problem is that this time is the spawning period for the fish. Discharging toxic effluent will affect the spawning of the fish, but not discharging reduces water level in the creek which is also not good for spawning. There are several ways in which this problem can be dealt with:

- the mines can reduce the volume or concentration of discharge from the mill effluent, by providing chemical treatment;
- diverting part of the catchment runoff e.g. NDR3 which discharges into Pond 1;
- increasing the capacity of Balmer Lake by raising the level of the present control structure

The effect of the diversion of NDR3 on the tailings management system is evaluated in Section 7.4.

The higher efficiency of Pond 1 during the warmer months is mainly due to dilution. From 1990 to 1992, the average effluent improvement efficiency due to dilution was 67% for the parameters: cyanide, copper and nickel. The effluent improvement due to dilution is theoretical since it is based on the assumption that there is complete mixing between mill effluent and natural inflow, which is not the case in Pond 1. The actual effect of dilution can be estimated by subtracting the mass removal efficiency from total efficiency. Almost all the natural inflow into the pond occurs from late spring to early fall, which coincides with the period of high overall efficiency. This clearly demonstrates that dilution has very significant in effluent improvement in this pond. During the same period (1990 to 1992) the overall effluent improvement efficiency of cyanide was found to be 66%. The evaluation of mass removal efficiency found that 31.7% of the total mass of cyanide entering the pond is removed in the pond. Since mass removal mostly occurs during warmer months, this can mainly be attributed to volatilization of cyanide. In order for volatilization to take place, free cyanide has to be in the molecular form and this significantly increases as you depress the pH below 9.31. This is confirmed by what happens in Pond 1, where influent pH averages 10.2, while average effluent pH is 8.5. Another significant mechanism is the dissociation of metal complexes of cyanide. As free cyanide volatilizes complex metals start to dissociate. Higher temperature and sunlight speed up the process of volatilization and metal dissociation, which accounts for the higher effluent improvement efficiency observed in warmer months. During winter the process is very slow or reduced to zero since the pond surface is covered by ice.

In the case of copper, the overall effluent improvement efficiency from 1990 to 1992 was found to be 32%. This is less than the effluent improvement due to dilution. During the same period, the mass removal efficiency was negative with a value of -34 %. This shows that more mass leaves the pond than comes in. This can be attributed to re-suspension taking place in the pond. Nickel exhibits similar characteristics. This indicates that this pond is not effective in reducing the mass of copper and nickel in the effluent. The cause of the ineffectiveness is the reduction in retention time caused by three factors in Pond 1. Firstly, over the years the accumulation of tailings at the bottom of the pond has reduced the pond capacity and made it shallower. The overall removal efficiency of the pond has been observed to decreased with time (Masala et al., 1993), this is also shown in Section 5.2.2. Secondly, retention time is reduced in the pond due to natural inflow from NDR3. The inflow velocity from this creek into a shallow pond, causes re-suspension in the pond (Masala et al., 1993). The third factor responsible for reduced retention time is short circuiting caused by channeling in the pond. Based on this analysis the pond is ineffective in improving effluent quality. In order to improve the performance of this pond the mine can take the follow corrective steps. Firstly, the mine should consider diverting the natural creek, NDR3. Then the mine should increase the capacity of the pond through raising the height of the dam. The retention time could also be improved through the prevention of short-circuiting by the construction of berms to control water flow.

In Pond 2, dilution at 6% from 1990-1992, is not as significant as in Pond 1. During the same period, the overall effluent improvement efficiency for cyanide was 53%. This indicates that dilution was not the main mechanism responsible for effluent improvement. In this pond pH is further depressed to 7.8 resulting in a higher proportion of cyanide being in molecular form, which is readily volatilized. Volatilization therefore, is probably the most significant mechanism in cyanide reduction. In the case of copper and nickel, the overall improvement efficiencies were 37% and 32% respectively. These are greater than the effluent improvement due to dilution, suggesting that other process are responsible for improving effluent. Unlike Pond 1, mass removal efficiency for copper for this pond was positive at 43% indicating that there is mass removal in this pond. This can be attributed to precipitation and sedimentation.

This pond is more effective in improving effluent quality than Pond 1. If the mine took the corrective steps suggested for Pond 1, Pond 2 will also perform better since the reduced flow volume from Pond 1 due to diversion of NDR3 will result in longer retention time in Pond 2.

The average effluent improvement efficiency due to dilution in Pond 3 from 1990 to 1992 was 58% for all parameters. The overall efficiency during the same period was 88% for cyanide. The mass removal efficiency was 89%. The removal of cyanide through volatilization is more significant than dilution. Therefore in this pond both dilution and volatilization are significant in effluent improvement. For copper the annual average effluent improvement efficiency was also positive at 51%. The mass removal efficiency for the pond was 23%, resulting from precipitation and sedimentation. Since this Pond is the final polishing pond, its performance is significantly dependent on the performance of the earlier ponds.

7.4. Water and Mass Balance Modeling

A tailings management system is constantly subjected to changing conditions due to changing environmental regulations and natural interference. These necessitate periodic modifications and improvements to the system. A water balance model was used to predict what would happen to the overall system should one inflow or outflow component change. It also, provides a good starting point for considering appropriate available options for increasing the effectiveness of the system. The water and mass balance evaluated all significant inflow and outflow components for each pond.

<u>Pond 1</u>

Total inflow volume into Pond 1 averaged 4,990,000 m^3/year during the 1990-1992 period. Natural inflow, which included runoff and direct precipitation into this pond was about 67% of the total inflow. The mass balance evaluation for this pond indicated that less than 1% of the total mass inflow into the pond is from natural inflow the rest comes from mill effluent. The main water and mass outflow from the pond is into Pond 2, accounting for 94% and 97% respectively.

Pond 2

Total inflow volumes into Pond 2 averaged about 5,010,000 m^3/year during the 1990-1992 period. Almost all the water and mass inflow into this pond is received effluent from pond 1. Natural inflow which is catchment runoff and direct precipitation is less than 6%, this is due to the fact that this pond has a very small catchment area.

Pond 3

Total runoff volumes into Pond 3 averaged about 17,970,000 m^3/year during the 1990-1992 period. Natural inflow for the pond is 60 % of the total inflow the rest is effluent from Pond 2 effluent and effluent from Campbell Mine which contribute 28% and 14% respectively. In terms of mass, natural inflow contributes less than 1% like the other two ponds. While Pond 2 effluent and Campbell Mine effluent mass inflow are about 50% each for cyanide and copper. For nickel the contributions are 38% from Pond 2 effluent and 61% from Campbell Mine.

In order to investigate how the overall water balance of Pond 3 would respond to a reduction in catchment area, an evaluation was conducted assuming that about 1/3 of the catchment, part of Upper Balmer Creek , was diverted. Using the model, it was found that the corresponding reduction in water inflow into Pond 3 was 25%. A lesser reduction is observed in the water inflow than the corresponding reduced catchment area due to the unchanged contribution of the mill effluents.

Based on the current retention period for Balmer Lake which is theoretically 220 days. (Calculated by dividing the volume of the pond (2.6 km^2 x 3m) by the effluent volume (12,700,000 m^3)). After the diversion of 1/3 of the catchment the resulting effluent from

Balmer Lake would be about 8,200,000 m^3 (about 1/3 less than without the diversion). With this effluent volume from Balmer Lake the resulting retention period is 347 days. This would eliminate the discharge problem caused by the excess flow during spring, since it will provide extra storage capacity in the pond of about 4 months.

It is of interest to see how much catchment area has to be diverted if only two months of extra storage is required to eliminate the current problem. This would require a retention period of 280 days, corresponding to an effluent volume of 10,200,000 m^3. This could be achieved with a catchment reduction of 20%, an area of 7 km^2. This area is equivalent to NDR3 catchment area and Pond 1 catchment area. If therefore, this area was diverted this would result in an improved overall performance of the tailings system and eliminate the need for emergency discharge. NDR3 would be diverted to the downstream of the control weir for Balmer Lake.

In order to evaluate the sensitivity of the catchment water balance to the rainfall-runoff coefficient, an investigation was conducted in which the rainfall-runoff coefficient was increased by 40% or reduced by 40%. The results from the model indicated that a 40% increase in the rainfall-runoff coefficient would result in 20% increase in total inflow into Pond 3, while reducing the rainfall-runoff coefficient by 40% results in a reduction of 30% of the total inflow into the pond. Again, the change in the overall water balance is less than that of the corresponding change in the rainfall-runoff coefficient due to the unchanged contribution from the mill effluents.

An investigation of the effect of increasing the volume of mill effluent on the overall water balance was also conducted. The results from the model showed that a 50% increase in mill effluent would result in only 9% increase in the overall water balance of the system. The overall water balance is less affected by the increase in mill effluent due to that fact that most of the inflow into the pond is due to natural runoff, which is unchanged in this case.

Evaluating the impact of increase in mill effluent quantity is significant in case the mill increases its output. It is of interest for the tailings system managers to know what impact it will have on the overall water balance, especially for Balmer Lake tailings management which is facing a quality and quantity problem in managing the tailings pond.

