# HYDROGEOLOGY OF WASTE ROCK DUMPS

## MEND Associate Project PA-1

**This work was done on behalf of MEND and sponsored by the Canada Centre for Mineral and Energy Technology (CANMET) through the CANADA/ British Columbia Mineral Development Agreement (MDA)**

**July 1995**

# Hydrogeology of Waste Rock Dumps

**Contract No: 23440-4-1317/01-SQ**

**Final Report to Department of Natural Resources Canada**

July, 1995

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## EXECUTIVE SUMMARY

Predictions of whether and when a waste rock pile may start to generate acidic water, and how long a pile may release elevated concentrations of metals to the environment, are related on a fundamental level to an understanding of fluid flow within a waste rock pile. Our analysis of the hydrogeological properties of waste rock piles is based on a synthesis of data from four mine sites; Myra Falls, B.C., Island Copper, B.C., Elkview Mine, B.C., and Golden Sunlight Mine, Montana. The emphasis in this study is on pile hydrostratigraphy and the textural properties of the rock mass, spatial and temporal variations in water content within a waste rock pile, temperature profiles within a waste rock pile and their response to the infiltration of water following a rainfall event, and the large-scale hydrogeologic characterization of a waste rock pile inferred from outflow hydrographs recorded in toe drains.

Four hydrostratigraphic models are proposed to characterize waste rock piles; they differ depending upon material types and construction methods. This framework differentiates between porous flow in finer sandy gravel materials and channelized flow in coarser materials. The models are non-segregated coarse-grained rock piles that transmit water rapidly to the base of the pile, non-segregated fine-grained rock piles that are likely to contain a basal saturated zone, segregated rock piles that contain a fine-grained crest zone that may not permit the passage of significant quantities of water; and layered, segregated dumps that contain a finer-grained crest and sandy gravel layers parallel to the face of the rock pile.

Volumetric water content is an important characteristic of the a waste rock pile. It appears to be closely associated with the textural properties of the pile, and it can be used to scan the pile hydrostratigraphy. For a given waste rock pile, at each depth, values of the water content appear fairly stable throughout the year. For the data from Golden Sunlight Mine, attempts to monitor matric potential using heat dissipation sensors, and to correlate changes in matric potential with rainfall events, were generally not successful. Temperature appears to be one of the more reliable parameters to use for tracing the movement of water in those regions of the pile that are reactive and generating heat. The fluctuation of the water table in response to infiltration is affected by the permeability structure of the pile and location within the pile. The permeability structure of the pile is the spatial distribution of permeability values within the different regions of the pile. The data we examine is suggestive of rapid infiltration of water through waste rock piles, although sampling frequencies were not adequate to develop precise estimates of fluid velocities.

A methodology is presented, based on kinematic wave theory, that relates the outflow hydrograph recorded in toe drains to large-scale parameters characterizing the hydraulic conductivity structure of the waste rock pile. The outflow in response to an infiltration event is treated as an integration of the outflows from different channel groups within the pile. Water transfer from the channels to the finer-grained matrix is taken account of in the analysis. Application to the Island Copper data set suggests that the approach holds promise as a means of characterizing large-scale flow processes in a waste rock pile.

Further work is warranted to improve the model in its representation of channelized flow, and to apply the method to rainfall events at a number of different sites to gain insight to the relationship between hydrostratigraphy, and flow responses.

The most significant limitation of the existing database is that no single site provided a complete data record of the important parameters required to characterize the hydrologic behavior of a waste rock pile, and the frequency of sampling was often insufficient for our purposes. In our opinion, to better understand the hydrology of a waste rock pile, the following measurements should be given priority: water content and temperature profiles through the unsaturated zone, water table elevation, volumetric discharge at toe drains, and rainfall and air temperature. Workplans are presented for three types of monitoring studies; a pile assembly study, a pile monitoring study, and a pile disassembly study. It may be advantageous to link these workplans to operations at a low-grade stockpile. It is important to coordinate the suite of measurements made prior to and during the disassembly of a pile.

## RÉSUMÉ EXÉCUTIF

Les prédictions concernant la possibilité et le moment où une halde de stériles peut commencer à produire de l'eau acide et le temps qu'elle peut dégager des concentrations élevées de métaux dans l'environnement, sont liées à un niveau fondamental pour comprendre l'écoulement du fluide à l'intérieur d'une halde de stériles. Notre analyse des propriétés hydrogéologiques de ces dernières se base sur une synthèse d'informations obtenues de quatre sites miniers: '*Myra Falls, Island Copper et Elkview Mine'* en Colombie-Britannique et '*Golden Sunlight Mine*' au Montana. Dans cette étude, l'accent porte sur un amas de roches hydrostratigraphique et sur les propriétés de texture de la masse rocheuse, les variations spatiales et temporelles dans la teneur en eau à l'intérieur d'une halde de stériles, les profils thermiques dans cette dernière et leur réaction à l'infiltration de l'eau suite à une chute de pluie, et la caractérisation hydrogéologique à grande échelle d'une halde de stériles qui résulte probablement d'écoulements hydrographiques, enregistrés dans les drains de pied.

Quatre modèles hydrostratigraphiques sont proposés pour établir une distinction des haldes de stériles, ils se différencient selon les types de matériaux et les méthodes de construction. Ce système fait la distinction entre l'écoulement poreux en substances de gravier sablonneux très fin et un écoulement dirigé dans des matières plus rugueuses. Les modèles sont les suivants: des amas de roches à grains grossiers non séparées qui transmettent rapidement l'eau à la base de l'amoncellement, des amas de roches à grains fins non séparées qui contiennent vraisemblablement une zone de base saturée, des amas de roches séparées qui comportent une zone supérieure à grains fins ne permettant peut-être pas le passage de quantités significatives d'eau et des couches de rejets séparés qui renferment des crêtes à grains très fins, et des couches de gravier sablonneux parallèles à la face de l'amoncellement de roches.

La teneur volumétrique en eau s'avère une importante caractéristique de la halde de stériles. Elle semble être directement associée aux propriétés de texture de l'amas de roches et elle peut être utilisée pour examiner l'hydrostratigraphie dans ce dernier. Dans le cas d'une halde de stériles, les mesures de la teneur en eau apparaissent assez stables à chaque profondeur durant toute l'année. En ce qui concerne les données de la '*Golden Sunlight Mine*', des tentatives effectuées pour surveiller un potentiel matriciel qui utilise des détecteurs de dissipation thermique et pour établir une corrélation des changements entre le potentiel matriciel et les chutes de pluie, n'ont pas été fructueuses dans l'ensemble. La température semble être l'un des paramètres le plus fiable pour suivre le mouvement de l'eau dans les régions de l'amas de roches qui réagissent et produisent de la chaleur. Suite à l'infiltration de l'eau, la fluctuation du niveau phréatique est modifiée par la perméabilité de la structure de l'amas de roches et de la location à l'intérieur de ce dernier. La perméabilité de la structure de l'amoncellement comporte la distribution spatiale des mesures de perméabilité dans les différentes régions de l'amas de roches. L'étude des données semble indiquer une infiltration rapide de l'eau à travers la halde de stériles, bien que les fréquences d'échantillonnage n'aient pas été adéquates pour fournir des estimations précises des vélocités de fluide.

Une méthodologie a été présentée: elle se base sur une théorie d'onde cinématique qui signale l'écoulement hydrographique enregistré dans les drains de pied aux paramètres à grande échelle déterminant la structure de conductivité hydraulique de la halde de stériles. Suite à une infiltration d'eau, l'écoulement s'intègre à d'autres écoulements venant de différents groupes de canaux dans l'amas de roches. Le transfert d'eau à partir des canaux jusqu'à la matrice à grains très fins, est noté dans l'analyse. La mise en application selon la série de données de '*Island Copper*' laisse croire que cette approche, considérée comme un moyen pour déterminer les processus d'écoulement à grande échelle dans une halde de stériles, est prometteuse. Un travail plus approfondi est justifié pour améliorer le modèle dans sa représentation d'écoulement canalisé, et pour utiliser la méthode aux chutes de pluie dans certains sites différents, afin de comprendre la relation entre l'hydrostratigraphie et les réactions d'écoulement.

La limite la plus révélatrice de la présente base de données montre qu'aucun site n'a fourni un enregistrement complet des informations des paramètres importants qui sont requis pour déterminer le comportement hydrologique d'une halde de stériles, et la fréquence de l'échantillonnage a souvent été insuffisante pour satisfaire nos objectifs. À nos yeux, la meilleure manière de comprendre l'hydrologie d'une halde de stériles, serait d'accorder une priorité aux mesures qui suivent: par exemple, une teneur en eau et les profils thermiques à travers la zone vadose, une élévation du niveau phréatique, l'écoulement volumétrique aux drains de pied, le régime des pluies et la température atmosphérique. On présente des plans de travail pour les trois catégories d'études mises sous surveillance: entre autres, celles de la construction d'un modèle d'un amoncellement de roches, l'application d'un suivi et le démontage du modèle. Il y aurait peut-être avantage à lier la mise en opération de ces plans de travail à un empilement de minerai à faible teneur. Il importe de coordonner la série de mesures prises avant et pendant le démontage de l'amoncellement de roches.

## ACKNOWLEDGMENTS

We want to express our thanks and recognition to some of the people that made it possible to carry out this project. The collection of the data for the different mines was possible with the cooperation of Roy Smith and Ray Lazuk of Golden Sunlight Mine, Lisa Kirk of Schafer & Associates, Ian Horne of Island Copper Mine, and Janet Wong of Rescan Environmental Services.

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# CHAPTER 1

## INTRODUCTION

At metal mines in British Columbia, hydrogeological processes can play a major role in determining the quality of water draining from a waste rock pile. Better understanding of water flow within and through waste rock piles, including its spatial and temporal variability, is needed to improve our capability to predict the long-term chemical evolution of water draining from waste rock piles. Uncertainty regarding water movement in waste rock piles can be a serious impediment both in predicting the behavior of new waste rock piles, and in decommissioning existing sites.

Recent evidence suggests that the metal concentrations in the water draining from an acid-producing waste rock pile are independent of the volume of water moving through the pile (e.g. Morin et al., 1994). Some success has been reported in predicting concentrations of the dissolved metals such as zinc and copper using equilibrium chemistry models that are tied to the presence of secondary minerals (carbonates, sulfates) that precipitate within the rock pile following oxidation of the primary sulfide and oxide minerals. Thus, it is possible to argue that an improved understanding of fluid flow within a waste rock pile is not essential to the development of predictions of metal concentrations in the water draining from the pile. What is clear, however, is that predictions of when a pile may start to generate acidic water, and how long a pile may release elevated concentrations of metals to the environment, are related on a fundamental level to an understanding of fluid flow within a waste rock pile. While mineralogy and dissolution/neutralization reactions control the chemical characteristics of the water discharging from any particular geochemical zone of a waste rock pile, its hydrogeological properties and connections between different stratigraphic and/or geochemical zones control the changes in water chemistry through time.

Our review of water flow through waste rock piles suggests that the relevant hydrogeological processes are best studied on two scales. One scale focuses on a larger-scale view that attempts to relate water input and drainage from the rock pile to a general characterization of the flow paths within the pile. The second scale takes a smaller-scale view in an attempt to explicitly represent the hydraulic processes internal to the pile. Both approaches are discussed in this report.

The generation of acidic water within a waste rock pile reflects a complex interaction between a number of hydraulic, chemical, and thermal processes. These processes include variably-saturated fluid flow and air circulation in the rock mass above the water table, heat generation and heat transfer in both the aqueous and gaseous phases, oxygen consumption and re-supply, reaction kinetics, and solute transport in the region both above and below the water table. These processes occur in an exceedingly heterogeneous medium containing both a porous matrix and open voids. Following an initial analysis of data from a number of mine sites, we concluded that the following issues or topics were more likely to provide insight to water flow through waste rock dumps:

1. Pile hydrostratigraphy and the textural properties of the waste rock, and how these characteristics influence the hydraulic properties of the waste rock pile, and the patterns of fluid flow,

2. Spatial and temporal variations in water content within a waste rock pile,

3. Temperature profiles within a waste rock pile, and their response to infiltration of water following a rainfall event,

4. The large-scale hydrologic behavior of a waste rock pile inferred from outflow hydrographs.

The reader should note that we do not examine thermal properties of a waste rock pile from the perspective of an ARD prediction, but rather as a tool in understanding water flow through a waste rock pile.

These topics form the main focus of this report. Undoubtedly, other process such as weathering, fines migration and deposition, sealing of channels, settlement of the rock pile, and temporal changes in the spatial distribution of permeable pathways are also important in determining water flow within waste rock piles. These processes will not, however, be addressed in this study because they are both difficult to assess with the available database, and they seem less likely to provide insight to the basic features of water flow through waste rock piles.

We have based our analysis of the hydrogeology of waste rock piles on a detailed examination of data from four mine sites: Myra Falls, B.C.; Island Copper, B.C.; Elkview Mine, B.C.; and Golden Sunlight Mine, Montana. The data were obtained either from the published literature, or in raw form from the mining companies. Except for the Elkview Mine, the waste rock piles at these mine sites contain reactive zones producing ARD. The Elkview Mine, formed from coarse coal refuse, is included in this study because reliable data are available on rainfall rates and water table fluctuations. It does not discharge acidic water. A description of the waste rock piles at each of these mine sites is provided in a subsequent section of this report.

The hydraulic conductivity structure and flow through a waste rock pile is best viewed in the context of a hydrostratigraphic model. The hydrostratigraphic model relates the textural properties of the waste rock, and the spatial distribution of the textural zones within the rock pile, to the expected hydraulic behavior of the rock mass. As discussed in Chapter 2, certain types of coarse rock piles contain open channels embedded within the pile. Throughout this report, we use the term channel to imply a continuous zone of coarse rock with a limited fines content located in the voids between the rock fragments. Flow within these channels can lead to a situation where water penetrates through the rock pile even though moisture contents within the rocks surrounding the channel are lower than that defining the specific retention of the waste rock. This type of behavior is not meaningfully described in terms of a model that represents the entire rock pile as a granular porous medium. We also draw a distinction between these channels, and preferential flow paths that develop within the granular matrix as a consequence of its spatial variability in permeability.

Chapter 2 describes hydrostratigraphic models for waste rock piles, and provides a compilation of the hydraulic properties of waste rock materials. In Chapter 3, we present our evaluation of monitoring data that provides insight to the flow of water interior to a waste rock pile. Chapter 4 describes a promising methodology that relates water input to a waste rock pile to the outflow hydrograph for toe drains, in a way that permits an initial characterization of channels and preferential flow paths within the pile. An assessment of methods for monitoring the hydrogeologic behavior of a rock pile is given in Chapter 5. The report concludes with the presentation of a workplan to address the issues identified as key factors in limiting present capabilities for predicting water flow through waste rock piles.

# CHAPTER 2

## HYDROSTRATIGRAPHY OF WASTE ROCK PILES

Most mine waste dumps in Western Canada can be broadly classified into one of five different categories according to material type:

1. Metal mine waste rock dumps

2. Rocky Mountain coal mines
   waste rock dumps
   coarse coal refuse dumps

3. Prairie coal mine waste rock dumps

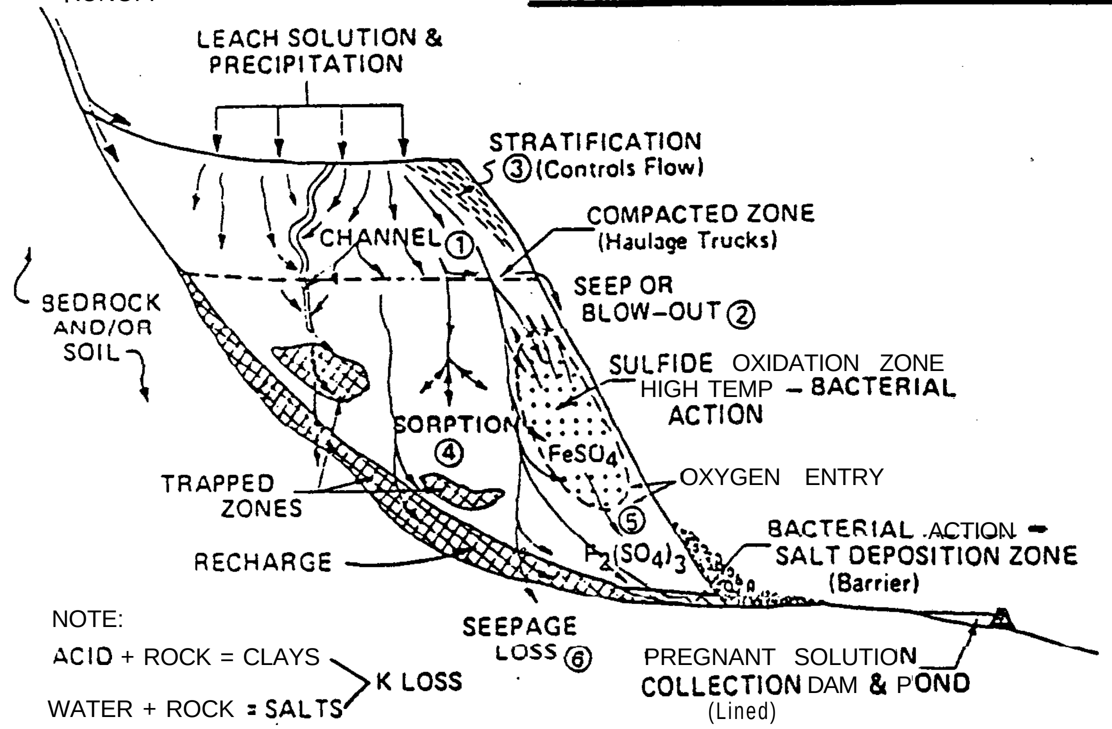
4. Non-lithified or highly weathered overburden dumps

In British Columbia (BC) most waste dumps are either metal mine or Rocky Mountain coal mine waste rock dumps. Rocky Mountain coal mine waste rock is distinguished from metal mine waste rock by a generally greater proportion of lower strength rock types (shales and lower strength siltstone) and from the prairie coal mine waste rock by the presence of higher strength sandstones and siltstones. In addition the shale materials in the Rocky Mountain coal mines are usually non-swelling as opposed to the bentonitic materials contained in the Prairie coal mine waste rock dumps. Note also that overburden dumps are present at all mine sites. Non-lithified (often termed unconsolidated) overburden materials are not always separated from waste rock materials and sometimes comprise large percentages of waste rock dumps.

There are many factors affecting the flow of water through a mine waste pile. Figure 2.1, derived from Whiting (1981), shows the interrelationship of some of

**Factors Affecting** Waste **Pile** Hydrology

| Physical | **Chemical** | others |
|---|---|---|
| Stratification | pH Control | Solution **Application** and **Collection** |
| Channeling | Precipitation/ Hydrolysis | **Pollution Control Methods** |
| Segregati on | Temperature | Precipitation Rates |
| Sorption | Alteration | Evapotranspiration |
| Foundatim | Oxidatf on | |
| **Permeability** | Solution Type | |
| construction | | |




**Typical Waste Dump Section**
**( after Whiting , 1981 )**

Figure 2.1. Factors Affecting Waste Pile Hydrology (after Whiting, 1981).

these factors. Several of the physical factors shown in this figure are strongly influenced by the internal stratigraphy of the pile. This chapter examines the influence of waste pile stratigraphy on the flow of water through a waste dump.

## 2.1 SPOIL MATERIAL CLASSIFICATION

Figure 2.2 shows grain size distributions for BC mine waste rock (also referred to as mine spoil) materials obtained from different sources. The figure shows that there is a wide range of materials present in waste rock dumps, ranging from silty and sandy gravels to cobbles and bouldery material that does not contain any sands or gravels. The wide range of material up to very large grain sizes and the distribution of these materials in a waste dump poses problems for characterizing mine spoils.

For comparison with BC spoil materials, Figure 2.3 shows grain size distributions obtained from sources outside of BC. This information was obtained from coal mine spoil piles in the UK and the Eastern US. Most of these materials consist of gravel sizes and smaller. In general, the BC coal mine spoil shows a much broader range of grain sizes than other coal mine waste rock materials with a larger percentage of coarser material. Additional information on mine spoil grain size distributions is contained in the Pit Slope Manual (CANMET, 1977); waste rock samples obtained from 11 mine sites across Canada exhibited sand contents (<2 mm material) ranging from 10 to 78%. This information seems to be biased towards finer grain sizes.

It is useful to differentiate between soil-like and rock-like materials. In rock-like material the mechanical behaviour is controlled by the point to point contacts

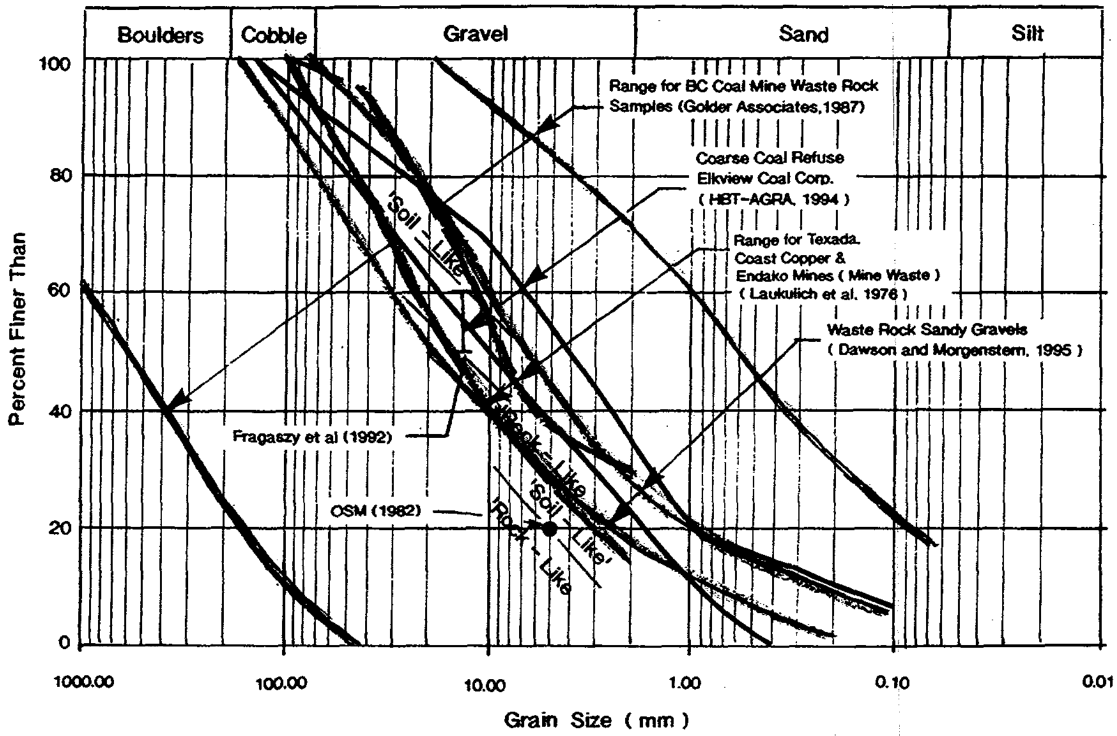



Figure 2.2. Grain Size Distributions from BC Mine Waste Rock Dumps.

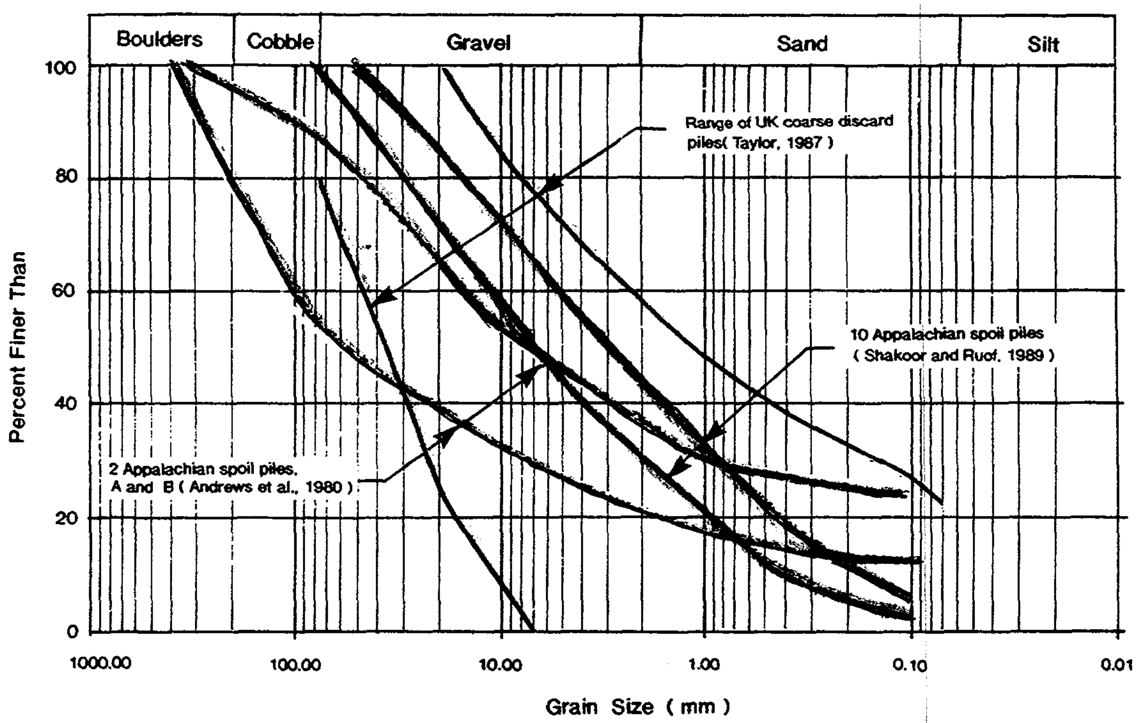



Figure 2.3. Grain Size Distributions from Appalachian and UK Coal Mine Spoil Piles.

between the coarse rock fragments. Flow takes place through fairly large voids between the coarse rock particles. In soil-like spoil the larger fragments 'float' in a matrix of soil particles and the mechanical and hydraulic behaviour is controlled by the properties of the sandy matrix. In soil-like materials, the larger fragments do not significantly influence mechanical and hydraulic behaviour and act mainly to reduce overall porosity. Thus addition of coarse particles to a soil-like spoil actually reduces hydraulic conductivity up to the point that the coarse particles start to interact with one another.

Based on work by Strohm et al (1978), the Office of Surface Mining Reclamation and Enforcement in the USA, (OSM, 1982) suggests that spoils with in excess of 20 percent material passing a No. 4 sieve (4.75 mm particle size) or slakeable rock should be considered as soil-like. Work by Fragaszy et al (1992) indicates that materials with in excess of 50 to 60 percent finer than 12.7 mm behave in a soil-like manner. Dawson and Morgenstern (1995) differentiate pile behaviour on the basis of sand content (less than 2 mm grain size), with a sand content of about 20% forming the boundary between rock-like and soil-like materials. These different criteria all lie within the same range (see Figure 2.2), at about the 10 to 30% sand content boundary.

Soil-like behaviour can be further subdivided into cohesionless and cohesive types. Cohesionless spoils comprise sandy gravels and gravelly sands which display drainage and strength characteristics consistent with granular materials. Cohesive materials are exemplified by spoils containing a large percentage of swelling clay minerals that readily disperse in water. These types of materials are particularly sensitive to weathering effects. The author's experience suggests that there may not be a large proportion of cohesive mine spoil material in BC waste piles.

## 2.2 HYDRAULIC CONDUCTIVITY AND INFILTRATION CAPACITY

The hydraulic properties of mine spoils varies widely as might be expected considering the variability of grain sizes shown in Figure 2.2. Morin (1991) reports values of hydraulic conductivity varying between $10^{-2}$ m/sec for igneous/metamorphic rock to as low as $10^{-9}$ m/sec for clayey basaltic andesite. The distinction between soil-like and rock-like spoil provides a useful break between lower and higher permeability spoil materials, respectively.

Table 2.1 shows some typical saturated hydraulic conductivity values measured in soil-like spoil piles and compacted shale dams. These values are typical of soil-like spoil materials with hydraulic conductivities mostly less than about $10^{-4}$ m/sec.

Results of field and laboratory tests in non-cohesive, soil-like BC spoil piles (Dawson and Morgenstern, 1995) are shown in Figure 2.4. This figure shows that saturated hydraulic conductivity values are generally within the range $10^{-6}$ to $10^{-4}$ m/sec and that hydraulic conductivity decreases with decreasing void ratio. It is noted that this range of hydraulic conductivity value is normally ascribed to finer non-gravelly materials, the very low void ratios are apparently reducing hydraulic conductivity below the normally expected range. The lowest values were obtained from measurements carried out on compacted dump surfaces (due to haul traffic) at void ratios less than 0.3.

TABLE 2.1 TYPICAL HYDRAULIC CONDUCTIVITIES OF SOIL-LIKE SPOIL AND COMPACTED MUDROCKS

| Location | Reference | Material | k (cm/sec) | Type of Test |
|---|---|---|---|---|
| B.C. Spoil piles (coal and metal mines) | Dawson & Morgenstern (1995) | end dumped waste rock (ground surface, crest) | $3x10^{-2}$ to $1x10^{-4}$ | Surface infiltration |
| B.C. Coarse coal refuse (Elkview Coal Corp.) | HBT AGRA (1994) | Computed coal refuse | $4x10^{-4}$ | In-situ tests in standpipes. |
| UK spoil piles | Thomson & Rodin (1972) | end dumped coarse discards. | Typical $1x10^{-3}$ to $1x10^{-4}$ (Range $5x10^{-2}$ to $5x10^{-7}$) "several orders lower" | In-situ tests in standpipes. Laboratory tests. |
| Horsley reclaimed pit, UK | Charles et al (1977) | end dumped mudstone and sandstone fragments, less than 10% passing 200 sieve. | $>1x10^{-2}$ | In-situ in borehole. |
| Appalachian spoil piles | Shakoor & Ruof (1989) | end dumped spoil | $1x10^{-3}$ to $3x10^{-6}$ | Laboratory tests |
| Balderhead rockfill dam | Penman & Charles (1976) | compacted shale | $1x10^{-3}$ | In-situ in boreholes. |
| Llyn Brianne rockfill dam | Penman & Charles (1976) | compacted mudstone | $1x10^{-2}$ to $3x10^{-3}$ | In-situ in boreholes. |

Figure 2.5 shows a plot of void ratio versus percentage saturation derived from sandy gravel materials listed by Dawson and Morgenstern. It is of interest that, at field capacity moisture content, the saturation versus void ratio relation is fairly linear. Over the void ratio range observed in compacted dump surfaces (0.2-0.3) field capacity corresponds to saturation levels greater than 50%. This information indicates that the material has a fairly high moisture retention capability.

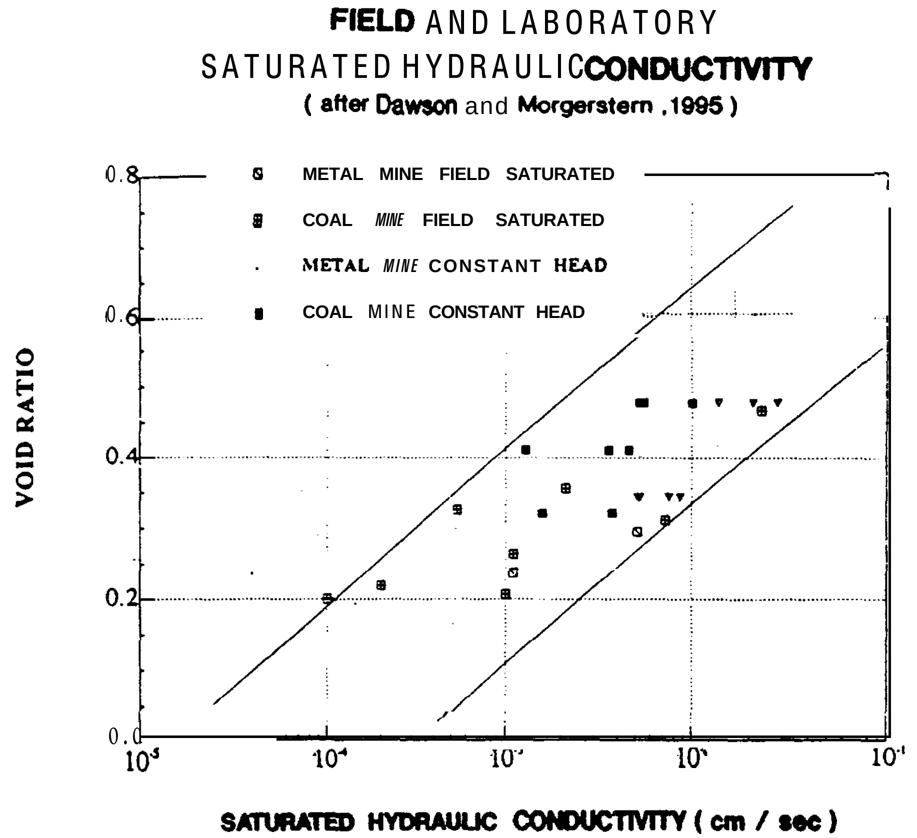



Figure 2.4. Non-Cohesive Soil-Like Spoil Saturated Conductivity Data (after Dawson and Morgenstern, 1995).

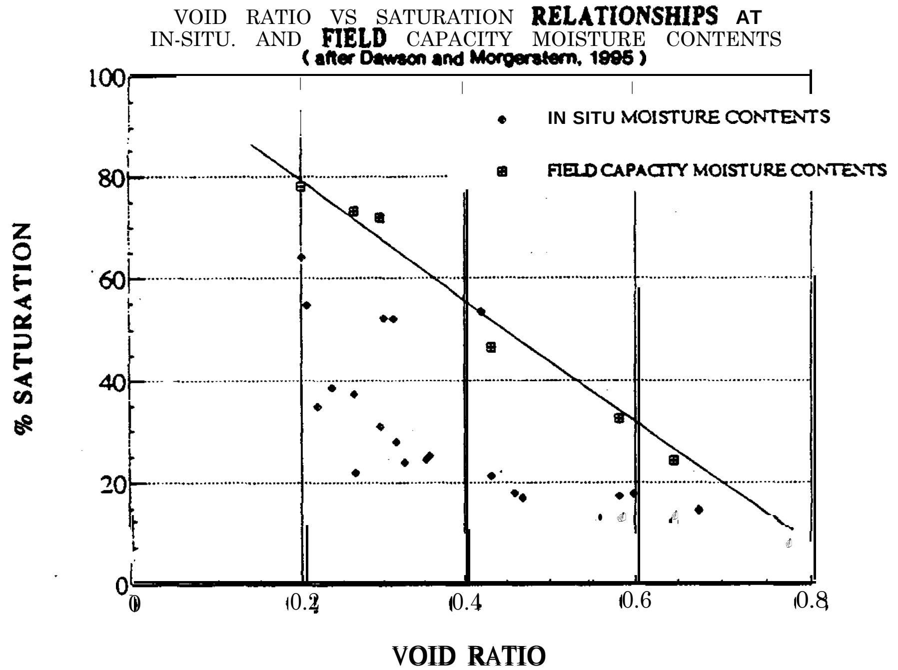



Figure 2.5. Void Ratio versus Saturation Relationships (after Dawsdn arid Morgenstern, 1995).

Vandre (1995) has carried out large scale infiltration tests on mine spoil materials at western US metal mines. Figure 2.6 shows Vandre's data plotted as infiltration rate (equivalent to hydraulic conductivity at a gradient of 1) versus percentage of material finer than 2.5 cm (1 inch). Vandre's data shows that beyond the soil-like/rock-like material break, shown as 30% -2.5 cm (equivalent to 20% sand content), the infiltration rates are very high and greater than about 1 cm/sec.

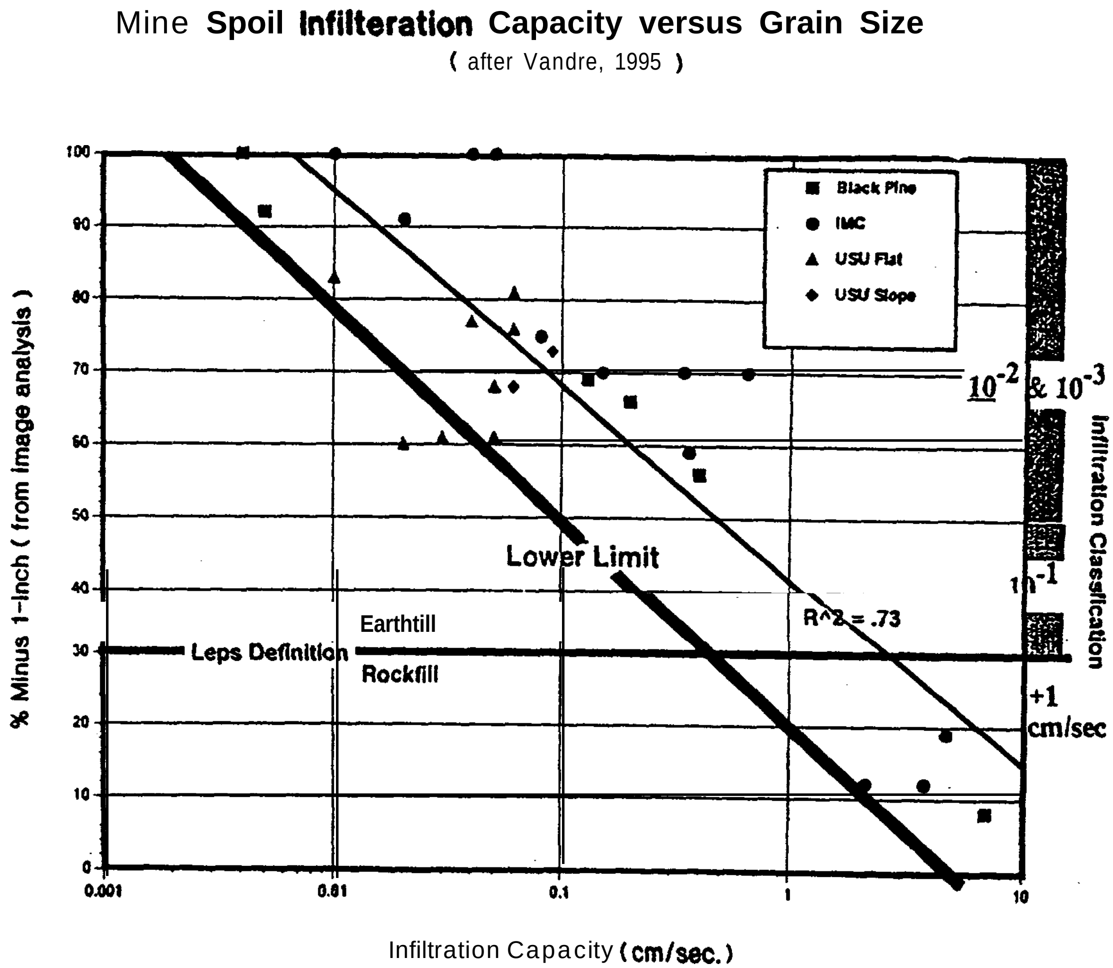



Figure 2.6. Surface Infiltration Data (after Vandre, 1995).

In conclusion, the distinction between rock-like and soil-like mine waste materials provides a useful break to distinguish between seepage behaviour through large void spaces and conventional porous flow behaviour. The break at about 20% sand content appears to provide a useful rule-of-thumb. Measured saturated hydraulic conductivity data suggests that non-cohesive soil-like materials exhibit saturated conductivity values in the range $10^{-6}$ to $10^{-4}$ m/sec.

## 2.3 GENERAL OBSERVATIONS

Although there have been several studies carried out examining waste pile hydrology, particularly regarding issues related to acidic drainage, the internal seepage behaviour of mine waste rock dumps is poorly understood. A review of the literature shows several observations that provide indications of the role that the waste pile stratigraphy may be playing in determining internal seepage behaviour. These observations are summarized below according to issues related to channeled flow, segregation, development of water tables, and weathering.

### *Channelling*

Whiting (1981) points out the important influence of channeling in controlling flow through mine waste piles. ElBoushi (1975) provides useful information on the effects of channeling on small-scale water movement in small rock piles and rock cylinders. ElBoushi's data suggests that channeling may be most important for rock particles greater than 1-2 mm grain size. Results of infiltration tests on coarse grained rock piles showed that water infiltrating through the surface was channeled through 15 to 20% of the rock at depths greater than about 1 m. It is assumed here that channeling is most important for rock-like spoils. Additional information on channeling is provided later in this report.

### *Segregation*

It has been well documented (Golder Associates, 1987) that end dumping of mine waste causes the material to segregate with the coarser cobbles and boulders rolling down to the toe and the finer sands and gravels remaining near the crest. This segregation results in a well defined stratigraphy comprising a fine grained crest and a free draining toe.

Nichols (1987) has conducted some model tests that define this segregation behaviour. Nichol’s tested end dumped material with a mean grain size of 7 mm in a model with a 2 meter long slope. These model tests produced three distinct zones:

1. A concentration of fines near the crest.

2. An evenly distributed, evenly graded material along the remainder of the slope to the toe.

3. A wide dispersion of coarse material beyond the toe.

The same tests carried out with finer material of similar grading and a smaller average grain size (4 mm) showed that while a coarse toe was present, the upper fine zone was not as well defined. Also, the fines were better distributed along the slope. This indicated that the degree of segregation from crest to toe is a function of grain size as well as grading. This finding is very significant as it means that during mining of finer grained material, a layer capable of retaining a significant amount of moisture can form as a continuous, potentially destabilizing zone within a waste dump.

Dawson and Morgenstern (1995) observed that fines layers were formed in Rocky Mountain coal mines when material comprised largely of argillaceous rock types was being end dumped. Layering formed parallel to angle-of-repose waste dumps may be strongly influencing waste pile hydrology.

### *Water tables*

This report reviews two data sets from waste rock piles that contain a water table. Additional case histories documenting the occurrence of water tables are contained in a literature review carried out by Morin (1991). Recent work by AGRA Earth & Environmental also documents incidences of water tables in waste rock dumps. These observations suggest that water tables in waste dumps form due to several different conditions:

- seepage through the base of the pile due to placement of a waste dump over a groundwater discharge zone. This could occur in either rock-like or soil-like materials.
- seepage backing up behind clogged channels in rock-like spoil. The channels could be clogged due to chemical precipitation or fines migration.

- perched water table development due to mounding at the pile/ground-surface contact of soil-like spoil. Studies carried out by Phelps (1991) showed that Appalachian coal mine spoils were most sensitive to the buildup of groundwater pressures when the ratio of saturated hydraulic conductivity to effective average rainfall was 1.0 or less.

- perched water table development on a haul traffic compacted layer in either a soil-like or rock-like spoil.

- perched water table development in fines layers formed parallel to the dump face.

***Weathering***

AGRA Earth and Environmental (1995) review geotechnical aspects of weathering processes in mine waste piles. They note that weathering is likely to be most pronounced in cohesive spoils where the fragments are susceptible to breakdown to grain sizes of the constituent particles (clays and silts). A number of studies of non-cohesive soil-like spoils shows that physical weathering processes are largely confined to depths of 1.5 to 2 m below the dump surface. Chemical weathering, aided by air convection through rock-like spoils, could extend to much greater depths.

## 2.4 HYDROSTRATIGRAPHIC CLASSIFICATION

In British Columbia, most waste dumps are constructed either by dumping material directly over an angle-of-repose face (end-dumping) or by free-dumping in lifts (about 2 m high). The dump construction methods produces two distinct dump types. End dumping tends to produce a segregated zonation with coarser particles in the lower portions of the slope. Free-dumped fills tend to be relatively non-segregated and flow may not be as strongly influenced by distinct textural zonation.

***Non-segregated Dumps***

Seepage through a non-segregated waste pile is expected to be dominated by channelized flow or porous flow depending upon the texture of the waste rock material in the dump. Figure 2.7 shows schematics of flow through non-segregated piles. The influence of the regional water table below the piles is not considered.

Flow through a coarse-grained, non-segregated dump should be dominated by channelized flow. The dump will respond to rainfall events in a short time period, measurable in hours. The mounding of a water table due to infiltration is not expected in this type of dump unless base flow is impeded. A saturated water table is only likely to form where these dumps are situated in natural groundwater discharge areas. The Island

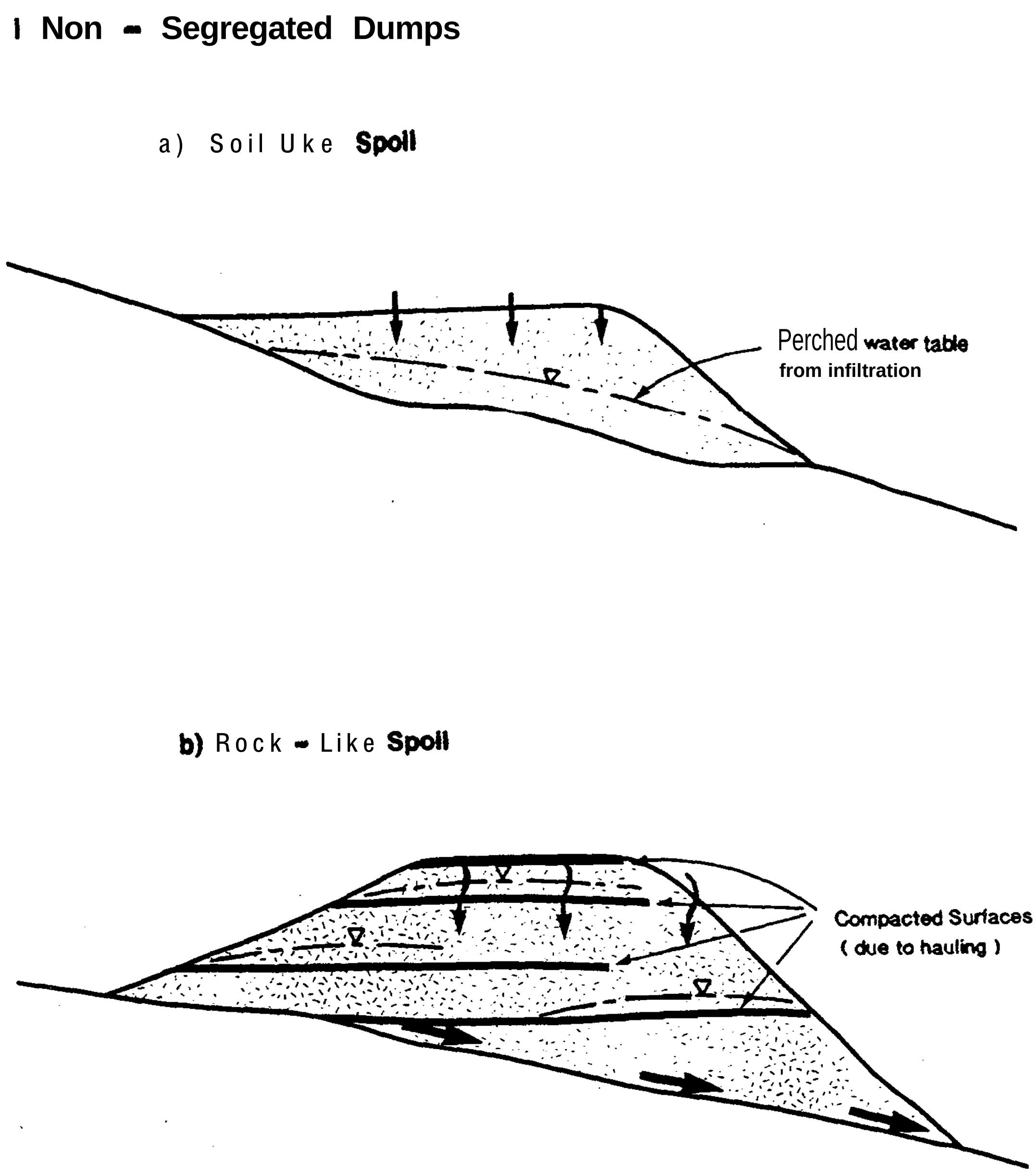



Figure 2.7. Hydrostratigraphy of Non-Segregated Dumps.

Copper mine waste dumps, discussed in Chapter 4, may be exhibiting a geo-hydrological response characteristic of a coarse-grained, non-segregated waste dump.

Flow through a fine-grained, non-segregated dump will be dominated by porous flow conditions. The mounding of a water table due to infiltration will depend mainly on infiltration rates and hydraulic conductivity. The Elkview coarse reject piles, discussed in Chapter 3, are an example of a non-segregated dump where flow through the sandy gravel matrix may dominate the hydrologic response.

### *Segregated Dumps*

Figure 2.8 shows schematics of flow through segregated waste rock piles. Again, the influence of the regional water table has not been considered.

Segregated waste dumps exhibit a dominant vertically-graded stratigraphy due to the segregation that occurs as materials roll down an angle-of-repose face. Finer sandy gravels are present at the crest and coarser materials further down-slope. The vertical thickness of the finer segregated crest zone depends on the source rock textural composition and the dump height. On average, most end dumped fills exhibit finer crest areas that are about one-third as high as the total dump height.

The compacted segregated surfaces of these dumps exhibit infiltration capacities several orders of magnitude lower than the slope areas. Thus flow through these dumps should be largely dominated by infiltration into the coarser rock-like angle-of-repose slopes

In addition to the vertically graded stratigraphy, several investigations have revealed a distinct layering parallel to the dump face formed as different materials are placed. Studies at Rocky Mountain coal mines (Dawson and Morgenstern, 1995) have shown that when materials consisting mostly of finer sandy gravel materials are end-dumped, little segregation occurs and a finer grained layer is formed in the dump. These layers could develop a perched water table as saturation approaches 100% due to infiltration or compression.

## II Segregated Dumps

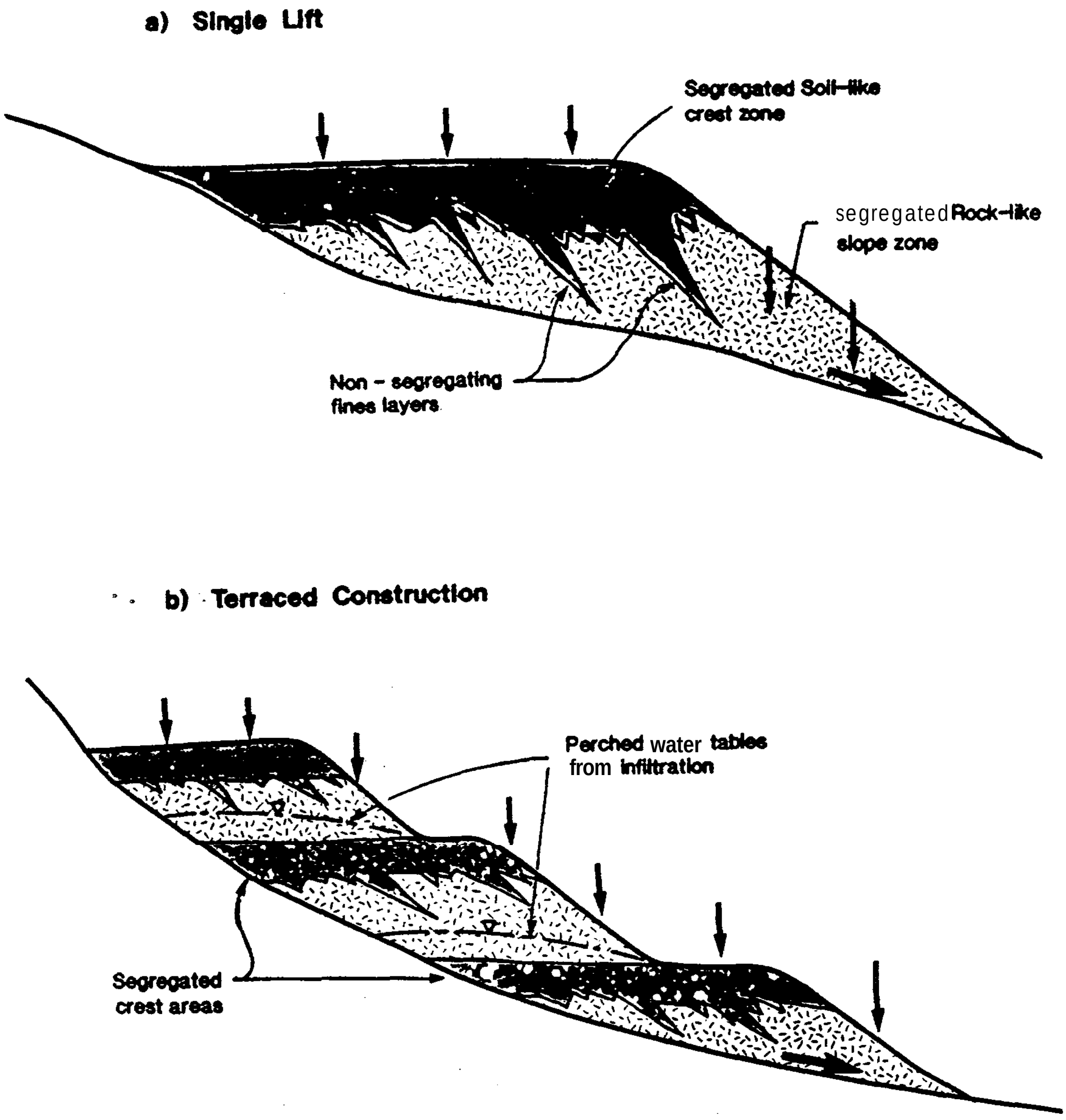



Figure 2.8. Hydrostratigraphy of Segregated Dumps.

Perching might continue to develop until the hydrostatic head exceeds the capillary barrier formed at the fine/coarse interface.

## 2.5 CONCLUSIONS

A preliminary framework for studying and understanding the hydrogeology of waste rock piles has been presented. The framework differentiates between porous flow in finer sandy gravel materials and channelized flow in the coarser materials. Four different waste pile hydrostratigraphic categories are considered.

1. Non-segregated, coarse grained rock piles pass water through very quickly. Unless these dumps are situated in a discharge area they should not pose geotechnical stability concerns. The finer grained matrix adjacent to the channels could be the source of long term acid drainage generation as flushing occurs through coarser grained channels.

2. Non-segregated, fine grained rock piles are likely to form basal water table zones which could cause long term geotechnical stability concerns. Sulfide oxidation and neutralization reactions can occur within the unsaturated zone. Water infiltration transports the oxidation and neutralization products that are soluble from the reaction sites to the saturated zone, and to the discharge points.

3. Segregated rock piles contain a fine grained crest zone which may not permit the passage of significant quantities of water. Most of the infiltration occurs on the angle-of-repose slopes. From a geotechnical stability perspective, the well draining toe area enhances stability. From the perspective of the oxidation and neutralization reactions within the pile, the preferential water infiltration through the slope of the pile should produce regions that are flushed more frequently. Water flow should be low in other regions of the pile allowing for the storage of a large proportion of reaction products.

4. Layered segregated dumps contain a finer-grained crest area and sandy gravel layers parallel to the dump face. These dumps have been observed at Rocky Mountain coal mines and appear to be responsible for liquefaction flowslides. Perched water tables, which can develop in the sandy gravel layers, could provide preferential flow paths through the piles.

# CHAPTER 3

## INTERNAL HYDROGEOLOGIC PROCESSES IN WASTE ROCK PILES

The infiltration into and movement of water through waste rock piles is not well understood. The flow of water is, however, the primary process involved in the transport of reaction products (redox and neutralization reactions) within and out of the pile to the surrounding environment. A better understanding of the physical processes governing water flow within a waste rock pile is needed to improve our capability to anticipate the long-term chemical evolution of water draining from waste rock piles. This problem is one that is not easy to tackle, the key hydrologic processes related to mobilization and transport of metals occur in the partially saturated zone above the water table. The formation of perched zones that could cause geotechnical instability has not been well studied for waste rock piles. Reliable water balances for waste rock piles are generally lacking. A rigorous theoretical framework has yet to evolve that can be used to characterize unsaturated flow in a coarse rock pile that contains both a porous matrix and open voids. In this chapter we present our analysis of monitoring data from several sites in British Columbia and the United States that provide insight to the flow of water within a waste rock pile.

### 3.1 Previous work and the basis for selection of piles analyzed in this study

The movement of water through a porous medium is described by measurements of hydraulic head in the saturated zone below the water table, and by measurements of the water content and matric potential in the partially-saturated zone above the water table. Such measurements are seldom obtained from a waste rock pile. Examples of rock piles where these measurements have been taken include the Clarion Mine in Pennsylvania (Diodato and Parizek, 1994), Golden Sunlight Mine in Montana (Schafer and Associates, 1994), Elkview Mine (HBT AGRA Limited, 1994) and Myra Falls in British Columbia (Morin et al., 1994). It is more common to find measurements of parameters, such as temperature, which are affected by water flow. Examples of rock piles where temperature has been monitored include Golden Sunlight Mine in Montana (Schafer and Associates, 1994), Myra Falls in British Columbia (Morin et al., 1994), Heath Steel Mine in New Brunswick (Nolan, Davis, and Associates, 1992), Mine Doyon in Quebec (Lefbvre et al., 1993), and Rum Jungle Mine in Australia (Harries et al., 1988). For all these rock piles, climatic information is also available, either from a local or a nearby meteorological station.

At the Clarion Coal Mine in Pennsylvania (Diodato and Parizek, 1994) subsurface data collected included volumetric water content using nuclear logging methods and bulk density using a gamma-gamma probe. Spatial variations of volumetric water content with depth were obtained at seven different sampling times over an 8-month period. Total porosity was calculated from volumetric moisture content and bulk density. Hydraulic conductivities in the partially-saturated zone were estimated using two methods: from the variations of volumetric water content with depth and time, and using bromide-79 in tracer experiments. Water samples were collected in pressure-suction lysimeters for the tracer test. Diodato and Parizek (1994) found cyclic variations of volumetric water content, bulk density, and porosity with depth. They proposed that these variations occur because of differences in compaction of the dump created by heavy equipment operating on the top of every 1.5 m of lift. Estimates of the unsaturated hydraulic conductivity derived from water content measurements versus depth, taken immediately after the end of a rainfall event, and one day later, ranged from $2.4x10^{-9}$ to $1.5x10^{-5}$ m/s, with a geometric mean of $1.3x10^{-6}$ m/s. Estimates of the unsaturated hydraulic conductivity inferred from travel times of bromide concentration peaks ranged from $2.8x10^{-8}$ to $7.2x10^{-7}$ m/s, with a geometric mean of $1.5x10^{-7}$ m/s. Hydraulic conductivities based on the tracer test are average values for the entire domain intercepted by the tracer during the travel time from the injection to the sampling points. In comparison, hydraulic conductivities obtained from the transient variations in water content along the well profile following an infiltration event reflect local values at a time of increasing water content in the pile. Unsaturated hydraulic conductivity is known to increase with increasing water content. It seems reasonable that estimates of hydraulic conductivity based on tracer tests should be lower than those obtained immediately after an infiltration event.

At the Heath Steele Mine in New Brunswick (Nolan, Davis, and Associates, 1992) four piles were studied, ranging in volume from 1900 to 100,300 $m^3$ (3,250 to 235,700 tonnes). Data collected in these piles included temperature and gas-phase oxygen concentrations. Saturated hydraulic conductivity was estimated using infiltration measurements in boreholes. The hydraulic conductivity varied from $10^{-4}$ to $10^{-2}$ m/s. These values can be compared with the value predicted using Hazen's equation (Freeze and Cherry, 1979), which gives $10^{-2}$ m/s for a grain size of 1 mm in these piles. Oxygen concentrations varied with depth, with the largest pile having the highest oxygen concentration at depth because convective circulation was driving air to the center of the pile. Oxygen concentrations and temperature were inversely correlated, which is consistent with the concept that oxygen concentrations will be reduced in more reactive zones of a waste rock pile. Highest oxygen concentrations at depth occurred during the winter months. In the largest pile, convective air flow from the sides of the pile seemed to be driven by high temperatures at the center of the pile, and the greater gradients in temperature between the center of the pile and the top of the pile. In this pile, as well as that at the Rum Jungle Mine in Australia (Harries et al., 1988), the frequency of the data does not allow correlations to be examined between temperature within the pile and water infiltration events.

The south dump of Mine Doyon in Quebec has been intensively monitored (Gelinas et al., 1992). Parameters measured in six boreholes include temperature and gas concentrations. Water fluxes and chemistry at the toe of the pile are also measured. The pile is formed from sericitic schists, diorites, and volcaniclastites, with 3.5-4.5 % pyrite and a high porosity (35%). $CO_2$, $O_2$, $N_2$, and water vapor has been identified in the gas phase. $O_2$ decreases and $CO_2$ increases with depth. Mass balance calculations on the flow of water indicate a 5% mass loss at the base of the pile. A porous medium approach (Lefevbre, in press ) has been used to model the movement of air, water, and heat in the system.  The results indicate that evaporation and air convection are important processes affecting water content and water movement within this pile.

These studies provide important information on redox processes, oxygen supply and consumption, and the generation and transport of heat within a waste rock pile. However, in order to gain better insight to water flow through waste rock piles we need information on water contents, water table fluctuations, variations in matric potential within the partially-saturated zone of a pile, and the response of the temperature field to rainfall infiltration events.  Several piles can provide information on one or several of these processes.  Myra Falls Mine, Golden Sunlight Mine, and Elkview Mine were selected for this study because they have been monitored more intensively for one or more of these parameters. In addition, Island Copper Mine in British Columbia provides important information on large scale hydrogeological processes because water outflow from the toes of the different piles have been measured as frequently as every 15 minutes during the last 4 years.  The data from Island Copper Mine will be analyzed in Chapter 4. Figure 3.1 shows the location of the waste rock piles we study in this report.

Fig 3.1

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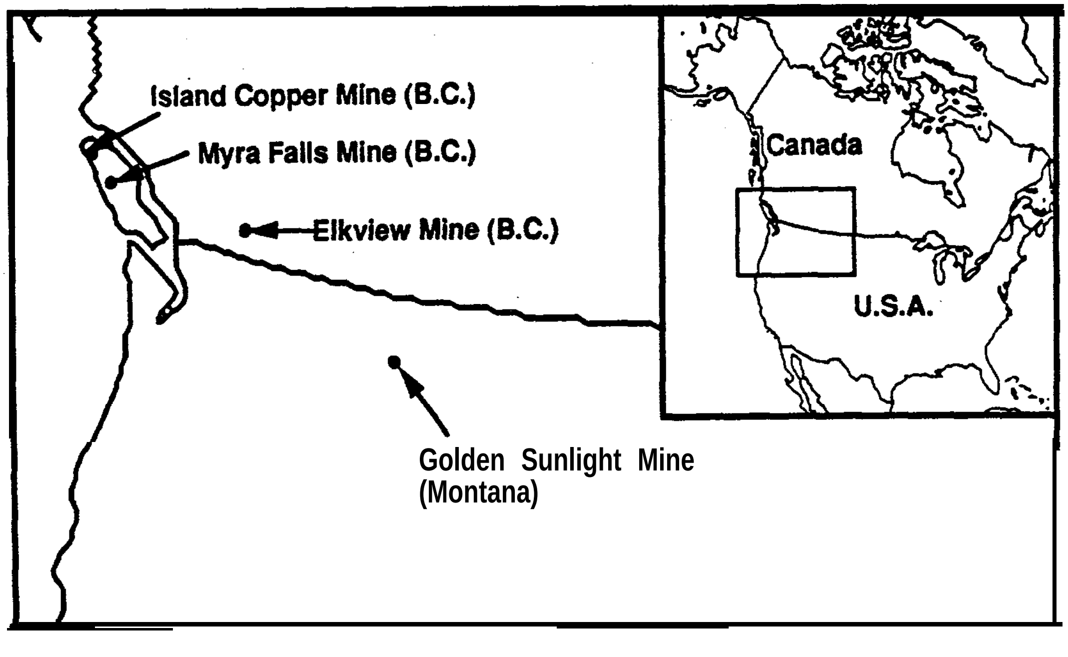



Figure 3.1. Location of waste rock piles studied in this project. Island Copper and Myra Falls Mines on Vancouver Island, Elkview Mine in eastern British Columbia, Canada, and Golden Sunlight Mine in Montana, U. S. A.

**Golden Sunlight Mine, Montana**

The west dump at Golden Sunlight Mine in Montana (Schafer and Associates, 1994) is shown in Figure 3.2. The waste rock of this large open-pit gold mine is formed from coarse sedimentary, intrusive and volcanic rocks. This pile has been intensively monitored since 1992, with five monitoring sites (Figure 3.2) on both recently reclaimed and unreclaimed parts of the pile. Monitoring data includes rainfall and air temperature, temperature inside the pile, volumetric water content determined using a neutron probe and suction lysimeters, soil matric potential measured by heat dissipation (AGWA II sensors), and gas phase concentrations ($O_2$ and $CO_2$). For all these parameters except volumetric water content and gas concentrations, the sampling frequency is every hour. The average temperature and matric potential have been recorded every 6 hours. Our analysis has indicated that it is sufficient to work with the data averaged over a 24 hour period for the purpose of a qualitative comparison between rainfall infiltration and variations in temperature and matric potential. The time between samplings of volumetric water content is variable, ranging from 1 up to 7 months. Data from April 1993 to October 1994 have been considered in our analysis because there are fewer gaps in the data during this period of time. Sites 6 and 7 (Figure 3.2) were studied because our interest is mainly in the processes occurring in unreclaimed piles. Site 2 is located in the reclaimed section of the pile and was included in this study for comparison.

**Myra Falls, British Columbia**

Mining operations over more than 25 years have produced four waste rock dumps at Myra Falls Mine (Northwest Geochem, 1992). Our attention is focused on Dump #1 because this dump has been heavily instrumented to measure concentrations of gases, temperatures, and water table elevations. This pile is formed by approximately 10 million metric tonnes of coarse-to-fine pyritic waste rock. This dump was built against a valley wall and is now laterally adjacent to a tailings impoundment. Figure 3.3 shows the three construction lifts in this pile: upper, middle, and lower lifts, and the location of monitoring wells for temperature, water levels, and gases (Morin et al., 1994).

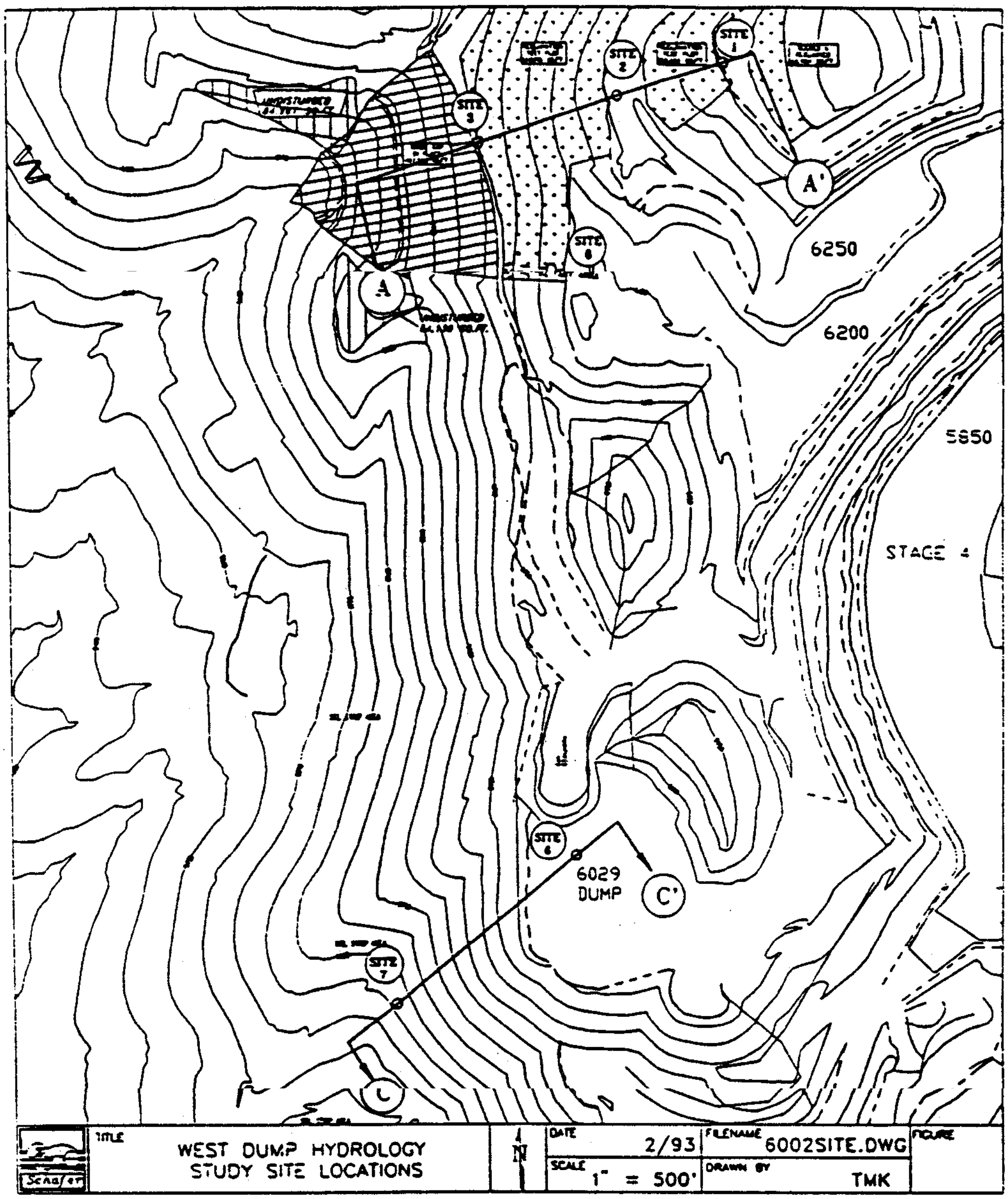



Figure 3.2. West Dump of Golden Sunlight Mine, Montana (Schafer and Associates, 1994).

Representative contours of water table elevation are also presented in this figure. The middle lift partially covers the lower lift, which is itself partially covered by the upper lift. During drilling of the wells, the upper and middle lift were found to have a very heterogeneous texture, varying from coarse boulders to fine-grained rock. Morin et al. (1994) associate the fine-grained layers to surfaces formed by crushing and compaction by the movement of heavy equipment delivering and dumping the waste rock. The lower lift is formed of fine-grained rock, wood and other waste materials. The dump is about 800 m long, 300 m wide and reaches a maximum height of 42 m. The monitoring data published for this site includes data on rainfall and air temperature, temperature inside the pile, and elevation of the water table. The frequency of monitoring is every 12 hours. Published data from October 1990 to November 1991 was considered in our analysis because fewer gaps in the data occur during that period of time.

**Elkview Mine, British Columbia**

Elkview Mine is a coal mine located in south central British Columbia (Figure 3.1). Three coarse coal refuse (CCR) dumps have been constructed at Elkview Mine; the smaller South and Goddar dumps to the south of Lindsay Creek and the larger North Dump. It is planned to construct a continuous dump by infilling Lindsay Creek with CCR material.