8.0 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the conclusions of the study are presented and are consistent with the objectives in Chapter 1 and the discussion in Chapter 7. This chapter also provides recommendations for further studies.

8.1 Conclusions

Almost 50% of the total precipitation in the Balmer Lake Catchment ends up as runoff into the Balmer Lake tailings system. Natural inflow from the surrounding catchment has a very significant impact on Balmer Lake Tailings Management System, accounting for up to 84% of the total final discharge from Balmer Lake. This excess water has both negative and positive implications on the tailings management system. Natural inflow into the tailings system was found to have the biggest impact on Pond 1 and Pond 3, where the natural inflow was 67% and 58% of the total inflow into the ponds respectively.

In Pond 1, the excess natural runoff reduces the retention period in the pond, reducing or eliminating completely the effect of natural pond processes in improving the effluent quality. Although this pond indicated improvement of effluent for all parameters evaluated, total cyanide, copper and nickel, the improvement was largely due to dilution in the case of cyanide and exclusively due to dilution in the case of copper and nickel. This means that this pond is not performing one of the most important functions of a tailings pond, that of mass removal of heavy metals through precipitation and sedimentation. Similarly, there is very limited removal of cyanide through volatilization.

In order to improve the performance of this pond the mine could take the following corrective steps. Firstly, the mine could divert the natural creek NDR3, which would result in a reduction of about 60% of the present inflow. Secondly, the capacity of the pond could be increased through raising the height of the dam. The retention time could also be improved through the prevention of short-circuiting by the construction of berms to control water flow.

In the short term, the excess runoff into Pond 3 (Balmer Lake) has a negative effect especially during late spring and early summer. While the excess runoff provides some dilution during this period, the limited retention time does not allow for natural degradation and other processes in the pond to improve the effluent to acceptable levels. This results in peak effluents from Balmer Lake during this time. This problem is further compounded by the fact that this is the spawning period for the fish. In either case, discharging toxic effluent or reducing water levels in the creek by not discharging effluent, will have a negative effect on the spawning fish.

However, in the long term, the excess natural runoff into Pond 3 will have a positive impact on the overall management of the Balmer Lake water basin. The plan of the Ministry of Environment is restore Balmer Lake to its natural state. Although the lake is still being used as a final polishing pond, it is hoped that it will cease to be part of the tailings system, in which case it will be part of the receiving environment. The excess natural water into this pond will help speed the rehabilitation of the lake, by shortening the flushing period of the lake. The lake is also used for mill water supply. The excess natural water, therefore, helps improve the water quality for the mill processes.

This study has established an effective methodology for making a quantitative evaluation of the effectiveness of a tailings management system, by combining the follow pond performance parameters:

- mass removal efficiency;
- improvement efficiency due to dilution; and
- overall efficiency.

This approach allows a complete evaluation of an overall mass balance evaluation and helps determine the fate of the removed contaminants. Providing a better basis for future planning and management.

Pond 1 was found to be ineffective in improving effluent quality. Over the years the accumulation of tailings in the pond has reduced its effectiveness by reducing the retention time effluent in the pond. A decline in effluent overall efficiency improvement efficiency was observed over a 7 year period. Although the overall efficiency for all parameters was positive, it was found that it was mainly due to dilution for cyanide and totally due to dilution for copper and nickel. In actual fact, the mass removal efficiencies for copper and nickel were found to be negative, implying that there was more mass leaving the pond than coming in. This is caused by re-suspension, resulting from the inflow velocity of the natural runoff. The mass removal efficiency for cyanide, which was positive can be attributed to volatilization, since mass removal occurred during warmer months and the effluent pH dropped to 8.5 from influent pH of 10.2.

Unlike Pond 1, the mass removal efficiency for Pond 2 was positive for all the water quality parameters. Mass removal was attributed to volatilization with pH at 7.8, while for copper and nickel, precipitation and sedimentation are the most likely removal mechanisms. Dilution had very little impact on this pond since only 6% of the total inflow into the pond was natural inflow.

In Pond 3, both mass removal and dilution had a significant impact on the overall effluent improvement.

Using the water and mass balance model developed for the Balmer Lake Tailings system, it was found that by diverting 20% of the catchment area an extra 2 month retention period in Balmer

Lake would result. This could significantly reduce the problem caused by the excess spring runoff into Balmer Lake. This would be achieved by diverting NDR3, just before it enters Pond 1, hence reducing the Pond 1 catchment area as well. Diverting NDR3, would also result in better performance for Pond 1 and 2 due to increased retention time.

This study has established essential data for the purpose of the mine closure plan. In particular:

- a water balance for the tailings management system
- identification of the main watercourses and data which can be used to predicted seasonal flows in each watercourse affecting tailings management
- data that will allow an assessment of the potential effects of the closure plan on water quality and fisheries habitation
- receiving stream flow, lake volume and drainage patterns.

8.2 Recommendations for Further Study

Due to the site specific nature of this study, some of the recommendations will be specific to Balmer Lake tailings system. Here are the recommendations for further study:

1. Evaluation of the retention periods for Pond 1 and 2 taking into account channeling and short circuiting. This will improve understanding of the natural processes in the pond, by providing a quantitative relationship between these processes and retention time. This information can be used to predict the impact of increasing retention time through diversion or increasing pond capacity. Also evaluation of pond geometry, which changes as the pond ages, can help determine whether minimum depth is maintained for the process of sedimentation. Change in pond geometry with time, can help establish the rate at which the ponds are filling with sediments.
2. Evaluate the actual effects of dilution on effluent quality to allow comparison with the theoretical values determined in this thesis. Studying the mixing processes and how they

are affected by channeling and short circuiting will improve the understanding and prediction of system behavior.

3. Develop a quantitative relationships between seasonal variations in effluent quality and the factors causing these variations.

   A tailings pond undergoing natural degradation receives mill effluent which varies irregularly. The effluent from the pond exhibit seasonal variations which reflect the varying effectiveness of the pond over a year. The effectiveness of the pond is mainly dependent on physical, chemical and biological mechanisms responsible for improvement of effluent such as volatilization, dissociation, oxidation, precipitation, sedimentation and dilution. These mechanisms are dependent on climatic factors such as temperature, sunlight, rainfall and wind, and other factors such as pond dimensions, pond conditions, carbon dioxide absorption of the water, influent quality and quantity (metal speciation, pH, concentration).

By comparing the effluent quality with the climatic factors which influence the pond mechanisms, a qualitative relationship has been established. A further study is required to try to establish a quantitative relationship between climatic factors and effluent quality. Due to the complexity of a tailings management system involving physical, chemical and biological processes, a purely mechanistic approach to developing a model might prove impractical. A semi-empirical approach might prove more feasible. A possible conceptual form of the semi-empirical approach is given below.

$$Eff_t = f(IV, Eff_{t-1})$$

Where Eff_t is the effluent water quality at time t

IV represents all the independent variables with affect effluent quality

Eff_{t-1} is the effluent water quality at time t-1

The effluent quality from the tailings pond at any one time is dependent on the various independent variables, which affect the natural degradation process in the pond and the effluent quality at a time t-1. Time is very important in modeling seasonal variations, since seasonal variations are time structured.

Further investigation is required for Balmer Lake tailings system to establish the mechanisms and factors responsible for the lag in the effluent quality from Balmer Lake. The effluents of Pond 1 and Pond 2 are consistent with the existing theory, where the effluent peak occurs from December to February. This is due to the fact that during this time the average temperature is below zero. As a result, the pond is covered by snow or ice. Under these conditions, the pond mechanisms responsible for removal of contaminants, particularly cyanide are inhibited. As the temperature starts to increase during spring, the effluent concentration starts to decrease, reaching a minimum concentration in summer.

4 For Balmer Lake, however, the peak in effluent occurs in April/May. This is not consistent with the other two ponds. Two explanations are possible:

1. The peaks in Balmer Lake effluent lag the peak in Pond 2 effluent due to the retention time in Balmer Lake.
2. The freeze/thaw cycle might be responsible for this. The basic principle of this process is that impurity components such as cyanide and other ion species are rejected from ice when water is frozen in a controlled directional manner as would occur naturally in a tailing pond over the winter season. Observation of the thaw and freeze cycle shows that cyanide concentration in the ice in the thaw cycle produces a lower cyanide concentration than the ice in the freeze cycle for any given volume percent of ice. During winter, Pond 2 is mostly frozen As the pond starts to thaw in spring, higher concentration of effluent enters Balmer Lake and this might cause the peak which is reflected in the effluent concentration in the April/May.

Alternatively, the reason might be a combination of the above factors. A study is required to investigate this further. The results will give some useful insight into understanding Balmer Lake tailings management, especially in understanding the effect of diverting NDR3 creek on the effluent quality of Pond 3. In addition, the results will give more useful information on the influence of the freeze/thaw cycle on tailings management and whether it can be used to increase the effectiveness of the system. Also the effects of turnover in spring thus are not well understood and future work should be done to investigate this process and to determine whether two ponds allowing the turnover re-suspension to occur in the idle pond are more effective in tailings management than the single pond system.