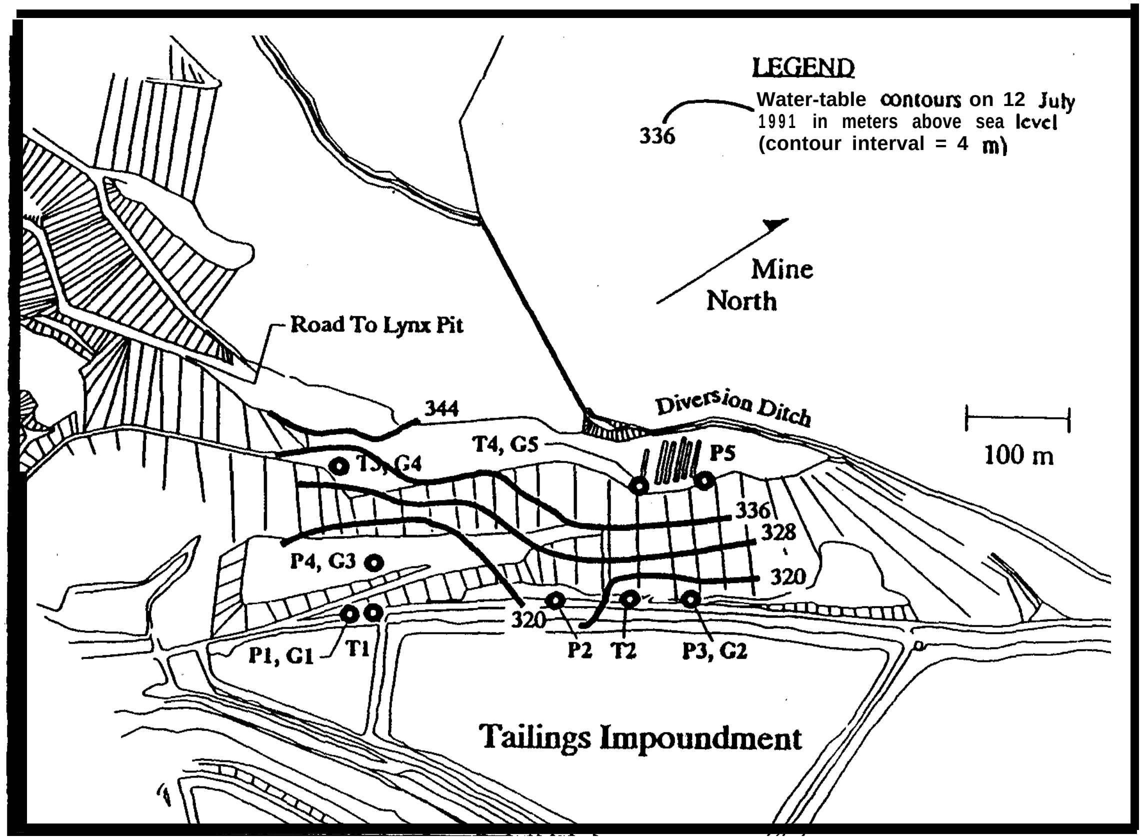



Figure 3.3. Location of boreholes and water table at Dump #1 , Myra Falls Mine (Morin et al., 1994).

The North Dump has been monitored for water table elevation since 1981 when 6 piezometers were installed. New boreholes have been added more recently to complete 16 piezometers (Figure 3.4). The dumps are formed by coarse coal refuse that has generally been processed to a 75 mm minus size. Fines with a grain size less than approximately 0.5 mm are also removed before delivery to the dumps. The coarse coal refuse dump overlies a clayey-till unit. At the sites where two wells are located close to each other (Figure 3.4), one of the wells is deeper and intercepts the clayey-till. The other well is shallower and is completed in the coarse coal refuse. Exceptions are wells OW3B and OW3C which are both completed in the clayey-till unit. The data set includes the following parameters: well elevations and depth, elevation of the contact between the clayey-till and the coarse coal refuse, water table elevation as a function of time, and daily rainfall. Additional information describing construction of the pile is also available (HBT AGRA, 1994). Initially the fill was hauled by scrapers and spread forming lifts about 0.3 m thick. For elevations above 1230 m, the coarse coal refuse was transported in trucks and spread in 1.8 m lifts. The monitoring frequency is variable, sampling intervals are sometimes as large as one month. We have analyzed the water table response for the year 1993 because that data set has higher continuity and monitoring frequency.

## 3.2 WATER CONTENT WITHIN WASTE ROCK DUMPS

Of the three piles discussed in this chapter, water content within the pile has been monitored only at Golden Sunlight Mine. Measurements of volumetric water content at Golden Sunlight Mine have been made using neutron probe access tubes (Schafer and Associates, 1994) and two types of suction lysimeters

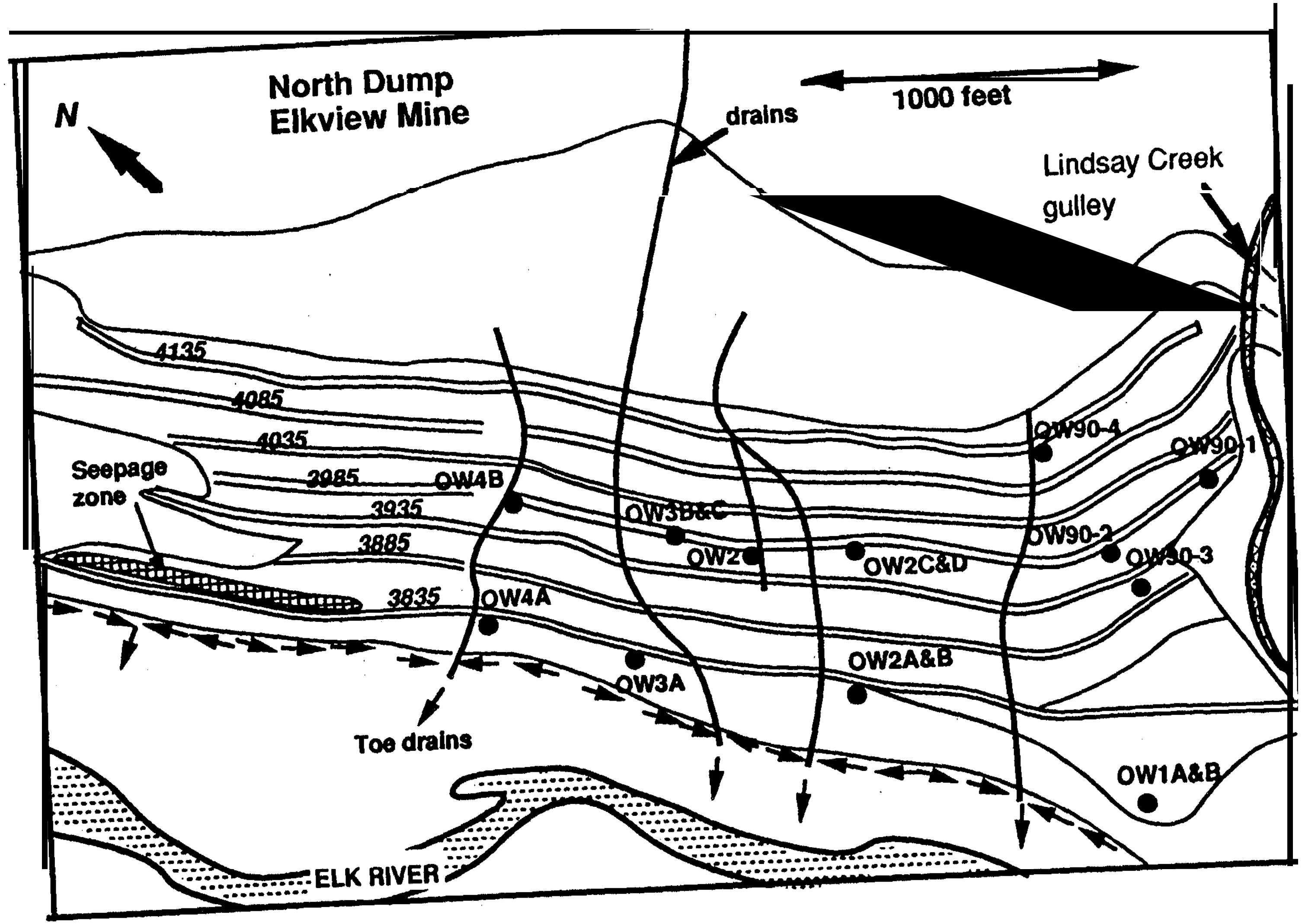



Figure 3.4. North dump of Elkview Coal Mine in British Columbia, Canada. Coarse coal refuse pile overlies clayey-till.

(Soil Moisture and BAT Envitech (BAT)). Volumetric water content is defined by the ratio of volume of water in a sample, to the total volume of the sample. At saturation, the volumetric water content is equal to the porosity of the sample. The purpose of the suction lysimeters was to collect water for pore water chemistry analysis. The access tubes were constructed of 6 m sections of 0.05 m black steel pipe which is transparent to the radiation source of the neutron probe (Campbell-Pacific Model 503). Details about the construction of the access tubes can be found in Schafer and Associates (1994). Emitted neutrons from the probe are slowed down when they collide with hydrogen atoms of similar mass. The source of hydrogen in soils and waste rock piles is mainly water. Calibration curves for undisturbed waste rock material were not available. Schafer and Associates designed a standard calibration equation for coarse textured rock:

$Y = 0.219(X) + 0.061$, where Y = volumetric water content, X = field count/shield count.

Water content in waste rock piles is a function of rock particle size, and water infiltration. According to Schafer and Associates (1994), freshly shot rock at Golden Sunlight Mine typically has less than 6% water at the time of emplacement on the pile. Figure 3.5 shows profiles of volumetric water content against depth for sites 6 and 7. See Figure 3.2 for site locations. Volumetric water content ranged from 9% to 21% for site 6, and from 10% to 39% for site 7. For site 6, oscillations of water content with depth can be observed. However, there are no dramatic changes in water content for a given depth at different times during the year. Differences can be as large as 5% but usually are not larger than 1%. The behavior is different for site 7. There are large variations in water content at depths between 10 and 30 feet, and for depths greater than 35 feet. As will be discussed later, temperatures inside the pile at site 7 indicate freezing conditions most of the year at all depths, only the upper part of the profile and the bottom are partially melted during the summer months. Melting and freezing processes at site 7 produce highly variable volumetric water content.

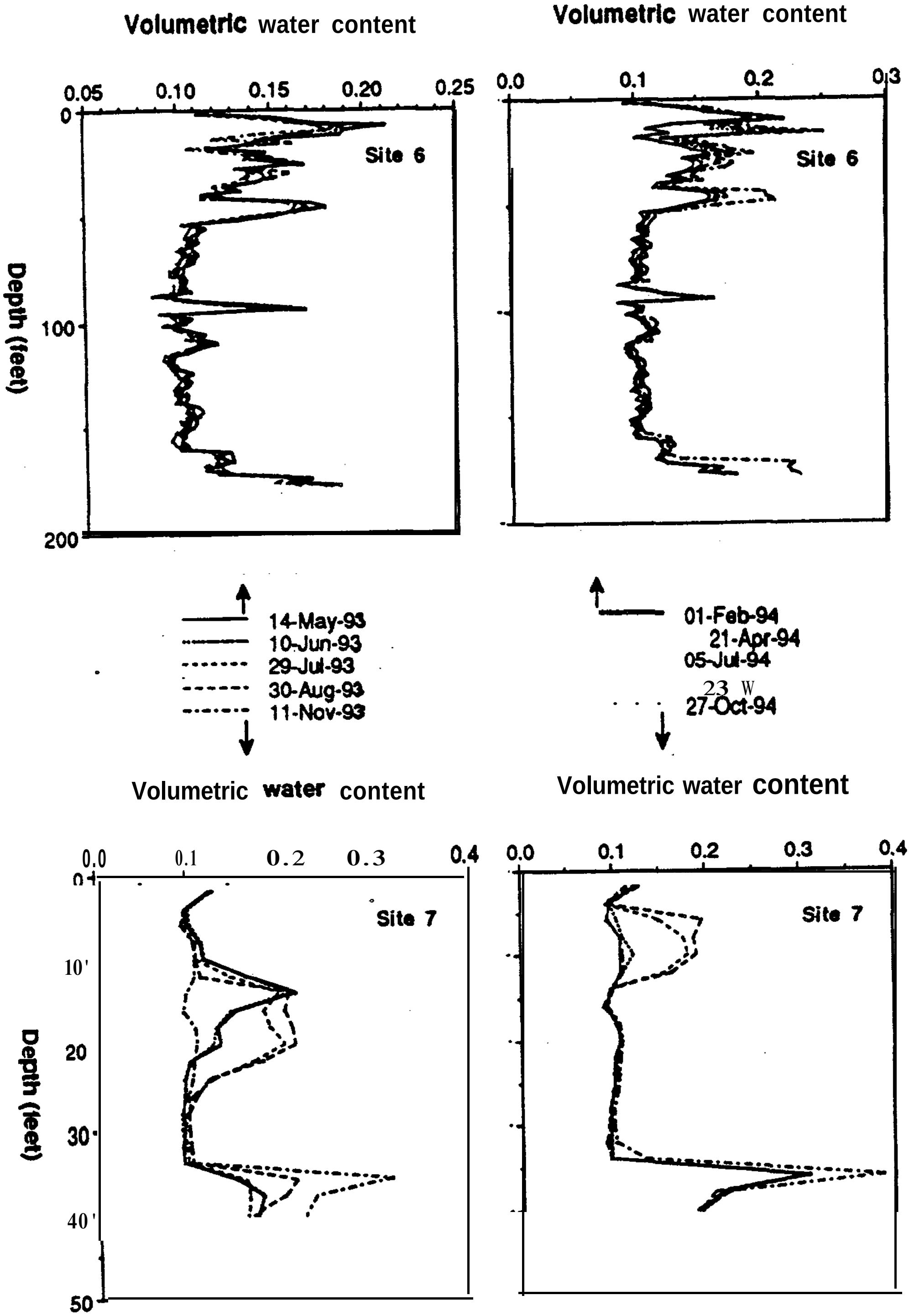



Figure 3.5. Volumetric water content at sites 6 and 7 of the West Dump at Golden Sunlight Mine, data from 1993 and 1994.

The variations in volumetric water content with depth at site 6 in Golden Sunlight Mine should be related to variations in grain size and the effects of compaction due to operation of heavy equipment during construction of the pile. Recall a similar behavior was noted at the Clarion Coal Mine (Diodato and Parizek, 1994). According to our discussion of the hydrostratigraphy of waste rock piles (Chapter 2), the upper part of the pile should contain a larger proportion of fines and consequently the capability of retaining a higher water content. Volumetric water content profiles at site 2, in the reclaimed portion of the dump, shows similar behavior to site 6. Figures 3.5 and 3.6 show that the seasonal increase in water content is greater in those regions of the pile that have higher water content (i.e. the wet sites get wetter).

If we compare volumetric water contents measured at sites 2 and 6 during 1993 and 1994, for similar dates in each year, it is apparent that the profiles are almost the same (Figure 3.6). The small variations are probably due to variations in rainfall during the two years. The fact that water content does not seem to change dramatically in this pile suggests that the permeability and porosity structures of the pile are stable during this period of time.

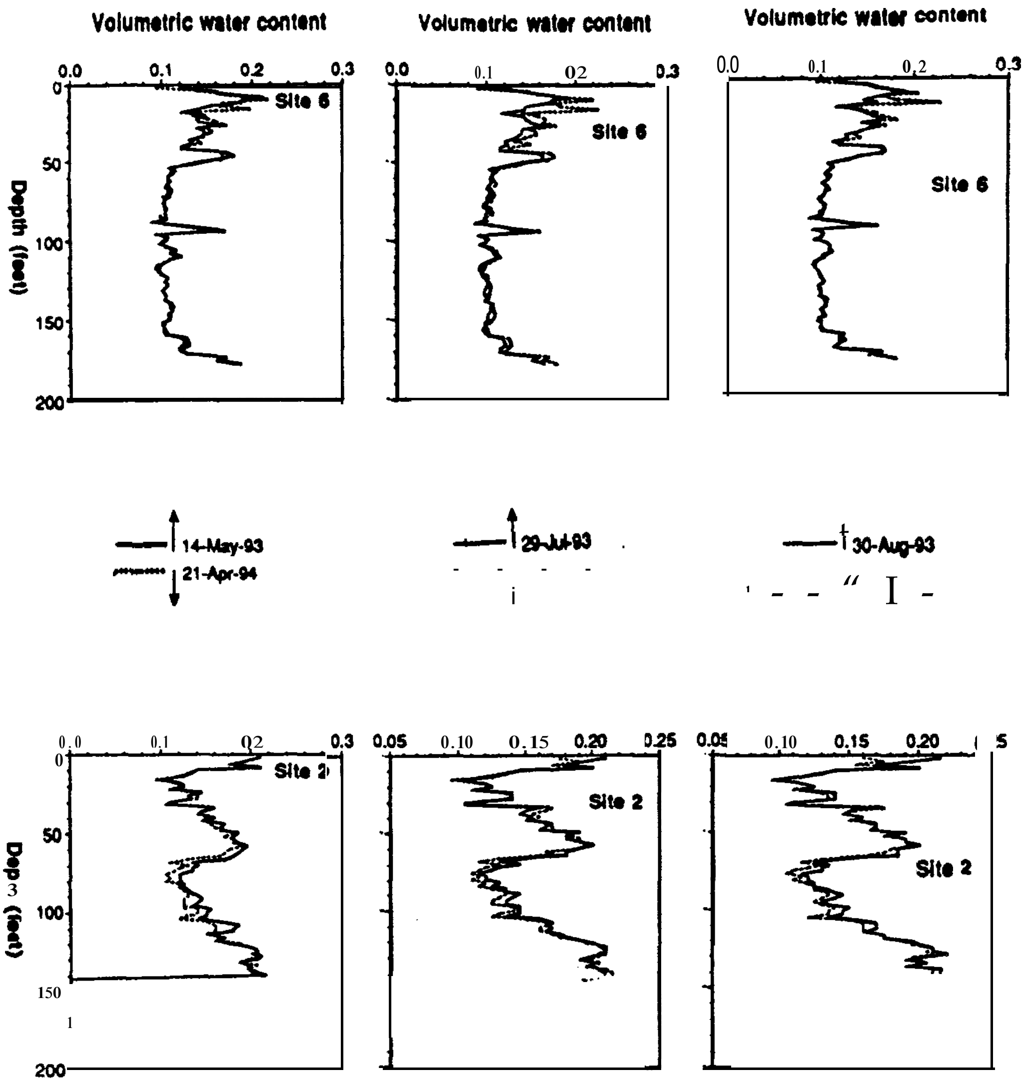



Figure 3.6. Volumetric water content at sites 2 and 6 of the West Dump of Golden Sunlight Mine, for similar dates during 1993 and 1994.

### 3.3 WATER TABLE FLUCTUATIONS WITHIN WASTE ROCK DUMPS

Monitoring wells at Myra Falls Mine and Elkview Mine penetrate saturated zones within and beneath the waste rock piles, providing information on water table fluctuations and the occurrence of perched zones of saturation above the main water table. The wells used to monitor water table elevation in Dump #1 at Myra Falls and in the North Dump at Elkview Mine have been completed a few meters below the water table. At the Elkview Mine the wells were completed at depths ranging from less than 1 m up to 8 m below the water table. In Dump #1 at Myra Falls, the piezometers penetrate between 2 and 7 meters below the water table. Because these wells are completed in the vicinity of the water table they can detect the fluctuations in the water table produced by infiltration of rainfall and/or snowmelt. An important distinction can be made between the Elkview and Myra Falls sites. In the Elkview waste rock piles, the water table is mounded on a clay till unit, and it reflects surface infiltration through the pile. At Myra Falls, the water table predominantly reflects seepage entering the waste rock pile from surrounding areas.

**Elkview Mine**

Sixteen wells at the North dump of Elkview mine (Figure 3.4) monitor the fluctuations of the water table within the coarse coal pile and within the clayey-till underlying the pile. Table 3.1 provides information on the wells: elevation of the completion zone, elevation of the collar or top of the steel pipe, elevation of the contact between the clayey-till and the waste rock, and the thickness of the pile at the well location. The collar elevations are corrected measurements taken in October 1993 (HBT AGRA Limited, 1994). The elevation of the contact between

Table 3.1. Elevation of well bottom and collar, and contact between clayey-till and the coarse coal refuse, north pile at Elkview Mine, B. C. (data from HBT Agra Limited, 1992).

| Well | Bottom elevtion (feet) | Well termination | Thickness of coal pile (feet) | Collar elevation (feet) October 1993 | Clay till elevation (feet) |
|---|---|---|---|---|---|
| OW1A | 3702.6 | till | 30.7 | 37833.5 | 3752.8 |
| OW1B | 3761.0 | ccr | 21.6 | 3782.8 | 3761.2 |
| OW2A | 3748.2 | till | 48.3 | 38244.4 | 3776.1 |
| OW2B | 3769.5 | ccr | 45.9 | 3824.5 | 3778.6 |
| OW2C | 3885.4 | ccr | 96.8 | 3978.4 | 3881.6 |
| OW2D | 3872.5 | till | 97.6 | 3979.7 | 3882.6 |
| OW3A | 3801.9 | till | 17.7 | 3831.7 | 3813.5 |
| OW3B | 3882.7 | till | 89.2 | 3980.2 | 3891.0 |
| OW3C | 3881.6 | till | 87.6 | 3982.6 | 3895.0 |
| OW4A | 3796.1 | till | 27.2 | 3830.8 | 3803.6 |
| OW4B | 3907.5 | ccr | 76.8 | 3980.1 | 3902.3 |
| 90-1 | 3957.3 | till | 12.3 | 3974.3 | 3962.0 |
| 90-2 | 3858.8 | till | 112.4 | 3975.9 | 3863.5 |
| 90-3 | 3840.0 | till | 82.7 | 3924.8 | 3842.1 |
| 90-4 | 3990.3 | till | 128.8 | 4124.9 | 3996.1 |
| OW-2 | 3874.9 | ccr | 105.4 | 3979.7 | 3874.3 |

the clayey-till is based on an original survey at the time of well installation. Most wells have a collar elevation lower in 1993 than at time of installation (up to 5.7 ft difference). Compaction and settlement of the waste rock may explain this difference in collar elevation ( HBT AGRA Limited, 1994).

Table 3.2 provides measurements of the water table elevation during 1993. In piezometer nests, one well is completed in the clayey-till, and the other in the waste rock (e.g. OW1A and OW1B; OW2A and OW2B). To study the response of the water table to rainfall events, the water table elevation and precipitation for the year 1993 have been plotted for well OW1A, which is completed in the clayey-till (Figure 3.7). The frequency of measurements is too low to examine the correlation between daily rainfall and water table elevation (Figure 3.7a). However, if the monthly rainfall is plotted instead of daily rainfall, a clear response of the water table to increasing rainfall is observed, with a decline when the monthly precipitation decreases (Figure 3.7b). Figure 3.8 shows a similar response for many of the other wells that intercept the clayey-till. Figure 3.9 shows the same relationship for the shallower wells located in the coarse coal refuse. In most wells, the water table is higher immediately after the period of heavier rainfall (July) and lower during winter time when snow covers the pile and infiltration is lower (February). Some wells seem to respond faster to the infiltration of rainwater (e.g. OW1A, OW3A) and other wells respond slower (e.g. OW2A, OW2D, OW2B), suggesting a different permeability structure or flow path. Preferred flow in and around borehole seals may be partially responsible for this response. Oscillations in water levels with higher frequency observed in these graphs are probably related to variations in infiltration produced by rainfall events, which are smoothed when the data are presented as monthly rainfall instead of daily rainfall. In general, these higher-frequency fluctuations in the water table are larger in the wells completed in the coarse coal refuse (Figure 3.9).

Table 3.2. Water table elevation during 1993 for wells in the North Dump at Elkview Mine, B.C.. Elevation of the water table in feet (data from HBT Agra Limited, 1992).

| Date | Day 1993 | OW1A | OW1B | OW2A | OW2B | OW2C | OW2D | OW3A | OW3B | OW3C | OW4A | OW4B | 90-1 | 90-2 | 90-3 | 90-4 | OW2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15-Jan-93 | 15 | 3729.4 | | 3767.7 | 3778.3 | 3899.1 | 3878.7 | 3813.7 | 3900.1 | 3889.9 | 3797.6 | 3908.8 | 3962.3 | 3864.3 | 3848.0 | 4001.6 | 3884.2 |
| 8-Feb-93 | 39 | 3729.5 | | 3767.2 | 3778.2 | 3899.1 | 3878.6 | 3812.9 | 3899.8 | 3889.7 | 3797.1 | 3907.4 | 3960.9 | 3864.3 | 3847.6 | 4001.5 | 3884.1 |
| 8-Mar-93 | 67 | 3729.4 | | 3767.5 | 3778.2 | 3899.1 | 3878.5 | 3813.9 | 3898.3 | 3889.7 | 3797.1 | 3907.9 | 3963.2 | 3864.2 | 3847.6 | 4001.5 | 3885.2 |
| 17-Mar-93 | 76 | 3729.6 | | 3767.5 | 3778.2 | 3899.1 | 3878.1 | 3813.8 | 3900.1 | 3889.7 | 3797.0 | 3908.0 | 3965.1 | 3864.1 | 3847.5 | 4001.5 | 3884.2 |
| 24-Mar-93 | 83 | 3729.7 | | 3767.4 | 3778.2 | 3899.1 | 3877.9 | 3813.6 | 3899.8 | 3889.5 | 3797.1 | 3908.0 | 3965.7 | 3864.3 | 3847.5 | 4001.5 | 3879.9 |
| 31-Mar-93 | 90 | | | | | | | | | | | | | | | | |
| 1-Apr-93 | 91 | 3729.7 | | 3767.4 | 3778.3 | 3898.9 | 3878.1 | 3813.6 | 3899.6 | 3889.6 | 3797.1 | 3908.9 | 3965.2 | 3864.2 | 3847.5 | 4001.5 | 3879.9 |
| 10-Apr-93 | 100 | 3729.8 | | 3767.1 | 3778.2 | 3899.1 | 3877.9 | 3814.2 | 3899.4 | 3889.6 | 3797.2 | 3909.3 | 3965.4 | 3864.3 | 3847.4 | 4001.5 | 3883.7 |
| 15-Apr-93 | 105 | 3729.8 | | 3767.4 | 3778.1 | 3899.1 | 3877.8 | 3814.2 | 3899.6 | 3889.6 | 3797.2 | 3909.8 | 3965.2 | 3864.2 | 3847.4 | 4001.5 | 3881.7 |
| 21-Apr-93 | 111 | 3729.6 | | 3767.4 | 3778.1 | 3899.1 | 3877.6 | 3814.2 | 3900.1 | 3889.5 | 3797.2 | 3909.9 | 3964.8 | 3864.2 | 3847.5 | 4001.5 | 3880.1 |
| 30-Apr-93 | 120 | | | | | | | | | | | | | | | | |
| 12-May-93 | 132 | 3729.8 | 3763.5 | 3767.4 | 3778.1 | 3899.0 | 3878.2 | 3815.0 | 3900.1 | 3889.6 | 3797.5 | 3911.1 | 3964.1 | 3864.3 | 3847.8 | 4001.3 | 3884.4 |
| 27-May-93 | 147 | 3729.7 | 3762.3 | 3767.5 | 3778.3 | 3899.0 | 3877.4 | 3814.8 | 3900.7 | 3889.8 | 3796.7 | 3911.2 | 3963.4 | 3864.3 | 3848.0 | 4001.4 | 3884.0 |
| 31-May-93 | 151 | | | | | | | | | | | | | | | | |
| 9-Jun-93 | 160 | 3729.7 | 3767.3 | 3767.5 | 3778.4 | 3899.1 | 3877.4 | 3814.7 | 3900.3 | 3889.8 | 3797.4 | 3911.1 | 3965.3 | 3865.1 | 3850.5 | 4001.4 | 3883.7 |
| 17-Jun-93 | 168 | 3729.7 | | | 3778.3 | | | | | | | | | 3864.3 | 3848.4 | | |
| 23-Jun-93 | 174 | 3729.9 | 3770.8 | 3767.5 | 3778.4 | 3899.0 | 3877.4 | 3814.7 | 3901.0 | 3889.9 | 3797.4 | 3911.5 | 3965.2 | 3864.3 | 3847.5 | 4001.8 | 3884.6 |
| 30-Jun-93 | 181 | | | | | | | | | | | | | | | | |
| 6-Jul-93 | 187 | 3730.0 | 3765.7 | 3767.5 | 3778.6 | 3899.2 | 3877.4 | 3815.0 | 3900.9 | 3889.8 | 3797.4 | 3912.0 | 3966.1 | 3864.8 | 3848.2 | 4001.9 | 3879.9 |
| 21-Jul-93 | 202 | 3730.4 | 3769.9 | 3767.7 | 3778.9 | 3899.1 | 3877.3 | 3815.0 | 3901.1 | 3890.0 | 3797.4 | 3912.0 | 3965.1 | 3864.4 | 3850.5 | 4001.9 | 3879.4 |
| 31-Jul-93 | 212 | | | | | | | | | | | | | | | | |
| 4-Aug-93 | 216 | 3730.3 | 3767.0 | 3767.6 | 3779.4 | 3899.2 | 3877.4 | 3815.0 | 3901.1 | 3890.0 | 3797.5 | 3908.8 | 3965.1 | 3863.4 | 3850.4 | 4002.1 | 3882.4 |
| 18-Aug-93 | 230 | 3730.0 | 3763.3 | 3768.1 | 3779.7 | 3898.3 | 3877.7 | 3815.1 | 3901.6 | 3889.9 | 3797.5 | 3912.3 | 3964.5 | 3864.5 | 3850.6 | 4002.1 | 3879.6 |
| 31-Aug-93 | 243 | | | | | | | | | | | | | | | | |
| 1-Sep-93 | 244 | 3729.9 | 3762.8 | 3768.5 | 3780.0 | 3898.3 | 3878.2 | 3815.0 | 3902.2 | 3889.9 | 3797.5 | 3911.8 | 3964.2 | 3863.0 | 3851.3 | 4001.7 | 3881.7 |
| 15-Sep-93 | 258 | | | | | | 3879.1 | | | | | | | | 3851.7 | | |
| 29-Sep-93 | 272 | 3730.0 | 3762.8 | 3769.1 | 3780.3 | 3898.7 | 3880.7 | 3814.9 | 3902.7 | 3890.2 | 3797.4 | 3911.1 | 3964.2 | 3864.1 | 3851.8 | 4002.0 | 3879.8 |

are larger in the wells completed in the coarse coal refuse (Figure 3.9).

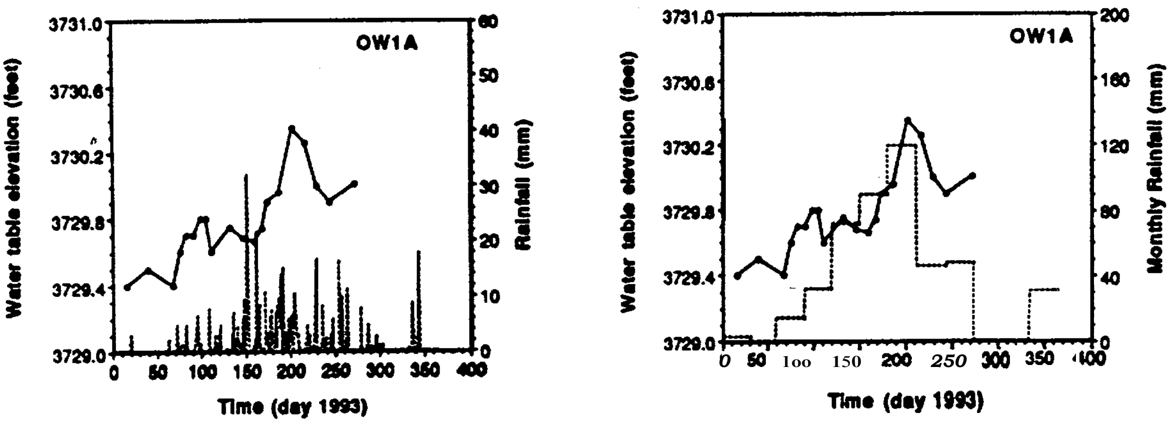



Figure 3.7. Daily and monthly rainfall and water table elevation at well **OW1** A **(Elkview** Mine) during 1993.

For the piezometer nests where one well is terminated in the clayey-till and the other in the coal pile, the data suggest the presence of a perched water table in the waste rock. The bulk hydraulic conductivity of the waste rock is estimated to be on the order of $10^{-6}$ m/s. Another possible explanation of the difference in water level elevations is a strong downward vertical flow at these sites. Note wells **OW1** A and **OW1B** are located very close to the Elk River. A vertical downward flow is not expected here, given the location of the wells relative to the river. The existence of a perched water table in this pile seems a more reasonable explanation.

Data in Tables 3.1 and 3.2 show that for some of the wells completed in the clayey-till and located in the upper regions of the pile, the water table is located. within the coal coarse refuse (wells **OW3B, 90-1, 90-2, 90-3, 90-4).** This pattern

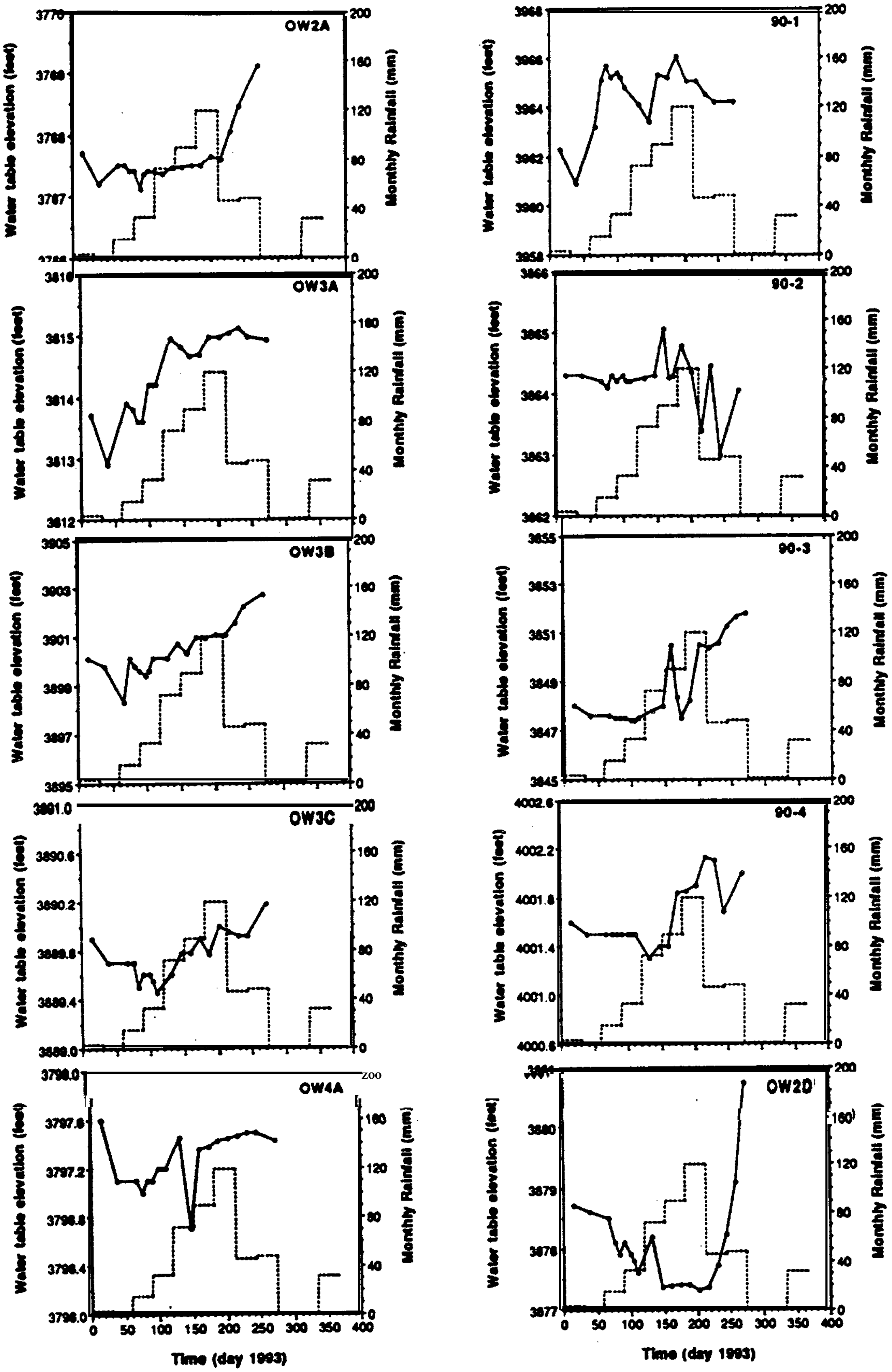



Figure 3.8. Monthly rainfall and water table elevation from wells completed in the clayey-till at Elkview Mine.

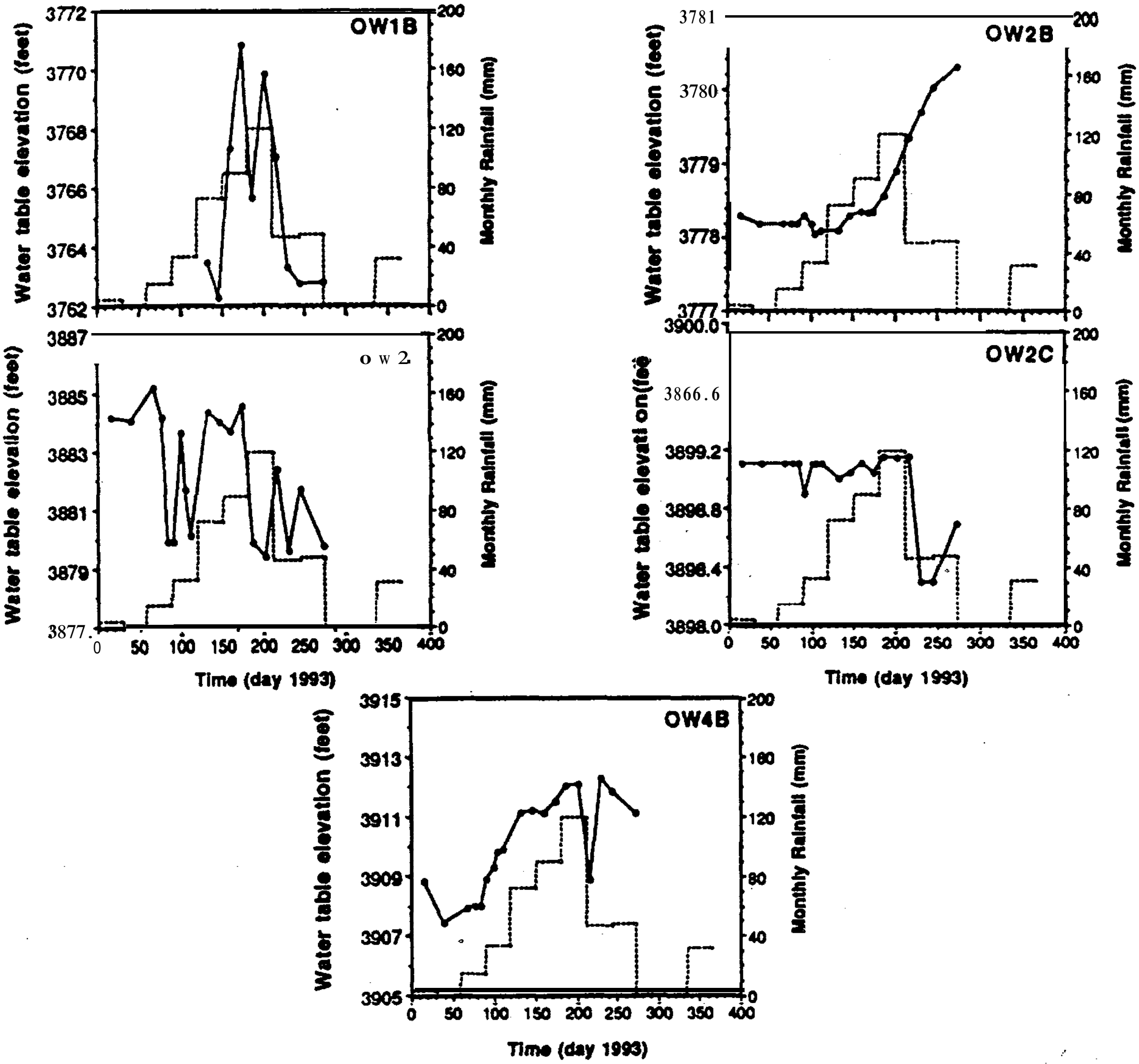



Figure 3.9. Monthly rainfall and water table elevation from wells completed in the coarse coal refuse pile at Elkview Mine.

indicates that the saturated zone is continuous in some regions of the pile (i.e. a distinct perched zone does not occur). A perched water table may be located above the main saturated zone as illustrated in the profile AA' shown in Figure 3.10 . The inferred location of the contact between the clayey-till and the waste rock, as well as the perched water table and main saturated zone are shown in Figure 3.10, using data from July 21, 1993. It is assumed that the bottom of the perched water table coincides with the contact between the pile and the clayey-till. The perched water table is thicker in the upper region of the pile and thinner close to the river. In comparison, the unsaturated zone within the clayey-till is thicker at the lower elevations near the river and disappears at higher elevations. The occurrence of perched water may be a transient feature related to construction of the waste rock pile on a low permeability till.

Figure 3.11 shows elevation contours for the contact between the clayey-till and the coal coarse refuse and contours for the regional water table elevation (or lower water table in the regions where two water tables exist). In general, the regional water table follows the shape of the original ground surface (i.e. contact between the clayey-till and the waste rock pile).

**Myra Falls Mine**

An understanding of water table fluctuations in the Myra Falls waste rock pile requires a consideration of both local infiltration and fluid input to the pile that can be attributed to its regional hydrologic setting. Northwest Geochem (1992) has developed simple calculations of the volumetric water flow within the saturated zone in Dump #1 at Myra Falls (Figure 3.3). They assumed:

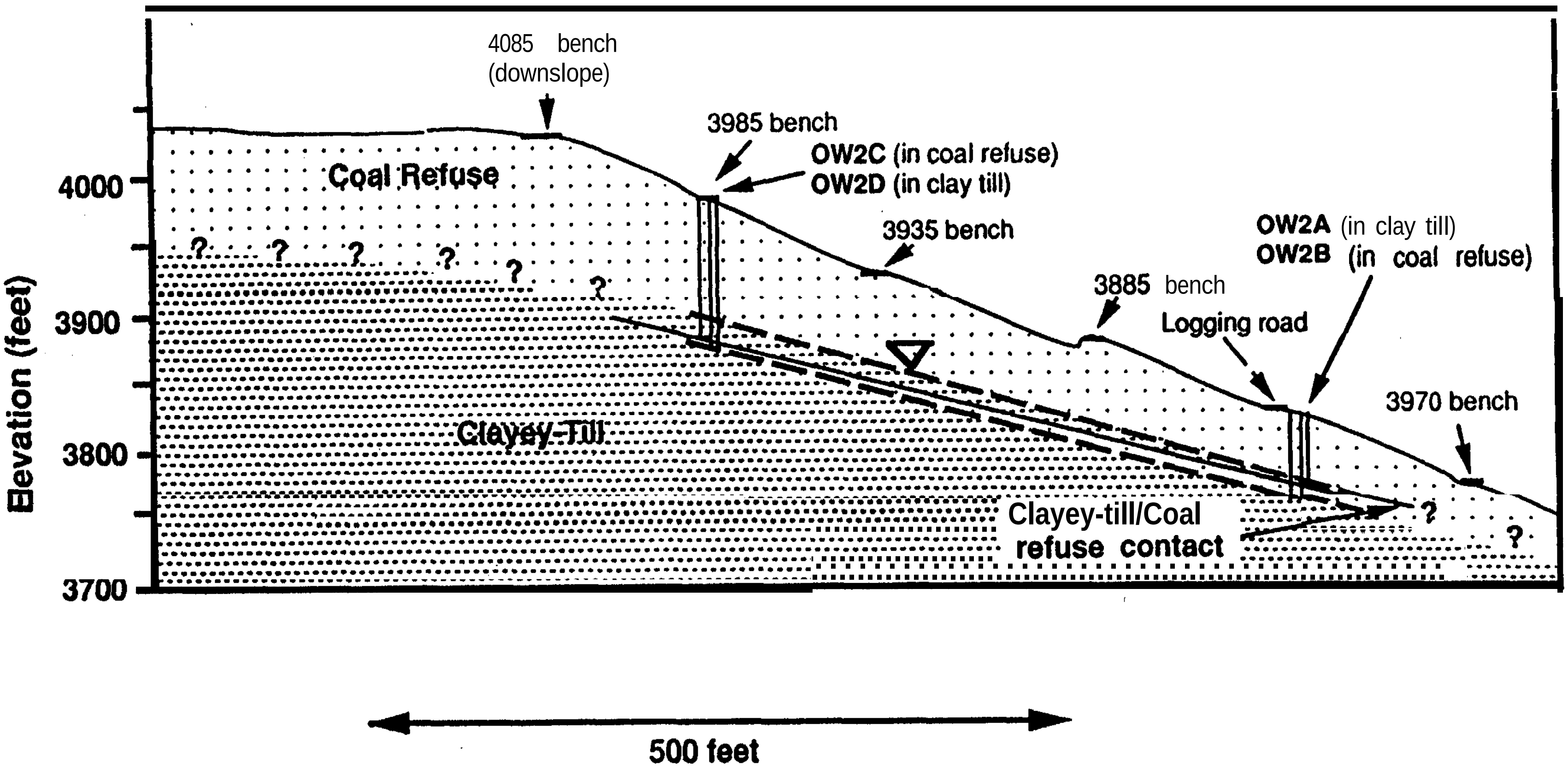



Figure 3.10. Cross section along the line connecting wells OW2C/OW2D and wells OW2A/OW2B in the north pile of Elkview Mine. Water table elevations in the wells show the formation of a perched water table in the coarse coal pile and a partially-saturated zone in the upper portion of the clayey-till.

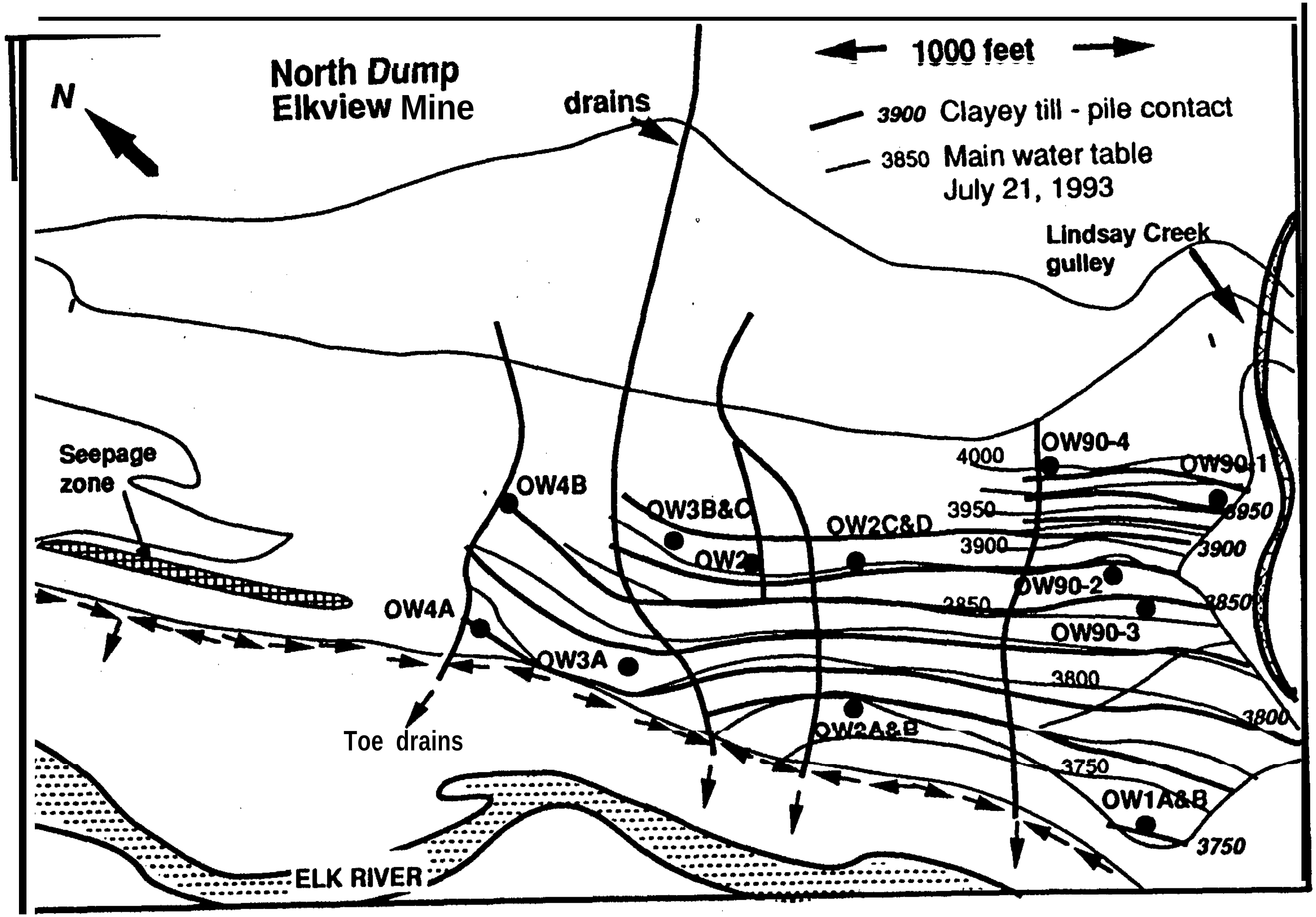



Figure 3.11. Main water table elevation and contact between the clayey-till and the coarse coal refuse pile at the north dump of Elkview Mine, British Columbia. The shape of the main water table follows the contact between the clayey-till and the pile.

a) No vertical flow within the dump,

b) A horizontal hydraulic gradient to the southeast of 0.25 based on water table elevations and the horizontal distance between the wells,

c) A width of 300 m for the southern part of the dump,

d) A vertical effective thickness for the flow of 10 m based on the depth to relative impermeable bedrock, which is 10m or more,

e) An average hydraulic conductivity of $10^{-4}$ m/s based on single well response tests which gave values ranging from $10^{-5}$ to $10^{-8}$ m/s, and

f) A 5% porosity based on the relative response of water levels to rainfall.

With these assumptions and using Darcy's equation they estimated that 6480 $m^3$/day (2,370,000 $m^3$/year) of water flows through the southern part of the dump at an average linear groundwater velocity of 43 m/day. This estimate of volumetric discharge is consistent with an estimate produced by Chorley and Smith (1983), based on measurements in the alluvial deposits downgradient from the waste rock pile. Northwest Geochem (1992) assumed an average annual precipitation of 1.5 m/year and 50% infiltration, to calculate that 3,160,000 $m^2$ of catchment area are needed to produce this flow volume. This area is 26 times greater than the lateral surface of Dump #1. They proposed that less than 10% of the groundwater flow at the base of the pile can be attributed to precipitation falling on the rock pile. The rest of the water crossing the southern portion of the dump presumably comes from the mountain massif adjacent to the pile. Alternately, it is conceivable that a significant component of this flow originates as surface runoff from the mountain, which then infiltrates the pile at its top end.

Figure 3.12 shows a schematic representation of selected piezometers, the main water table, and the location of the contact between the original ground

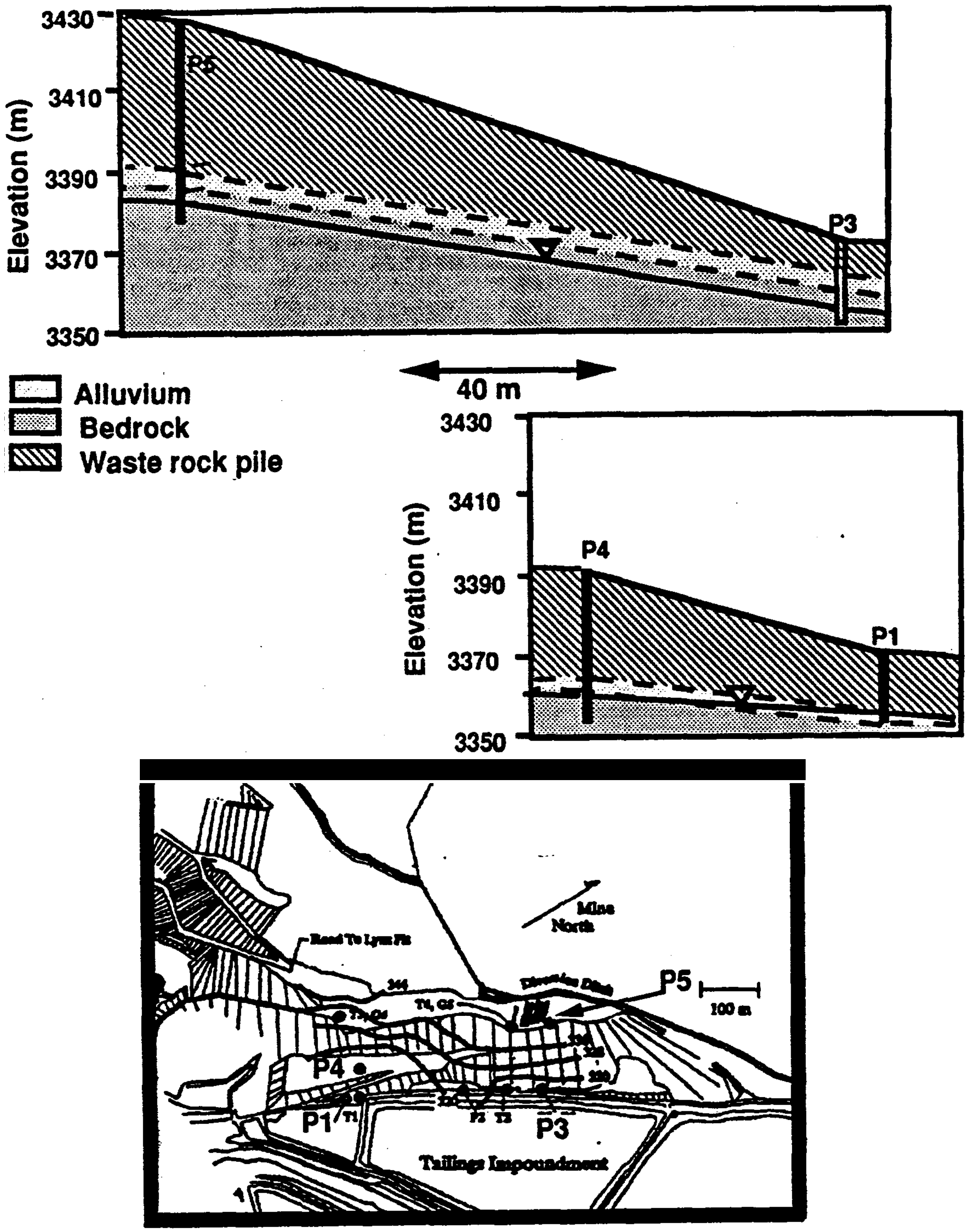



Figure. 3.12. Cross sections along the transects from piezometer P 5 to piezometer P3, and from piezometer P4 to piezometer P1 at Dump #1 , Myra Falls Mine, British Columbia.

surface and the pile. Piezometers P1 and P3 are located on the lower lift of the pile, P4 is located in the middle lift, and P5 in the upper lift. The frequency of water level measurements (every 12 hours) does not allow for a precise identification of the arrival time for the water reaching the water table. However, the frequency is sufficient to permit an analysis of the correlation between daily rainfall and water table elevation (Figure 3.13). Figure 3.13 indicates a fast response of water table elevation to rainfall events. A distinct signature of the water table response can be observed in these diagrams, depending on the location of the wells. Figure 3.14 shows amplified views of Figure 3.13 for two different time periods. In these Figures, piezometers 1 and 3 in the lower lift show sharper peaks of higher amplitude and shorter duration. If water moves vertically in the unsaturated zone, a shorter path is expected for piezometers 1 and 3 than for piezometers 4 and 5. Piezometer 5 in the upper lift shows wider peaks with smaller amplitude, and piezometer 4 in the middle lift shows an intermediate behavior.

Figure 3.14 also shows that changes in the water table elevation after the initiation of a rainfall event are detected sooner in piezometers 1 and 3 (lower lift) than in piezometers 4 and 5 (middle and upper lifts). Figures 3.13 and 3.14 indicate that only a few hours (less than one day) are needed for the initial response of the water table to rainfall events. The inflection point (change in slope of the water table elevation versus time curve) is used here to indicate the arrival time rather than the position of the peak in water table elevation. Figure 3.14 shows that the shape and position of the peak in water table elevation is clearly related to the duration and shape of the rainfall event and cannot be used properly to identify the arrival time of infiltrating rainwater.

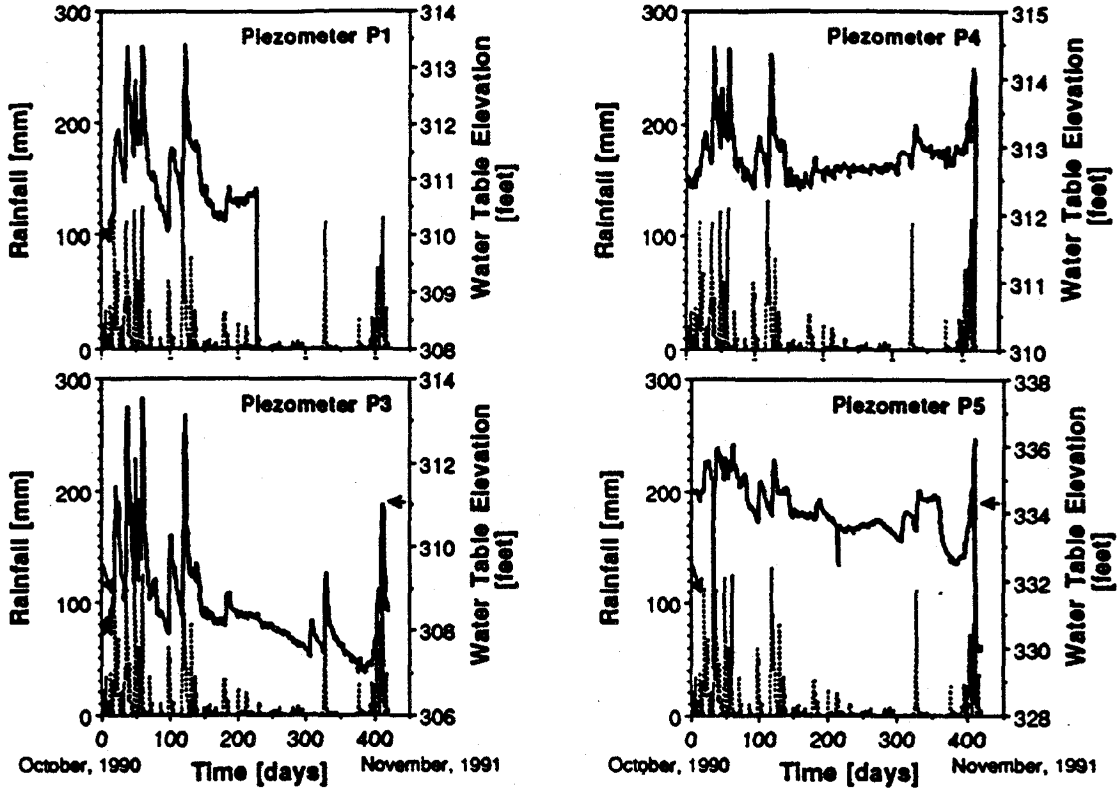



Figure 3.13. Elevation of the water table as a function of time at piezometers located in Dump #1 at Myra Falls Mine. Piezometers 1 and 3 are located on the lower lift, piezometer 4 on the middle lift, and piezometer 5 on the upper lift.

Northwest Geochem (1992) has attributed the higher amplitude water level fluctuations in the piezometers in the lower lift to the accumulation of water in the waste rock pile as groundwater moves from the valley wall to the toe of the pile. They also indicated that the higher amplitude and lower width of peaks at piezometer $P_3$ in comparison to piezometer $P_1$ suggests that permeabilities are higher in the vicinity of $P_3$ than $P_1$. Perched zones of saturation are also reported above the main water table; perched zones are likely to be a common feature in heterogeneous piles.

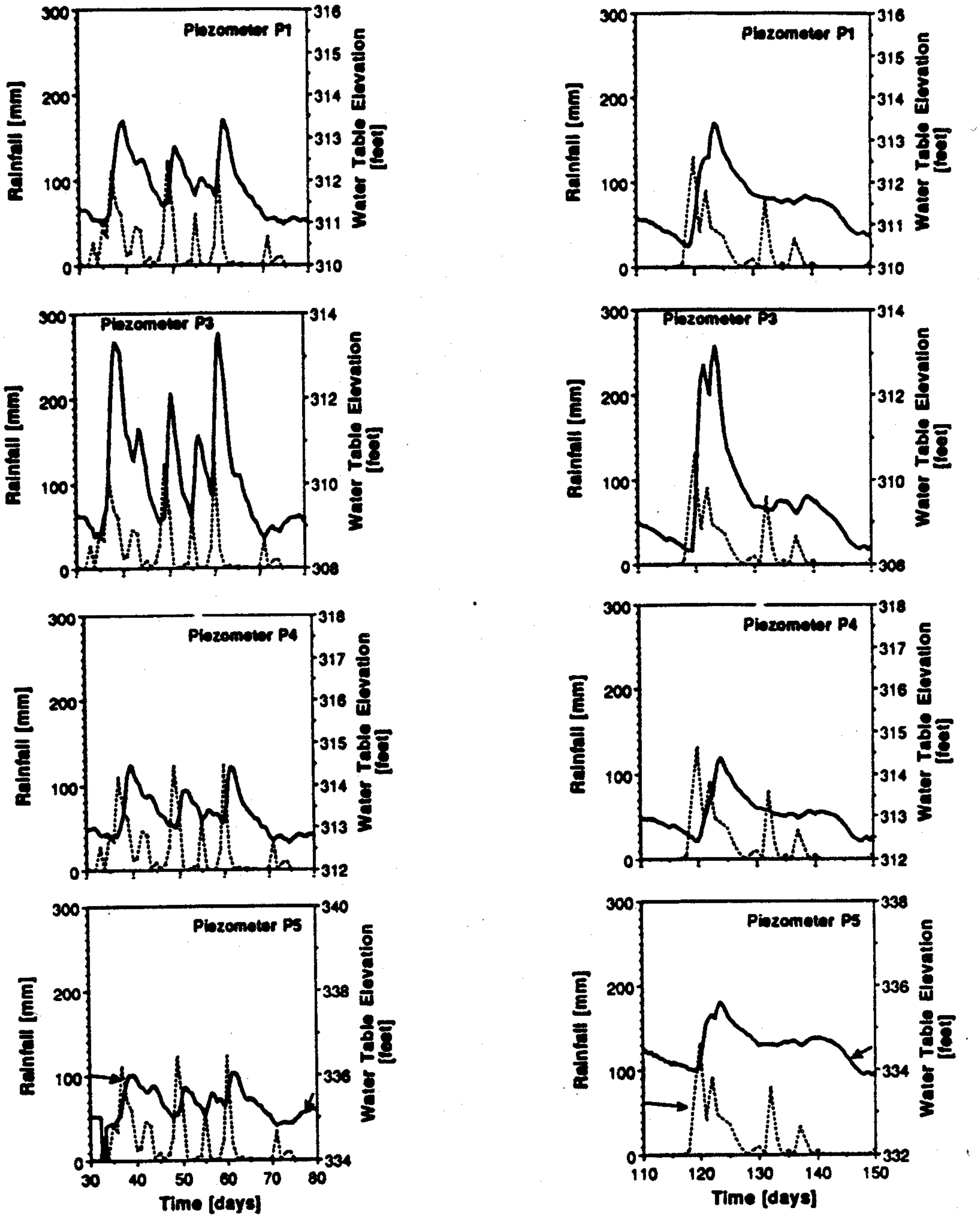



Figure 3.14. Expanded views of Figure 3.13 showing elevation of the water table as a function of time at piezometers located in Dump #1 at Myra Falls Mine. Piezometers 1 and 3 are located on the lower lift, piezometer 4 on the middle lift, and piezometer 5 on the upper lift.

### 3.4 MATRIC POTENTIAL WITHIN WASTE ROCK DUMPS

Of the four piles that we have studied in this project, measurements of matric potential (capillary suction) within waste rock piles have been made only at Golden Sunlight Mine (Schafer and Associates, 1994). Suction is higher when water content is lower. Matric potential is measured in bars, a negative sign indicating the water is held in tension. As the material increases in water content, the matric potential approaches zero. At saturation the matric potential is zero. AGWA II heat dissipation sensors have been used at Golden Sunlight to measure matric potential. The design of these sensors is based on the observation that the hydraulic properties of ceramics and soils are similar and that the thermal conductivity of ceramic is directly proportional to its volumetric water content. A heat sensor and a heat source are located at the center of a ceramic cup. The increase in temperature ($\Delta T$) within the ceramic cup is a function of the heat released to the surrounding environment and the thermal conductivity of the ceramic cup. $\Delta T$ is determined by measuring the temperature of the surrounding environment and the interior of the device. A low water content produces a low thermal conductivity and a high $\Delta T$. The AGWA II sensors are factory calibrated and equations of the form $SMP = a + b (\Delta T)$ are used in the calculation of matric potential (SMP), where a and b are calibration constants. The precision of the sensors is typically +/- 10 millibars. No sampling was implemented to verify the estimates of matric potential made using the AGWA II sensors. Matric potential was monitored at depths of 3, 5, 10, and 175 feet at site 6; at 40 feet at site 7; and at depths of 3, 5, 10, 35 and 40 feet at site 2 at Golden Sunlight Mine.

Graphs of soil matric potential and daily rainfall versus time were prepared to identify any correlations between rainfall events and increasing matric potential. In some cases a good correlation is observed (e.g. Figure 3.15 for a depth of 3 feet) and the rapid response of matric potential to rainfall is observed. Data quality is not sufficient to permit any inferences on how this correlation may vary with depth. In most instances a clear correlation between rainfall and changes in matric potential is not apparent. Some data points even show erroneous positive values for matric potential (measurements above a matric potential of zero are not plotted in Figure 3.15).

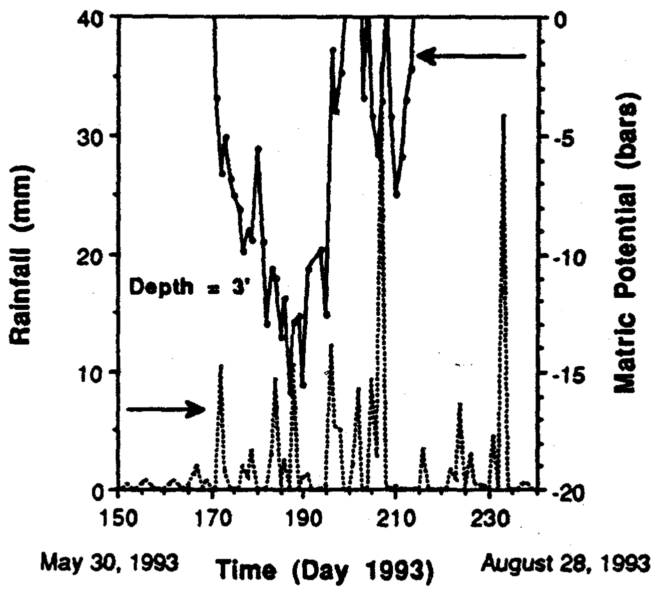



Figure 3.15. Matric potential and daily rainfall during 1993 at site 6 at the west dump of Golden Sunlight Mine.

Plots of matric potential versus ambient temperature, and matric potential and daily rainfall versus time allow the recognition of three different patterns of behavior for matric potential measurements in this pile. The first group of data points correspond to regions of the pile with low volumetric water content, with rapid increases in the matric potential when rainfall infiltrates the pile (Figure 3.15). The second group corresponds to data points that give erroneous positive measurements of matric potential. Figure 3.16 shows soil matric potential versus temperature that provides examples of these kinds of points. It is observed that the erroneous positive measurements occur in the regions of the pile that are hot because of the heat released by the sulfide oxidation reactions. Figure 3.16 suggests that the heat dissipation method used to measure matric potential does not work in the regions of the pile where heat is released by the redox reactions. The erroneous positive values for matric potential imply that heat is transferred from the pile to the measuring device because the sources of heat in the pile probably exceed the source of heat in the AGWA II sensors.

The third group of measurements occur in regions of the pile that are relatively cold, close to 0 ºC. Figure 3.17 shows graphs of soil matric potential versus temperature for examples of these kinds of data points. An almost linear trend between temperature and matric potential is observed for the points that are far from saturation. It was mentioned earlier that temperatures at site 7 indicate the existence of a frozen region in this site. The thickness of the frozen region changes seasonally. As temperature increases, ice melts and water content increases with temperature in some regions of the pile as observed in Figure 3.17. Increases in matric potential in those sites are related to melting of ice rather than infiltration produced by rainfall events. This situation is observed more clearly in Figure 3.18 for site 7 at a depth of 40 feet. The only time when matric potential and ambient temperature are not correlated is when the pile is close to saturation and matric potential is close to zero. When the pile is highly unsaturated at site 7, matric potential and ambient temperature are well correlated.

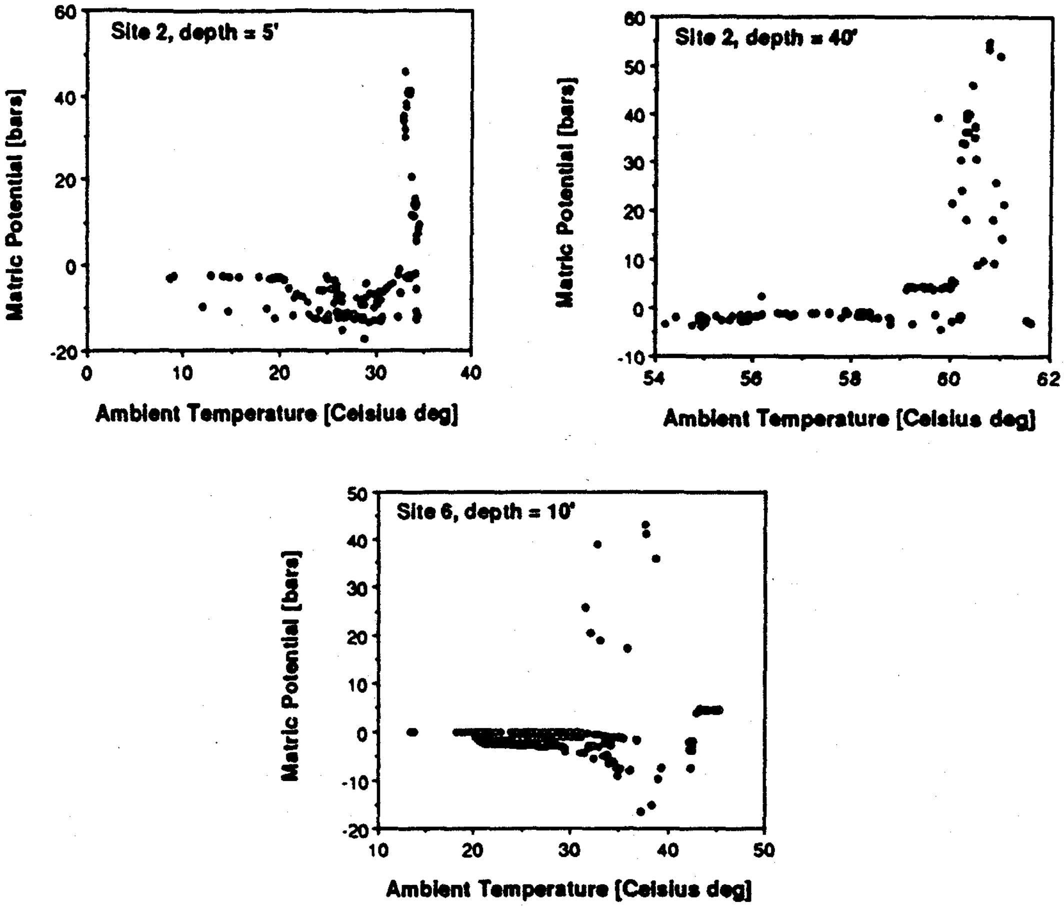



Figure 3.16. Matric potential as a function of pile temperature at selected depths for sites 2 and 6 at the west dump of Golden Sunlight Mine.