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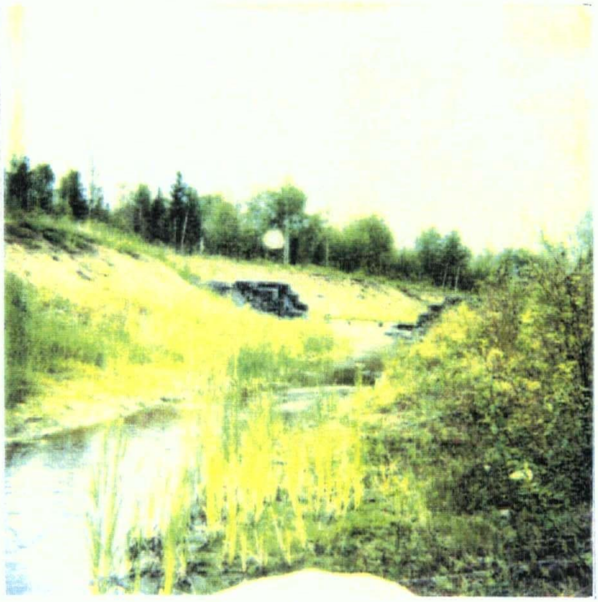
APPENDIX I

A1.1 Photographs of the flow measuring stations

Station #1 Upper Balmer Creek

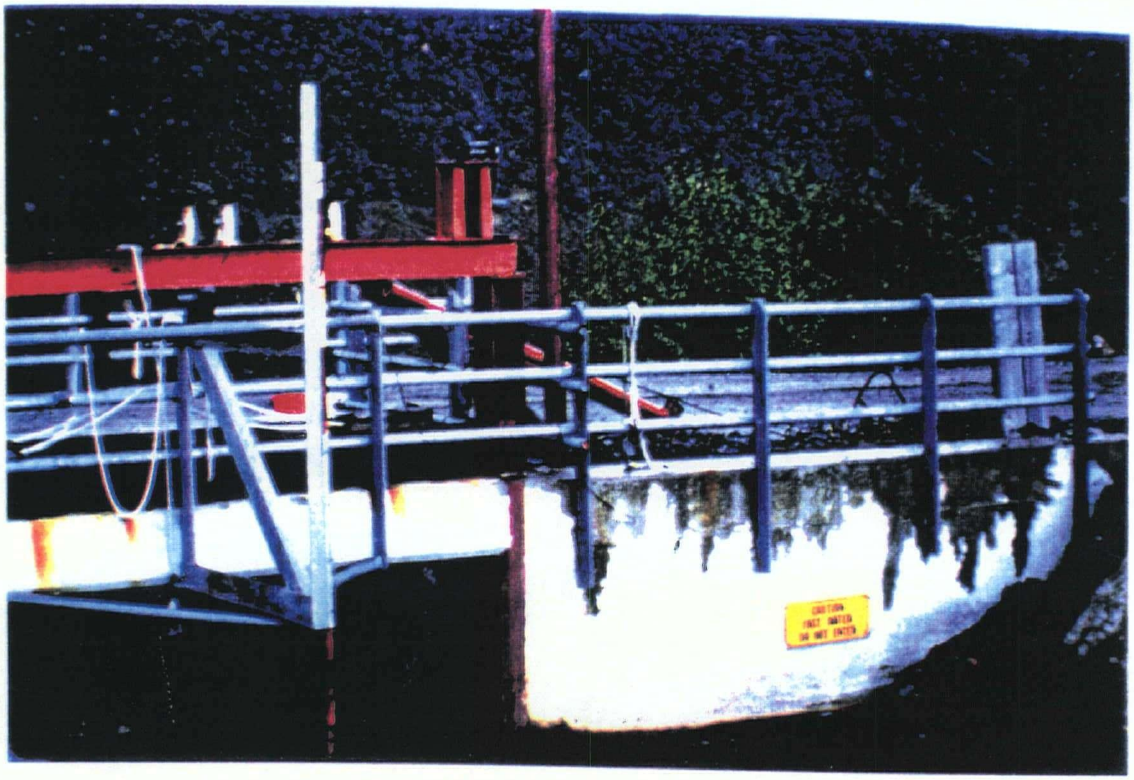
Station #2 Beaver Creek

Station #3 Pond 1 Effluent



Station #4 Diversion Ditch

Station #6 Control Weir



A1.2 Using a Current Meter

The "AA" model 1210 current meter was normally used. In cases where flow was very low, the "MINI" model 1205 was used. The balanced bucket wheel is mounted on a vertical pivot and is rotated by water flow. Water velocity is determined by counting the number of revolutions of the bucket wheel (by counting the audible signal from a model 902 headset) over a given period of time, say 40 seconds. A rating chart is used to convert the revolutions of the meter directly to velocity in meters per second.

The stage-discharge curves for Upper Balmer Creek, Pond 1 Effluent, NDR3 and Diversion Ditch are given in Figures A1 to A4.