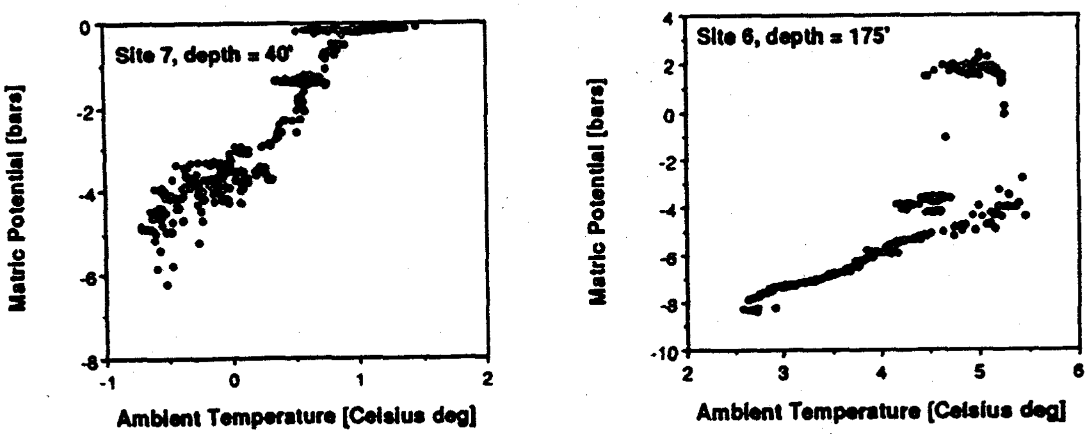



Figure 3.17. Matric potential as a function of pile temperature at selected depths for sites 6 and 7 at the west dump of Golden Sunlight Mine.

unsaturated at site 7, matric potential and ambient temperature are well correlated.

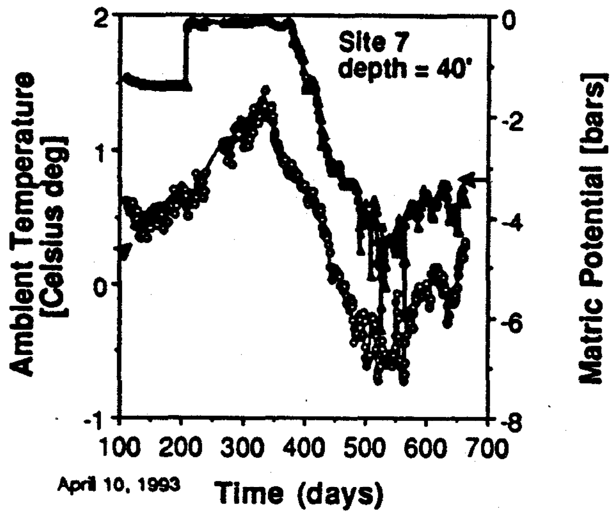



Figure 3.18. Pile temperature and matric potential as function of time, at a depth of 40 feet at site 7 of the west dump of Golden Sunlight Mine.

### *3.5 Effect of water flow on the temperature field of waste rock dumps*

The redox reactions occurring within waste rock piles are exothermic. The heat generated within the pile, as well as the chemical products of oxidation and neutralization, are transferred within the pile and out to the surrounding environment. Heat transfer mechanisms include conduction through both the rock matrix and water, and advection with moving water. In addition, other physical processes such as evaporation of water and convection of air can transfer considerable amounts of heat. Besides the internal sources of heat, atmospheric conditions at the surface of the pile play an important role in defining the heat transfer processes within the pile. The gradients of temperature which determine conductive heat transfer between the interior of the pile and the surface change seasonally. Our attention here is on the heat transfer processes associated with water movement within a waste rock pile.

The waste rock dumps at Myra Falls Mine (Dump #1) and Golden Sunlight Mine (West Dump) have data on temperature inside the pile, as well as daily rainfall and air temperature. Both data sets provide important information on the flow of water within the pile and its effect on temperature. We note again that our focus here is in using temperature measurements to better understand the hydrologic behavior of a waste rock pile, and not in the use of temperature measurements as an indicator of the potential of a waste rock pile to generate acidic water.

**Myra Falls Mine**

Variations of temperature with depth and time are observed at Myra Falls. Seasonal effects are important in these measurements because the upper boundary of the pile is subject to the seasonal changes in air temperature. Figure 3.19 shows daily air temperature and the temperature within the pile at a depth of 2 m for well T4 (see Figure 3.3). The temperature at this shallow depth follows the daily air temperature with a very small phase shift.

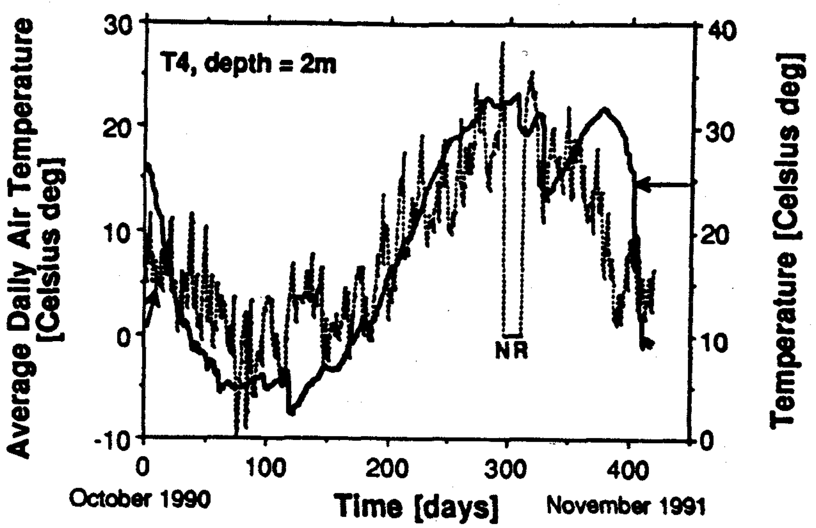



Figure 3.19. Air temperature and pile temperature at a depth of 2m at borehole T4, Dump #1, Myra Falls Mine. NR = non-registered.

Figure 3.20 shows temperatures at different depths versus time for well T4. Also included on this plot is the daily rainfall. Figure 3.21 shows similar data for wells T2 and T3. Water flow has an important effect on pile temperature if the infiltrating water passes through regions of high temperature (chemically reactive zones) such as the upper region of T4 (Figure 3.20). Two types of thermal variations can be observed in Figures 3.20 and 3.21. One is the long period sinusoidal base line defining the seasonal variations in temperature (Figure 3.19), and the other is the high frequency perturbations clearly associated with rainfall events. The seasonal variation follows the air temperature at shallow depths and becomes delayed (out of phase) and attenuated with increasing depth. At 30 m the seasonal fluctuation in temperature have been reduced to less than 1

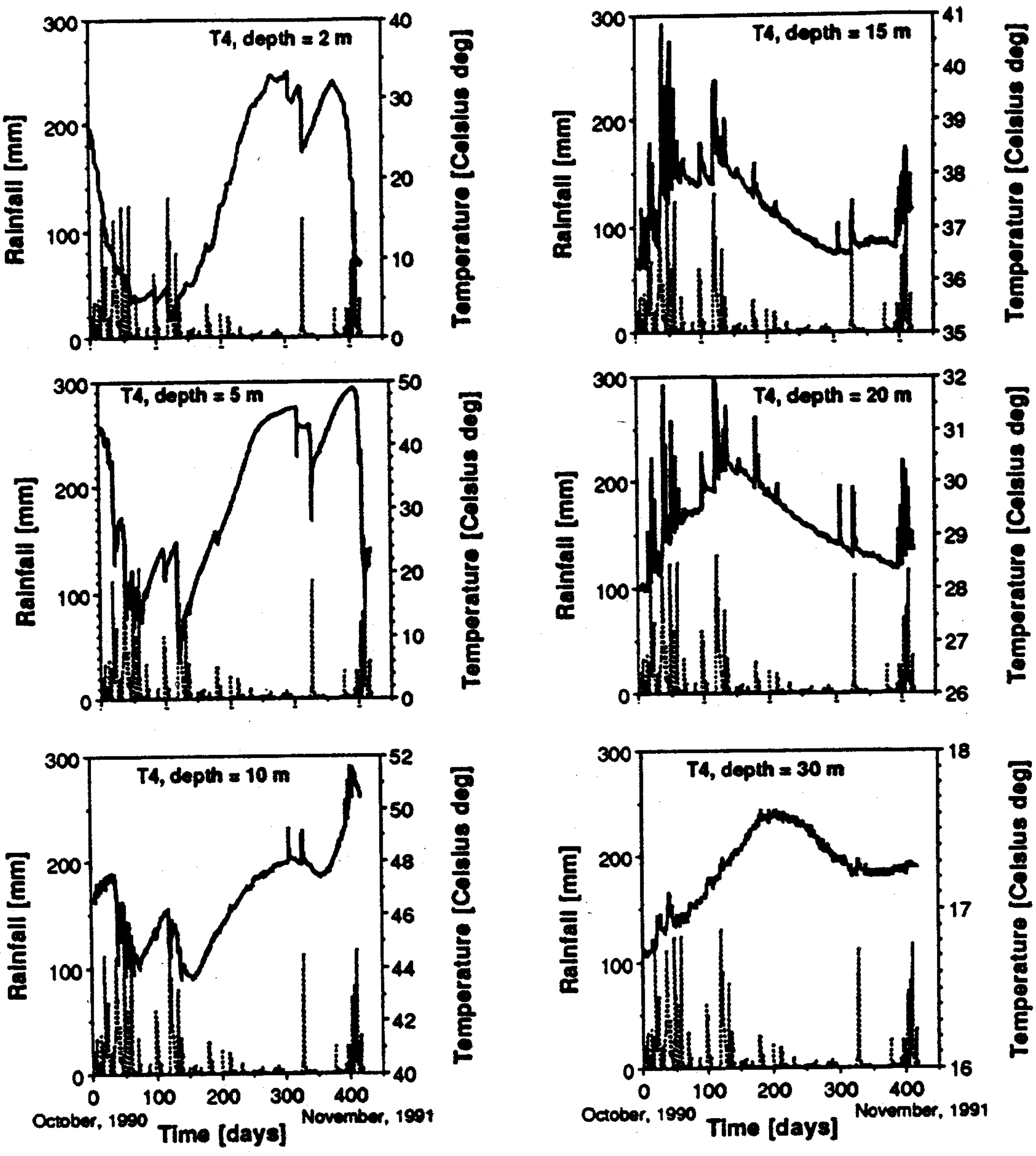
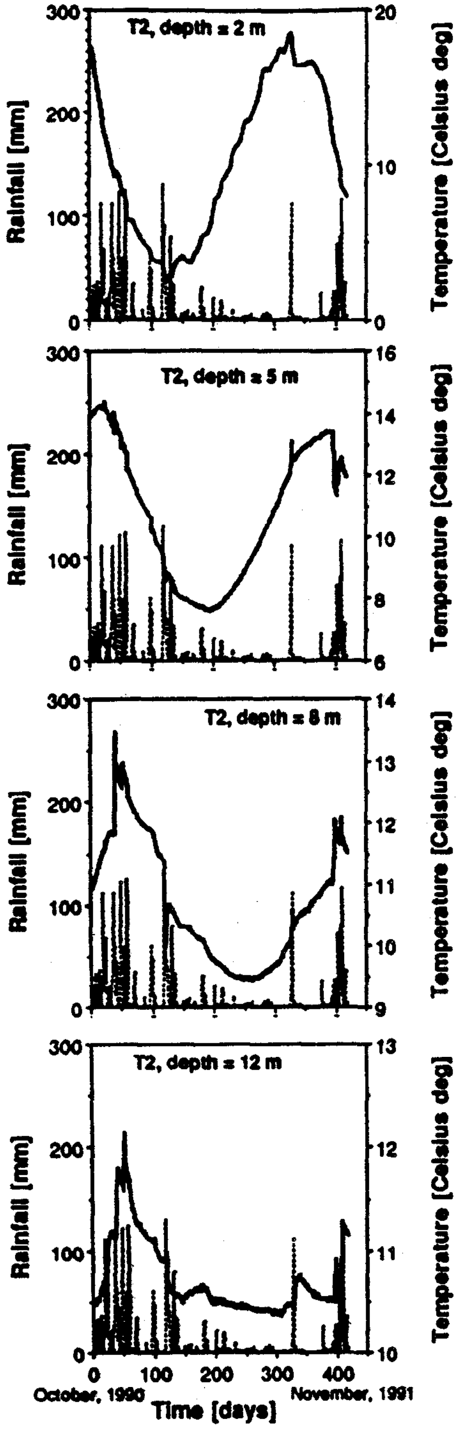



Figure 3.20. Daily rainfall and pile temperature as a function of time at borehole T4, Dump #1, Myra Falls Mine.



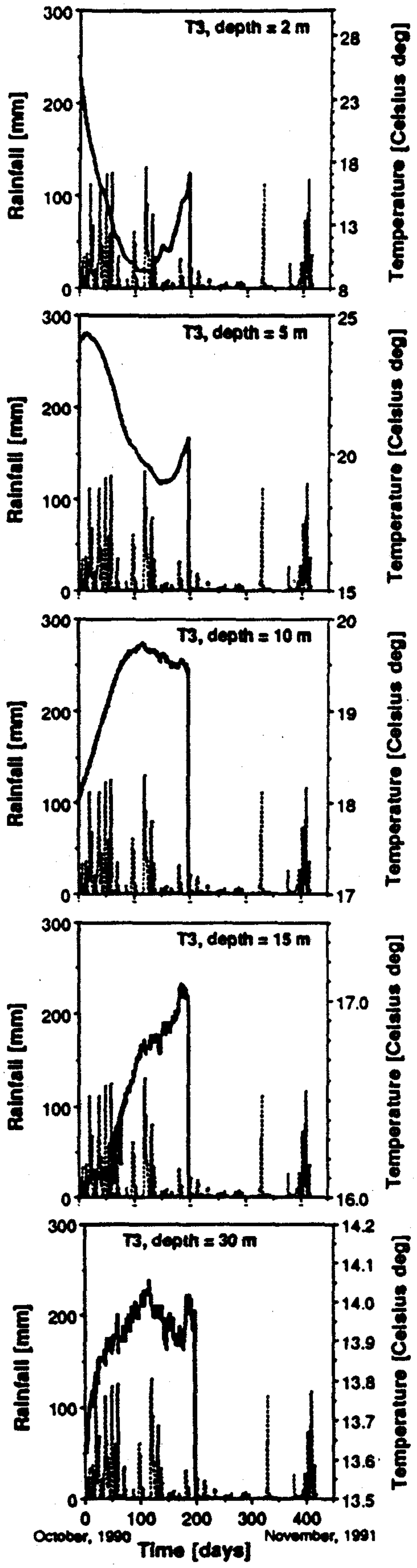



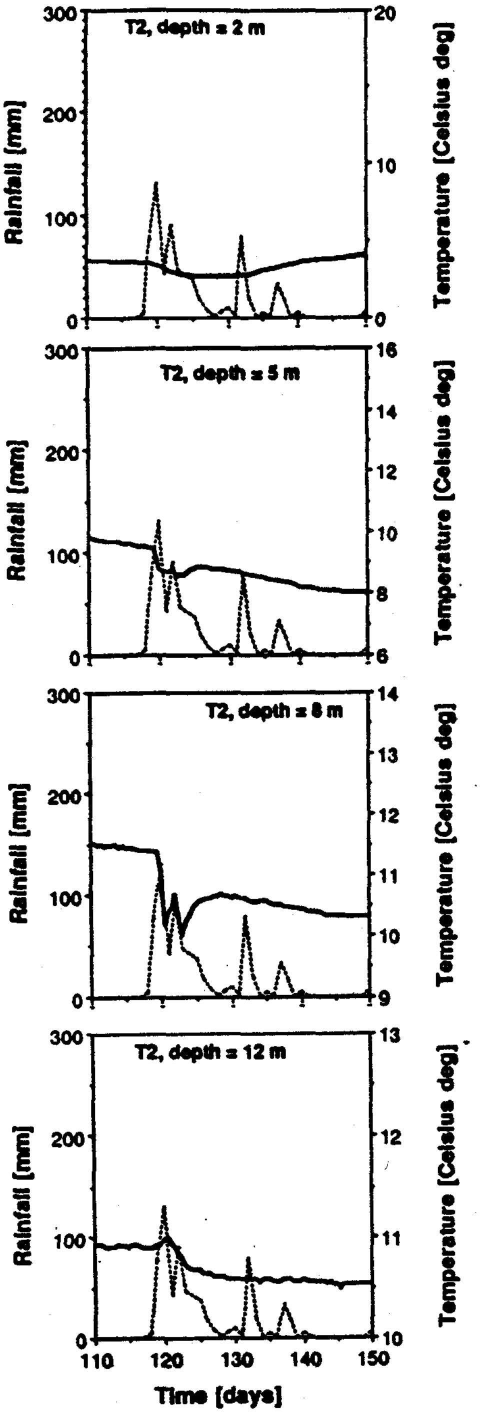

Figure 3.21. Daily rainfall and pile temperature as a function of time at boreholes T2 and T3, Dump #1, Myra Falls Mine.

degree centigrade. Because the monitoring intervals are 12 hours apart, it is not possible to identify the arrival times for the temperature perturbations associated with individual rainfall events.

Infiltration of water transfers heat from the upper and hotter regions of the pile to its lower levels. The appearance of temperature maxima and minima, corresponding to rainfall events, suggests that water velocities are high, indicating preferential flow through channels. For regions of the pile that are not hot, heat transfer by flowing water is less important (well T2), or negligible as in T3.

Figure 3.22 shows expanded views of Figures 3.20 and 3.21 on a smaller time frame. The cooling effect of infiltrating water is better observed in this figure. The depth of the cooled region depends on the volumetric water flow (which is related to rainfall and water infiltration), and the temperature of the hot region (which is related to the redox chemical reactions occurring in the zone). As shown in Figure 3.22, the variations in temperature closely follow the shape of the rainfall events. The hottest region of the pile at T4 is at a depth of about 10 m. The seasonal variations in temperature at 5 and 10 m in T4 are less well defined because the temperature of the pile in that region has been increased, probably due to either the redox reactions or to a lower cumulative rainfall during the second half of the time period.

Figure 3.20 shows that during the first half of the time interval, rainfall penetrating the pile was able to cool the pile to a depth of between 10 and 15 m. Below that depth, infiltrating water is heating the pile. During the second half of this time period, infiltrating water was cooling the pile to depths up to 10 m. For



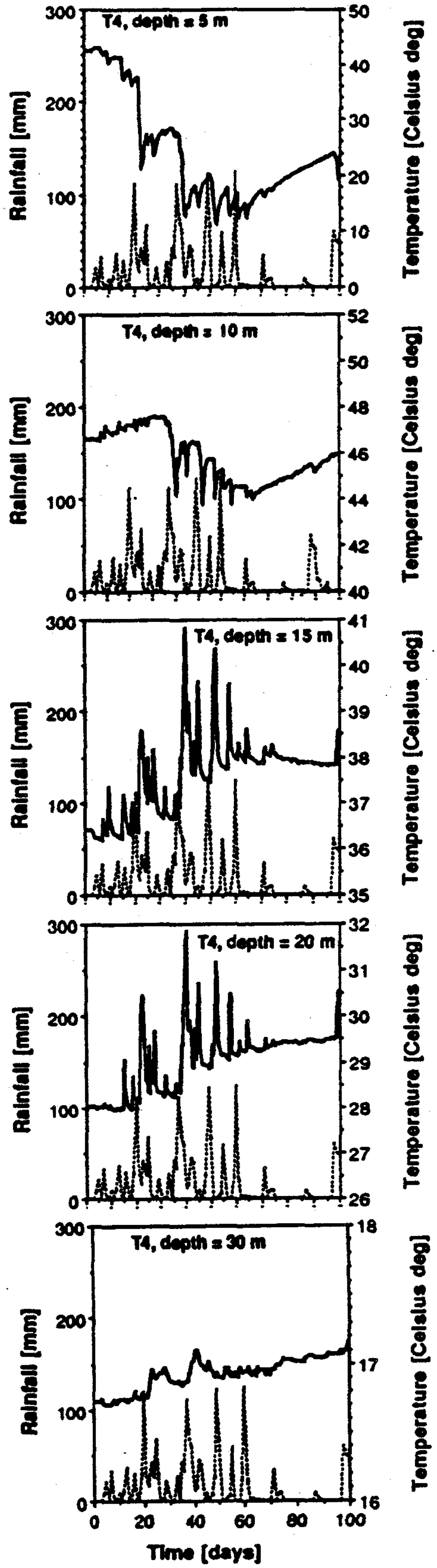




Figure 3.22. Expanded views of Figure 3.20 and 3.21 showing daily rainfall and pile temperature as a function of time at boreholes T2 and T4, Dump #1, Myra Falls Mine.

regions of the pile that are not oxidizing and have low temperatures, water flow seems to have a negligible effect on temperature (e.g. borehole T3). Figures 3.20 to 3.22 show that the response of the temperature field to infiltration events is fast, taking only a few hours. This fast response suggests that water flow occurs through preferential paths or a network of channels. However, using this data it is not possible to know how these channels are interconnected, nor how many channels may be involved along the flow path.

### Golden Sunlight Mine

The advective transport of heat at the West dump of Golden Sunlight Mine is different from that observed at Myra Falls. Figure 3.23 shows average daily air temperature and temperature at a depth of 3 feet as a function of time for site 6. Two types of perturbations of the temperature field are again observed; long period seasonal sinusoidal fluctuations and high frequency perturbations associated with rainfall events. A phase shift between the two sinusoidal curves is observed, indicating that it takes some time for the seasonal perturbation to travel from the surface to the measurement point. This behavior differs, however, from that at Myra Falls in that at Myra Falls the response of the temperature field is faster. One possible explanation is that finer, low permeability material at the top of the west dump at Golden Sunlight Mine could delay the seasonal temperature perturbation. A lower thermal conductivity in this finer and loose material should be expected.

Figure 3.24 shows the variations in temperature with time at different depths (3, 5, 10, 33, 75, and 175 feet) at site 6. Superimposed on this plot is the rainfall data for the period of time under consideration. From 3 to 10 feet, there is little fluctuations (Figure 3.23) and attenuation is low. Temperature perturbations produced by rainfall events, however, are attenuated quickly. At 10 feet the temperature perturbation produced by water flow has almost disappeared. This behavior suggests that water flow in this pile is somewhat different than at Myra Falls. It is possible that the finer material at the top of the dump in Golden Sunlight, with a greater retention capacity, precludes the rapid penetration of water to greater depths.

Fig. 3.23 Air temperature and pile temperature at a depth of 3 feet as function of time at site 6, Golden Sunlight Mine.

The measurements of temperature at site 2 have had frequent calibration problems. Figure 3.25 shows rainfall and temperature at different depths for a period of time when the temperature measurements were consistent with rainfall events. As in the previous cases, infiltrating water cools the upper region of the pile and transfers heat to a lower level.

delay in the seasonal fluctuations (Figure 3.23) and attenuation is low. Temperature perturbations produced by rainfall events, however, are attenuated quickly. At 10 feet the temperature perturbation produced by water flow has almost disappeared. This behavior suggests that water flow in this pile is somewhat different than at Myra Falls. It is possible that the finer material at the top of the dump in Golden Sunlight, with a greater retention capacity, precludes the rapid penetration of water to greater depths.

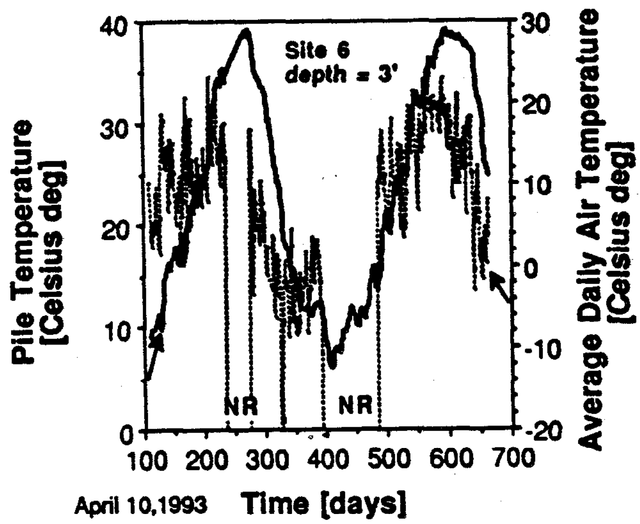



Figure 3.23. Air temperature and pile temperature at a depth of 3 feet as function of time at site 6, Golden Sunlight Mine.

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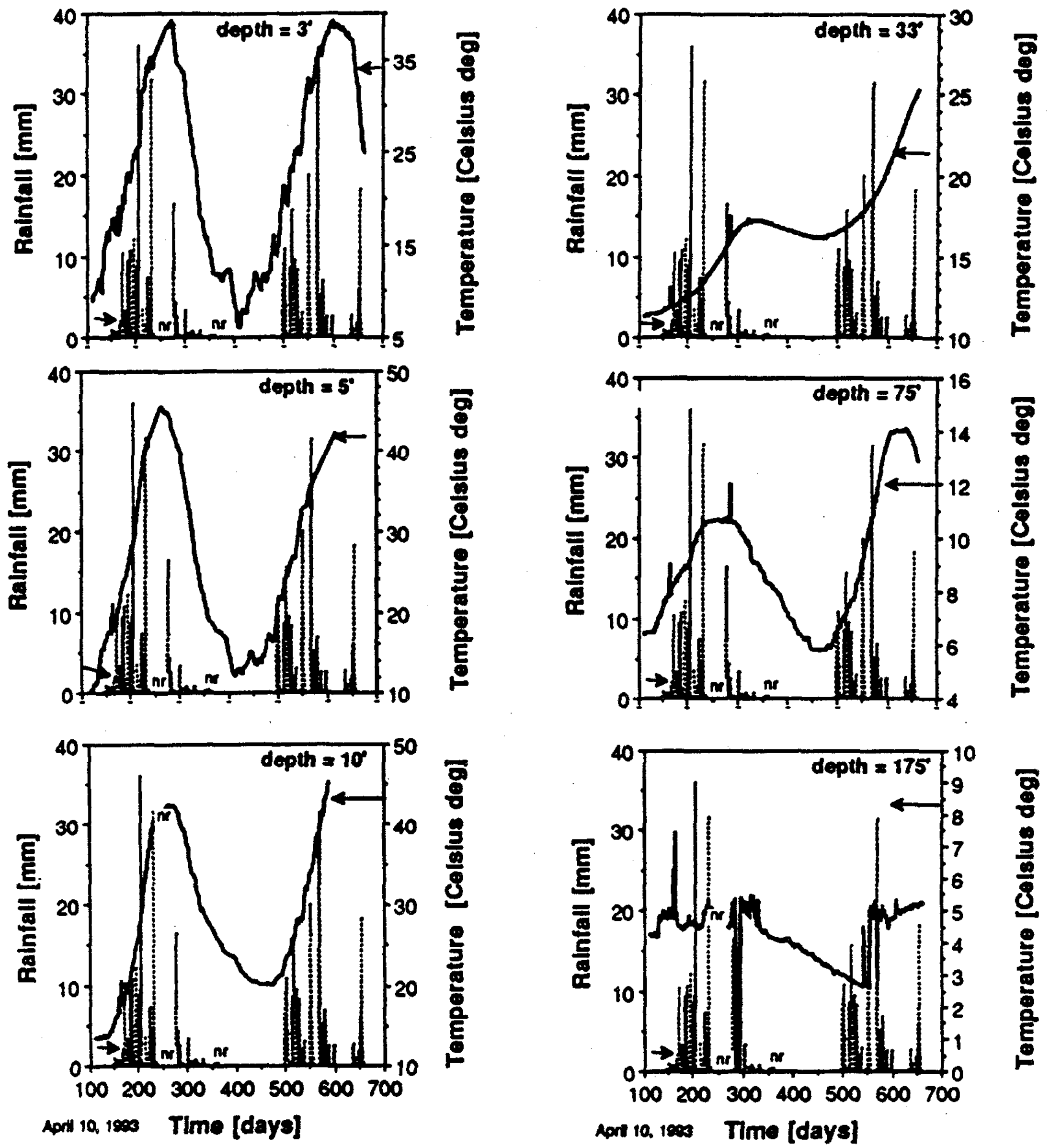



Figure 3.24. Daily rainfall and pile temperature as function of time at site 6, Golden Sunlight Mine.

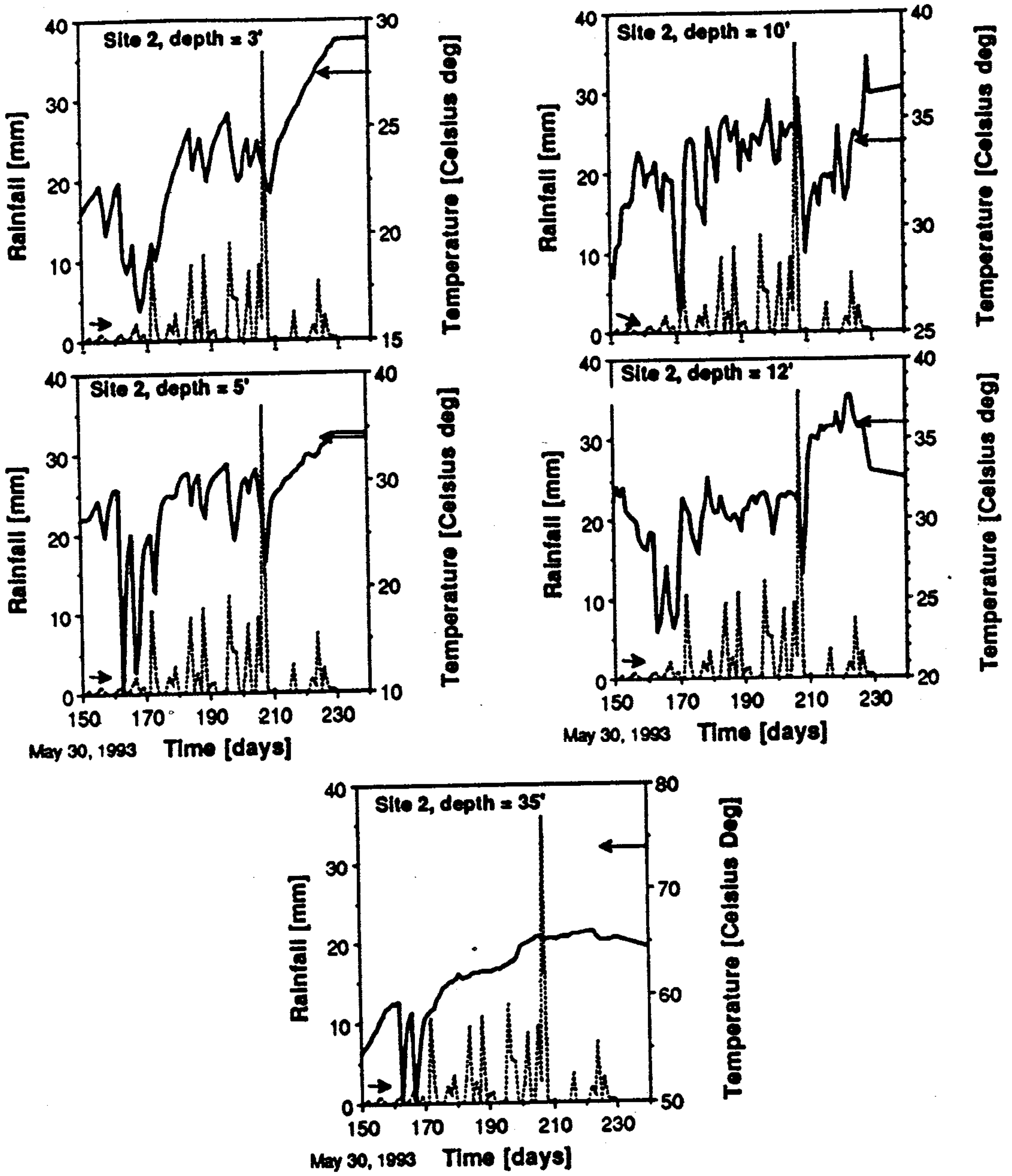



Figure 3.25. Daily rainfall and pile temperature as function of time at site 2, Golden Sunlight Mine.

The temperature field at site 7 allows us to observe a different physical process. Figure 3.26 shows the seasonal fluctuations in air temperature and the temperatures inside the pile at site 7. For most of the year, the temperature at this site is below freezing at the different depths. Only in the summer months do the temperatures rise to values slightly higher than the melting point of ice. Figure 3.27 shows the fluctuations in temperature at this site. There is little correlation between the pile temperature and rainfall events. As suggested by Schafer and Associates (1994), the frozen region in this part of the pile may not melt completely during the summer months. Melting and the formation of ice would obscure the temperature effects caused by the infiltration of water.

## 3.6 CONCLUSIONS

The hydraulic conductivity and porosity structure of a pile are difficult to identify once the pile has been constructed. Even if the grain size distribution is recorded when the material is placed on the pile, compaction and crushing during pile construction will change the original textural properties of the pile, reducing the porosity and increasing the proportion of fine grains. Our observations at the west dump of Golden Sunlight Mine indicate that water content in waste rock piles is closely associated with the textural properties of the pile. Water content can be used as an indicator of zones of low and high porosity to scan the pile hydrostratigraphy. To verify this dependence, and to better quantify the relationship, measurements should be obtained during a pile disassembly experiment (see Chapter 6).