Figure A1. Stage Discharge Curve for Upper Balmer Creek

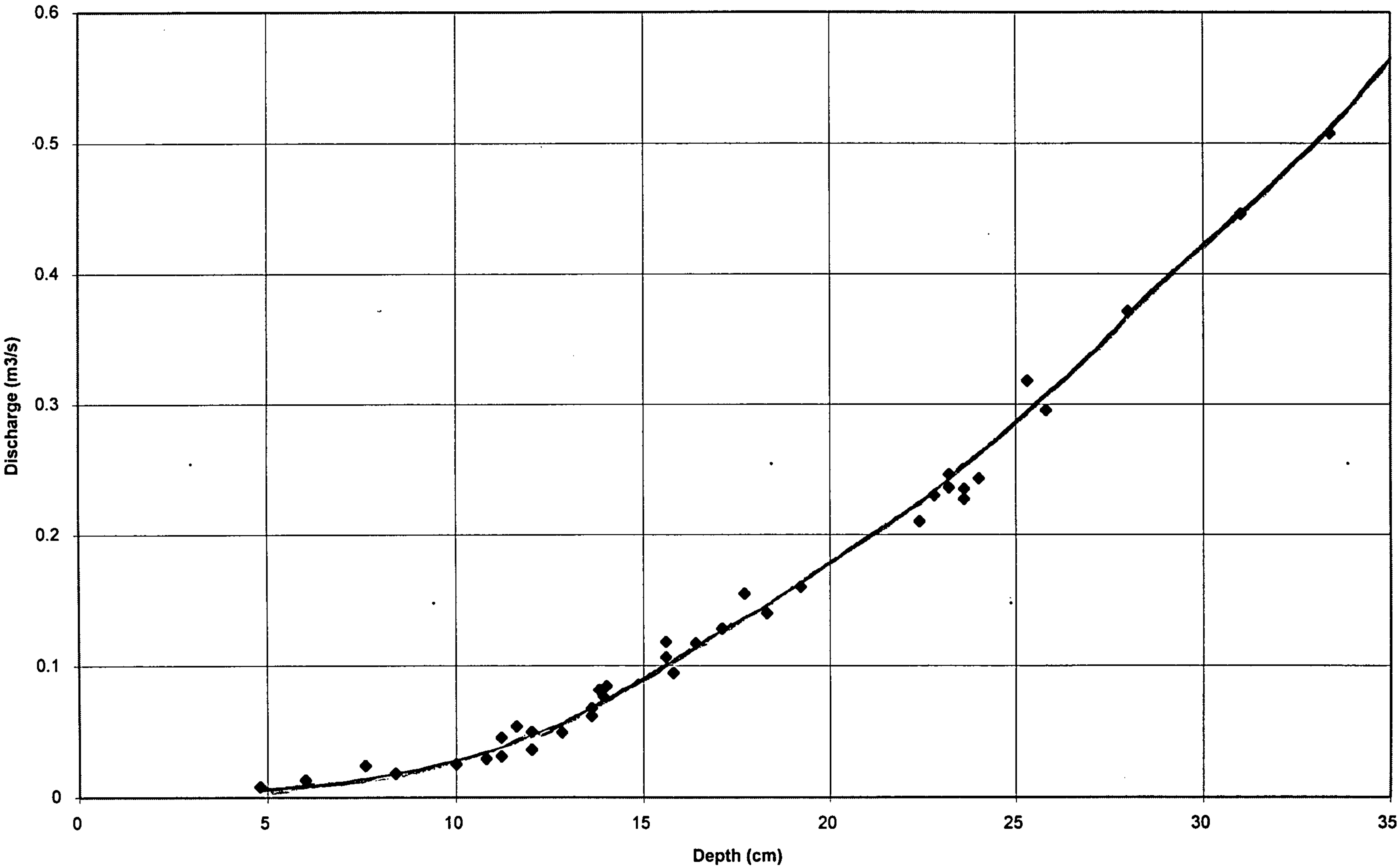


Figure A3. Stage Discharge Curve for Pond 1 Effluent

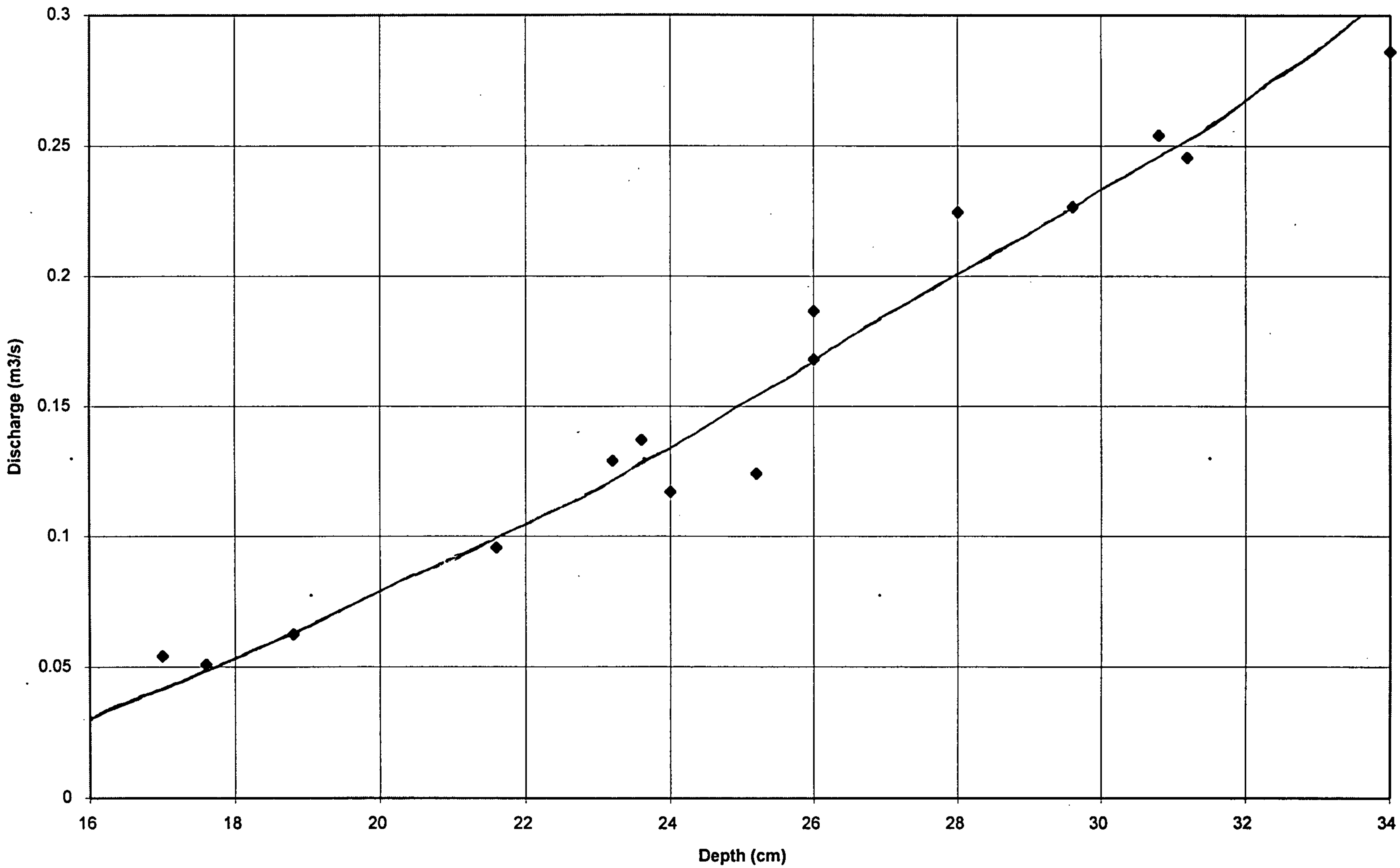


Figure A2. Stage Discharge Curve for NDR3

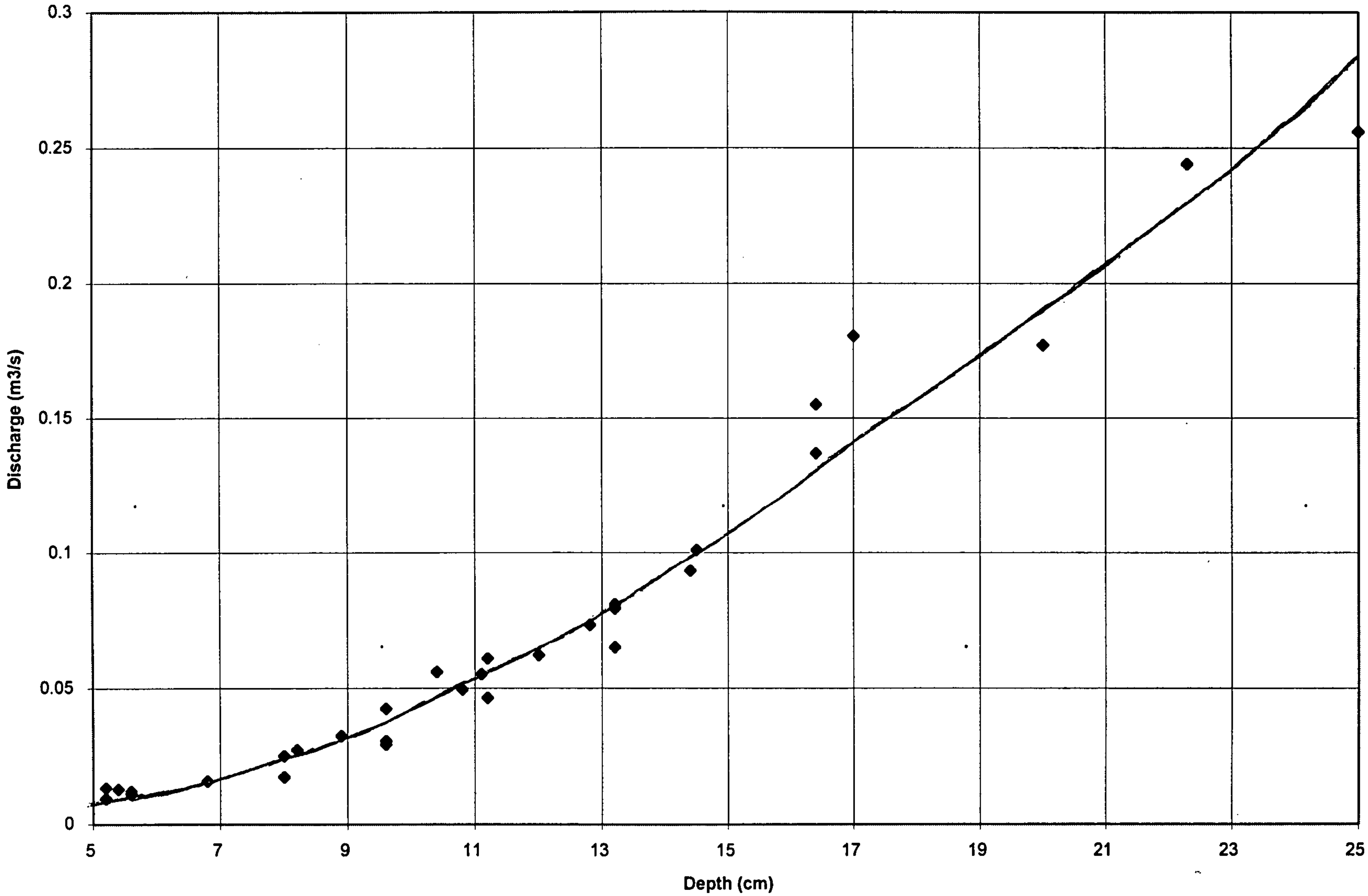
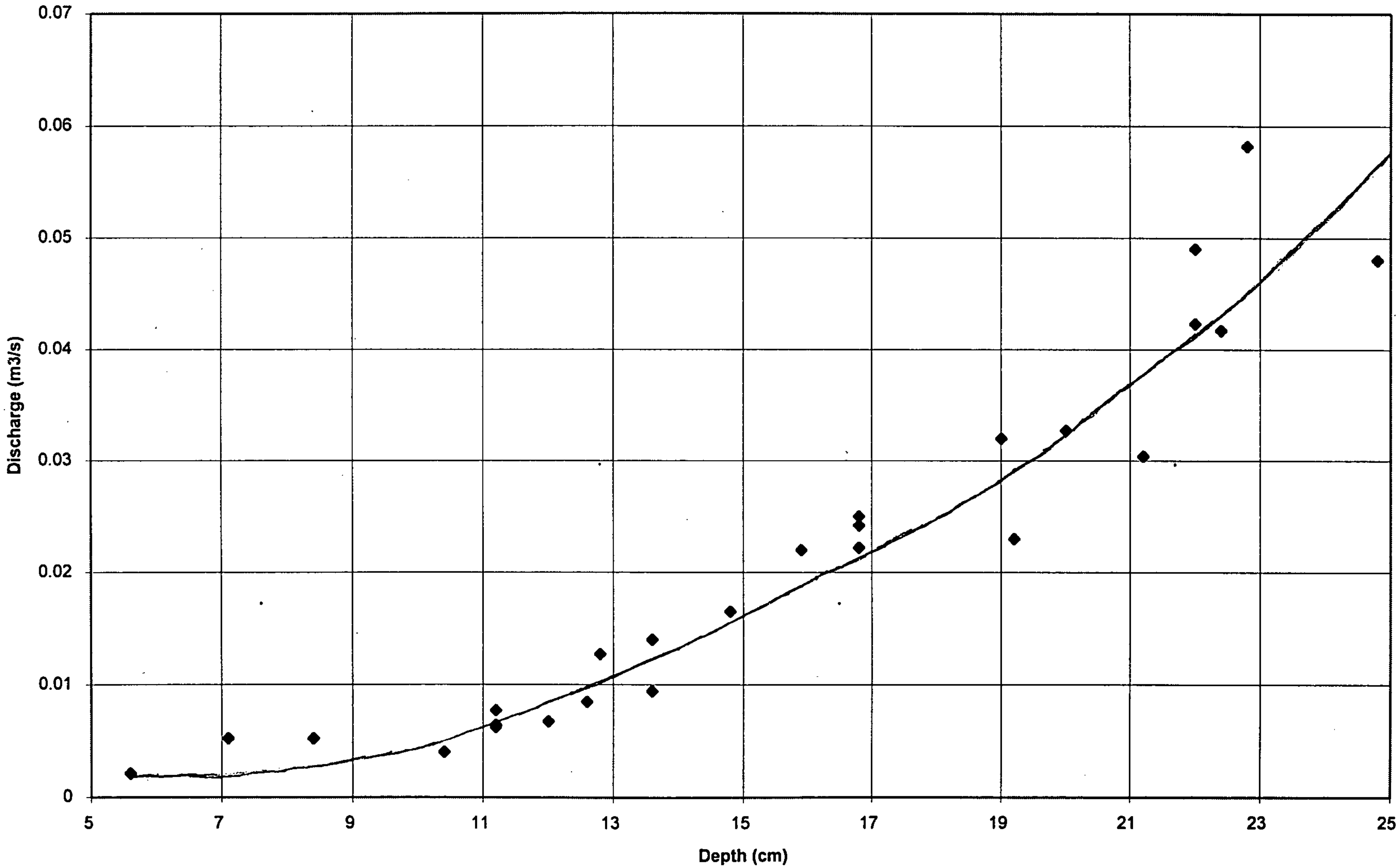