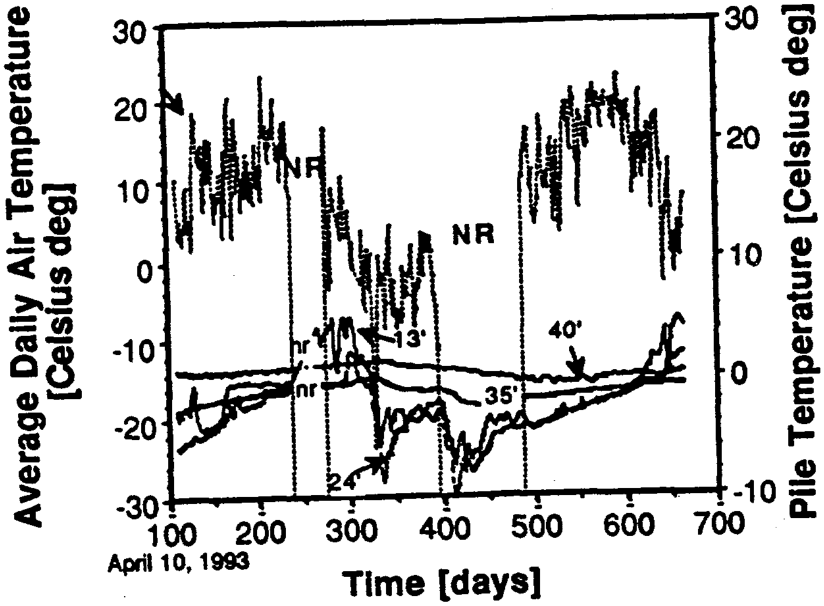



Figure 3.26. Air temperature and pile temperature as function of time at site 7, Golden Sunlight Mine.

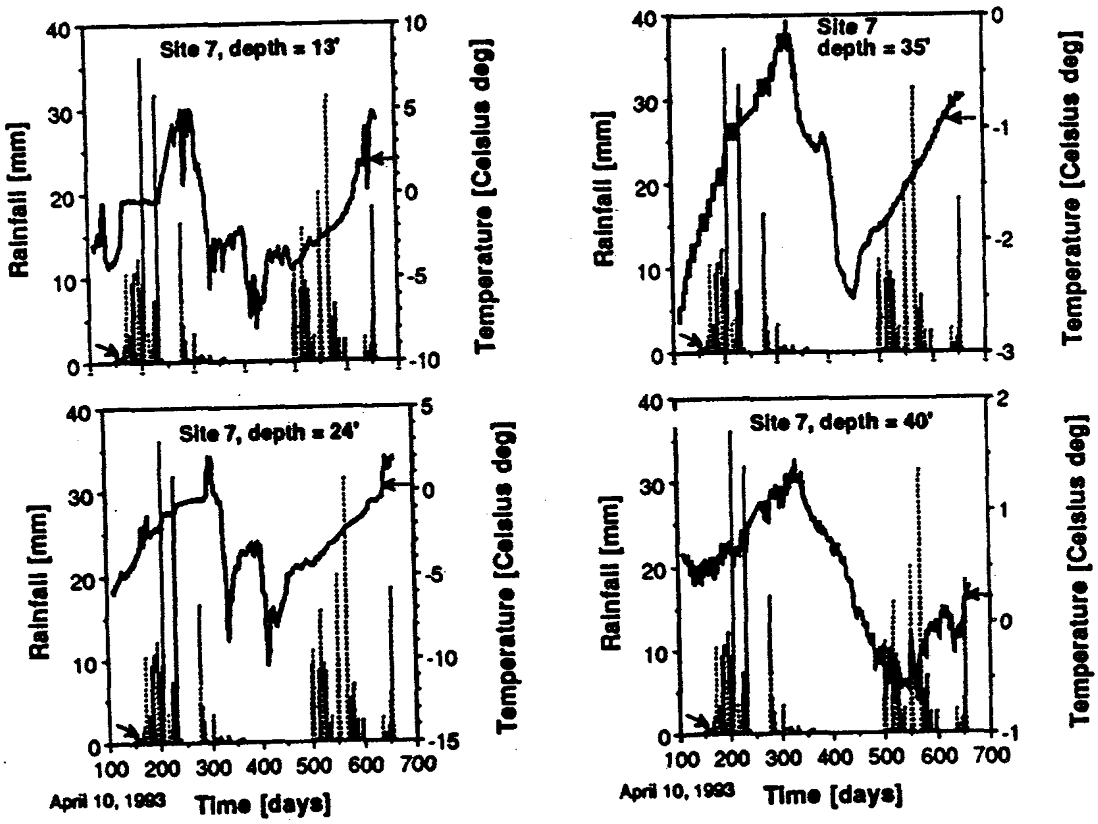



Figure 3.27. Daily rainfall and pile temperature as function of time at site 7, Golden Sunlight Mine.

In piles where a water table exists at the base of the pile, monitoring of water table elevations and their response to rainfall events could provide important information about the hydraulic conductivity structure of the pile. The observed response of the water table appears to be affected by the hydraulic conductivity structure of the pile, the position of the piezometers within the pile (upper region, slope, and toe of the pile), and the regional configuration of the water table.

AGWA II sensors (or similar equipment) can be used to monitor matric potential in regions of the pile with a granular porous matrix, and where the pile is not reactive. Heat dissipation methods are not appropriate for measuring matric potential in regions of a waste rock pile that are reacting and producing acid rock drainage. Matric potential measured with AGWA II sensors correlate well with rainfall events only when the pile is highly unsaturated and the measuring site is not close to reactive zones or to frozen regions of the pile. Near reactive zones, the heat generated by the redox reactions interferes with the heat released by the measuring device. Near the frozen portions of the pile, melting of ice when temperature increases produce increased water content and higher matric potential. During the times that portions of the pile are closer to saturation (matric potential close to zero), the matric potential measurements do not provide a clear indication of the infiltration of water.

Temperature appears to be one of the more reliable parameters to trace the movement of water within the pile in the regions of the pile that are reactive and generating heat. When water infiltrates the pile, heat is transferred from the pile to the water and transported with it to the lower levels of the pile that are colder. The data proves evidence to support, but not demonstrate, the concept of rapid movement of water through the partially-saturated zone of waste rock piles. Sampling frequencies were not adequate to develop precise estimates of water velocity. If the pile is not reactive and has low temperature, flowing water was not detected with temperature measurements because there is not a large difference in temperature between the rocks and the flowing water.

At Golden Sunlight Mine, measurements of temperature, water content, and matric potential at the toe of the pile (site 7) indicate that portions of the pile can be frozen. Ice might have been trapped inside the pile at the time the pile was constructed. It is unknown to what extent this frozen zone can be viewed as a permanent feature of the waste rock pile. Most high altitude regions of British Columbia may be subject to colder winters, and cooler summers, than at Golden Sunlight Mine. As a consequence, the formation and melting of ice in waste rock piles located in the interior of British Columbia could be also an important hydrogeological process. However, as every pile has its own physical and chemical properties, and is constructed in a particular way, temperature measurements inside the pile at different times during the year are needed in order to identify possible frozen regions.

# CHAPTER 4

## LARGE-SCALE HYDROGEOLOGICAL PROCESSES IN WASTE ROCK PILES

The focus in this chapter is on the relationship between the volumetric flow and chemical composition of the water that discharges from the toe of a waste rock pile, and the hydrogeological processes occurring within the pile. Using kinematic wave theory, we characterize infiltration through a coarse waste rock pile as flow through a channel system surrounded by a partially-saturated, porous matrix.

### 4.1 Physical Processes: Channelization and water discharge through coarse waste rock

In the previous chapter, fluctuations in water table elevations were observed to correlate with rainfall infiltration events. In a similar way, fluctuations in the volume of water discharging at the toe of a pile are expected to correlate with rainfall. The monitoring data for waste rock piles at Island Copper Mine in British Columbia illustrates that correlation ( Figure 4.1). Water discharged from this pile responds relatively quickly to rainfall events. The internal response of the system (water table elevations) and the overall response (volumetric water discharge) should be determined by the types of fluid flow regimes operating within the waste rock pile. In this chapter, we explore the possibility of extracting information about the internal hydraulic structure of a waste rock pile by analyzing the overall response of the system to rainfall events. The transient response in the volume of water discharging at the toe of the pile may give us insight to processes occurring inside the pile.

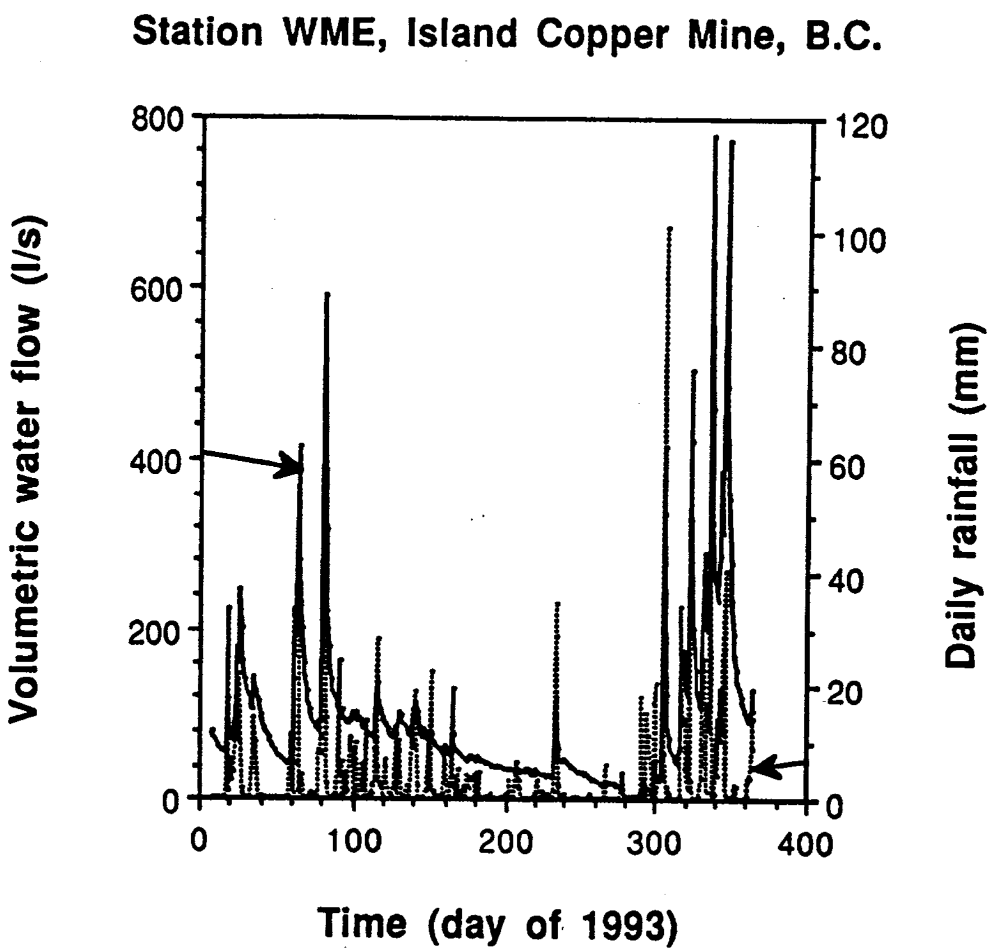



Figure 4.1. Rainfall and water discharged at station WME, Island Copper Mine, British Columbia. Data from 1993.

Water flow inside waste rock piles has been treated previously as water flow through a porous medium, for example at Rum Jungle in Australia (Pantelis and Ritchie, 1991) and Mine Doyon in Quebec (Lefebvre, in press). However, the data sets that we analyzed in Chapter 3 do not support a porous flow model for highly heterogeneous, coarse piles. The rapid response of the temperature field and water table elevation to water infiltration events suggests preferential flow through channels within waste rock piles. Turbulent water flow within rockfill embankments has been modeled using a modified Darcy equation with the permeability assumed to be a function of the flow gradient (Kells, 1993). However, this approach does not yield any insight to the distribution of channels in the system. Recently, Eriksson and Destouni (1994) have proposed a stochastic-advective approach to model field-scale transport of weathering products within a waste rock pile. They have assumed unimodal and bimodal distributions for the residence time of water within the pile, reflecting the occurrence of preferential flow paths. Their theoretical results suggests that preferential flow paths are important in determining peak concentration values and the duration of the solute discharge.

A number of authors have observed that water flow in waste rock piles occurs preferentially through channels and voids (e.g. Harries and Ritchie, 1983). A literature review of preferential flow in other geological systems suggests that water flow in waste rock piles is similar to the flow of water in structured soils. Water flow occurs preferentially through macropores and channels in structured soils (e.g. Germann and Beven, 1981; Germann, 1988). While the porosity and hydraulic conductivity structure of waste rock piles is different from structured soils because the channels and voids are larger, it may be considered an end member of the hydraulic conductivity structure characteristic of waste rock piles. Consequently, as a first approximation some of the observations and experimental and theoretical methods used to describe water flow in macropores in soils can be used for waste rock piles.

Germann and Beven (1981) have proposed two modes of water flow in structured soils. Flow mode 1 occurs in the macropore and channel system. Within the macropores and channels, water moves under gravity forces alone. The upper limit of hydraulic conductivity for flow mode 1 is the hydraulic conductivity of the soil at saturation. The lower limit in hydraulic conductivity for flow mode 1 corresponds to the point where capillary forces become important in holding water in the macropores. Flow mode 2 occurs within the micropore system where capillary forces are dominant. Flow mode 2 can be described by the conventional form of the flow equation for unsaturated porous media. Water may flow in the channels and macropores somewhat independently of the hydraulic conditions in the smaller pores. The hydraulic conductivities of the macropore region can be up to several orders of magnitude higher than the micropore hydraulic conductivity.

Beven and Germann (1981) have identified different stages of water flow in a macropore (Figure 4.2). When rainfall starts, water infiltrates the dry macropore (Figure 4.2a). Flow along their walls will occur as soon as the water entering the system exceeds the infiltrability of the matrix. A rising water table forms inside the macropore region. Water slowly infiltrates the micropore region (Figure 4.2b). In this stage the water table inside the macropore is higher than the water table in the micropore region. When the macropore is full, surface runoff occurs (Figure 4.2c). When rainfall and infiltration stops at the surface, drainage of the macropore begins (Figure 4.2d). The water table inside the macropore region begins to fall. The water table can fall to elevations lower than the water table inside the micropore region. The flow in the micropore region is reversed and water flows from the micropores to the macropore (Figure 4.2e). Figure 4.2

represents a vertical macropore or channel. If the channel is not vertical, the process described above still occurs but it will not be symmetrical. The slope of the channel will affect the sorption of water from the channel to the micropore region.

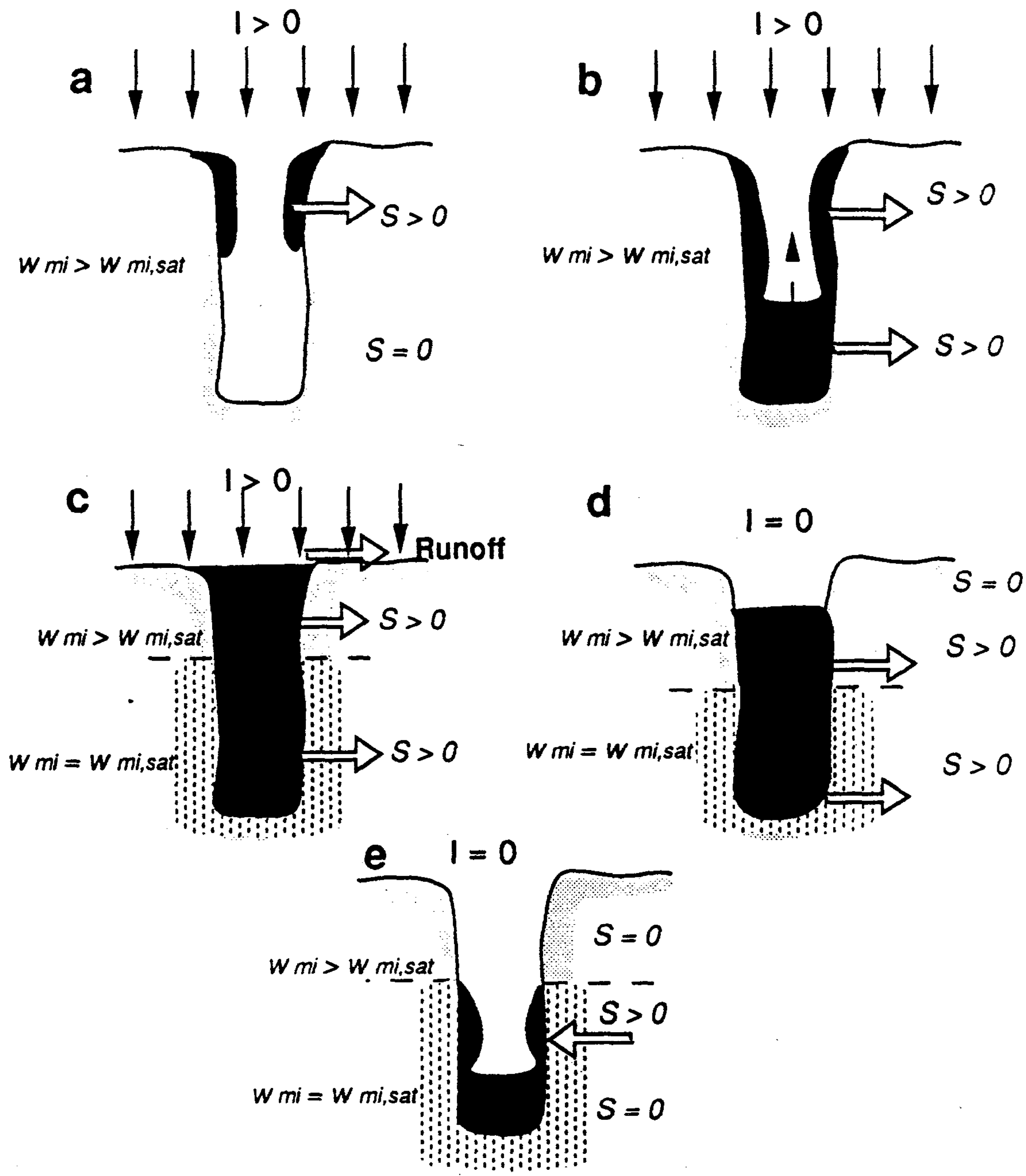



Figure 4.2. Different stages of water iinfiltration during a rainfall event within a macropore or channel. *mi* is the micropore system, *sat* is saturation, *w* is volumetric water content, and *S* is the micropore sorbance (Beven and Germann, 1981).

Water flow in soil macropores can be studied considering either saturated or partially saturated soils. Water flow in saturated structured soils was studied by Germann and Beven (1981a). They considered the flow of water in saturated channels embedded in a low permeability matrix. Saturated, unconfined, laminar flow due to gravity forces occurs in a system of $n$ vertical cylindrical pores distributed over a cross-sectional area $A$ ($m^2$). Water flow occurs only through the channels. $Q_{ma}$ is the saturated volume flux density of water or specific discharge (m/s), defined as $n$ times the volume flux of water ($m^3/s$) discharging from each channel per unit area. The saturated volume flux density of water through the macropores $Q_{ma}$ is given by

$$Q_{ma} = \frac{r_w g A}{8mpn} e^2 \qquad (1)$$

where $_w$ is the density of water ($kg/m^3$), is the dynamic viscosity of water (kg m $s^{-1}$) and $e$ is the porosity of the macropore system. A similar expression can be found if a saturated crack or channel of width D is considered. Experimental results for soils with a pore size distribution rather than pores of uniform size (Germann and Beven, 1981a) showed that the saturated volume flux density of water through the macropores $Q_{ma}$ (cm/s) can be approximated by a relationship of the form

$$Q_{ma} = Q^* e^2 \qquad (2)$$

where the coefficient $Q^*$ is defined empirically and reflects the hydraulic connectivity, geometric structure, tortuosity, and other properties of the macropore network affecting the flow rate through the system.

Equations 1 and 2 describe the volumetric flux density for water discharging from a saturated single channel and from a saturated channel network in structured soils. If the soil is not saturated and exchange of water occurs between the micropore region and the channels, a more rigorous physical approach is needed in order to consider the sorption of water by the porous matrix. The kinematic wave approach to water flow within channels or macropores considers the exchange of water between the porous matrix and the channels during water infiltration events.

## 4.2 Kinematic wave approximation to water flow within waste rock piles

Kinematic wave theory has been applied to structured soils to describe water movement within channels and macropores (Germann and Beven, 1985). In this section, channelized flow in waste rock piles is approached using kinematic wave theory. Water moves within the channels and macropores by gravity alone. Capillary forces are assumed to be negligible in the channels. In comparison, flow in the partially-saturated matrix is governed by capillary forces. A mathematical expression describing water loss due to sorption by the surrounding rock matrix is included in the formulation. The equations used in our approach were developed by Germann and Beven (1986) and Germann et al. (1986). A brief summary of the equation development is presented here to explain the method.

During a rainfall event, water infiltrates the channels as described in Figure 4.2. Water flow within vertical channels occurs when the volume of water entering the channel exceeds the sorption of the porous matrix forming the walls of the channel. The next description focuses on water infiltration and flow within the channel region, assuming that the water input to the channel exceeds the sorption of water from the porous matrix. Water infiltration and flow within the channel proceeds in three stages. We assume that water begins to infiltrate the channel at $t = 0$. The duration of the rainfall infiltration event is $t_s$. In the first stage ($0 \leq t \leq t_s$), the wetting front propagates downward with a constant discharge profile behind the depth of the wetting front. The moisture profile for $t = t_s$ is shown in Figure 4.3a. In the second stage ($t_s \leq t \leq t_i$), after the rain has stopped , there is the propagation of a draining front and the development of a trailing wave. An unsaturated zone forms at the top of the channel, which reaches greater depths with time, and a shrinking saturated zone travels downward (Figure 4.3a). At depth $z_i$ and time $t_i$ , the draining front reaches the wetting front. In the third stage ($t_i < t <$ ), attenuation of the wetting front occurs after the wetting front has been intercepted by the draining front. Figure 4.3b shows the drainage pattern for a depth $z < z_i$ .

The mass balance equation for vertical water flow through a channel or macropore can be expressed as

$$\frac{\partial q}{\partial t} + c\,\frac{\partial q}{\partial z} - c\,s = 0 \qquad (3)$$

where $q\ (z,t)$ is the volumetric flux density in the channel (m/s), $c$ is the kinematic wave velocity (m/s), $s$ is the rate of water loss from the channel to the matrix ($s^{-1}$), and $z$ is depth (m). The kinematic wave velocity $c$ is different from the water velocity and describes the rate of change of volumetric flux density with increasing channel moisture content $w$ ($m^3$ water/$m^3$ porous space). $c$ is given by the expression $c = \frac{\partial q}{\partial w}$ .

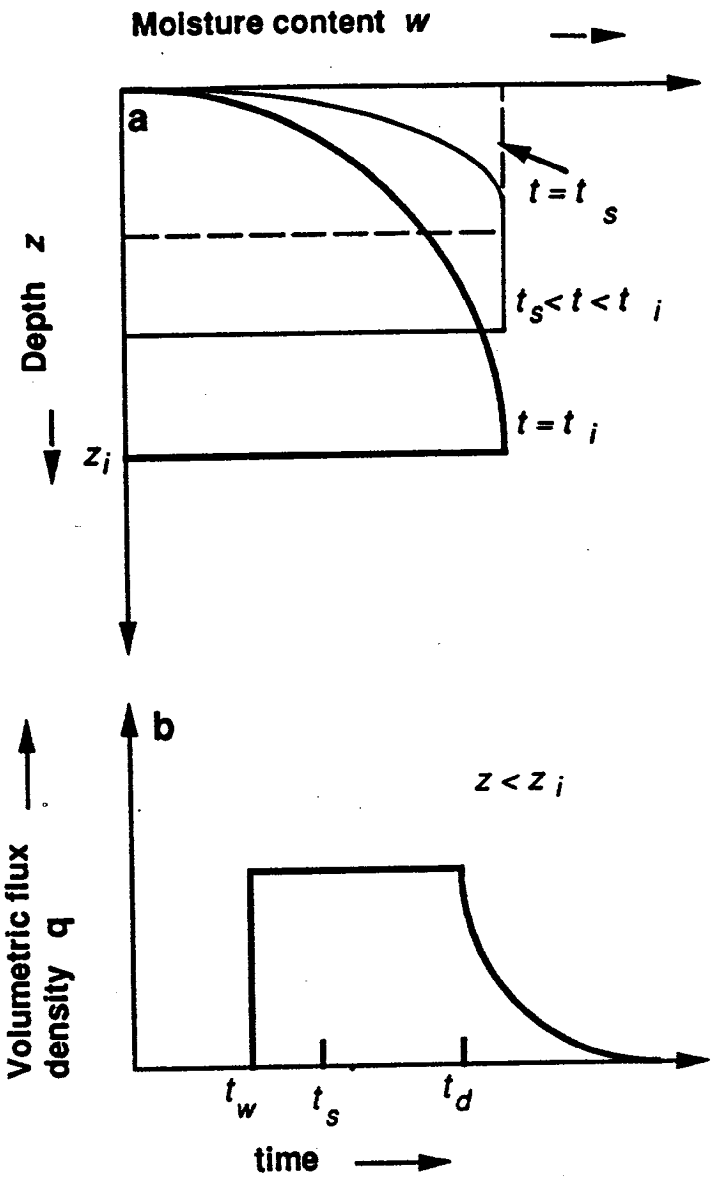



Figure 4.3. a) Moisture profile at different stages of water infiltration in a channel or macropore. b) Hydrograph at depth $z$ in a channel. $z$ is smaller than the depth of interception between the wetting and draining front after rainfall stops. $t_w$ is the arrival time of the wetting front to depth $z$. $t_s$ is the duration of the rainfall even, and $t_d$ is the arrival time of the draining front at depth $z$.

The vertical volumetric flux density under a unit hydraulic gradient (i.e. gravity-driven flow) is assumed to follow the equation

$$q = b\, w^{a} \tag{4}$$

where $b$ is the channel conductance (m/s), $w$ is the channel moisture content, and $a$ is a dimensionless exponent.

The rate of water loss $s$ from the channel is described by the function $s = r\, w$ where $r$ is the matrix sorbance given by

$$r = \frac{1}{w}\frac{\partial w}{\partial t} = \frac{1}{a\, q}\frac{\partial q}{\partial t} \tag{5}$$

The kinematic wave velocity is also defined by

$$c = \frac{\partial q}{\partial w} = a\, b^{1/a}\, q^{(a-1)/a} \tag{6}$$

If a square pulse of duration $t_S$ and volume flux density $q_S$ is infiltrating the surface of the pile (a rainfall event), the boundary conditions are:

$$\begin{array}{llll} t \le 0 & ; \quad 0 < z < & q(z, t) = 0 & \\ 0 \le t \le t_s & ; & q(0, t) = q_s & (7) \\ t_s \le t & ; & q(0, t) = 0 & \end{array}$$

Note that $q_s$ is not equivalent to the rainfall rate, but the rainfall rate times the area of the pile expressed in the appropriate units. Expressions for the velocities of the wetting front and the draining front have been used to deduce the following equations. The time of interception between the draining and the wetting front $t_i$ is given by the equation

$$t_i = t_S \cdot \frac{a}{(a-1)} \tag{8}$$

At a depth $z < z_i$, the equations that describe the drainage hydrograph for the channel are:

$$0 \le t \le t_w(z) \qquad q(z, t) = 0 \tag{9a}$$

$$t_w(z) \le t \le t_d(z) \qquad q(z, t) = q_S \left(1 - \frac{z}{z^*}\right)^{a/(a-1)} \tag{9b}$$

$$z^* = q_s^{(a-1)/a} \,.\, b^{1/a} \frac{a}{[r\,(a-1)]}$$

$$t_d(z) \le t \le t_i \qquad q\,(z,t) = [\, z\,.\,r.\,(\,a-1\,)\,/\,\{\,[\,e^{(t - t_s).\,(a-1)\,.r} - 1\,]\,.\,(\,a\,b^{1/a}\,)\,\}\,]^{a/(a-1)} \qquad (9c)$$

with $t_d(z)$ defined by the equation

$$t_d(z) = t_s + \frac{t_w}{a} \qquad (10)$$

In these equations $t_w(z)$ is the arrival time of the wetting front and $t_d(z)$ is the arrival time of the draining front at depth $z$ (Figure 4.3b). For a depth smaller than the depth of interception between the draining and wetting fronts $z_i$, the volumetric flux density defined by equation 9b is constant for the time span between the arrival time of the wetting front and the arrival time of the draining front. Equation 9c represents the decreasing volumetric flux density for the time period between the arrival time of the draining front at depth $z$ and the time of interception between the draining and wetting fronts at depth $z_i$.

Using equations 5 and 6 and the propagation of the wetting and draining front within a channel, the matrix sorbance r and channel conductance during the time period $t_w(z) \le t \le t_d(z)$ have been found to be:

$$r = \frac{1}{t_w\;(z)} \; ln\,[\,q_s\,/\,q\,(z,t)\,] \qquad (11)$$

$$b = [z\;(a-1)\;\; r\,/\,\{a\;[\,q_s^{(a-1)/a} - q\,(z,t)^{(a-1)/a}\;]\}]^{\,a} \qquad (12)$$

In a waste rock pile, there are many different types of channels, rather than a single channel type. The channel system will have a complex pattern of different sizes, shapes, depths, and orientations. Fluid exchange occurs between the different types of channels within the pile. We simplify the complexity of the system by assuming that the pile is formed by multiple independent channels of unknown geometry. In our model (Figure 4.4), each channel group is characterized by a conductance $b_j$ and a fraction of the surface area of the pile. Water flow within the different channels is described by equations 3 and 4, and the different flow stages are described by equations similar to equations 8 to 12. The exponent $a$ and the matrix sorbance $r$ are assumed to be constant for all channel systems. Water flowing vertically through the channels in the pile is assumed to accumulate at the bottom of the pile and to be discharged at the toe of the pile. It is assumed here that there is not mass or energy loss when water moves horizontally at the bottom of the pile. In addition, the lapse of time for the water to flow from the bottom of the channel to the toe of the pile is very small in comparison with the time for the water to flow through the length of the channel. The schematic drainage hydrograph produced at the pile toe is illustrated in Figure 4.5. It is generated by superimposing the individual hydrographs of the *n* channel groups forming the pile. We divide the pile in *n* channel groups of conductance parameter $b_j$. . The volume flux density at the base of the pile is given by

$$q\,(z,t) \;=\; \sum_{j=1}^{n} A_j\; b_j\, w_j\;(z,t)^{a} \qquad (13)$$

$$\sum_{j=1}^{n} A_j \;<<\; 1.0$$

where $A_j$ are probability weights for the relative abundance of each channel group. These parameters can be considered as fractions of the surface area of the pile supplying water to the *jth* channel group. However, in a real pile, the different channel groups are interconnected within the pile and $A_j$ cannot be given a complete physical interpretation.

For the different channel groups equations 10 to 12 take the following form during the time period ( $0 < t < t_i$ ):

$$r = \frac{1}{t_{w\,j}\;(z)}\;\; ln\;[\,q_s\,\frac{DA_j}{Dq_j}\,]$$

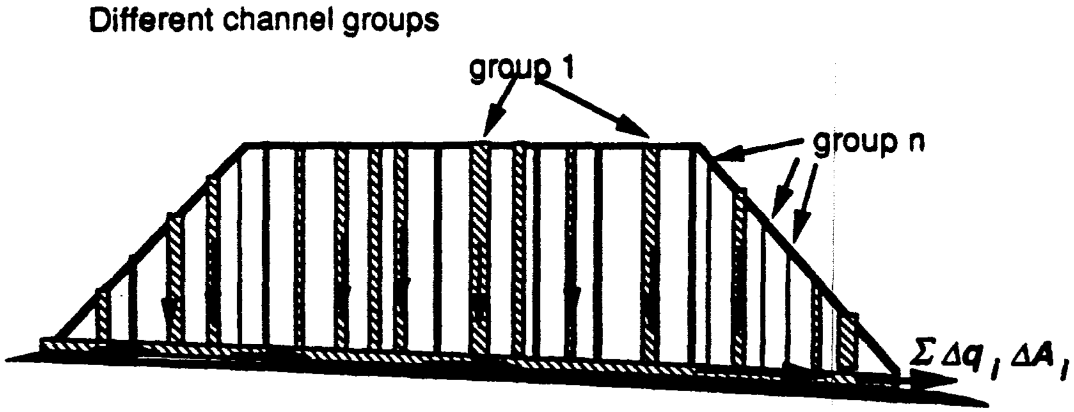



Figure 4.4. Conceptual model of groups of channels in a waste rock pile. Water moves vertically within each channel and it is accumulated at the bottom of the pile where it moves horizontally to be discharged at the pile toe.

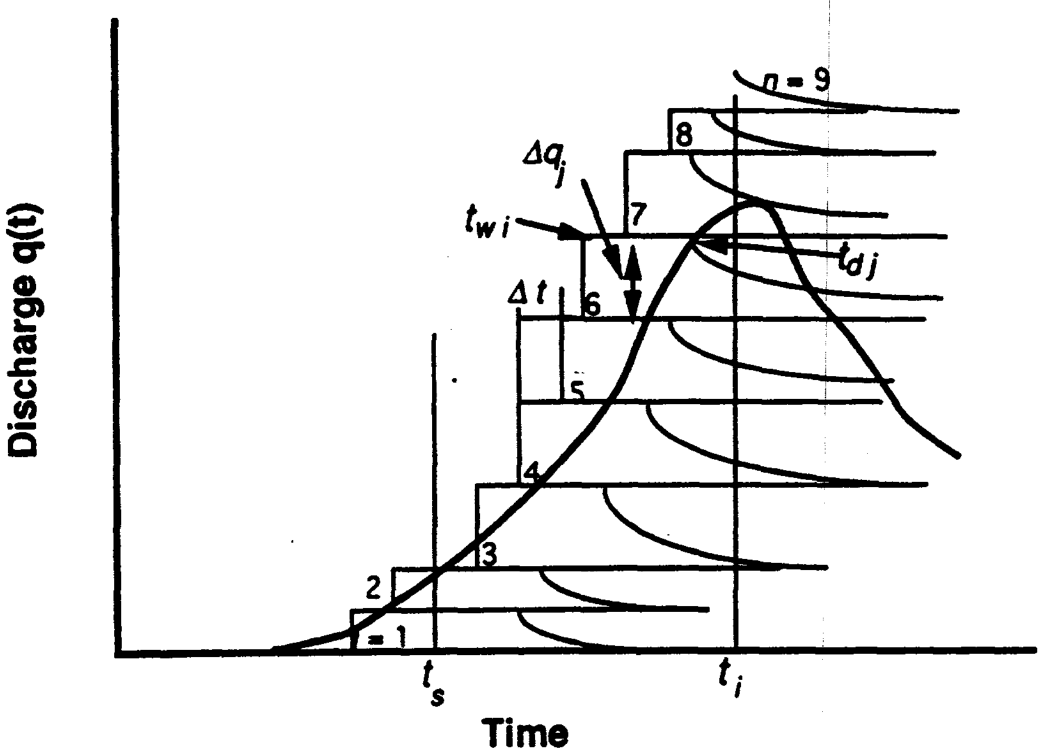



Figure 4.5. Drainage hydrograph formed by superimposing the hydrographs of the different channel groups found in the preferential flow system (after Germann and Beven, 1986).

$$\text{or} \quad ln(A_j) = r\, t_{w,j}(z) - ln(\frac{q_s}{Dq_j}) \qquad (14)$$

$$b_j = [z\,.\,(a-1)\,.\,\frac{r}{a}\,.]^{a}\;.\;[\,q_s^{(a-1)/a} - (\frac{Dq_j}{DA_j})^{(a-1)/a}\,]^{-a} \qquad (15)$$

$$t_{d,j}(z) = t_s + \frac{t_{w\,j}}{a} \qquad (16)$$

where $q_j$ is the incremental volume flux density from channel group $j$ (Figure 4.5) and $z$ is the average elevation of the pile. The conductance $b_j$ can be divided by $z^a$ to produce a new ratio. This ratio is independent of our estimation of the average elevation of the waste rock pile:

$$\frac{b_j}{z^{a}} = [(a-1)\,.\,\frac{r}{a}\,.]^{a}\;.\;[\,q_s^{(a-1)/a} - (\frac{Dq_j}{DA_j})^{(a-1)/a}\,]^{-a} \qquad (17)$$

The drainage hydrograph produced at the toe of the pile can be divided into $n$ different arrival times $t_{w,j}$ for the $n$ different channel groups. $q_j$ for each channel group can be determined from the hydrograph as illustrated in Figure 4.5, and the distribution of areal weighting factors $A_j$ and ratios of channel conductance $\frac{b_j}{z^a}$ can be found using equations 14 and 17.