Figure A4. Stage Discharge Curve for the Diversion Ditch



A1.3 Using an Open Channel Monitor II (OCM II)

By Millitronics

The OCM II is a microprocessor based flow measurement system which utilizes ultrasonic sound for non-contacting measurement. The system employs the principle of echo ranging to determine level. Centered above the channel, the OCM II transducer emits a precisely defined burst of ultrasonic sound. The echo reflected from the liquid surface, delayed in time relative to the distance it traveled, is received by the transducer. This time interval, between transmitted pulse and received echo, is electronically converted into a digital indication of the target level of head.

The relationship that exists between head and flow for a rectangular weir used by the OCM II is expressed as follows:

$$Q = Q\_cal * Ce / Ce\_cal * (h + k_h / h\_cal + k_h)^{1.5}$$

Q_cal	- The flow rate at full head	=	2.315 m^3/s
h_cal	- The head at which Q_cal occurs	=	48.83 cm
b	- Width of the notch	=	364.3 cm
B	- Width of approach channel	=	364.3 cm
p	- Height of the crest above the bottom of the approach channel	=	103.7 cm
k_h		=	0.1 cm

Values calculated automatically by the monitor

Ce - Coefficient of discharge at current head

Ce_cal - Coefficient of discharge at h_cal

For more details refer to the Instruction Manual of the OCM II

A1.4 Precipitation and Evaporation Data

A1.4.1. Daily precipitation data for the field study period

Table A1.2. Daily precipitation data for April and May - 93

Date April-93	Rain mm	Snow cm	Precpt mm	Date May-93	Rain mm	Snow cm	Precpt mm
1	0.00	0.00	0.00	1	0.00	0.00	0.00
2	0.00	0.00	0.00	2	2.00	0.00	2.00
3	0.00	0.00	0.00	3	1.40	0.00	1.40
4	0.00	0.00	0.00	4	0.00	0.00	0.00
5	0.00	0.00	0.00	5	0.00	0.00	0.00
6	0.00	0.00	0.00	6	0.00	0.00	0.00
7	0.00	0.00	0.00	7	0.00	0.00	0.00
8	0.00	0.00	0.00	8	0.20	0.00	0.20
9	2.60	0.00	2.60	9	0.00	0.00	0.00
10	0.00	0.00	0.00	10	0.00	0.00	0.00
11	0.00	0.00	0.00	11	0.00	0.00	0.00
12	0.00	0.00	0.00	12	0.00	0.00	0.00
13	0.90	5.00	5.80	13	0.80	0.00	0.80
14	0.80	0.20	1.00	14	1.80	0.00	1.80
15	0.00	0.00	0.00	15	0.00	2.00	2.00
16	0.00	0.00	0.00	16	1.00	0.00	1.00
17	0.00	0.20	0.20	17	0.80	0.00	0.80
18	0.00	0.00	0.00	18	0.00	0.00	0.00
19	0.00	0.00	0.00	19	2.40	0.00	2.40
20	0.00	0.00	0.00	20	0.00	0.00	0.00
21	0.00	0.00	0.00	21	0.00	0.00	0.00
22	0.00	0.00	0.00	22	1.00	0.00	1.00
23	0.00	0.00	0.00	23	0.00	0.00	0.00
24	0.00	0.00	0.00	24	0.00	0.00	0.00
25	0.00	0.00	0.00	25	1.20	0.00	1.20
26	0.00	0.80	0.80	26	0.00	0.00	0.00
27	10.20	2.00	12.20	27	0.80	0.00	0.80
28	0.40	12.40	12.60	28	0.60	0.00	0.60
29	0.80	0.00	0.80	29	0.40	0.00	0.40
30	0.00	0.00	0.00	30	0.00	0.00	0.00
				31	0.20	0.00	0.20
Total	**15.70**	**20.60**	**36.00**	**Total**	**14.60**	**2.00**	**16.60**

Source: Redlake Weather Station, Redlake, Ontario

Table A1.3. Daily precipitation data for June and July - 93

Date June-93	Rain mm	Snow cm	Precpt mm	Date Jul-93	Rain mm	Snow cm	Precpt mm
1	1.20	0.00	1.20	1	1.00	0.00	1.00
2	0.20	0.00	0.20	2	3.20	0.00	3.20
3	0.00	0.00	0.00	3	0.00	0.00	0.00
4	0.00	0.00	0.00	4	12.00	0.00	12.00
5	1.60	0.00	1.60	5	2.80	0.00	2.80
6	3.80	0.00	3.80	6	6.60	0.00	6.60
7	0.00	0.00	0.00	7	0.00	0.00	0.00
8	8.80	0.00	8.80	8	3.00	0.00	3.00
9	0.00	0.00	0.00	9	0.20	0.00	0.20
10	10.00	0.00	10.00	10	0.00	0.00	0.00
11	0.20	0.00	0.20	11	3.20	0.00	3.20
12	0.00	0.00	0.00	12	0.80	0.00	0.80
13	5.60	0.00	5.60	13	2.00	0.00	2.00
14	6.20	0.00	6.20	14	0.00	0.00	0.00
15	0.00	0.00	0.00	15	0.00	0.00	0.00
16	3.00	0.00	3.00	16	0.40	0.00	0.40
17	0.00	0.00	0.00	17	18.60	0.00	18.60
18	0.00	0.00	0.00	18	0.00	0.00	0.00
19	0.00	0.00	0.00	19	11.80	0.00	11.80
20	0.00	0.00	0.00	20	0.40	0.00	0.40
21	0.00	0.00	0.00	21	0.00	0.00	0.00
22	0.00	0.00	0.00	22	0.00	0.00	0.00
23	0.40	0.00	0.40	23	0.00	0.00	0.00
24	12.80	0.00	12.80	24	3.80	0.00	3.80
25	9.00	0.00	9.00	25	15.20	0.00	15.20
26	6.60	0.00	6.60	26	25.60	0.00	25.60
27	2.00	0.00	2.00	27	8.60	0.00	8.60
28	0.00	0.00	0.00	28	29.00	0.00	29.00
29	0.00	0.00	0.00	29	0.40	0.00	0.40
30	4.40	0.00	4.40	30	0.00	0.00	0.00
				31	0.00	0.00	0.00
Total	**75.80**	**0.00**	**75.80**	**Total**	**148.60**	**0.00**	**148.60**