A computer program has been written to estimate the distribution of areal weighting factors $A_j$ and $\frac{b_j}{z^a}$ ratios. The outflow hydrographs are interpreted to be the result of superimposed flows discharging from the different groups of channels. The measured hydrograph is discretized and the end of each time interval is interpreted as the arrival time of the flow discharged from a channel group. The smaller the time intervals, the larger the number of channel groups in the model (Figure 4.5). Each channel group should be considered as being formed by a number of channels with an average conductance $b_j$ and an areal contribution $A_j$ to the surface area of the pile. If we arbitrarily select a larger number of channel groups (more arrival times in the hydrograph), each channel group will represent a smaller range in conductance parameter and will have a smaller areal contribution, improving the resolution of the conductance and $A_j$ distributions. However, the number or arrival times for the wetting fronts of the different channel groups is limited by the frequency of the volumetric flow discharge measurements.

The input to the program includes: rainfall versus time, the beginning time of the drainage hydrograph, the arrival times and discretized values of the volumetric flow from the hydrograph, the drainage area of the waste rock pile, and the sorbance coefficient. The rainfall data is averaged during the rainfall time span because the method considers square pulses of rainfall only. The rainfall events for our analysis are selected on the basis of rainfall intensity, the absence of other rainfall events immediately preceding or following the event, and the degree to which the rainfall event could be represented as a square pulse.

After the analysis of the measured hydrograph, a synthetic hydrograph can be constructed. The synthetic hydrograph of the different channel groups are superimposed to form the total hydrograph. For each channel group, during the time interval $0 \leq t \leq t_{w,j}$ the volumetric flux density is $q_j(z, t) = 0$. For $t_{w,j} \leq t \leq t_{d,j}$, $q_j(z, t) = q_j$. For $t_{d,j} \leq t \leq t_i$, $q_j(z, t)$ is found using equation 9c. The total hydrograph after time $t_i$ was not calculated because we have not considered the behavior of the individual hydrographs beyond that point. The method was applied to the water discharged to toe drains at Island Copper Mine, British Columbia.

**Volumetric water discharge at Island Copper Mine, B. C.**

Island Copper Mine is located at the northern end of Vancouver Island (Figure 3.1). Open pit operations have produced several dumps around the pit. Toe drainage from these dumps is carried by ditches to a water management pond. Eight monitoring stations on these ditches have been in operation since 1991 (Figure 4.6). Data collected includes ditch flow and water chemistry (Rescan Environmental Services, 1992, 1994). Data frequency is variable. Ditch flows have been obtained as frequently as every 15 minutes with automated equipment. Climatic data has been collected at a meteorological station. This data set is unique because the frequency of the data provides for the possibility of examining the correlation of outflow from the dumps with rainfall events.

Of the eight monitoring stations located at Island Copper Mine, station EMO is the one that appears to receive water only from the adjacent waste rock pile. The other stations are probably receiving or loosing water to the small lakes in the area, or to the open pit (Figure 4.6). For this reason data from station EMO was used in the analysis. We selected the rainfall event of October 19, 1992 because of its relatively simple shape, being close to a square pulse of rain.

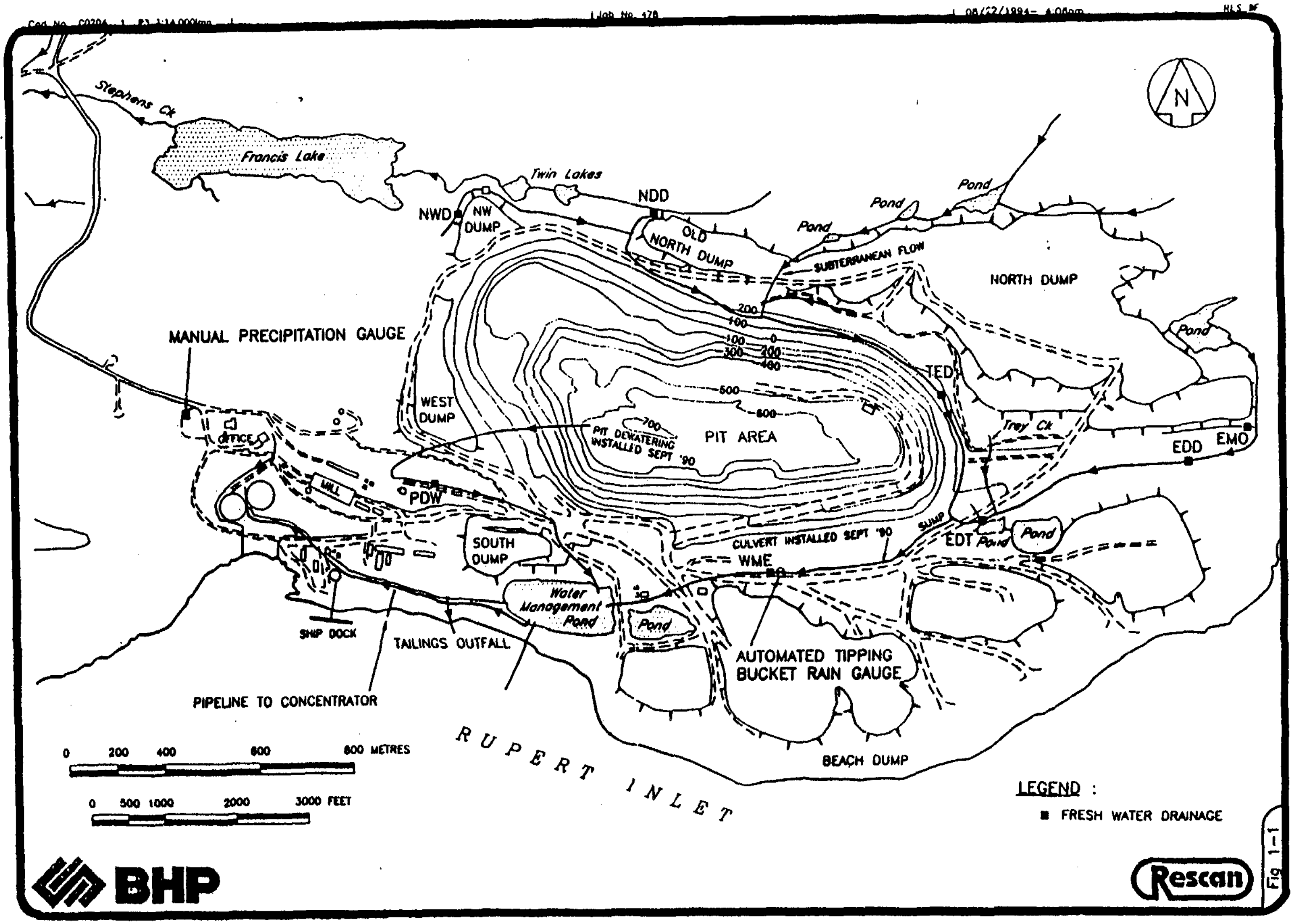



Figure 4.6. Location of waste rock piles and flow measurement stations at Island Copper Mine, British Columbia (Rescan Environmental Services, 1994).

**Discussion of results**

Figure 4.7 shows the rainfall data (dash line) and hydrograph (solid line) for the October 19, 1992 storm event at Island Copper Mine (station EMO). We have modeled this rainfall event and the preliminary results are shown in Figures 4.8 and 4.9. Volumetric flow in the toe drains averaged every hour was used in this study to eliminate high frequency perturbations in the hydrograph which could be related to variations in rainfall intensity. We have selected the time interval between volumetric flow values as the discretization interval for the hydrograph. As a consequence, the pile is conceptualized in terms of 13 types of channel groups. Each channel group represents the average of a number of channels that are present in the pile and cannot be studied individually.

The number of channel groups is defined by the number of intervals in the rising limb of the hydrograph. A decrease in the size of the discretization interval generates a larger number of channel groups, each one representing a smaller range of real channels in the pile in comparison with the larger discretization interval case. The choice of the discretization interval is limited by the frequency of the measurements. However, measurements with higher frequency can have short period perturbations that are not related to the channel structure of the pile. Short period perturbations could be produced by variations in rainfall rate. The application of kinematic wave theory to waste rock piles requires a smooth hydrograph. Hourly averages of the volumetric water flow draining from the toe of the pile seem to produce a smooth hydrograph and a reasonable number of channel groups to characterize the channel structure of the pile.

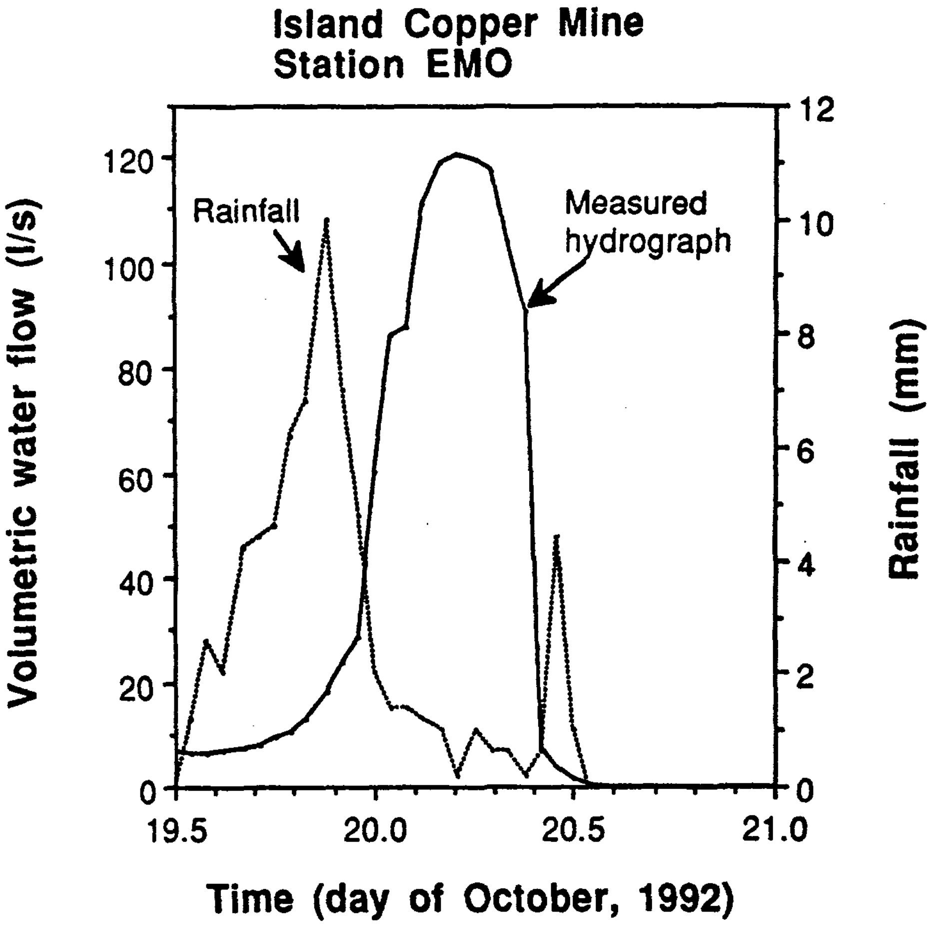



Figure 4.7. Volumetric water flow discharged at station EMO (solid line) and rainfall (dashed line) as function of time for the rainfall event around October 19, 1992.

A sorbance coefficient r of $1.0 \times 10^{-6}$ is needed to match the measured hydrograph. This value indicates that a very small volume of water is lost to the porous matrix. For comparison, Germann and Beven (1986) found that r values between $10^{-3}$ and $10^{-4}$ described flow through macropores in structured soils. Channels and macropores in soils are much smaller than those observed in waste rock piles. Figure 4.8a shows the areal probability weighting factors plotted against the incremental volume flux density for each channel group.

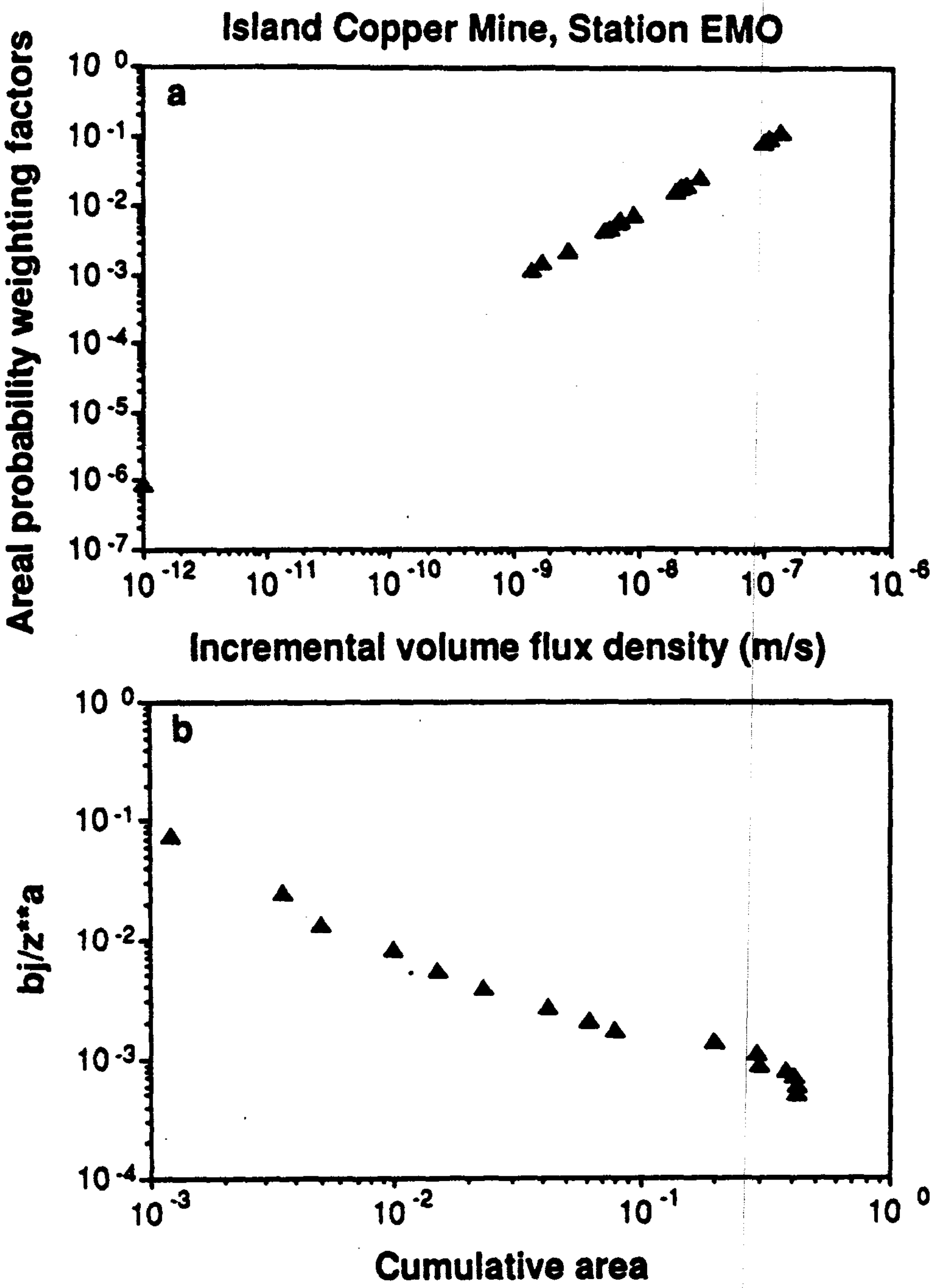



**Figure 4.8.** Parameters for modeled rainfall event around October 19, 1992 at station EMO. a) Areal probability weighting factors (or effective area) versus incremental volume flux density. b) Ratio bj/Z**a versus cumulative area, where bj is the macropore conductance of the j macropore group, Z is the average elevation of the pile, and a is a constant in the equation describing the volumetric flow in the kinematic wave approach (a=2.3).

Channels with greater areal probability weighting factors contribute a greater volume flux density to the outflow hydrograph. There is a linear correlation between these two parameters in logarithmic space. Figure 4.8b shows a negative linear trend between channel conductance and cumulative areal probability weighting factors. The points to the left correspond to the channels with higher conductance whose contribution to the hydrograph arrives first. The conductance of the channels decreases with increasing arrival time and increasing cumulative probability weighting factor. The negative slope in Figure 4.8b shows that the channels with higher conductance occupy a smaller area (and volume) within the pile, and that the channels with lower conductance are more abundant and occupy a larger area within the pile.

Figure 4.9 shows the modeled rainfall event (square pulse), the synthetic hydrograph, and the measured hydrograph. We can see that the match is good for the rising portion of the hydrograph. The falling portion of the hydrograph does not match as well, probably because the equations that we are using to calculate the time at which the drainage front intercepts the wetting front (after the rain has stopped) for each channel group are not appropriate. In this particular simulation, the total areal weighting factor (a function of the total area occupied by the channels) is 43% of the total area of the pile. This number is likely too large. However, if our estimate of the area drained by this station (EMO) is too low, this percent could be lower. Figure 4.10 shows the synthetic hydrographs generated using different values for the parameter $a$ in equation 2. We can see that the best value for the exponent $a$ describing the dependence of the specific discharge on channel moisture content for this particular pile, appears to be 2.3.

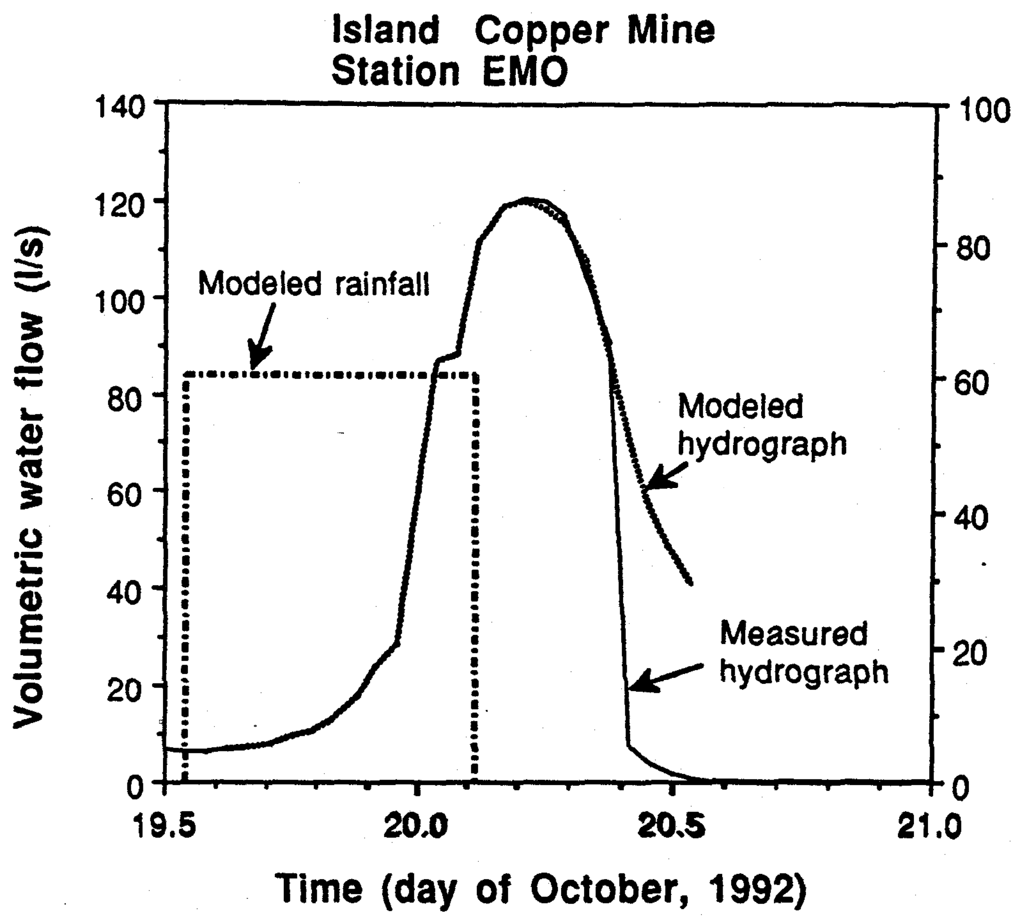



Figure 4.9. Modeled rainfall event around October 19, 1992.

Our analysis suggests that the methodology outlined here holds considerable promise in relating the outflow hydrograph to parameters characterizing the internal hydrologic structure of a waste rock pile. Further work appears warranted to improve the model in its representation of channelized flow in a waste rock pile, and to apply it to rainfall events at a number of different sites to gain insight to the distribution of channels and matrix material in a waste rock pile.

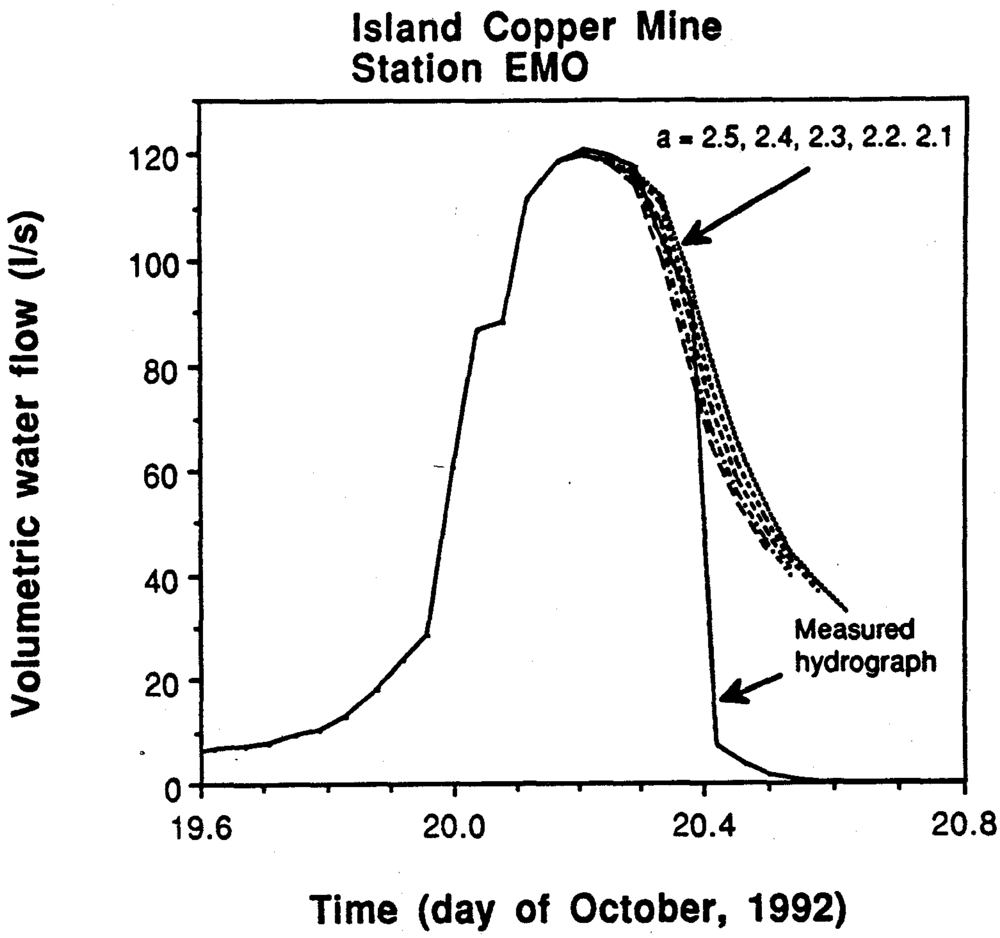



Figure 4.10. Measured hydrograph (continuous line) and synthetic hydrographs (dashed lines) produced using different values of the dimensionless exponent "a".

### *4.3 Geochemical processes*

Although the current study focuses on water movement through waste rock piles, the ultimate goal is to identify the manner in which water flow affects the chemistry of water draining from waste rock piles. At this time, the understanding of geochemical processes in waste rock piles is rudimentary and is often examined on an "empirical" basis. In other words, field monitoring data

data is evaluated through statistical techniques with little regard for actual processes, which are for the most part unknown. By reviewing some of the empirical concepts here, ways of linking chemistry with flow models may become apparent.

Field studies in British Columbia of water chemistry in waste rock toe ditches (Figure 4.11) have revealed that aqueous concentrations behave much like storm events with short-term peaks and return periods (Morin et al., 1993 and 1994). Figure 4.11 shows temporal trends of flow, copper, and zinc at Island Copper Mine. It is important to note that the concentrations are not correlated with flow (Figure 4.12) and thus appear to be independent of flow. This is contrary to a popular belief that increasing flow should either rinse more metals and acidity from mine rock (higher concentrations) or provide dilution (lower concentrations). This discrepancy has now been documented at a few mines in British Columbia (Morin and Hutt, 1993; Morin et al., 1994).

With the recognition that flow does not regulate drainage concentrations, attention has turned to identifying the dominant controlling factors. For several decades, a conceptual link has been made between the rate of sulfide oxidation and the concentration of acidity, sulfate, metals, and pH. As a result, reaction rates were thought to be a dominant control on concentrations in mine-rock drainage.

A *de facto* standard for measuring bulk reaction rates is a laboratory-based humidity cell (Figure 4.13). This cell contains a sample of known weight and is rinsed thoroughly once a week to remove all reaction products. Based on the volume of rinse water and its concentrations, bulk rates can be obtained (e.g. 40 mg Cu / kg of sample / week). Reaction rates for acid generation, acid

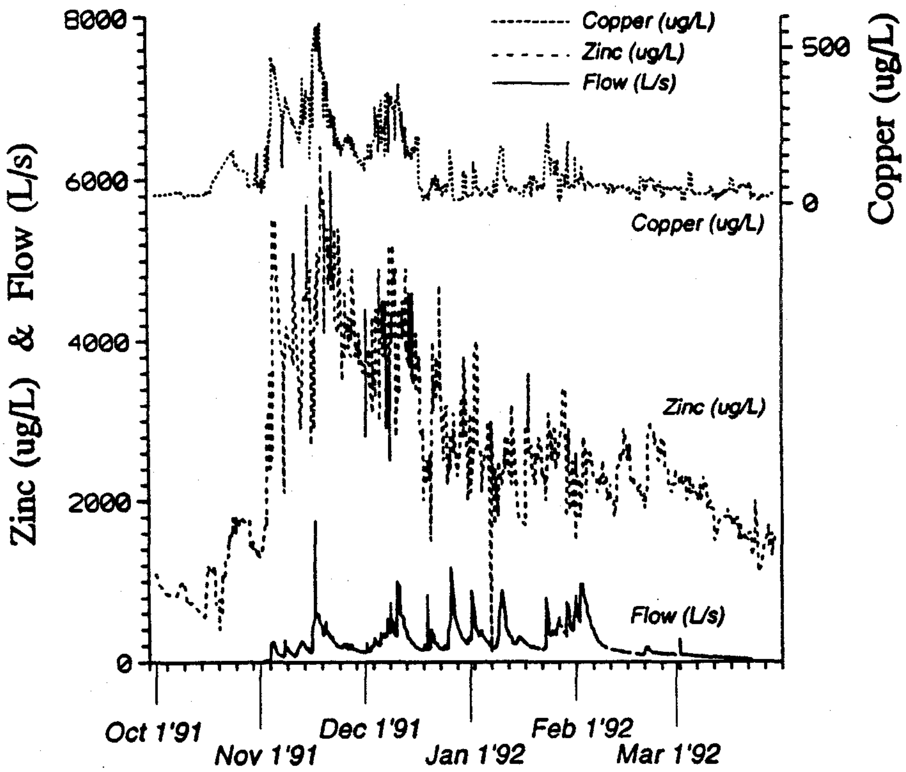



Figure 4.11. Temporal trends of flow, copper, and zinc at WME (Island Copper Mine) from 1 October 1991 to 31 March 1992 (from Morin et al., 1994).

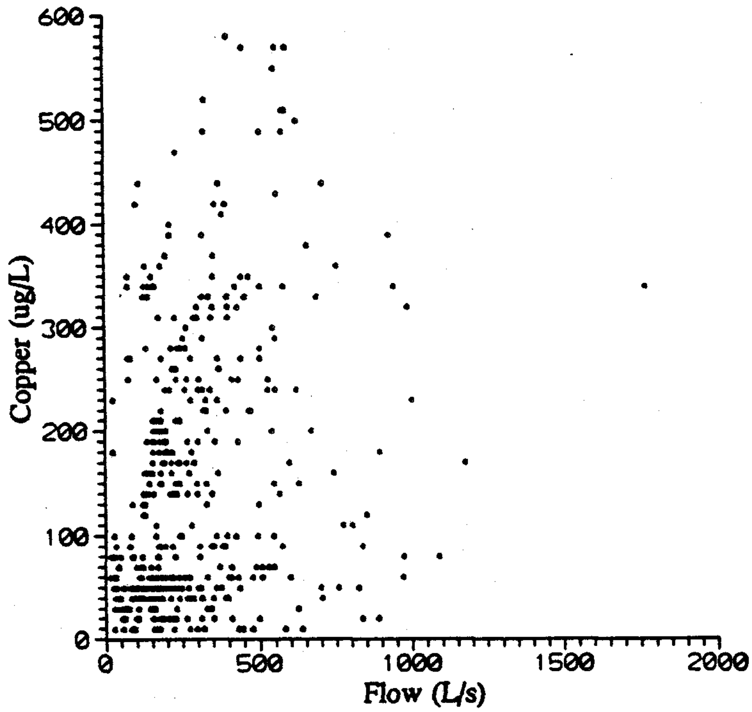



Figure 4.12. Scatterplot of flow and copper at WME at Island Copper Mine for the 1991-1992 data set (from Morin et al., 1994).

neutralization, and metal leaching span more than four orders of magnitude (e.g., Figure 4.14) in the International Kinetic Database (Morin et al., 1995a and b).

When reaction rates determined from a humidity cell are applied to the entire pile, a discrepancy has been noted between the total production rate of metals and the amount of metals leaching out of the pile (Morin and Hutt, 1994; Day and Harpley, 1993). Up to 95% of total annual production is not removed, but accumulates within the rock pile year after year. There are physical and chemical explanations for this accumulation and retention. For example, ElBoushi (1975) showed that the percentage of rock surfaces rinsed by infiltrating water decreases with depth so that less than 20% is rinsed below depths of 1 m (Figure 4.15). This is equivalent to a geochemical retention of 80% and is obviously dependent on the pattern of water movement through a pile. Additionally, some minerals have a low solubility and thus cannot be dissolved and rinsed completely, which is a geochemical effect partly dependent on water movement. Also, some minerals are locked inside larger rocks and boulders, and are thus not available for reaction. This lack of availability is not strongly dependent on water movement or geochemistry, but on the physical and geotechnical characteristics of the rock units and the type of blasting and hauling used to mine the rock. The relative contribution to retention from each of these processes is unknown at this time.

In order to explain in general terms the cumulative retention attributable to the various physical and chemical processes, a primary and a secondary geochemical reservoir within a waste rock pile can be envisioned (Figure 4.16). The primary Reservoir #1 contains sulfide and oxide minerals which react at $RATE_1$, which is the rate obtained from humidity cells (Figure 4.13). $RATE_1$ can

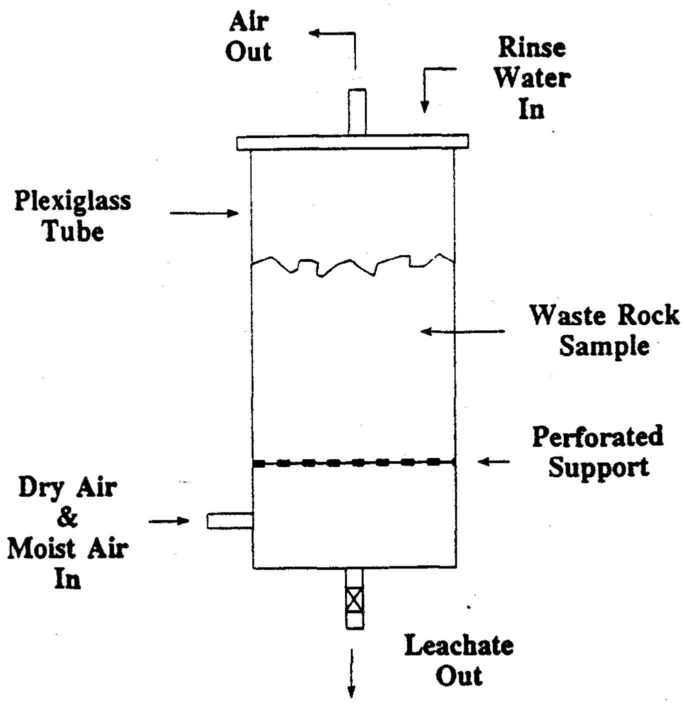



Figure 4.13. Example of a humidity cell.

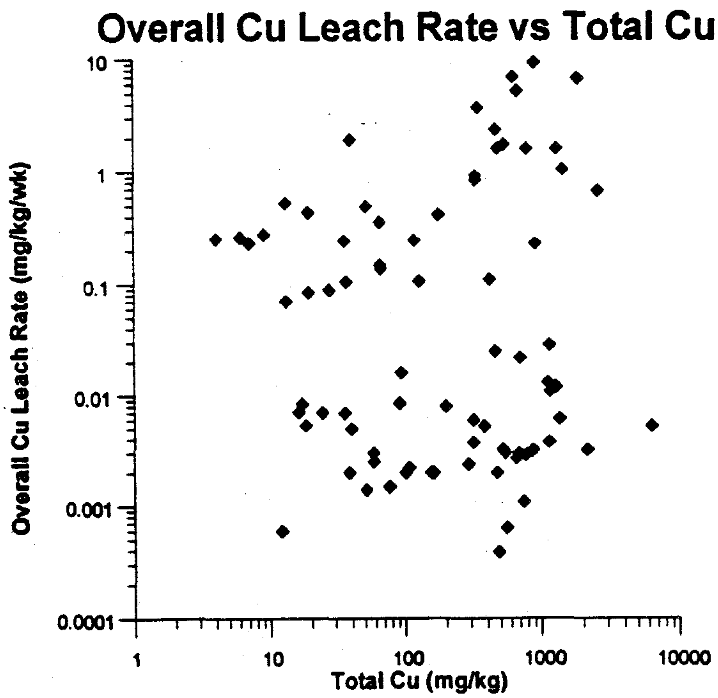



Figure 4.14. Solid-phase copper leach rate versus total copper.