Source: Redlake Weather Station, Redlake, Ontario

Table A1.4. Daily precipitation data for April and May - 92

Date April-92	Rain mm	Snow cm	Precept mm	Date May-92	Rain mm	Snow cm	Precept mm
1	0.00	0.00	0.00	1	0.00	0.00	0.00
2	0.00	0.00	0.00	2	0.00	0.00	0.20
3	0.00	0.00	0.00	3	0.00	0.20	0.00
4	0.00	0.20	0.20	4	0.00	0.00	0.00
5	0.20	0.00	0.20	5	0.00	0.00	0.00
6	0.00	0.00	0.00	6	0.00	0.00	0.00
7	0.00	0.00	0.00	7	0.00	0.00	0.00
8	0.00	1.00	0.60	8	0.00	0.00	0.00
9	0.00	2.50	1.80	9	0.00	0.00	0.00
10	0.00	1.40	1.20	10	13.20	0.00	13.20
11	0.00	0.00	0.00	11	0.00	0.00	0.00
12	0.00	0.00	0.00	12	0.00	0.00	0.00
13	0.00	0.00	0.00	13	0.00	0.00	0.00
14	0.00	0.00	0.40	14	9.90	0.00	9.90
15	0.00	0.00	0.40	15	0.00	0.00	0.00
16	0.00	0.00	0.00	16	6.60	0.00	6.60
17	0.00	0.00	0.00	17	0.00	0.00	0.00
18	13.60	0.00	13.60	18	0.00	0.00	0.00
19	17.60	5.40	23.00	19	0.00	0.00	0.00
20	0.00	1.90	1.80	20	0.00	0.00	0.00
21	0.00	25.40	22.80	21	2.80	0.00	2.80
22	0.00	2.20	1.90	22	12.00	0.40	12.20
23	0.00	0.00	0.00	23	0.00	0.00	0.00
24	0.20	0.80	0.80	24	0.00	0.00	0.00
25	0.00	1.20	1.00	25	2.20	0.00	2.20
26	0.00	0.00	0.00	26	0.00	0.00	0.00
27	0.00	0.00	0.00	27	0.00	0.00	0.00
28	0.00	0.00	0.00	28	0.00	0.00	0.00
29	1.00	0.00	1.00	29	0.40	0.00	0.40
30	1.00	6.20	6.70	30	0.00	0.00	0.00
				31	0.90	0.00	0.90
Total	**33.60**	**48.20**	**77.40**	**Total**	**48.00**	**0.60**	**48.40**

Source: Redlake Weather Station, Redlake, Ontario

Table A1.5. Daily precipitation data for June and July - 92

Date June-92	Rain mm	Snow cm	Precpt mm	Date Jul-92	Rain mm	Snow cm	Precpt mm
1	0.40	0.00	0.40	1	0.00	0.00	0.00
2	7.00	0.00	7.00	2	5.50	0.00	5.50
3	5.40	0.00	5.40	3	2.40	0.00	2.40
4	7.00	0.00	7.00	4	3.70	0.00	3.70
5	5.10	0.00	5.10	5	0.00	0.00	0.00
6	1.60	0.00	1.60	6	0.00	0.00	0.00
7	0.00	0.00	0.00	7	8.60	0.00	8.60
8	0.00	0.00	0.00	8	1.80	0.00	1.80
9	4.90	0.00	4.90	9	2.60	0.00	2.60
10	0.00	0.00	0.00	10	0.00	0.00	0.00
11	0.00	0.00	0.00	11	0.00	0.00	0.00
12	0.00	0.00	0.00	12	0.60	0.00	0.60
13	0.00	0.00	0.00	13	3.80	0.00	3.80
14	0.00	0.00	0.00	14	0.00	0.00	0.00
15	0.00	0.00	0.00	15	13.90	0.00	13.90
16	1.30	0.00	1.30	16	5.00	0.00	5.00
17	31.90	0.00	31.90	17	0.00	0.00	0.00
18	1.80	0.00	1.80	18	0.00	0.00	0.00
19	0.00	0.00	0.00	19	1.40	0.00	1.40
20	0.00	0.00	0.00	20	0.00	0.00	0.00
21	0.00	0.00	0.00	21	0.00	0.00	0.00
22	1.40	0.00	1.40	22	0.00	0.00	0.00
23	0.00	0.00	0.00	23	0.00	0.00	0.00
24	5.80	0.00	5.80	24	4.00	0.00	4.00
25	0.20	0.00	0.20	25	0.60	0.00	0.60
26	0.60	0.00	0.60	26	0.00	0.00	0.00
27	7.80	0.00	7.80	27	7.00	0.00	7.00
28	0.40	0.00	0.40	28	2.40	0.00	2.40
29	0.40	0.00	0.40	29	3.90	0.00	3.90
30	0.00	0.00	0.00	30	0.00	0.00	0.00
				31	2.90	0.00	2.90
Total	**83.00**	**0.00**	**83.00**	**Total**	**70.10**	**0.00**	**70.10**

Source: Redlake Weather Station, Redlake, Ontario

A1.4.2. Monthly precipitation data 1990 to 1993

Table A1.6. Monthly precipitation data 1990 to 1993

Month	1990	1991	1992	1993
Jan	78.0	33.0	27.2	16.9
Feb	23.0	1.2	16.4	3.8
Mar	50.2	29.8	21.0	16.3
Apr	41.8	21.8	77.4	36.0
May	58.0	57.6	48.4	16.6
Jun	105.8	169.6	83.0	75.8
Jly	127.8	97.8	91.7	148.6
Aug	52.0	57.0	102.8	
Spt	91.4	108.4	119.8	
Oct	18.2	49.8	29.4	
Nov	23.6	59.4	38.0	
Dec	28.6	32.8	34.9	
Year	**698.4**	**718.2**	**690.0**	

Source: Redlake Weather Station, Redlake, Ontario

Table A1.7. Total hydrological year snow1989/90 to 1992/93

Hydrological Year	Snow (mm)
1989/90	220.6
1990/91	131.0
1991/92	269.6
1992/93	166.5

Source: Redlake Weather Station, Redlake, Ontario

Table A1.8. Water use and mill effluent

	Discharge
Water use for DML	$0.04 m^3/s$
Water use for PDI	$0.05 m^3/s$
Daily mill effluent DML	$4000 m^{3}$/day

A1.4.3. Average monthly evaporation data (1957-1966)

Table A1.9. Monthly precipitation data 1990 to 1993

Month	Evaporation (mm)
Jan	0
Feb	0
Mar	0
Apr	0
May	25.3
Jun	101.2
Jly	113.8
Aug	88.6
Spt	50.6
Oct	20.2
Nov	10.1
Dec	0

Source: Department of Transport Meteorological Branch Climatic Maps, 1970.

APPENDIX II

A2.1 Measured Flow Data

Table A2.1 Daily flow data for May 1992 in m^3/day

1992 - May	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1	0					10374		
2	0					10374		
3	0					10374		
4	0					16968		
5	64583					16968		
6	175135					16968		
7	168009					16968		
8	160974					16968		
9	67462					16968		
10	0					16968		
11	0					16970		
12	0					16970		
13	0					16970		
14	0	42250	25834		5862	16970	12851	14011
15	0	41645	27821		5938	16970	12667	13811
16	0	40176	27590		5927	16970	12220	13324
17	0	38707	27360		5966	16970	11773	12837
18	0	37238	27130		6101	16970	11326	12349
19	0	34387	25661		6010	8418	10459	11404
20	0	29894	24192		4335	8418	9093	9914
21	0	25402	22680		2836	8418	7726	8424
22	0	24538	21168		2740	8418	7463	8137
23	0	27907	16762		2953	8418	8488	9255
24	0	25200	15293		2500	8418	7665	8357
25	0	22493	13824		2091	8418	6841	7459
26	0	19786	12355		1726	6050	6018	6562
27	0	19526	11362		1471	6050	5939	6476
28	0	16157	10368		999	6050	4914	5358
29	0	14688	9461		936	6050	4468	4871
30	0	12960	8608		763	6050	3942	4298
31	0	11232	7754		578	6050	3416	3725
Total	**636163**	**484186**	**335221**		**59733**	**370510**	**147270**	**160572**

Table A2.2 Daily flow data for June 1992 in m^3/day

1992 July	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1	0	9504	6901		304	7200	2891	3152
2	0	7776	6048		133	7200	2365	2579
3	0	9504	9936		172	7200	2891	3152
4	0	15898	18144		396	7200	4835	5272
5	0	23846	23501		675	7200	7253	7908
6	0	24307	21110		708	7200	7393	8061
7	0	24768	18720		699	7200	7533	8214
8	0	25229	16330		1256	7196	7674	8367
9	0	22118	14731		1610	7196	6728	7335
10	0	19008	13133		3601	7196	5781	6304
11	0	16330	11707		3681	7196	4967	5415
12	0	13651	10282		1770	7196	4152	4527
13	0	11693	8698		600	7196	3556	3878
14	0	9734	8074		1044	7196	2961	3228
15	0	7776	5530		659	7196	2365	2579
16	0	7396	6826		473	7196	2250	2453
17	0	7016	8122		407	7196	2134	2327
18	15000	29290	43286		1442	7196	8909	9713
19	33000	53309	35683		2104	7196	16214	17679
20	40000	46541	31824		1343	7196	14156	15434
21	82500	39773	27106		686	7196	12097	13190
22	125000	33005	24106		572	8418	10039	10945
23	120000	26482	17669		461	8418	8055	8782
24	115000	19958	11232		2016	8418	6071	6619
25	110000	17902	10702		5251	8418	5445	5937
26	110000	15846	10171		4378	8418	4820	5255
27	100000	13789	9641		2291	8418	4194	4573
28	90000	11733	9110		1545	8418	3569	3891
29	85000	9677	8580		745	11046	2943	3209
30	1025500	11405	11057		1037	11046	3469	3782
TOTAL	**2051000**	**584263**	**457956**	**0**	**42057**	**232162**	**177709**	**193761**

Table A2.3 Daily flow data for July 1992 in m^3/day

1992-July	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1	75000	13133	13535		1169	11046	3994	4355
2	60000	14861	16012		1295	11046	4520	4928
3	50000	16589	18490		1466	11046	5046	5501
4	50000	20304	21773		1813	11046	6176	6733
5	50000	23069	23500		2076	11046	7017	7650
6	50000	25834	21600		3594	8418	7858	8567
7	50000	23846	18100		2744	8418	7253	7908
8	67964	21859	14602		1866	8418	6649	7249
9	67964	19267	12995		1333	8418	5860	6390
10	62714	16675	11388		1127	8418	5072	5530
11	62714	14083	9780		916	8418	4284	4670
12	62714	12355	8173		746	8418	3758	4097
13	67964	10627	6566		541	7799	3232	3524
14	235294	9072	6005		369	7799	2759	3009
15	189660	8381	5443		416	7799	2549	2779
16	189660	12000	11500		766	7799	3650	3980
17	133799	16000	18000		1657	7799	4867	5306
18	133799	20000	15750		3214	7799	6083	6633
19	133799	16250	12200		2624	7799	4943	5389
20	96146	12500	10000		2208	8118	3802	4145
21	96146	10973	8208		2157	8118	3337	3639
22	96146	8847	7344		1142	8118	2691	2934
23	96146	6800	6273		178	8118	2068	2255
24	84501	4752	5201		944	8118	1445	1576
25	84501	4147	5098		1238	8118	1261	1375
26	84501	3309	4666		1204	8118	1007	1097
27	62714	2471	4234		444	7799	752	819
28	62714					7799		
29	57601					7799		
30	57601					7799		
31	52631					7799		
TOTAL	**2271429**	**422524**	**363313**	**0**	**45060**	**264570**	**128515**	**140123**

Table A2.4 Daily flow data for April 1993 in m^3/day

1993 - April	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1	4750					173		
2	4778					173		
3	5000					173		
4	5000					173		
5	5225	432				173		
6	5500	562				173		
7	1830	691				173		
8		907				173		
9		1123				173		
10		1555				173		
11		1987				173		
12		2419				11046		
13		3110	10886		2246	11046	1330	1450
14		2678	15034		1987	11046	1158	1263
15	8799	3110	26179		1987	7196	1265	1380
16	11999	4221	20477		1210	7196	1348	1470
17		5331	14774		1008	7196	1573	1716
18		5577	13306		874	7196	1601	1746
19		5823	11837		605	7196	1596	1740
20		5028	11491		605	7196	1398	1525
21		4234	11146	1210	605	7196	1201	1309
22		4255	10930	1158	907	7196	1281	1397
23		4277	10714	1106	1210	7196	1362	1485
24		4631	10109	5368	1097	7196	1422	1550
25		7413	11146	3254	816	7196	2043	2227
26		10195	12182	1140	536	7196	2664	2904
27		9634	13349	2575	1680	7196	2808	3062
28		9072	14515	4009	2825	7196	2953	3220
29		13133	20995	5616	3482	285	4124	4497
30		28858	26611	22118	5337	7196	8488	9254
Total	**52881**	**142025**	**396300**	**71734**	**55969**	**143264**	**55563**	**60341**

Table A2.5. Daily flow data for May 1993 in m^3/day

May - 1993	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1		30000	26000	15000	5618	7196	8841	9640
2		27000	25000	10000	5182	7196	7988	8710
3		20995	24710	6333	4767	7196	6395	6972
4		21133	22961	7198	4944	7196	6473	7058
5		21272	21211	8063	3738	7196	6208	6768
6		20451	20395	7477	3670	7196	5987	6528
7		19630	19578	6892	3603	285	5767	6288
8		20304	21946	6852	3655	285	5947	6484
9		20347	19034	6921	3141	285	5830	6357
10		20390	16122	6990	2627	7196	5713	6229
11		19272	17764	6126	2359	7196	5369	5854
12		18153	19405	5262	2091	7196	5025	5479
13		15988	14541	4769	2004	7196	4466	4870
14		13824	9677	4277	1918	7196	3907	4260
15		12280	9204	3779	1751	7196	3483	3797
16		10737	8732	3280	1584	7196	3058	3334
17		9193	8260	2782	1417	7196	2634	2871
18		8675	6869	2657	1421	7196	2506	2732
19		8156	5478	2532	1426	7196	2378	2593
20		7716	5409	2346	1119	7196	2193	2391
21		7275	5340	2160	812	7196	2007	2189
22		6576	5239	1895	734	7196	1815	1979
23		6206	5138	1630	657	7196	1703	1857
24		5835	5037	1365	579	7196	1592	1736
25		6088	4717	2000	566	7196	1652	1801
26		6340	4398	2635	553	7196	1711	1866
27		5965	4895	1793	449	7196	1592	1736
28		5589	5391	950	346	12446	1473	1606
29		5010	7788	903	319	12446	1323	1442
30		7000	10184	855	412	12446	1840	2006
31		9810	12580	808	505	12446	2560	2792
Total		**417210**	**393001**	**136529**	**63966**	**223343**	**119437**	**130225**

Table A2.6. Daily flow data for June 1993 in m^3/day

June-1993	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1		12505	8294	1484	399	12446	3203	3492
2		17232	8035	2160	294	12446	4350	4743
3		15000	7776	1356	271	12446	3791	4133
4		10000	7001	1391	249	12446	2544	2774
5		8000	6225	1426	226	8418	2042	2226
6		6999	5450	1460	204	8418	1788	1949
7		6432	4674	1495	181	11739	1642	1790
8		5988	5270	1525	298	11739	1560	1701
9		5697	5867	1555	415	11739	1517	1654
10		5153	7880	1974	976	11046	1521	1659
11		6823	9893	2393	1538	11046	2075	2263
12		8163	10649	2056	1058	12446	2289	2496
13		11278	11405	1719	579	12446	2943	3209
14		13772	9893	2592	1477	14655	3785	4127
15		14316	10778	3197	1214	14655	3855	4203
16		14861	11664	3802	950	14655	3925	4279
17		17885	12528	3629	1037	6039	4697	5121
18		11405	9418	3110	562	6039	2970	3239
19		10944	8294	2563	432	6039	2824	3079
20		10483	7171	2016	302	6039	2677	2919
21		10022	6048	1469	173	1475	2531	2759
22		9979	5616	1469	173	1475	2520	2748
23		9936	5184	1469	173	1475	2509	2736
24		7128	6480	1469	720	786	1948	2124
25		4320	7776	1469	1267	786	1387	1512
26		6566	11837	1901	1814	48	2080	2268
27		13781	11923	3413	2290	48	3989	4349
28		20995	12010	4925	2765	113	5898	6430
29		17064	10195	4139	1313	113	4562	4974
30		11405	9331	3629	1037	113	3088	3367
Total		**324133**	**254564**	**68254**	**24388**	**223374**	**86510**	**94323**

Table A2.7. Daily flow data for July 1993 in m^3/day

1993-July	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1		11405	8122	3456	1015	113	3083	3361
2		11405	6912	3283	994	48	3078	3355
3		13363	12816	5501	1181	113	3610	3936
4		15322	18720	7718	1368	113	4143	4517
5		17280	24624	9936	1555	48	4675	5098
6		19872	20304	13392	2765	48	5619	6126
7		25531	22378	15587	2938	48	7067	7705
8		28339	16978	12156	2419	48	7635	8324
9		27475	11578	8726	1901	48	7292	7950
10		22349	10166	7430	1511	48	5922	6457
11		17222	8755	6134	1120	48	4553	4964
12		12096	7344	4838	730	48	3184	3471
13		11578	6700	3802	590	48	3020	3293
14	53454	11059	6057	2765	449	48	2857	3115
15	74935	9050	5620	2549	449	48	2358	2571
16	64798	7042	5184	2333	449	48	1859	2027
17	62112	9677	16589	3283	1002	48	2651	2890
18	57709	9677	9331	3888	1555	48	2788	3040
19	51765	13375	10454	4761	2160	48	3856	4204
20	46714	11742	8878	4212	2074	48	3429	3739
21	42113	10109	7301	3663	1987	48	3002	3274
22	37681	8364	5863	2696	1080	48	2344	2556
23	33135	6618	4425	1728	173	48	1686	1838
24	31531	9020	9516	5098	1791	48	2684	2926
25	31007	11422	14608	8467	3410	48	3682	4014
26	34161	13824	19699	11837	5028	48	4680	5102
27	39755	43874	33394	21082	7888	48	12848	14009
28	56308	93658	71712	55555	40003	48	33177	36174
28	56308	104803	128131	75427	55836	48	39874	43475
29	72572	157248	97027	42941	17539	48	43386	47304
30	101118	206237	52654	22982	10254	48	53737	58591
31	106090	164311	42623	19729	8749	48	42957	46837
Total	**1053262**	**1134346**	**724461**	**396956**	**181964**	**1731**	**326733**	**356245**