# RELATIONSHIP OF ROCK-SURFACE FLUSHING TO MINE-ROCK DEPTH

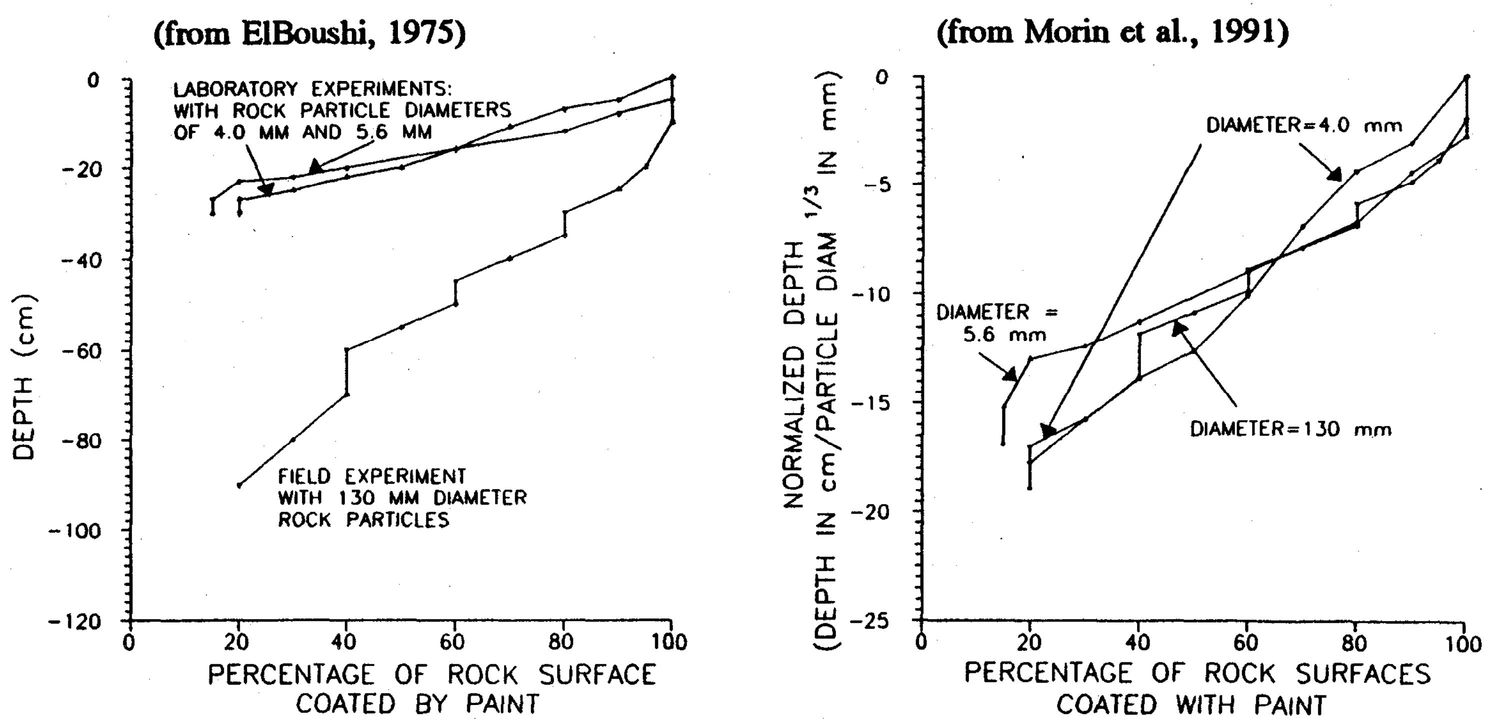
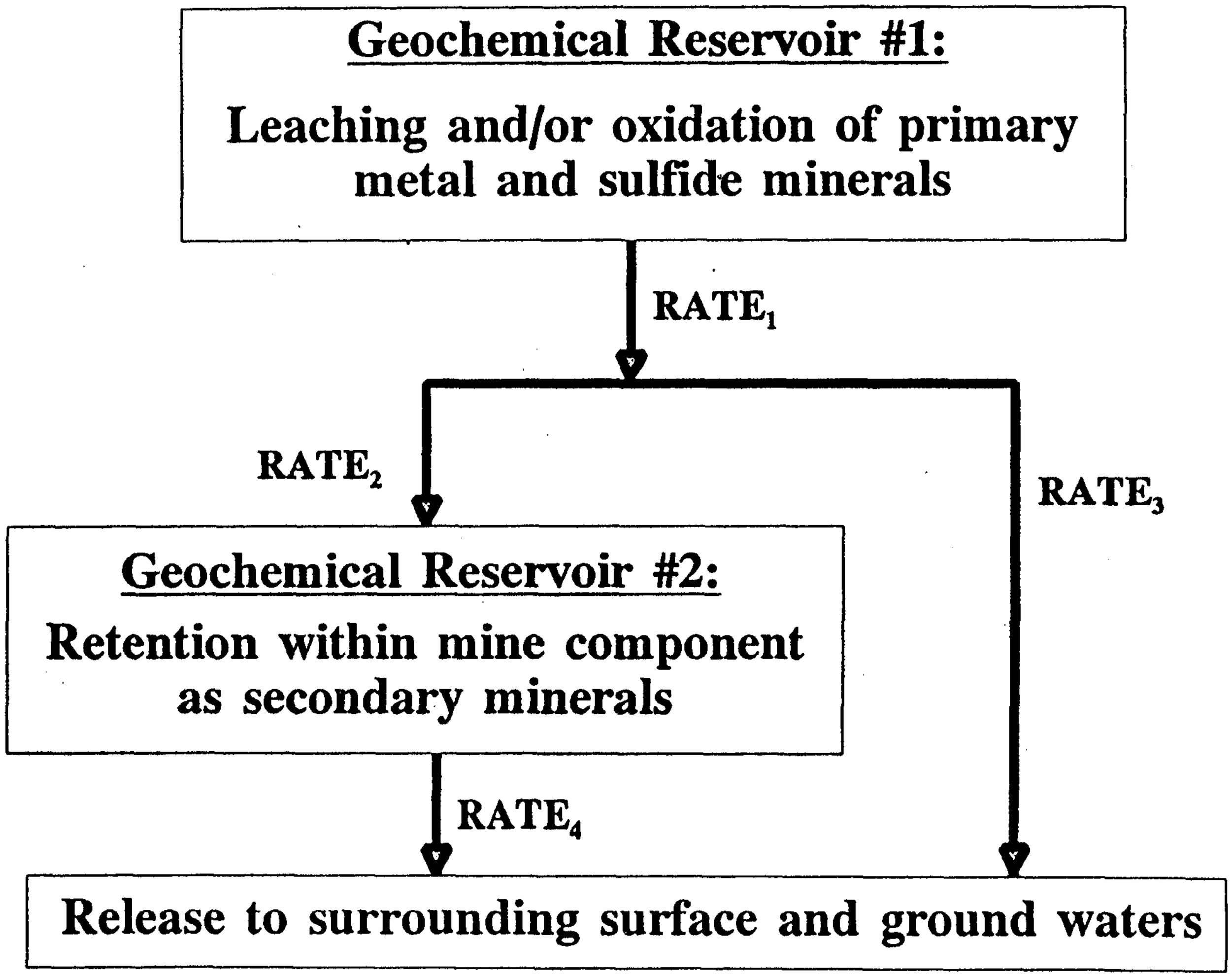



Figure 4.15. Results of experiments on rock-surface flushing.




NOTE: during primary leaching and oxidation, $Rate_1 > 0$; after primary leaching, $Rate_1 = 0$.

Figure 4.16. Geochemical reservoirs and rates affecting drainage chemistry (from Morin et al., 1995c).

be divided into $RATE_2$, which feeds Reservoir #2, and $RATE_3$ which represents metals released into the environment. The aforementioned studies on retention indicate that $RATE_3$ is negligible except in strongly acidic systems. Therefore, Reservoir #2 grows quickly due to retention and continues to grow until Reservoir #1 is exhausted.

Studies of drainage chemistry using geochemical models such as MINTEQ (Allison et al., 1990) indicate that Reservoir #2 is composed of secondary minerals such as sulfates and carbonates. The dissolution and removal rate of these minerals, $RATE_4$, is controlled by equilibrium chemistry, which in theory produces the same concentration in each liter of water that contacts these minerals, independent of the number of liters and the total amount of minerals. In reality, fluctuating conditions such as pH and temperature cause some variation around the average equilibrium value, but the equilibrium value holds as a long-term average. By focusing on the equilibrium dissolution of Reservoir #2, predictions of future chemistry become easier.

The dissolution of Reservoir #2 has typically been modeled by defining best-fit lines on pH vs. concentration diagrams (Figure 4.17) and then calculating a standard deviation from the scatter of data points about this line (Figure 4.18). This leads to a "predictive water chemistry model" of Reservoir #2 (Table 4.1). As indicated in Table 4.1, one parameter (often pH) must be independently predicted, and then all other concentrations can be determined from it. The prediction of future pH is rooted in some standard predictive tests, known as static and kinetic tests, which have been used globally with varying degrees of success since the 1960's. For example, a humidity cell (Figure 4.13) will provide rates of sulfate and acidity production and allow predictions of future rates until

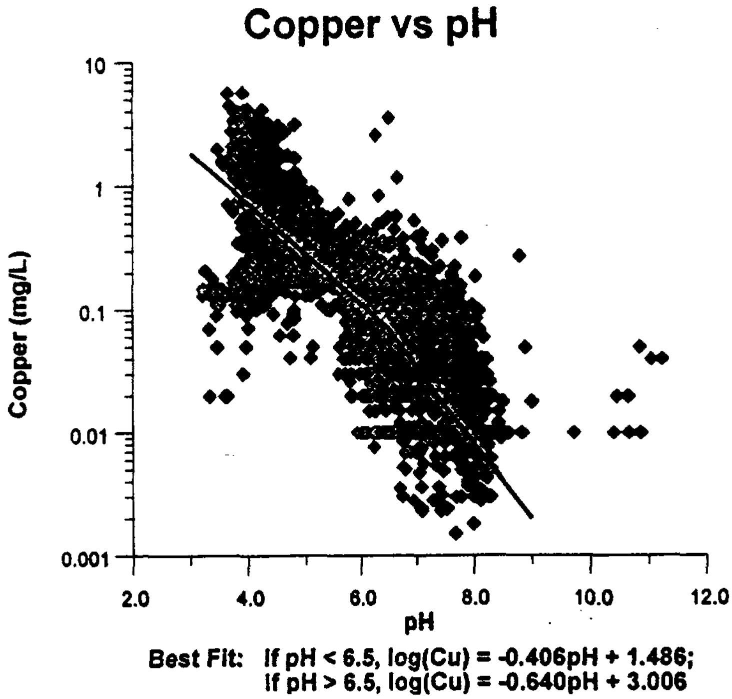



Figure 4.17. $Log_{10}$(copper) versus aqueous pH with best-fit equation (from Morin et al., 1995c).

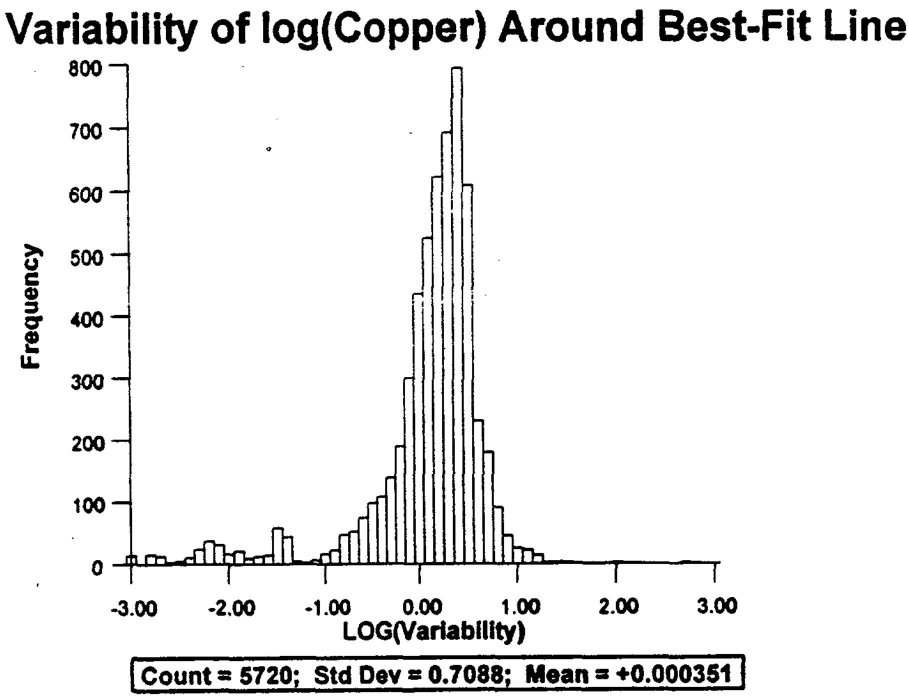



Figure 4.18. Variability of $log_{10}$(copper) around best-fit line of Figure 4.17.

| TABLE 4-1<br>PREDICTIVE WATER-CHEMISTRY MODEL FOR ON-LAND DUMPS AT ISLAND COPPER MINE (from Morin et al., 1995d) | | | |
|---|---|---|---|
| Parameter (log scale) (mg/L) | Valid pH Range | Predictive Equation for Mean | Standard Deviation from Mean |
| Conductivity (mS/cm, N=5010) | pH ≤ 4.5 | = -0.475 pH + 5.237 | 0.1568 |
| | pH > 4.5 | = +3.099 (set value) | |
| Alkalinity ($CaCO_3$, N=2309) | 4.5 < pH ≤ 6.5 | = +0.730 pH - 3.120 | 0.3062 |
| | pH > 6.5 | = +0.370 pH - 0.780 | |
| Acidity (to pH 8.3, N=2032)) | pH < 8.0 | = -0.932 pH + 6.381 | 0.3373 |
| Copper (N=5720) | pH ≤ 6.5 | = -0.406 pH + 1.486 | 0.7088 |
| | pH > 6.5 | = -0.640 pH + 3.006 | |
| Zinc (N=5775) | pH ≤ 5.0 | = -0.559 pH + 3.482 | 0.9851 |
| | 5.0 < pH < 6.5 | = -0.245 pH + 1.912 | |
| | pH ≥ 6.5 | = -0.974 pH + 6.650 | |
| Cadmium (N=5708) | pH ≤ 5.0 | = -0.538 pH + 1.012 | 0.8279 |
| | 5.0 < pH < 6.35 | = -0.110 pH - 1.127 | |
| | pH ≥ 6.35 | = -0.502 pH + 1.362 | |
| Sulphate (N=4105) | pH ≤ 4.75 | = -0.348 pH + 4.587 | 0.2148 |
| | pH > 4.75 | = -0.030 pH + 3.077 | |
| Calcium (N=4507) | pH ≤ 4.5 | = -0.294 pH + 3.665 | 0.3141 |
| | pH > 4.5 | = 2.342 (set value) | |
| Magnesium (N=450) | pH ≤ 4.8 | = -0.284 pH + 2.929 | 0.3790 |
| | pH > 4.8 | = -0.083 pH + 1.963 | |
| Aluminum (N=4186) | pH ≤ 5.65 | = -1.341 pH + 6.908 | 1.3156 |
| | pH > 5.65 | = -0.068 pH - 0.285 | |

minerals are exhausted. These rates combined with static-test results can be scaled to full-size mine components, leading to predicted concentrations of acidity through time (Morin and Hutt, 1994). From these concentrations, the inverse equation relating pH and acidity (e.g., Table 4.1) will provide predicted pH through time. From this pH, all other parameters can be predicted.

A field-based alternative to predicting pH through time lies in the recognition that aqueous pH at a particular mine site tends to cluster around one typical near-neutral pH and a typical acidic pH (Morin et al., 1995d). Based on static and kinetic tests, the year when a sample evolves towards the typical acidic pH, and the year when it returns to the typical near-neutral pH, can be estimated. From this pH time line, concentrations of other parameters can also be predicted (e.g., Table 4.1). These estimates are based on a number of assumptions that may be difficult to verify.

Since Reservoir #2 is apparently regulated by equilibrium chemistry, the aqueous concentrations are not dependent on flow (as shown in Figure 4.12). However, the annual dissolution of the reservoir is determined by flow since each liter of water contributes to the removal. From this perspective, flow is not important for determining concentrations, but for determining how long the concentrations will persist.

Additionally, the lack of full rinsing of rock surfaces, as explained above, contributes to Reservoir #2 (Figure 4.16) to some unknown degree. This also affects the time to depletion of Reservoir #2. However, the full rinsing of all rock surfaces may require ongoing weathering of rock particles and shifting of flowpaths until all surfaces are rinsed. The ability to predict shifting flowpaths is not possible at this time, and this study has not uncovered information that would help to estimate or predict that process.

## 4.4 Conclusions

We consider the kinematic wave approach to hold good promise as a means of characterizing large-scale flow processes through a waste rock pile. At this point, we have used only a simple square pulse of water infiltration to the pile to show that it is possible to apply this theory to a waste rock pile. Using this approach we can obtain information about the textural properties of the pile and the distribution of channels within the pile. The outflow from the pile is an integration of the outflows from the different channel groups within the pile. This approach could be extended to more complicated water infiltration functions using numerical methods as suggested by Germann and Beven (1985). In this way a more reliable distribution of areal weighting probability factors and channel conductance parameters could be obtained. These parameters could be used to predict synthetic hydrographs produced by new rainfall events. Investigation of the behavior of water flow within a channel after the time the draining front intercepts the wetting front is needed in order to improve the prediction of the falling limb of the hydrograph. At Island Copper, no monitoring data have been collected interior to the waste rock piles. Studies of the kind proposed here would be greatly strengthened if data on both the internal hydrogeologic response, and rainfall/outflow hydrographs were available.

An advantage of continuing the investigation of the kinematic wave approach to water flow within waste rock piles is that this theory allows for the simulation of advective transport of chemical species (Levy and Germann, 1988). This approach could be a simplified way to treat water flow and the movement of the oxidation and neutralization reaction products from the reactive portions of the pile to the surrounding environment.

In some ways, the geochemical processes in waste rock piles which affect water chemistry are relatively simple and easily described, such as with equilibrium chemistry. In other ways, the processes can be complex and difficult to decode. For example, the retention of metals and acidity inside waste rock piles are dependent on a number of physical, chemical, geologic, and mining mechanisms. The relative contribution from each mechanism is unknown, but is a current focus of field studies. Most importantly for this study, the movement of water through rock affects to some unknown degree the retention of metals and determines the final time when all soluble metals are rinsed from the system. This final time, decades to centuries in the future for most acid-generating mine rock in British Columbia, is the point when environmental impacts and control requirements cease.

# MONITORING METHODS

While our review of data from four mine sites sheds light on the key hydrologic processes within waste rock piles, it also raises many questions which can only be investigated with additional monitoring and research. In this chapter, we assess monitoring strategies which could provide the data required to better understand the hydrology of waste rock piles. We structure the chapter around the most important hydrogeologic questions to be answered, and suggest monitoring methods to gather the appropriate data.

Before we assess monitoring needs, we note that the most significant limitations of the existing database were that no single site provided a complete and complementary data record of the important parameters required to characterize waste rock hydrology, and that the frequency of sampling was often inadequate for our purposes. For example, water content data was available only for the Golden Sunlight pile, and for that data the temporal sampling frequency is too low to draw inferences about the importance of channel flow on water redistribution. The frequency of rainfall and temperature measurements was too low at Myra Falls to use temperature data to quantify rates of infiltration through the reactive zones of the waste rock pile. To understand the complex interaction between processes, it is essential that both the hydrostratigraphy of the pile be characterized, and a complete set of appropriate measurements be planned.

This call for more complete instrumentation must be balanced by the recognition that characterization of the hydrogeological behavior of a waste rock pile is hampered by the kinds of measurement devices that are available. There is no instrument that can directly identify the geometry of the preferred pathways for the flow through an unsaturated rock pile, nor determine fluid transfer between channels and the porous matrix. We are forced to make inferences on flow behavior from water content measurements, fluid potentials, measurements of parameters such as temperature which may respond to infiltration events, or by using various tracer techniques. These measurements should then be integrated with appropriate models to interpret the significance of the observations. Innovative application of these standard hydrogeological tools and approaches will be necessary to achieve progress in understanding the hydrogeologic properties of waste rock piles.

## 5.1 Key Questions

Our key questions are given in two lists; one related directly to hydrologic processes, the other related to the link between hydrologic processes and the chemical characteristics of the water migrating through a waste rock pile.

A. Hydrologic processes

1. Where is the flow concentrated within a waste rock pile, and what are the dominant flow mechanisms?

Hydrostratigraphic descriptions of waste rock piles point to the potential for flow in open channels, and through a granular porous matrix. The relative importance of these two regions acting as conduits in the different hydrostratigraphic regions of a pile is not understood, nor do we understand how these mechanisms may vary from pile to pile, nor how they may be influenced by pile construction techniques. The features defining a conduit likely vary in different portions of a rock pile, from pile to pile, and with different moisture regimes (seasonal and geographical differences). In general, at greater depths in the pile, the flow is likely to become more diffuse. Infiltration through waste rock piles can be characterized by monitoring water levels, water contents, and temperatures within the pile. Tracer tests may also indicate the location and rate of the flow through the unsaturated zone.

2. How can we characterize the channels and their role in flow processes?

Channel flow is a fast process compared to matrix flow. In a rock pile composed of coarse rock fragments, with a limited fines content, we expect flow to occur predominantly through partially-saturated channels, for which hydraulic head and water content measurements may not be meaningful. Water may cascade vertically through the unsaturated portion of the pile, perhaps displacing water from intermittent zones of saturation. These saturated zones are likely associated with regions in a pile where finer grain sizes are dominant; such as segregated crest areas, compacted surfaces, and layers of fines parallel to the dump face.

Temperature data, like that collected at Myra Falls Mine, may be suited to characterize channel flow when water infiltrates from hotter to cooler regions in the pile. High frequency sampling, perhaps every 15 minutes, and short distances between measurement points (1 - 2 m) may be required to characterize the movement of individual infiltration events through channels to the water table.

Tracer experiments can also be used to characterize channel flow. A conservative tracer will not be influenced by sources and sinks in the way that temperature can be affected by heat gain from active redox zones and heat loss to the rock mass. The principal limitation of tracer tests is the difficulty obtaining water samples from partially saturated channels.

3. How can we characterize the porous matrix and its role in flow processes?

In finer-grained rock piles, channels may be discontinuous or absent. Infiltrating water moves through a granular matrix due to gravity and capillary forces. In rock piles with open channels, capillary forces will also draw infiltrating water into the porous matrix along the walls of the channel. Between infiltration events, water within the unsaturated zone will be in storage in the finer-grained matrix material. If water contents exceed the retention capacity of the matrix, the water will drain downwards through the matrix toward the water table. For the matrix material, it should be possible to establish lab-based estimates of the relationships between grain size and moisture retention characteristics. Neutron probes can be used to record moisture content with depth. Above the water table, water content measurements can provide information on regions of finer grain sizes (higher water contents) and regions of coarser grains (lower water contents), even if we do not know the grain size distribution within the pile.

Water content will depend not only on grain size, but also on hydrostratigraphic controls on moisture redistribution within the pile. While water content measurements can be used to map water content profiles through a waste rock pile, it will be difficult to draw inferences on flow conditions from these data. If the matrix is partially saturated, matric potential measurements are required to determine the gradient in hydraulic head. Given the difficulty and apparent unreliability of matric potential measurements in reactive zones within rock piles, we do not expect data of sufficient quality to make quantitative inferences on flow rates, flow directions, or for calculations of in situ, unsaturated hydraulic conductivity. Matric potential measurements should be useful in regions of a pile with finer grained matrix, that are non reactive.

The saturated zone at the base of the pile may be the largest reservoir of water in the pile. Water-table elevations can be monitored by piezometers to determine the change in storage in the system and to characterize lateral flow conditions. It will be important to determine the relative contributions of local infiltration through the pile, and that component which may enter the base of the pile from subsurface or surface sources outside the pile. If open channels form a connected network in the saturated zone of the waste rock pile, they may act much like a fracture network, providing the dominant control on fluid flow patterns.

<u>4. What is the relationship between the total discharge from the toe of the pile and the internal flow processes within the pile?</u>

To obtain a water balance for a waste rock dump, it is important to characterize the total infiltration, evaporation and discharge from the pile. The analysis is straight forward if no groundwater enters the pile, and if the discharge is entirely captured at the base of the pile. The discharge can be measured in a toe drain with a calibrated weir. This discharge can be related to infiltrating rainfall, and water movement through the pile. The horizontal gradients measured in the saturated zone, along with total discharge data, can be used to calculate a pile "base-flow" and thus characterize the bulk hydraulic conductivity of the saturated zone. To better understand spatial relationships between metal concentrations monitored in toe drains, and concentrations interior to the pile, water samples should be collected from the boreholes monitoring the water table elevation.

For piles which receive groundwater flow through their sides or base, long-term monitoring of the discharge from the pile should allow one to identify in the hydrograph the regional water flow and the high frequency signals produced by rainfall events (e.g., Island Copper Mine data). The signals produced by the rainfall events can be analyzed with the kinematic wave theory to provide information about the internal hydraulic conductivity structure of the pile.

5. How does hydrostratigraphy change with time as the dump subsides and fines migrate through the pile?

These questions can be addressed by measuring grain size distributions during pile construction, disassembly, or in situ. Longer-term studies of changes in the outflow hydrograph measured in toe drains, interpreted in the context of the kinematic wave model discussed in Chapter 4, may also indicate changes in patterns of flow within a consolidating waste rock pile. Fines migration could be studied with simple column tests similar to tests carried out for graded filter design testing.

**B. The link between hydrology and water geochemistry**

1. What is the nature of the connection between the dominant flow paths and the other portions of the waste rock pile, especially with reference to those zones which may be geochemically distinct?

This question is central to issues related to the prediction of whether or not a pile may discharge high metal concentrations, and the time scale for metal release. A better understanding of these issues is probably best addressed by hydrostratigraphic and geochemical mapping, carried out in conjunction with pile assembly/monitoring/disassembly studies described in Chapter 6.

## 5.2 SUMMARY: PARAMETERS TO MONITOR

In light of the questions raised above, and the review of data provided in Chapters 3 and 4, the following parameters should be monitored in an existing pile:

1. Water content

Neutron probes or lysimeters can be used. Neutron probes are likely easier to operate and can be used to generate water content profiles along boreholes (see Golden Sunlight data in Chapter 3). Weekly measurements are recommended in order to track seasonal effects and correlations between grain size and water retention. Calibration of the neutron probe and the possibility of preferential flow along borehole walls are concerns. Installation and monitoring of lysimeters would be difficult and likely requires special designs.

2. Temperature within the pile

At least one thermistor nest, instrumented at regular intervals along the vertical direction, should be installed at the center of the pile. Vertical chains of thermistors should be installed in regions of the pile that are releasing heat due to redox reactions. Temperature can be used as a tracer of water flow near the hot regions of the pile. The need for additional monitoring sites should be evaluated on a case-by-case basis. The temperature of discharge water should also be monitored.

3. Volumetric discharge

Collection drains at the toe of a waste rock pile should be directed over calibrated weirs and the discharges recorded.

4. Water table elevations

At least 3 piezometers should be placed within the pile to characterize flow directions and water stored in the saturated zone below the water table. One piezometer should be placed on the top of the pile and the other two at different levels of the pile slope. The number of piezometers is best tied to individual site conditions. If it is suspected that the pile is gaining or loosing water to the local groundwater system, then additional piezometers should be completed below the base of the pile to allow fluxes to be estimated. If perched water tables are encountered (e.g. Elkview Mine), then piezometers should be completed in both the perched zones and in the main water table below.

5. Meteorological data

Rainfall and temperature data should be recorded to determine the quantity and temperature of water entering the pile. Net infiltration to the pile is likely best characterized by intensive monitoring of changes in water content, or via interception of infiltrating water in lysimeters, at a small number of targeted areas on the surface of the pile.

The monitoring which we describe above should be sufficient to characterize the water flow and hydraulic properties of a pile. However, if the objective is a complete assessment of the acid rock drainage processes, additional parameters should be monitored. Some of these parameters are: water chemistry within the pile and in the total discharge, gas concentrations ($O_2$ and $CO_2$), and alteration mineralogy of the pile. In this work, our attention is focused upon water movement within the pile. Monitoring of acid rock drainage parameters not directly related to water movement is discussed by Morin et al., 1991.

## 5.3 FREQUENCY AND DURATION OF MONITORING

Sampling frequency depends on the time scale of the process that is being tracked within the pile. If the purpose is to track the effect of water infiltrating during a rainfall event on the temperature field and water table fluctuations, the frequency of temperature and the water table elevation measurements should be at least every hour. Our analysis of the four data sets studied in this project indicates that water infiltrating a coarse pile takes only a few hours to travel through the pile.

If the purpose of the measurements is to observe the long term behavior, daily measurements are sufficient.  Examples of long term processes include: seasonal effects on temperature and water table elevations, increase of temperature due to the oxidation reactions, and the advance of the thermal front produced by the redox reactions within the pile.

The large scale hydrogeologic behavior of the pile can also be studied on two time scales.  On one hand, the characterization of the large scale hydrogeologic behavior of waste rock piles and its relationship to the channelized flow within the pile requires high frequency in the data.  Measurements of the outflow of the pile at least every hour are recommended.  On the other hand, for the purpose of defining the water budgets and to observe seasonal effects, daily measurements are sufficient.

## CHAPTER 6

# WORKPLAN

In this chapter we outline a workplan to investigate the relationship between the internal hydraulic conductivity structure of a pile and water movement within the pile. Our purpose in this workplan is to present a general method to investigate the hydrogeology of a waste rock pile rather than selecting a particular pile for future studies. The workplan does not cover the complete study of the acid generation processes in a waste rock pile but only the processes directly related to water movement. Methodologies to study the chemical properties of the solid and fluid phase in a waste rock pile, and other physical processes such as the advective transport of oxygen in the gas phase, are described elsewhere (e.g. Morin et al., 1991; Steffen Robertson and Kirsten et al., 1989).

To study the relationship between the internal hydraulic conductivity structure of a pile and water movement, we must characterize the textural and mineralogical properties of the waste rock materials, and their distribution within the pile at the time of emplacement and after the pile has been constructed and in place for several years. The workplan is centered on three types of monitoring studies; a pile assembly study, a pile monitoring study, and a pile disassembly study. In this chapter, we present an overview of each study's objectives and methodologies. It may be advantageous to link these workplans to operations at a low-grade stockpile at a suitable mine site in British Columbia. Ideally, an opportunity would arise to instrument a stockpile, to monitor it for some period of time, and then to disassemble the pile. As indicated in Chapter 5, our proposal would be to focus on water content and redistribution, temperature profiles, water table fluctuations, outflows at toe drains, and material property characterization.

## 6.1 PILE ASSEMBLY STUDY

The objectives of this study are to account for the quantities and spatial distribution of materials entering in the pile and to characterize the hydraulic properties and spatial distributions of materials within the pile as it is constructed. Early in the planning stages it would need to be decided to what extent the pile construction would attempt to replicate one or more of the hydrostratigraphic models presented in Chapter 2. It is our view that a framework equivalent or similar to that proposed in Chapter 2 is essential to the experimental design.

The waste rock pile location will likely be restricted to a convenient area near a mine site. Ideally, the pile would be hydrologically isolated from the local groundwater system. The pile should be placed on a drainage collection system which directs water flow through calibrated weirs that can measure discharge. Monitor wells should be installed around the expected perimeter of the pile months before construction.

Groundwater levels and chemistry should then be characterized.

The mineralogical composition of the waste rock should be determined from representative samples taken as the pile is constructed. Samples should be rated using the Munsell Colour ratings, and analyzed geochemically using acid-base accounting methods. A pile with a relatively simple mineralogy or one rock type, such as a low-grade stockpile, is recommended for this study. At least part of the rock pile should be constructed with coarse rock fragments, with a limited fines content.

The texture of the waste rock pile should be documented and photographed as it is constructed. In this way, the stratigraphy will be known and will not require extensive drilling for confirmation. This procedure will also allow comparisons during the disassembly study. Textural variations caused by dump construction methods and compaction should be noted. For example, in Chapter 2 we suggest that end-dump construction may give rise to fining-up sequences within each lift. Water contents, and grain-size distributions should be measured on selected samples to allow comparison with measurements taken in situ and during disassembly.

The top of each lift in the dump should be surveyed before burial. This will provide information on dump settlement and changes in textural properties caused by construction activity. The same locations should be surveyed upon dump disassembly. This information may permit an interpretation of how the hydraulic properties of the pile evolve over time, should such a response be observed.

### *Smaller-scale experiments*

Prior to the assembly of a pile, it would be valuable to test some of the ideas on the relationships between hydrostratigraphy and fluid flow in smaller-scale experiments. For example, test "cells" could be constructed to examine channelized flow, or to study the effects of water retention in a finer-grained zone of waste rock sitting atop a zone of coarser rock fragments. We view these test cells to be on the order of 1-3 $m^3$.

As an example, wood forms could be used to construct a simple channel geometry using coarse rock fragments, that was embedded in a sandy gravel matrix. Instrumentation could be placed in the cell as it was being built. Several versions of the experiment could be run, to explore the effects of fragment size, matrix properties, and channel geometry and connectivity on flow paths and flow rates. Scaling relations would have to be given due consideration. The use of different types of tracers, dyes, or paints could also be evaluated as means of identifying pathways through the rock mass in the test cell.

## 6.2 PILE MONITORING STUDY

In Chapter 5, we recommended that the following parameters be monitored within the pile:

1. Moisture content.

2. Temperature.

3. Water-table elevations.

4. Discharge out of pile.

A meteorological station should be installed to record precipitation and air temperature. In addition to monitoring natural conditions, infiltration and tracer tests should be implemented.

It would be advantageous to install and bury some monitoring instrumentation as the dump is constructed. This will save on later drilling costs and likely allow more accurate placement of monitoring equipment. However, only those instruments which are likely to survive the abuse of heavy equipment and initial dump settlement should be buried as the waste rock pile is constructed. Thermistors, protected by steel pipe and large steel/concrete lysimeters (basically buckets or funnels) are the most likely equipment to survive emplacement and burial. The only relevant reported effort in the literature located by Morin et al. (1991) was an instance of lateral thermistors which functioned for several years after burial in Equity Silver's dump. Data loggers may be necessary during periods of high-frequency monitoring. Monitoring frequency and duration are discussed in Chapter 5.

## 6.3 DISASSEMBLY STUDY

The objectives of this study are to examine the internal structure of the pile in terms of the distribution of rock types, grain sizes, indications of channeling, zones of oxidation, zones of precipitation of secondary minerals, and the effect of these parameters on the hydrogeological behavior of the pile. In terms of hydrostratigraphic characterization, the disassembly of a pile would be a far superior strategy to one based solely on characterization of material delivered to a dump, or one where the hydrostratigraphy was inferred from surface sampling and correlations between grain size and water content.

### *Before disassembly*

If possible, points of preferential discharge should be identified on the exterior of the pile before disassembly. Flow paths within the pile can be marked before disassembly by releasing an appropriate dye, paint or tracer over a small area on the surface. Lateral spreading and mixing can be characterized by releasing more than one dye from near-by locations on the surface of the pile. A few releases should be repeated at the same locations at later times, perhaps a few months apart, to determine if flow paths change significantly with time. Small-scale field trials should be performed to select appropriate dyes and release quantities.

### *Disassembly*

The material quantities and textures within the pile should be mapped and photographed as the pile is stripped away. Water contents and grain-size distributions should be characterized at those locations sampled during the pile assembly study. Correlations between grain size and water content, and the extent to which the hydrostratigraphy of the pile influences this relationship, should be examined. These kinds of observations could lead to an improved predictive capability for hydrostratigraphic characterization. If feasible, in situ pore water should be extracted or centrifuged and chemically analyzed on site (pH, alkalinity or acidity, temperature), and by a lab. An attempt should be made to minimize the disturbance of pore-water chemistry by rainfall. Munsell colour ratings and geochemical analysis, including acid-base accounting, should be performed on all samples. Indications of flow paths such as oxidation patterns, secondary mineral precipitation and dye staining should be noted.

After disassembly, monitor wells should be installed within the former perimeter to detect changes in groundwater levels and chemistry. These wells would be monitored in conjunction with those installed outside the perimeter of the rock pile during the assembly study.

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