Table A2.8. Daily flow data for August 1993 in m^3/day

1993 - August	Balmer C.	UBC	PPeff	BC	DD	#3 D	NDR1	NDR2
1	100518	122386	32591	16476	7244	48	32177	35083
2	89549	80460	22560	13224	5739	48	21396	23329
3	85690	38534	12528	9971	4234	48	10616	11575
4	78706	35307	23501	12636	5996	48	10252	11178
5	77459	32080	34474	15301	7759	48	9889	10782
6	72616	29635	19440	15293	5573	48	8739	9529
7	69069	25229	18086	14602	4913	48	7482	8158
8	66063	20822	16733	13910	4253	48	6224	6786
9	65661	16416	15379	13219	3593	48	4967	5415
10	0	16243	12658	9850	3093	48	4800	5233
11	0	18058	9936	12576	3447	48	5338	5820
12	0	19872	19440	15301	3802	48	5876	6407
13	0	15552	15379	21859	2592	48	4504	4910
14	0	22594	17410	20209	4280	48	6670	7273
15	0	29635	19440	18559	5967	48	8837	9635
16	0	30845	15379	11750	7655	48	9556	10420
Total	**2329897**	**1107337**	**609866**	**469472**	**160279**	**1536**	**314647**	**343066**

A2.2 Evaluation of the Runoff Coefficient - 1992/3

Month	Average Rainfall (mm)	Upper Balmer Ck. Measured Flow (m^3)	Upper Balmer Ck. Total Rainfall Volume (m^3)	Upper Balmer Ck. Runoff Coeff.	NDR3 - Measured Flow (m^3)	NDR3 Total Rainfall Volume (m^3)	NDR3 Runoff coeff.
Apr.	16	142417	847847	0.17	142662	331086	0.43
May	31	692791	1694420	0.41	246155	661675	0.37
Jun.	79	454198	1020194	0.45	155638	398388	0.39
Jul.	84	745473	1066975	0.70	280711	416656	0.67
Aug.	126	1107337	1601418	0.69	469472	625358	0.75
Average				**0.48**			**0.52**

Month	Average Rainfall (mm)	Pond 1 Effluent Measured Flow (m^3)	Pond 1 Effluent Rainfall Volumes (m^3)	Pond 1 Runoff Coeff.	Diversion Ditch Measured (m^3)	Diversion Ditch Rainfall Volumes (m^3)	Diversion Ditch Runoff Coeff.	Overall Averages Runoff Coeff.
Apr.	16	396317	623906	0.64	58035	191081	0.30	**0.38**
May	31	531722	1246875	0.43	91716	381875	0.24	**0.36**
Jun.	79	356260	750731	0.47	33223	229923	0.14	**0.36**
Jul.	84	516387	785156	0.66	110097	240467	0.46	**0.62**
Aug.	126	609866	1178438	0.52	160279	360915	0.44	**0.60**
Average				**0.54**			**0.32**	**0.47**

A2.3 Evaluation of the Snow Runoff

Snow	mm
1991/2	269.6
1992/3	166.5

Upper Balmer Creek
Runoff Estimation — Area 12740000

Month	Runoff 1992	Runoff 1993	Measured flow UBC 1992	Measured flow UBC 1993	Total flow UBC 1992	Total flow UBC 1993	Runoff Coefficients 1992	Runoff Coefficients 1993	Snow runoff Coefficien 1992	Snow runoff Coefficien 1993	Snow Runoff 1992	Snow Runoff 1993	Total Annual Snow 1992	Total Annual Snow 1993	% Snow Runoff 1992	% Snow Runoff 1993
April	33.6	15.7		142417		200018		0.712021		0.212021		42408	3434704	2121210		0.019992
May	48.4	16	968371	417209	616616	203840	1.57046	2.046747	1.07046	1.546747	660063	315289	3434704	2121210	0.192175	0.148636
June	83	75.8	584262	324133	1057420	965692	0.552535	0.335648								
July	91.7	148.6	368004	1122941	1168258	1893164	0.315002	0.593156								
August				1107337												

Pond 1 Effluent
Runoff Estimation — Area 9035098

Month	Precipitation 1992	Precipitation 1993	Measured flow 1992	Measured flow 1993	Total flow 1992	Total flow 1993	Runoff Coefficients 1992	Runoff Coefficients 1993	Snow runoff Coefficien 1992	Snow runoff Coefficien 1993	Snow Runoff 1992	Snow Runoff 1993	Total Annual Snow 1992	Total Annual Snow 1993	% Snow Runoff 1992	% Snow Runoff 1993
April	33.6	15.7		276317		141851		1.947938		1.447938		205391.5	2435862	1504344		0.136532
May	48.4	16	550442	273002	437298.7	144561.6	1.258732	1.888483	0.758732	1.388483	331792.6	200721.2	2435862	1504344	0.136212	0.133428
June	83	75.8	337956	134564	749913.1	684860.4	0.45066	0.196484								
July	91.7	148.6	196434	596339	828518.5	1342616	0.237091	0.444162								
August				489866												

NDR3
Runoff Estimation — Area 4475000

Month	Precipitation 1992	Precipitation 1993	Measured flow 1992	Measured flow 1993	Total flow 1992	Total flow 1993	Runoff Coefficients 1992	Runoff Coefficients 1993	Snow runoff Coefficien 1992	Snow runoff Coefficien 1993	Snow Runoff 1992	Snow Runoff 1993	Total Annual Snow 1992	Total Annual Snow 1993	% Snow Runoff 1992	% Snow Runoff 1993
April	33.6	15.7		142662		70257.5		2.030559		1.530559		107533.3	1206460	745087.5		0.144323
May	48.4	16	355781	136529	216590	71600	1.642647	1.90683	1.142647	1.40683	247486	100729	1206460	745087.5	0.205134	0.135191
June	83	75.8	243022	68254	371425	339205	0.654296	0.201218								
July	91.7	148.6	167921	393500	410357.5	664985	0.409207	0.591743								
August				469472												

Diversion Ditch
Runoff Estimation — Area 2871000

Month	Precipitation 1992	Precipitation 1993	Measured flow 1992	Measured flow 1993	Total flow 1992	Total flow 1993	Runoff Coefficients 1992	Runoff Coefficients 1993	Snow runoff Coefficien 1992	Snow runoff Coefficien 1993	Snow Runoff 1992	Snow Runoff 1993	Total Annual Snow 1992	Total Annual Snow 1993	% Snow Runoff 1992	% Snow Runoff 1993
April	33.6	15.7		58035		45074.7		1.287529		0.787529		35497.65	774021.6	478021.5		0.07426
May	48.4	16	119466	63966	138956.4	45936	0.859737	1.392503	0.359737	0.892503	49987.8	40998	774021.6	478021.5	0.064582	0.085766
June	83	75.8	42057	24388	238293	217621.8	0.176493	0.112066								
July	91.7	148.6	39246	180949	263270.7	426630.6	0.149071	0.424135								
August				160279												

Total Catchment Area
Runoff Estimation — Total Area 29121098

Month	Precipitation 1992	Precipitation 1993	Measured flow UBC 1992	Measured flow UBC 1993	Total flow UBC 1992	Total flow UBC 1993	Runoff Coefficients 1992	Runoff Coefficients 1993	Snow runoff Coefficien 1992	Snow runoff Coefficien 1993	Snow Runoff 1992	Snow Runoff 1993	Total Annual Snow 1992	Total Annual Snow 1993	% Snow Runoff 1992	% Snow Runoff 1993
April	33.6	15.7		619431		457201.2		1.354832		0.854832		390830.4	7851048	4848663		0.08
May	48.4	16	1994060	890706	1409461	465937.6	1.414768	1.911642	0.914768	1.411642	1289329	657737.2	7851048	4848663	0.16	0.14
June	83	75.8	1207297	551339	2417051	2207379	0.499492	0.249771								
July	91.7	148.6	771605	2293729	2670405	4327395	0.288947	0.530048								
August				2226954												

Final estimates based on the overall evaluation	Snow Runoff Coefficient of the total snow received	% Monthly runoff of the total snow runoff
March (no data avaliable, guess)	0.02	8
April (1993 data)	0.08	32
May (1992 and 1993 data, average)	0.15	60
Overall snow runoff coefficient	0.25	